Canadian Rail Research Laboratory

Report on

Literature Review on Cognitive Impacts of In Cab Warning Systems

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Executive Summary

The Canadian Railway Research Laboratory (CaRRL) was contracted by Transport Canada (TC) to review warning systems in locomotive cabs. The objectives of the study were to provide a better understanding of in cab warning system technology, characterize potential cognitive impacts, and allow for the creation of strategies to mitigate negative potential cognitive impacts. To achieve these objectives, the scope of work included the following principal components:

1. Overviews of concurrent, multiple, or sequential warnings that arise in normal operating conditions, such as highly complex situations with multiple or sequential warnings, as well as how current locomotive crews respond to these warnings;
2. Categorization and nomenclature of crew notifications, such as warnings, notifications, and reminders versus alarms, including recommended interaction types such as visual, audible, or haptic;
3. Types of warnings that exist and are required in a rail operating environment, based on the type of risk assessments, such as excess speed, missed signals, the presence of work zones, and other factors;
4. Human factors and usability implications (pros and cons) of the deployment of warning systems that act as a crew mechanism and that do not automatically enforce penalties (the train does not automatically stop if the crew ignores the warning);
5. A summary of follow up actions for the crew after receiving a warning, such as reminders, acknowledgments, instructions on how to turn off warnings, and the potential cognitive impacts of these follow up actions;
6. An overview of if data is captured when warnings are issued and, how that data are used for follow up or operational analysis; and
7. An analysis of the relevant accident investigation reports identifying where warnings or the absence of warnings have failed to provide an effective barrier to unsafe conditions.

This report completed the scope of work through a review of: (**§2**) in cab warning systems; (**§3**) alarm handling and train operator behaviour modelling; (**§4**) alarm management; (**§5**) human factor issues for in cab warking systems; and, (**§6**) alarm related accidents within the railway and other industries. The primary findings of the report are as follows.

From **§2**, the prevention of signal passed at danger, overspeed, collisions, and train operators' vigilance are the primary focus of in cab warning systems. These systems commonly use visual and auditory alarms sequentially or concurrently to warn the train operators of a hazardous situation. Systems can be categorized into three generations: first generation, consists of a warning only system without the requirement for train operator acknowledgment or automatic brake intervention; second generation, consists of a warning system which requires the train operator to acknowledge warnings and an automated application of brakes to stop the train upon failure to acknowledge; and third generation, which enhances second generation capabilities with monitoring of train speed and an application of brakes in the event of over speed. Within the reviewed literature concerns were raised that upgrading of systems through generations has

resulted in the confusing array of controls and displays, and recommend a consolidated control system and interface when possible.

From **§3** and **§4**, the ability of a train operator to handle (i.e., alarm notification, acceptance, analysis, and clearance) and cope (i.e., filtering, queuing, categorizing, similarity matching, and extrapolation) with alarms differs between persons (e.g., affected by their experience, route knowledge, and mental state) and situations (e.g., expected versus unexpected situations). Thus, both the train operator, and the context in which warning and alarms are issues need to be addressed through alarm management to ensure the intended response by the train operator.

From **§5**, most negative cognitive impacts of in cab warning and train protection systems on train operators are a result of workload; with an under-load of the train operator resulting in boredom, fatigue, over confidence and complacency; and, an over load resulting in irrational reactions, confusion, exhaustion and low self-esteem. And, due to the potential for negative cognitive impacts, automated braking should be a result of the emergence of an unsafe situation not reliant on a failure of the train operator to acknowledge.

From **§6**, automation related accidents in the railway industry, including the Ladbroke Grove accident in the UK, the Yong-Wen rail accident in China, and the Haft-Khan collision in Iran demonstrate that automated system failure, complacency of the train operator, inconsistency of alarm performance with user expectations, and poor alarm design and management were common reasons for most of these accidents.

Acronyms

AAR	Association of American Railroads
ACARP	Australian Coal Association Research Programme
ACSES	Advanced Civil Speed Enforcement System
ADU	Aspect Display Unit
AI	Artificial Intelligence
AIAs	Alarm initiated Activities
AIS	Automatic Identification System
ALIAS	Aurora's Aircrew Labor In-cockpit Automation System
ANP	Analytic Network Process
ANSI	American National Standards Institute
API	American Petroleum Institute
ASCI	Advanced Safety Concepts Inc
ASES	Advanced Speed Enforcement System
ASFA	Anuncio de Señales y Frenado Automático
ASRS	Alarm System Requirement Specification
ASRS	Aviation Safety Reporting System
ATB	Automatische Trein Beïnvloeding
ATC	Automatic Train Control
ATO	Automatic Train Operation
ATP	Automatic Train Protection
ATS	Automatic Train Stop
AWS	Automatic Warning System
BN	Burlington Northern Railroad
BN	Bayesian network
BNSF	Burlington Northern
CaRRL	Canadian Railway Research Laboratory
CAS	Collision Avoidance System
CAWS	Continuous Automatic Warning System
CBTC	Communications-Based Train Control
CBTM	Communications-Based Train Management
CCS	Continuous Cab Signals
CDU	cab Display Unit
C-HIP	Communications-Human Information Processing
CP	Canadian National
CPA	Critical Path Analysis
CPC	Common Performance Condition
CPRS	Complacency-Potential Rating Scale
CRH	China Railway Highspeed
CRT	Choice Reaction Time
CSG	Circular Speed Gauge
CTA	Cognitive Task Analysis

CTC	Centralized Traffic Control
CWA	Cognitive Work Analysis
DALI	Driving Activity Load Index
DB AG	Deutsche Bahn AG (German Railways)
DEMATEL	Decision Making Trail and Evaluation Laboratory
DLR	German Aerospace Centre
DLR	Docklands Light Railway
DMD	Drowsiness Monitoring Device
DMI	Driver Machine Interface
DMQ	Decision Making Questionnaire
DRA	Driver's Reminder Appliance
DSD	Driver Safety Devices
DVS	Driver Vigilance Systems
DVTCS	Driver Vigilance Telematic Control System
ECS	Empty coaching stock
EDA	Driver's Electrodermal Activity
EDVTCS	Engine Driver Vigilance Telemetric Control System
EEMUA	Engineering Equipment and Materials Users Association
EEW	Earthquake Early Warning
EJTCS	East Japan Train Control system
EOA	End of Authority
EPC	Error Producing Condition
ERA	European Union Agency for Railways
ERTMS	European Rail Traffic Management System
ESR	Emergency Speed Restriction
ETC	Enhanced Train Control
ETCS	European Train Control System
ETMS	Electronic Train Management System
ExPL	External Perception for Locomotives
FIFO	first in, first out
FRA	Federal Railroad Administration
FRAM	Functional Resonance Analysis Method
GB	Great Britain
GNSS	Global Navigation Satellite System
GSM-R	Global System for Mobile Communications-Railway
HDM	Hypovigilance Diagnosis Module
HEPs	Human Error Probabilities
HF/E	Human Factors/Ergonomics
HFACS-RA	Human Factors Analysis and Classification System-Railway Accidents
HFACS-RR	Human Factors Analysis and Classification System-Railroad version
HFES	Human Factors and Ergonomics Society
HMI	Human-Machine Interface

HRA	Human Reliability Analysis
HST	High Speed Train
HTA	Hierarchical Task Analysis
HUD	Head up Display
ICSRD	In cab Signal Reminder Device
IDOT	Illinois Department of Transportation
IEA	International Ergonomics Association
IEC	International Electrotechnical Commission
I-ETMS	Interoperable Electronic Train Management System
IOT	Internet of Things
ISA	International Society of Automation
ISA	Instantaneous Self Assessment
IST	Information Society Technologies
ITCS	Incremental Train Control System
ITCS	Incremental Train Control System
IWS	Integrated Workload Scale
JR	Japan Rail
KPIs	key Performance Indicators
KVB	Contrôle de Vitesse par Balises
LDS	Location Determination System
LOPA	Layer of Protection Analysis
LS	Limited Supervision
LUL	London Underground Library
MADB	Master Alarm Database
MCDM	Multi-Criteria Decision Making
MEFA	Monitoring Engineer Fatigue
MINDStm	MicroNod Detection System
MOC	Management of Change
NAMUR	Normenarbeitsgemeinschaft für Mess- und Regeltechnik in der chemischen Industrie (Association for Standardization of Measurement and Control Engineering in the Chemical Industry)
NASA-TLX	NASA-Task Load Index
NGLC	Next Generation Locomotive Cab
NGLC	Next Generation Locomotive Cab
NORAC	Northeast Operating Rules Advisory Committee
NTSB	National Transportation Safety Board
OS	On Sight
OSS	Overspeed Sensor
OTMR	On-Train Monitoring Recorder
P&IDs	Piping and Instrumentation Diagrams
PA	Public Address
PAF	Performance Affecting Factor

PARRC	Priority, Adapt, Resource, Regulate, and Conflict
PHA	Process Hazard Analysis
PIF	Performance Influencing Factor
PSFs	Performance Shaping Factors
PSR	Permanent Speed Restriction
PTC	Positive Train Control
RAC	Railway Association of Canada
RCMs	Railway Communication Means
RETB	Radio Electric Token Block Signalling
RIAC	Railway Industry Advisory Committee
RP	Pipeline Recommended Practices
R-PSFs	Railway-Performance Shaping Factors
RSSB	Rail Safety and Standards Board
RV	Reversing
RWWS	Roadway Worker Warning System
SA	Situation Awareness
SAGAT	Situation Awareness Global Assessment Technique
SCADA	Supervisory control and data acquisition
SH	Shunting
SMEs	Subject Matter Experts
SMS	Safety Management System
SN	National System
SNCF	Société Nationale des Chemins de Fer Français (French National Railways)
SOR	Stimulus, Organism, and Response
SOW	Scope of Work
SPAD	Signal Passed at Danger
SR	Staff Responsible
SRT	Simple Reaction Time
STAMP	Systems Theoretic Accident Model and Processes
SWAT	Subjective Workload Assessment Scale
TASS	Tilt Authorization and Speed Supervision
TBL	Transmission Balise Locomotive
TC	Transport Canada
TCAS	Traffic Alert and Collision Avoidance System
TCC	Train Control Centre
TCEWS	Train Collision Early Warning System
TO	Trip Optimizer
TPWS	Train Protection Warning System
TS	Train Stop
TSR	Temporary Speed Restriction
TTB	Time to Brake
UK	United Kingdom

UN	Unfitted
USA	United States of America
VDADA	Vehicle Driver’s Anti-Dozing Aid
VDD	Vigilance Driver Device
VDU	Visual Display Unit
WAT	Workload Assessment Tool
WCML	West Coast Main Line

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1 Introduction

The first use of warnings in the railway dates back to when a horseman in front of the train waved a flag to warn people that the train was close by. Later, cab warning systems were introduced first to alert the train operator that the train was approaching a stop signal and then later to warn of other types of safety issues. While these systems can improve safety and efficiency, they may introduce potential weaknesses related to design and usability and have adverse effects on the train operator. These weaknesses include distraction, high workload, over reliance on the system, poor redistribution of attention, automatic responding, human machine communication challenges, and poor display design.

The Canadian Railway Research Laboratory (CaRRL) was contracted by Transport Canada (TC) to review warning systems in locomotive cabs. The objectives of the study were to provide a better understanding of in cab warning system technology, characterize potential cognitive impacts, and allow for the creation of strategies to mitigate negative potential cognitive impacts. To achieve these objectives, the scope of work (SOW) included the following principal components:

1. Overviews of concurrent, multiple, or sequential warnings that arise in normal operating conditions, such as highly complex situations with multiple or sequential warnings, as well as how current locomotive crews respond to these warnings;
2. Categorization and nomenclature of crew notifications, such as warnings, notifications, and reminders versus alarms, including recommended interaction types such as visual, audible, or haptic;
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4. Human factors and usability implications (pros and cons) of the deployment of warning systems that act as a crew mechanism and that do not automatically enforce penalties (the train does not automatically stop if the crew ignores the warning);
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6. An overview of if data is captured when warnings are issued and, how that data are used for follow up or operational analysis; and
7. An analysis of the relevant accident investigation reports identifying where warnings or the absence of warnings have failed to provide an effective barrier to unsafe conditions.

This report addresses the abovementioned topics and presents them through: a review. First, the range of cab warning systems adopted in railways all around the world is reviewed to provide in-depth knowledge about different types of in cab warning systems, the types of risks they control, the types and sequences of warnings they provide, and the acknowledgment they require. The reviewed systems include, but are not limited to, cab signalling systems, automatic train control systems, anti collision technologies, train operators' vigilance systems, train operators' reminder devices, and earthquake early warning systems. As such, **§2** addresses components (2) and (3) and the first parts of components (1) and (5) of the SOW. **§3** describes how train operators respond to warnings and how they use the provided data to perform follow up action and alarm handling (i.e., component (5) and the second part of component (1) of the SOW). **§4** summarizes alarm management and design guidelines (i.e., component (6) of the SOW). **§5** discusses the human factors and usability implications of the deployment of warning systems as well as the potential cognitive impacts of follow up actions (i.e., component (4) and the second part of component (5) of the SOW). **§6** reviews the last component (7) of SOW, i.e., alarm related accidents. Finally, **§7** summarizes the conclusions of this review.

2 In cab warning systems

2.1 Warnings, alerts, and alarms

Warnings are the last resort of risk control, and a way of communicating with the train operator to inform them about hazards so that negative consequences are avoided or mitigated (Wogalter, 2006). The European Union Agency for Railways (ERA)(2019) defines warnings as "an audible and/or visual indication to alert the driver to a condition which requires a positive action by the driver". A good warning system should differentiate between the urgency of warnings so that train operator s can appropriately prioritize their attention allocation (Stanton, 1994).

There is no consensus about the definition and level of urgency conveyed by the words of warnings, alarms, and alerts.

Crampin (2017) defined alerts as a general term that can be classified into alarms, warnings, events, and messages, defined as follows:

- Alarm – needs operator response within seconds;
- Warning – needs operator response within minutes;
- Events – normal system operations that require monitoring but not necessarily an operator response;
- Messages – notes between operators, e.g., a report following a test.

The International Society of Automation (ISA) 18.2 standard (ISA, 2016) defines an alarm as "an audible and/or visible means of indicating to the operator an equipment malfunction, process deviation, or abnormal condition requiring a response"; the International Electrotechnical Commission (IEC) 62682 standard (IEC, 2014) adds the word "timely" to end of the ISA definition, i.e., "…abnormal condition requiring a timely response" (Hollifield, 2020). The ISA definition of an alert is "an audible and/or visible means of indicating to the operator an equipment or process condition that requires awareness, that is indicated separately from alarm indications, and which does not meet the criteria for an alarm". The IEC definition is "audible and/or visible means of indicating to the operator an equipment or process condition that can require evaluation when time allows" (Hollifield, 2020). A comparison of these definitions reflects that alarms have a higher priority for a train operator response. A similar approach towards alarms and alerts can also be seen in the London Underground Library (LUL) standard, where both alarms and alerts are considered a type of system response called notifications (Wackrow, 2015).

In this report, the terms alarm and warning are used interchangeably and do not reflect any difference in the degree of urgency.

2.2 Summary of in cab warning systems

In cab warning systems were first introduced to assist train operators with respect to upcoming signal aspects and train control. The "Crocodile" acoustic warning system built in 1872 was one of the first systems introduced, upon which the 1906 British Great Western Railway (GWR)'s automatic train control (ATC) was later developed. This latter system had an in cab mechanical display and automatic emergency brake intervention in addition to the acoustic warning signal. The continuous cab signals (CCS) system, which is often regarded as a milestone in the history of train control, was created in the U.S. in 1920. Siemens provided INDUSI, the first widely used train control system with brake curve monitoring, for the German railways (Vincze and Tarnai, 2006).

To obtain detailed knowledge about the types of risks that in cab warning systems address and the means of interactions they employ, a wide range of warning systems used in locomotive cabs is reviewed herein. The reviewed systems include cab signalling devices (e.g., Automatic Warning System (AWS)), automatic train control technologies (e.g., Positive Train Control (PTC) and European Train Control System (ETCS)), train-to-train Anti-collision systems (e.g., Train Collision Early Warning System (TCEWS)), train operator reminder devices (e.g., Driver's Reminder Appliance (DRA) and In cab Signal Reminder Device (ICSRD)), train operators' vigilance devices (e.g., Driver Vigilance Systems (DVS) and Monitoring Engineer Fatigue (MEFA)), and Earthquake Early Warning (EEW) systems. The complete review and a summary of these systems are provided in Appendix A and Table 2-1, respectively.

Table 2-1. Summary of the in cab warning systems reviewed

Region	Warning system	Risks related to							alarms		Automatic Brake Intervention	Description
		SPAD	Overspeed	Collision	Work zone	Level crossing	Vigilance	Other	Visual	Audible		
Northern American	I-ETMS											If a train locates within the warning distance of a speed restriction and the system predicts the train will exceed the speed by at least 5 mph, a speed reduction message (black message on a yellow bar) and time to brake (TTB) application countdown are displayed. In cases when the train exceeds the maximum speed allowed for the track by 3 mph and/or exceeds the maximum speed allowed for the current location by at least 5 mph, the speed reduction and "Braking in Progress" messages (in red) are displayed. The brake profile and the distance to target are shown.

												Nonconformity with mandatory directives such as movement authorities, speed restrictions, and work authority are also provided along with audible alarms.
	ACSES											If the train speed exceeds the warning profile, an audible warning is activated, and the speed restriction is displayed as a changed speed in the track speed display. The ACSES' aspect display unit (ADU) shows the signal aspect and enforcement through indicators, and cab signal speed limit and civil speed limit (i.e., the maximum track speed) through numbers.
	ASES											The ASES display shows current speed, target speed at the upcoming speed restriction, and instantaneous maximum authorized speed as calculated from the braking curve on the colour coded circular speedometer. The distance to the target is shown as a bar, and a text message is presented in the centre of the speedometer gauge in red.
	ITCS											The ITCS shows a TTB countdown 30 s prior to applying the brakes. If the locomotive engineer does not obey the braking curve in the first 20 s of the TTB, the system sounds an audio alarm. When the countdown reaches zero, the brakes are activated. The TTB is adjustable with the train speed and will disappear if the train reaches the target speed or the TTB is sufficiently large. The ITCS in cab display shows the actual speed, current speed limit, target speed limit, distance to the target, and TTB countdown. Status mode, overspeed, and brake application are also presented by indicators.
	Alerters											This system provides synchronous or asynchronous visual and audible alerts, typically with increasing frequency and/or intensity. The time intervals between alerts (usually between 25 and 120 s) as well as time to acknowledgment (usually 3-15 s) are sometimes functions of speed and required braking distance. In activity based Alerter, timers are altered in relation to the train operator's activities. In Next Generation Locomotive Cab (NGLC) design, three levels of Alerter warnings are provided: the first level, 20 to 10 s before the brake application (flashing yellow bar with black time to brake counter); second level, 10 to 5 s before the brake (flashing red bar with white time to brake counter and warble audible alarm); and third level, 5 to 0 s before the brake (same as the second level but faster visual and audible alarms).
	MEFA											MEFA can detect situations in which the train operator is physically engaged but mentally disengaged (i.e., automatic behaviour) in addition to ones that Alerters could detect (i.e., both mentally and physically disengagement).
	ORBIT											ORBIT provides the train operator with a verbal warning whenever the train approaches a signal at danger with excess brake curve and speed. It does not apply the brakes automatically to reduce the speed.
	ExPL											ExPL detects railway signal lights, detects and reads railway signs, observes rail track and merging conditions, and detects long distance objects in day/night conditions. It provides visual alerts and improves crew situational awareness.
	De novo											This IOT based system warns the train operator of the existence of an object at a grade crossing.

	CAS											
	RWWS											With RWWS, the train crew receives either an in cab or wayside visual indication of the presence of the workers. The train will automatically slow down or stop until the track becomes clear of all workers.
European	ETCS											ETCS driver machine interface (DMI) displays visual signals such as analog and digital values, target distance bars, symbols, and system status text messages. It also plays audible signals, i.e., S1, S2, Click, and Sinfo sounds. Colour coding with white, grey, yellow, orange, and red is used to reflect the degree of urgency.
	AWS											The AWS provides audible (bell for a green signal/horn for a restrictive aspect) and visual (sunflower) warnings. If the train operator fails to acknowledge the AWS horn within the time limit, an automatic emergency brake applies. After the acknowledgment, the sunflower indicator changes to yellow and black as a reminder.
	Extended AWS											
	ICSRD											The ICSRD enhances the memory of signal aspects and the AWS system by a constant reminder for the signal aspect. The train operator is required to press the related button regarding the aspect of the displayed signal, and then the visual indication is displayed according to the subsequent acknowledgment.
	TPWS (newly designed DMI)											This system applies the brakes to a train signal passed at danger (SPAD), overspeeding at permanent speed restrictions (PSRs), and overspeeding on the approach to the buffer stops. In '3 indicators' DMI, separate flashing indicators are used for each SPAD, overspeed, and 'late to cancel' AWS event. Audible alarms and speech warnings are used for SPAD and overspeed.
	TASS											This system checks overspeed during tilting operation. It displays an intervention indicator and audible alarm. If speed is not reduced, the train brakes are applied automatically; if speed is reduced to the permitted level, the brakes are released and the alarm is reset.
	CAWS											If the signal is changed to a less restrictive aspect, e.g., double yellow to green, a momentary audible 'warble' will sound. If there is a change to a more restrictive aspect, e.g., single yellow to red, a continuous audible tone accompanied by activation of the Acknowledge Switch illumination. The train operator must acknowledge the alarm within 7 s to prevent automatic emergency brake application. However, after acknowledgment, the train operator can override the system and continue the trip without reducing speed.
	EBI Cab											EBI Cab provides train operators with information including the distance to the next target, target speed, maximum permitted speed, current speed, time to service brake intervention, and faults in wayside or vehicle equipment. EBI Cab can supervise permanent, temporary, and emergency speed restrictions, dynamic brake profile, level crossing, and landslide detector status, slip compensation, stopping point, and authorized passing signal at stop. An audible warning is activated when the train speed is more than 5 km/h for EBI Cab 700 (3 km/h for EBI Cab 900) above the speed limit. If the train speed exceeds the permitted speed by 10 km/h (5 km/h for EBI Cab 900), service braking is initiated and the TTB intervention is shown. EBI Cab will brake sufficiently regardless of train operator action. The emergency brake is only used in a real emergency, e.g., where service braking is not sufficient.

	RCAS											RCAS prevents train-to-train, train-to-road vehicle, and train-to-obstacle collisions.
	DRA											DRA prevents passing a signal at danger when a passenger train is moving away from a station. There are two types of DRA, i.e., the train operator set (passive) DRA and the AWS activated (or active) DRA.
	DVS/DSD											These systems have basic or multi resettable forms. In the basic version, the DVS alarm periodically sounds and resets by releasing and repressing the DSD pedal or canceling the AWS warning. In the multi resettable version, it is automatically reset by pressing the AWS acknowledgment button, moving the brake controller, power handle, or warning horn.
Japan	ATS-S											This system creates a bell or a chime sound as well as a red display. The train operator has 5 s to confirm it; otherwise, the automatic brakes are triggered.
	ATS-P											This system does not need the train operator's confirmation and applies the brakes when the train operator does not reduce the train's speed to the safe level.
Australia	Vigilance Alerter											If a train operator control remains inactive for 17 s (Dash-9) or 26 s (Acella Express), the alarms (i.e., an oscillating tone alarm sound as well as text) will go off. Unless the reset button is pressed or a driving control action is made, the emergency brakes will be triggered.
China	TCEWS											TCEWS prevents train-to-train collisions. It provides the train operator with a colour based visual alarm. Time remaining to the potential collision, a verbal alarm, and advisory measures follow to avoid a collision. In principle, the TCEWS does not involve in train control and only provides the information of the preceding train and warnings for collision avoidance. The train operator who received the warnings decides the safety responses (slow down or stop)
Multiple countries	EDVTCS											EDVTCS illuminates a vigilance indicator and countdown display whenever it detects the train operator is losing their alertness. If the alertness reaches the predefined lower limit, a sound alarm is activated that must be acknowledged by pressing a response button before the activation of automatic brakes.
	Dead man's switch											This system stimulates the train operator to react through visual and auditory alarms. It makes an emergency brake application after a predetermined delay (usually 2 to 3 s) in depressing the food pedal or handle.
	EEW											EEW detects significant earthquakes quickly and sends alerts before shaking begins. It automatically decelerates or stops the train.

In addition to the abovementioned warning systems, new designs of locomotives and displays are under study to improve train operator performance. One of the current research topics in the UK, US, and Australia is a head up display (HUD). Inspired by fighter airplanes, a HUD provides a virtual image in the line of the train operator's sight to reduce head down and enhance situation awareness, task performance, and detection of outside events (Thomas and Davies, 2008; Davies et al., 2012; FRA, 2020). Other ongoing research includes a US Federal Railroad Administration (FRA) program for Next Generation Locomotive Cab (NGLC), which aims to achieve an integrated locomotive control system and end the hodgepodge of controls and displays that have been added to the cab over time (DiFiore et al., 2012) (see Appendix A for more information).

2.3 Categorizing types and sequences of warnings

Visible and audible signals are the two common types of driver system interactions in train cabs. Visual warnings are used in situations with a lower degree of danger while auditory warnings in conjunction with visual warnings are usually employed when there is a higher urgency. The level of urgency of auditory warnings is indicated with their intensity, frequency, attention getting ability, psychological salience, and noise penetration ability.

Visual signals are used to inform the train operator about the system status, e.g., the operative/ failure message, indicator, and/or symbol, to provide the train operator with monitoring information including the current location and speed of the train, to warn the train operator of an unsafe situation such as a speed reduction message or time to brake (TTB) intervention countdown, and to give advisory information to the train operator such as the advisory brake profile and safe speed. These types of visible information are conveyed by a symbol, indicator, text, number, diagram, gauge, semaphore, etc. They are also integrated with colours, flashing forms, as well as sounds to reflect higher urgency for the train operator's action.

In more urgent situations, visual alerts/alarms are sequentially or concurrently followed by auditory ones because sounds have a higher probability of generating a response with a faster reaction time compared to visual displays. In general, a visual signal such as a flashing red light, speed reduction message, and/or TTB application countdown is first shown to inform the train operator of a hazardous situation. If the train operator does not react to them, then an auditory warning is activated to accompany the visual alarm. Thereafter, more visual signals are adopted to provide the train operator with relevant and advisory information, including the nature of the problem and which action should be taken (e.g., advisory braking profile), or to play the role of a reminder, e.g., sunflower indicator in AWS.

Although visual and auditory warnings are the most popular modalities to provide in cab information, train operators sometimes use haptic signals, such as haptic feedback of brake position and/or position of the acknowledgment button.

Blanchard and Hill (2004) extracted and summarized the information available regarding information sources, their modalities, and their locations for Cambrian train operators in the UK. For in cab information, they found three modalities: auditory, visual, and psychomotor (type of haptic) (see Appendix B). Their study revealed that the visual modality has the majority share of in cab information sources, followed by auditory and then psychomotor. Auditory information was mostly related to audible feedback from signallers, from devices to confirm they are operative, and from driver safety devices (DSDs) and AWSs to alert the train operator. The Rail Safety and Standards Board (RSSB) (2010a) also categorized the existing cab warnings into European Rail Traffic Management System (ERTMS), Global System for Mobile Communications-Railway (GSM-R), Vigilance, AWS, Tilt Authorization and Speed Supervision (TASS), and Automatic Train Protection (ATP) related warnings and then presented their tone types and properties (Wickens, 2002). Another useful source of information for in cab warning systems is materials from the ETCS, such as the ETCS drivers' handbook (ERA, 2019).

Note that, according to multiple resources theory, performing two similar tasks such as both tasks demanding visual perception (e.g. reading a text message while monitoring the road ahead) can result in poorer performance versus performing dissimilar tasks such as one visual task and one auditory task (e.g. listening to music while monitoring the road ahead) (Verstappen et al., 2017).

2.4 An overview of warnings according to the types of risks

In cab warning systems are adopted to alert train operators of risky situations. They can warn the train operators that a restrictive signal is ahead and/or they have not taken the appropriate action regarding the upcoming signal aspect such as slowing down or stopping the train. These types of warnings are designed to prevent or mitigate the risk of signal passed at danger (SPAD). Another type of warning is activated whenever the train speed exceeds safe and/or maximum speed limits to reduce the risk of overspeed and derailments. Some alarms also address the risks of train-to-train collisions, train-to-vehicle/obstacle collisions, entering work authority, broken rails, and earthquakes. Moreover, train operator safety and vigilance devices trigger alarms to tackle the risks associated with train operator sleepiness, fatigue, faintness, and death.

The overview of in cab warning systems indicates that although warnings related to different types of risks are usually designed in a way to be distinguishable by the train operator, there is no direct relationship between the type of risk and type of warning (e.g., visual or audible warnings). The appropriate types of warnings and their characteristics are chosen based on factors including the required perceived urgency, alarm states (e.g., normal, unacknowledged alarm, and acknowledged alarm), and the environment.

2.5 An overview of follow up actions for a warning

In cab warning systems have evolved regarding the follow up actions they need, type of intervention, continuity, and technologies of information transmissions, etc. To the best knowledge of the authors, the first generation of in cab warning systems only alerts the train operator of an upcoming hazardous condition; they need no train operator acknowledgment and have no automatic brake intervention. A cab warning device that only warns the train operator that the train is approaching a stop signal is an example of a first generation in cab warning system. In second generation systems, the train operator must acknowledge the warning, usually by pressing an acknowledgment button; if the train operator fails to do so, the emergency brake will be applied to bring the train to stop. In some systems, the remaining TTB intervention and/or a reminder of an acknowledged warning such as a semaphore are displayed to the train operator. The downside of such systems is that, after acknowledgment, the train operator overrides the automatic brake system; thus, the train will not stop if the train operator cancels the warning unconsciously or forgets to take appropriate action. Finally, in third generation in cab warning systems the train speed is continuously checked with the dynamic speed profile, and warnings, service brakes, and/or emergency brakes are activated whenever needed. Emergency brakes are triggered in the situation when the train operator takes no action after the warnings and/or when the brake curve speed is violated. Warning systems of this generation typically display useful information to the train operator including the current speed, speed limit, target speed, distance to the next target, and TTB intervention.

3 Alarm handling and train operator behaviour modelling

Modelling and analyzing a train operator response to warnings play a crucial role in the improvement of alarm design. Analysis of alarm handling provides a thorough understanding of alarm and fault initiated activities, sources of problems, and coping strategies in complex systems (Dadashi, 2012). Higher conformity of a train operator's behaviour in practice with the instructions reflects higher warning effectiveness (Wogalter, 2006). Therefore, a variety of methods to model driving behaviour and alarm handling have been developed. For example, the Communications-Human Information Processing (C-HIP) model is a framework for modelling and analyzing behaviour compliance and warning effectiveness. The main stages of C-HIP and their typical assessment techniques are: (a) attention switch and maintenance stages, using eye tracking, response time, and looking behaviour; (b) comprehension/memory, using recall and recognition tests; and (c) attitudes, beliefs, and motivations, using subjective and self-report measures (Figure 3-1) (Wogalter, 2006).

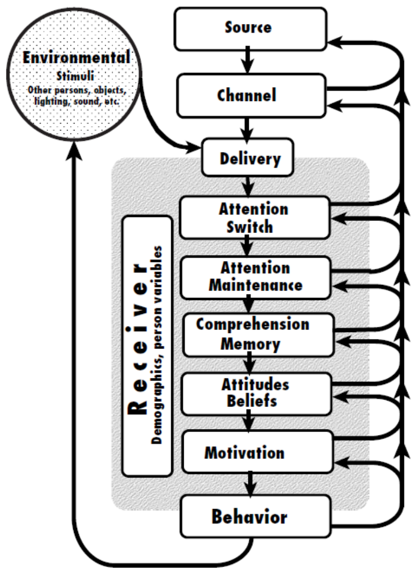


Figure 3-1. Communication-Human Information Processing (C-HIP) model (Wogalter, 2006).

Cognitive work analysis (CWA) is another method that helps researchers understand the sequence of activities in the course of alarm response. It analyzes human information interaction with sociotechnical systems. CWA was first presented by Rasmussen et al. (1994) and then modified by other researchers such as Vicente (1999) and Lintern (2009). The classic stimulus, organism, and response (SOR) model, Rasmussen's decision ladder, knowledge acquisition models, joint cognitive systems, and Bainbridge's human information processing model are other examples of models to identify the information processing required for decision making in sociotechnical systems (Dadashi, 2012). Bainbridge (1997) classified human information processing models into sequential and contextual models: sequential models consider cognitive processing as a sequence of processing stages while contextual models examine the temporary structure of inference made to describe the task situation and how this affects later processing. Rasmussen's decision ladder and SOR models are sequential models whereas knowledge acquisition models are contextual models (Dadashi, 2012).

Dadashi (2012) applied CWA to model alarm handling in the railway electrical control room and divided alarm handling into two domain functions, i.e., “alarm recognition” and “alarm clearance”. Stanton and Edworthy (1999) named those activities initiated by the presence of alarms as alarm initiated activities (AIAs). In the alarm handling taxonomy recommended by Stanton and Baber (1995), alarm initiated activities are categorized into observe, accept, analyze, investigate, correct, monitor, and reset (Figure 3-2).

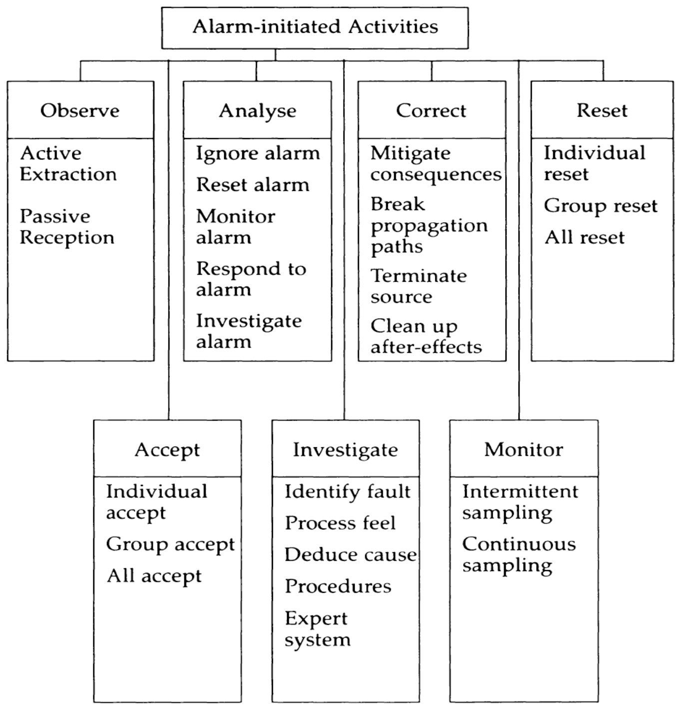


Figure 3-2. Taxonomy of alarm handling activities (Stanton and Baber, 1995)

Stanton and Edworthy (1999) also depicted stages and pathways of alarm initiated activities model for routine and critical events involving alarms and underpinned that the investigation activity is the only distinguishing stage of alarm handling for these two event types (Figure 3-3). Each one of the five pathways could be followed during alarm handling because alarm initiated activities are context dependent and not all alarms are handled in the same way (Stanton and Baber, 2008).

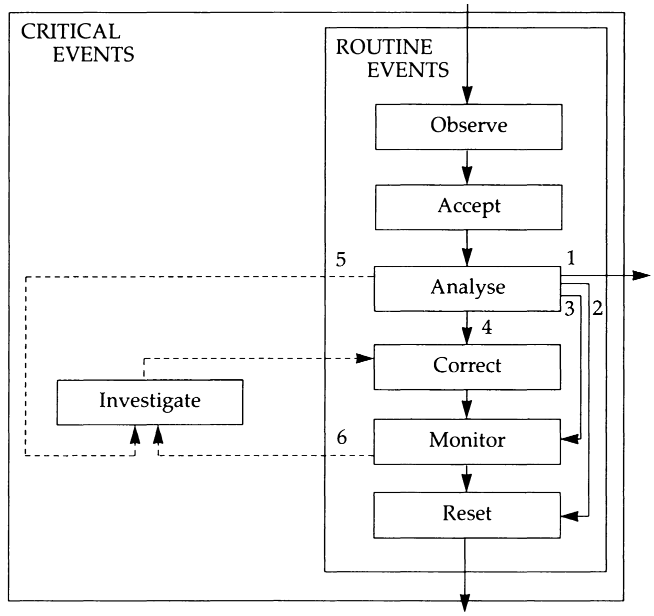


Figure 3-3. Stages in alarm initiated activities (Stanton and Edworthy, 1999)

Moreover, Stanton and Baber (2008) estimated minimum and maximum response times for each stage of alarm initiated activity (Table 3-1).

Table 3-1. Estimates of minimum and maximum reaction times (Stanton and Baber, 2008)

Alarm initiated activity	Minimum reaction time (s)	Maximum reaction time (s)
Observation	1	2
Acceptance	1	7
Analysis	2	6
Investigation	6	30
Monitoring	Variable*	Variable*
Correction	7	45

*Monitoring is assumed to be a continuous activity that can be performed in parallel with other actions.

Stanton and Baber (2008) also use the multimodal critical path analysis (CPA) technique for alarm handling. CPA is a project management method that calculates the critical path based on the tasks' order, durations, and dependencies. This idea can be applied to any time based activity, such as human performance.

Dynamic alarm handling, with strategies to suppressing alarms and adjust alarm configuration based on operating state and predefined criteria, is an advanced alarm handling method. It stops alarm floods through suppression of multiple alarms (Jerhotova et al., 2012, Emerson, 2019,). Alarm shelving, alarm flood suppression, state based (condition based) alarming, and first-out alarming are examples of dynamic alarm handling strategies (Hollifield and Habibi, 2007, Jerhotova et al., 2012, Emerson, 2019). Alarm Shelving, which is also known as disabling or inhibiting, is temporary alarm suppression to temporarily remove alarms. The purpose is to allow train operators to hide nuisance alarms or temporarily invalid alarms so that they can focus on more urgent alarms (Hollifield and Habibi, 2010). For example, in state based (condition-based) alarming, alarm settings are altered according to the different process or equipment states (e.g., startup and shutdown states). Alarm flood suppression involves configured groups of alarms to be suppressed whenever a predetermined system state is identified. In first-out alarming, alarms are suppressed when multiple alarms occur for a single process event (Hollifield and Habibi, 2007, Jerhotova et al., 2012, Emerson, 2019).

3.1 Influencing factors of alarm handling

Analysis of on train monitoring recorder (OTMR) data revealed that train operators do not show a fixed behavioural response to an alarm (McLeod et al., 2005a). Research carried out by McLeod et al. (2005b) revealed factors that determine train operators' interpretation of and reaction to AWS alarms. The factors include the form of the alarm (bell or horn), visibility of track signals and AWS magnets, train operator understanding of the alarm, train operator expectations, current and expected speeds, and available time to make the speed change. Contextual factors such as train operator level of fatigue and situational awareness also influence train operator alarm handling.

In another research, McLeod et al. (2005a) highlighted the individual factors of the train operator, type of rolling stock, nature of the movement, and situation and context at which the alarm activates as factors that contribute to how and when the train operator responds to the alarm. Therefore, what happens immediately preceding or concurrent to the alarm is highly relevant.

The RSSB (2015) also investigated factors that influence the way a train operator responds to a signal or sequence of signals. These factors were categorized into train operator (e.g., errors in interpreting signal sequences), Infrastructure (e.g., signal spacing), Train (e.g., rolling stock braking performance), External environment (e.g., weather and darkness), and Operations (e.g., rules, training, operational speed). A complete list of the extracted influencing factors for UK train operator responses to consecutive caution sequences is provided in Appendix C.

3.2 Case studies of alarm handling in the railway industry

3.2.1 Alarm handling by railway electrical control room

Dadashi (2012) modeled alarm handling in railway electrical control rooms in the UK, and divided it into two domain functions, i.e., "alarm recognition" and "alarm clearance", which are respectively related to 'acceptance' and 'clearance'. These domain functions contain notification, acceptance, analysis, and clearance activities that are depicted in the decision ladder derived for alarm handling in the railway electrical control room (Figure 3-4).

Dadashi (2012) ascertained that filtering, queuing, categorizing, similarity matching, and extrapolation are common strategies among electrical control room operators to tackle alarms. The alarm initiated activities determined and the coping strategies adopted are also shown in Figure 3-5. In summary, operators first categorize and filter several sources of information to get insight into the alarm. In the case of multiple alarms, the alarms are queued based on the operators' experience. Sometimes, the operators almost immediately accept and silence the alarm;

in other situations, they evaluate the criticality of the alarm according to their knowledge and experience in previous cases. Thus, alarm acceptance and alarm analysis are usually correlated. Finally, the operators determine the possible courses of action, assess them, and implement the optimum action to clear the alarm.

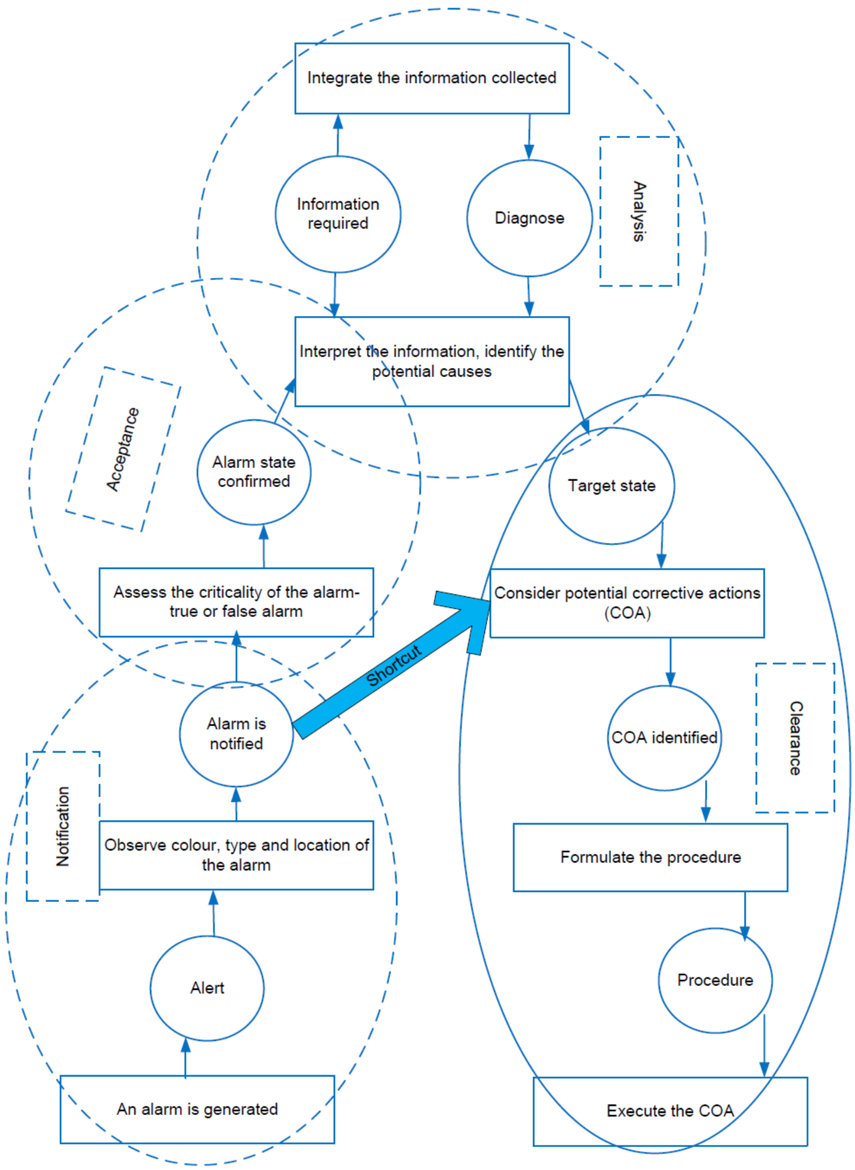


Figure 3-4. Alarm handling decision ladder for a railway electrical control room (Dadashi, 2012)

Dadashi (2012) also identified relations between the types of artifacts used by operators and types of alarm (i.e., expected or unexpected), types of alarm handling activities (i.e., notification, acceptance, analysis, and clearance), and amount of information (i.e., high or low). The list of utilized artifacts in the control room includes the menu, alarm banner, display area, page buttons, overview display, static board, paper, phone, and face-to-face communication. Moreover, this study incorporated time into strategy analysis to acquire a good understanding of the order of activities as well as the strategies adopted during expected and unexpected alarms (Figure 3-6 to Figure 3-9).

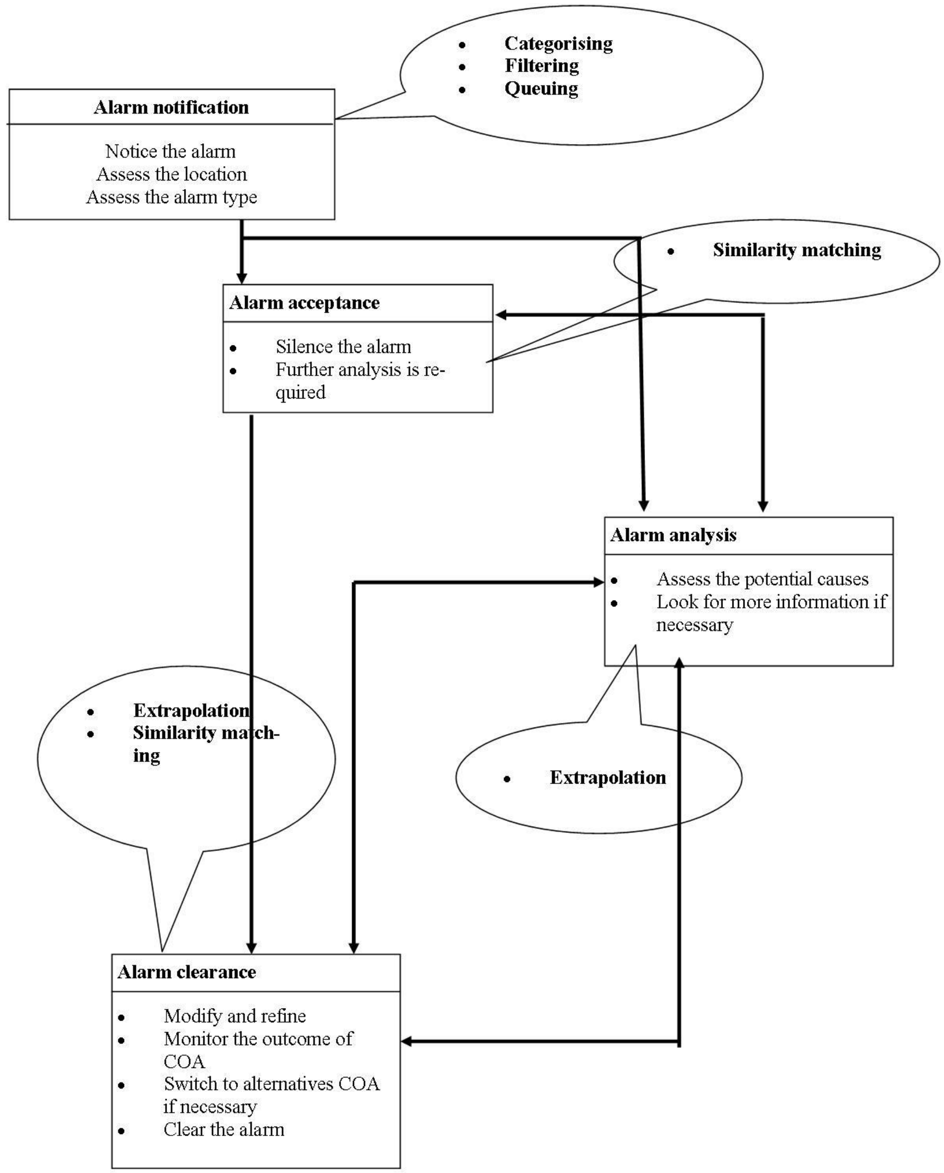


Figure 3-5. Alarm handling activities and strategies for a railway electrical control room (Dadashi, 2012)

Figure 3-6 and Figure 3-7 respectively illustrate the order of alarm handling activities for unexpected and expected alarms. The 'Y' axis shows each of the 11 episodes of alarms and the 'X' axis displays the duration of alarm handling in 15 second intervals.

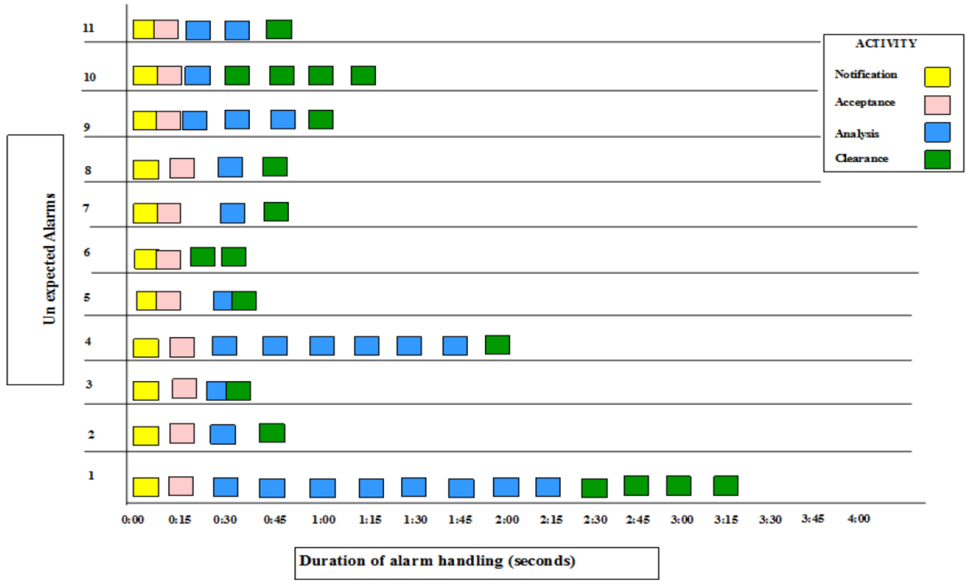


Figure 3-6. Order of alarm handling activities (notification, acceptance, analysis, clearance) for unexpected alarms (Dadashi, 2012)

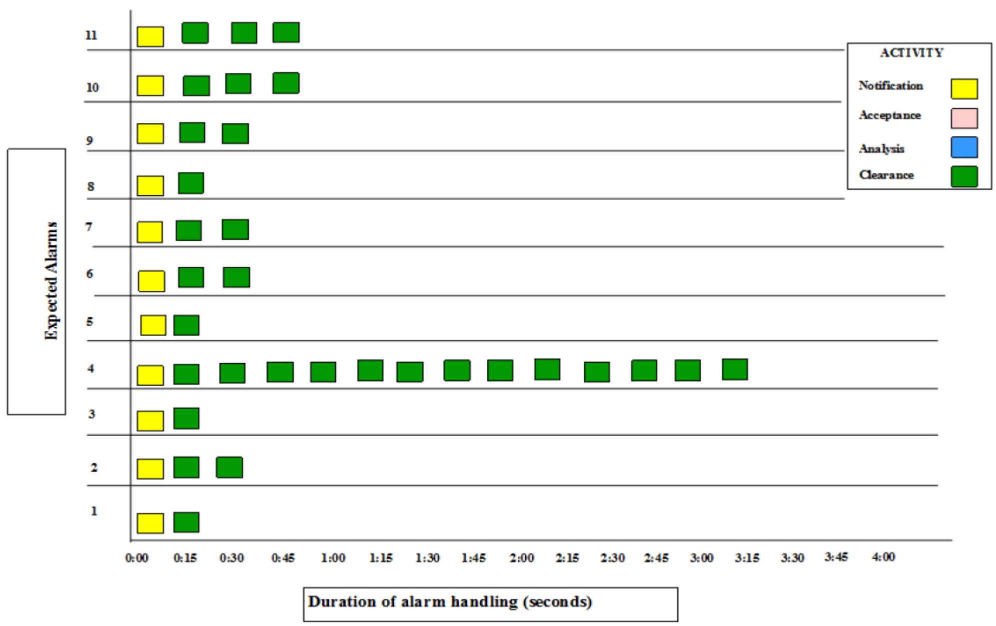


Figure 3-7. Order of alarm handling activities (notification, acceptance, analysis, clearance) for expected alarms (Dadashi, 2012)

The comparison between the order of alarm handling activities for expected vs. unexpected alarms illustrates that only notification and clearance activities are undertaken for expected events as the alarm is already known and there is no need for acceptance and analysis.

Figure 3-8 and Figure 3-9 respectively show the order of alarm handling strategies for 'unexpected' and 'expected' alarms.

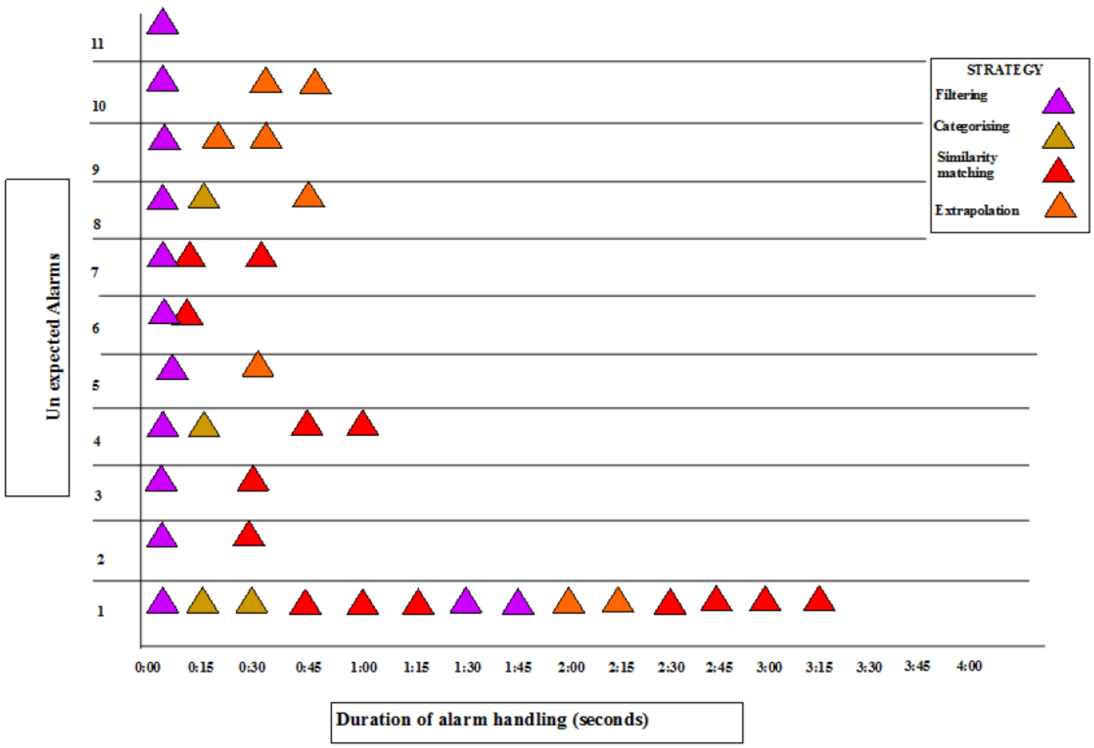


Figure 3-8. Order of alarm handling strategies (filtering, categorizing, similarity matching, extrapolation) for unexpected alarms (Dadashi, 2012)

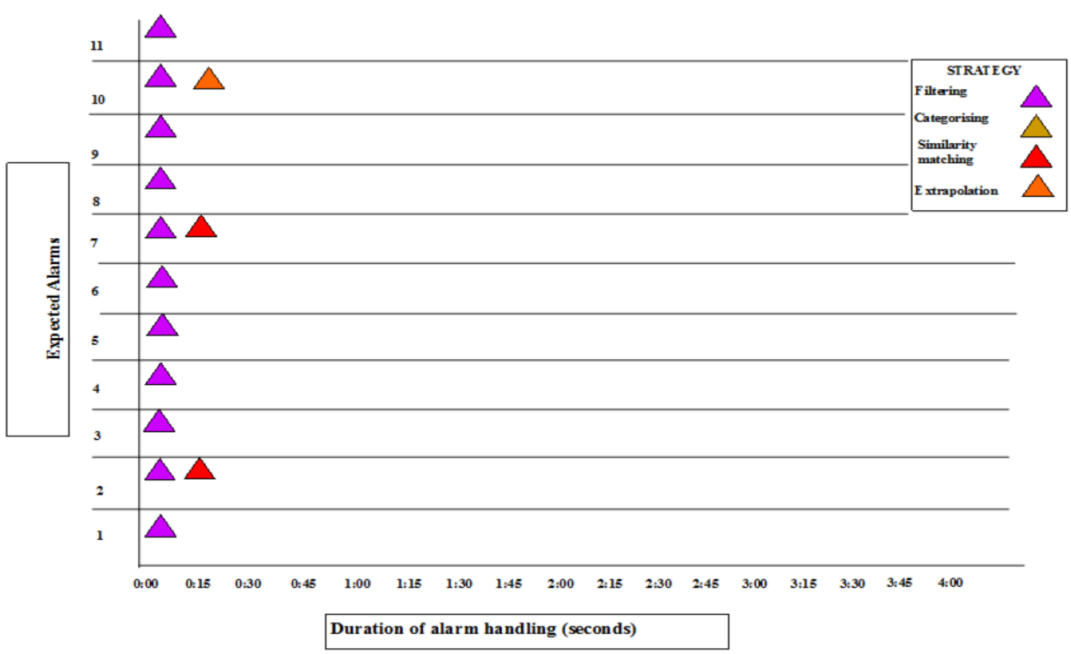


Figure 3-9. Order of alarm handling strategies (filtering, categorizing, similarity matching, extrapolation) for expected alarms (Dadashi, 2012)

Figure 3-8 and Figure 3-9 also reveal that limited numbers of alarm handling strategies are required during expected alarms. The operator filters the type of alarm, occasionally performing similarity matching or extrapolation when clearing the alarm (Dadashi, 2012).

In well designed intelligent systems, sufficient information is expected to be provided to the operator in a way that should not require acceptance and analysis activities. Thus, alarm handling activities for unexpected alarms become similar to those for expected ones, i.e., notification and clearance only. Dadashi (2012) proposed design guidance for alarm systems in the railway domain (see Appendix D).

In summary, alarm notification, alarm acceptance, alarm analysis, and alarm clearance are alarm initiated activities in the railway electrical control rooms. Experiments revealed that while all four alarm handling activities are undertaken for unexpected events, for expected events, only notification and clearance activities are undertaken and thus there is less cognitive load. Operators adopt filtering, queuing, categorizing, similarity matching, and extrapolation strategies to handle the alarm initiated activities and consequently tackle alarms. Analyses illustrated that all operators do not adopt the same strategies and the same order to handle either expected or unexpected alarms. Moreover, limited numbers of alarm handling strategies are required during expected alarms.

3.2.2 Advanced Warning System (AWS) alarm handling

The tasks that UK train operators undertake to handle AWS alarms were identified by Halliday et al. (2005) and are summarized in Table 3-2 and Table 3-3.

Table 3-2. Task analysis of passenger train operator tasks using AWS (Halliday et al., 2005)

Level 0	Level 1	Level 2	Level 3
1. Drive Passenger Train	1.1 Prepare to drive train	1.1.1 Enter cab	
		1.1.2 Receive briefing from train operator	
		1.1.3 Sit in driving seat; set vigilance device/DSD (driver safety device) using hands or feet	
		1.1.4 Insert and turn key (AWS sounds horn and 'sunflower' shows yellow/black, Vigilance device sounds warning)	
		1.1.5 Acknowledge AWS (press AWS cancellation button; Horn stops, 'sunflower' shows black)	
		1.1.6 Reset vigilance device/DSD (raise/lower feet/press hand down or feet) (Warning sound stops)	
		1.1.7 Set radio channel (Red light on DRA button extinguishes)	
		1.1.8 Disengage DRA (pull button or twist – depends on type)	
		1.1.9 Await then respond to guard's signal to go (bell)	1.1.9.1 Hear guard signal (train operator will be aware of signal aspect but will make a final check on receiving start signal

			(bell) from guard (when in station). At other locations, omit task 1.1.9.1)
			1.1.9.2 Observe signal ahead (If red wait; if green, yellow or double yellow, proceed)
			1.1.9.3 Decide if safe to proceed
			1.1.9.4 Observe speed limit sign
	1.2 Drive train attending to all safety requirements and making appropriate stops	1.2.1 Take power, accelerate to required speed	1.2.1.1 Release brake / Move control lever to required setting
			1.2.1.2 Monitor speed
			1.2.1.3 Adjust power and brake controller (PBC) or apply brake as necessary to maintain required speed
		1.2.3 Continue driving, obeying speed limits and signals	1.2.3.1 (Whilst train is running) maintain attention on or near the line
			1.2.3.2 See AWS magnet and associated signal
			1.2.3.3 Tasks related to signal aspects, AWS warning received, and required train operator response (explained in a separate table with task numbers from 1.2.3.3.1 to 1.2.3.3.8
		1.2.4 Observe track and external conditions and adjust driving accordingly	
	1.3 Stop train at final destination		
	1.4 Isolate and make safe		

Table 3-2 reveals that train operators may receive warning sounds, including AWS and vigilance device/DSD related warnings, when preparing to drive a train. They also receive the upcoming signal aspect and AWS alarms during driving, which they are required to acknowledge. Tasks related to these warnings, shown by task numbers 1.2.3.3.1 – 1.2.3.3.8 in Halliday et al. (2005), are summarized in Table 3-3.

Table 3-3. Tasks related to AWS warnings received and requiring acknowledgment (Halliday et al., 2005)

Signal Aspect	AWS Response	Required train operator Response	Consequence	Notes
Green	Bell	1.2.3.3.1 None	Bell silences after a short time Sunflower display shows black	Train operators have considerable route knowledge and have various 'cues' that drive their expectations about warning signals from
Double yellow	Horn	1.2.3.3.2 Acknowledge warning (press AWS	Horn silenced Sunflower display	

		cancel button within 2.5 s of hearing warning). Be aware that next signal is at single yellow. Take action brake or coast.	shows black and yellow	AWS: e.g., from memory, they will know where AWS magnets are placed and will see them within their normal focus area. Average response time to an AWS horn is 1.3 s. In the event that an unexpected signal is received e.g., a horn when the signal ahead is clearly green, or a bell when the signal is clearly not green, the train operator will stop the train (if bell instead of horn) and contact the signaller for information. He will also fill out RT3185 report form. train operators will know through route knowledge or from markings on the signals, which are automatic and which are controlled. In low traction conditions, the train operator may be using the brake before observing the signal to ensure that he can stop. train operators constantly anticipate the next signal and what they will do in response to the signal. If train is kept waiting at a signal for more than a few minutes, the train operator will usually contact the signaller for a status update. Signaller can advise to pass on red if there is a problem with the signal. The main distractions for the train operator are:
Single yellow	Horn	1.2.3.3.3 Acknowledge warning (press AWS cancel button within 2.5 s of hearing warning). Be aware that next signal is at red. Begin braking. train operator will already be decreasing the train speed	Horn silenced Sunflower display shows black and yellow	
Red	Horn	1.2.3.3.4 Acknowledge warning (press AWS cancel button within 2.5 s of hearing warning). Maintain braking to reduce speed to 15 mph for 200 yards before signal then come to a stop at the signal (SWT defensive driving policy)	Horn silenced Sunflower display shows black and yellow	
Flashing yellow	Horn	1.2.3.3.5 Acknowledge warning (press AWS cancel button within 2.5 s of hearing warning). Be aware that a route change signal or high speed crossing is ahead	Horn silenced Sunflower display shows black and yellow	
Any	Horn	1.2.3.3.6 Acknowledge warning (press AWS cancel button within 2.5 s of hearing warning). Identify cause of warning – speed indicator or other.	Horn silenced Sunflower display shows black and yellow	
End of speed restriction notice board	Horn	1.2.3.3.7 Acknowledge warning (press AWS cancel button within 2.5 s of hearing	Horn silenced Sunflower display shows black and yellow	

		warning). Identify cause of warning – speed indicator or other.		• weather conditions – thick fog or those causing low traction • sights external to the cab – wildlife, track workers, etc. • personal issues – family/relationship problems, house moves etc. • noises: radio, departure bell, passenger emergency call handle operation, area change radio bleep, mobile phone
Changing - after passing over AWS magnet, signal aspect changes from a more to a less restrictive aspect	None. Horn sounded (and cancelled) when passing over magnet before signal changed	1.2.3.3.8a Notice change Respond as conditions dictate (may increase speed if appropriate)	Sunflower display remains yellow and black	
Changing - after passing over AWS magnet, signal aspect changes from a less to a more restrictive aspect	None. Horn sounded (and cancelled) when passing over magnet	1.2.3.3.8b Notice change. Slow down.	Horn already cancelled by train operator response to original signal Illuminates single yellow light on ICSRD display Sunflower – black/yellow	

In summary, when the AWS horn sounds, the train operator should press the cancellation button within 2.5 s to prevent the automatic brake application. After the acknowledgment, the sunflower display shows black and yellow. Since the AWS horn is activated for all types of upcoming restrictive signals (i.e., double yellow, single yellow, and red), the train operator must slow down or stop based on what the exact aspect of the upcoming signal is. The extended AWS can impose more cognitive loads on the train operator as the horn alarm can be related to not only the restrictive signals but also other situations such as speed restrictions, route change signal, the high speed crossing, etc., and thus the train operator must identify the cause of a warning.

3.2.3 ICSRD alarm handling

The task analysis for driving a passenger train in the UK using ICSRD provided by Halliday et al. (2005) is described in Table 3-4 and Table 3-5.

Table 3-4. Task analysis of train operator tasks using ICSRD (Halliday et al., 2005)

Level 0	Level 1	Level 2	Level 3
1. Drive passenger train	1.1 Prepare to drive train	1.1.1 Enter cab	
		1.1.2 Receive briefing from train operator	
		1.1.3 Sit in driving seat; set vigilance device/DSD using hands or feet	
		1.1.4 Insert and turn key (AWS sounds horn and 'sunflower' shows yellow/black, Vigilance device sounds warning)	
		1.1.5 Acknowledge AWS (press AWS cancellation button; Horn stops, 'sunflower' shows black, ICSRD lights remain unlit)	
		1.1.6 Reset vigilance device/DSD (raise/lower feet/press hand down or feet) (Warning sound stops)	
		1.1.7 Set radio channel (Red light on DRA button extinguishes)	
		1.1.8 Disengage DRA (pull button or twist – depends on type)	
		1.1.9 Await then respond to guard's signal to go (bell)	1.1.9.1 Hear guard signal (train operator will be aware of signal aspect but will make a final check on receiving start signal (bell) from guard (when in station). At other locations, omit task 1.1.9.1)
			1.1.9.2 Observe signal ahead (If red wait; if green, yellow or double yellow, proceed)
			1.1.9.3 Decide if safe to proceed
			1.1.9.4 Observe speed limit sign
	1.2 Drive train attending to all safety requirements and making appropriate stops	1.2.1 Take power, accelerate to required speed	1.2.1.1 Release brake / Move control lever to required setting
			1.2.1.2 Monitor speed
			1.2.1.3 Adjust PBC or apply brake as necessary to maintain required speed
		1.2.3 Continue driving, obeying speed limits and signals	1.2.3.1 (Whilst train is running) maintain attention on or near the line
			1.2.3.2 See AWS magnet and associated signal
			1.2.3.3 Tasks related to signal aspects, AWS/ICSRD warning received, and required train operator response

			(explained in a separate table with task numbers from 1.2.3.3.1 to 1.2.3.3.8
			1.2.3.4 Notice errors made in operating ICSRD (tasks 1.2.3.4 and 1.2.3.5 may be required if the train operator operates the ICSRD incorrectly, for example, having received an AWS signal for a restrictive aspect and correctly identifying the aspect as single yellow, enters double yellow in error)
			1.2.3.5 Correct error made in operating ICSRD
		1.2.4 Observe track and external conditions and adjust driving accordingly	
	1.3 Stop train at final destination		
	1.4 Isolate and make safe		

Tasks 1.2.3.3.1 to 1.2.3.3.8, which are related to the ICSRD device, are summarized in Table 3-5.

Table 3-5. AWS/ICSRD warnings and required response tasks for the train equipped with ICSRD (Halliday et al., 2005)

Signal Aspect	**AWS/ICSRD Alert**	**Required train operator Response**	**Consequence**
Green	Bell	1.2.3.3.1 None	Illuminated green light on ICSRD Sunflower - black
Double yellow	Horn	1.2.3.3.2 Press yellow button twice in quick succession	Cancel horn, Illuminates double yellow lights on ICSRD Sunflower – black/yellow
Single yellow	Horn	1.2.3.3.3 Press yellow button	Cancel horn, Illuminates single yellow light on ICSRD display Sunflower – black/yellow
Red	Horn	1.2.3.3.4 Press red button	Cancel horn, Illuminates red light on ICSRD display Sunflower – black/yellow
None – TSR or PSR	Horn	1.2.3.3.5 Press white button	Cancel horn, Illuminates white lights on ICSRD display Sunflower – as appropriate for last signal aspect
Flashing yellow – route change	Horn	1.2.3.3.6 Press appropriate yellow button (single or double press – unless already showing yellow) to acknowledge aspect. Press white button	Cancel horn Illuminates white lights ICSRD lights and sunflower – as appropriate for new or last signal aspect

End of speed restriction notice board	Horn	1.2.3.3.7 Press ICSRD reset button	Cancel horn Extinguishes white lights ICSRD lights and sunflower - as appropriate for last signal aspect
Changing - after passing over AWS magnet, signal aspect changes from a more to a less restrictive aspect	None. Horn sounded (and cancelled) when passing over magnet	1.2.3.3.8a Press and hold green button	Horn already cancelled by train operator response to original signal, illuminates green light. Sunflower – from black/yellow to black
Changing - after passing over AWS magnet, signal aspect changes from a less to a more restrictive aspect	None. Horn sounded (and cancelled) when passing over magnet	1.2.3.3.8b Press yellow button	Horn already cancelled by train operator response to original signal illuminates single yellow light on ICSRD display Sunflower – black/yellow

Comparison between the AWS and ICSRD task analysis clarifies that, except for some changes in AWS/ICSRD alerts and required acknowledgments, tasks 1.2.3.4 and 1.2.3.5 are the only ones that may be needed in addition to those tasks required for AWS (Halliday et al., 2005).

In summary, in the train equipped with ICSRD, the AWS horn alarms are acknowledged differently regarding the situation instead of pressing only the same cancellation button. For example, for a double yellow signal aspect, the train operator must press the yellow button of ICSRD twice while for a single yellow signal aspect, the button is pushed once. If the signal aspect is red, then the red button of ICSRD will be pressed. After an alarm is acknowledged, the sunflower shows in black and yellow, and the indicator similar to the acknowledged signal aspect is illustrated on ICSRD (e.g., double yellow lights, single yellow light, or red light).

3.2.4 Cognitive task analysis of AWS horn/bell response

RSSB (2015) provided a thorough cognitive task analysis (CTA) building block for driving a train. The extracted CTA contains four journey stages: monitor platform, depart the station, driving between stations, and signal response. Each journey stage consists of tasks and subtasks performed, their descriptions, and their resource demands (i.e., visual, auditory, cognitive, psychomotor). This information for the “AWS Horn/Bell Response” task group is shown in Table 3-6.

In summary, encoding/decoding, recall, sign/signal recognition, evaluation/judgment, and automatic information processing are cognitive task demands during AWS horn/bell response.

3.2.5 Task analysis for train driving on the Cambrian line

Blanchard and Hill (2004) conducted a detailed task analysis for train driving on the Cambrian line in the UK. Table 3-7 summarizes the subtasks related to the safety systems task, i.e., “Adhere to safety systems”.

Table 3-6. Cognitive task analysis of task group AWS Horn/Bell Response (RSSB, 2015)

<table>
<tr><th rowspan="2">Task</th><th rowspan="2">Action description</th><th colspan="4">Task resource demand</th></tr>
<tr><th>Visual</th><th>Auditory</th><th>Cognitive</th><th>Psychomotor</th></tr>
<tr><td>Anticipate AWS horn/bell</td><td>Anticipate AWS horn/bell about to sound</td><td></td><td></td><td>Encoding/Decoding, Recall</td><td>Discrete Actuation</td></tr>
<tr><td>Hear AWS horn/bell</td><td>Hears and recognizes the horn/bell</td><td></td><td>Detect/ Register Sound</td><td>Sign/Signal Recognition</td><td></td></tr>
<tr><td>Check AWS alert</td><td>Compare AWS alert with expectations</td><td></td><td></td><td>Evaluation/Judgement</td><td></td></tr>
<tr><td>If horn, cancel AWS horn</td><td>Return hand to desk</td><td></td><td></td><td></td><td>Discrete Actuation</td></tr>
<tr><td></td><td>Detect offset</td><td></td><td>Verify Auditory Feedback</td><td>Automatic</td><td></td></tr>
<tr><td></td><td>Cancel horn</td><td></td><td></td><td></td><td>Discrete Adjustive</td></tr>
</table>

Table 3-7. Subtasks of "Adhere to safety systems" task on the Cambrian line (Blanchard and Hill, 2004)

<table>
<tr><th>Level 1</th><th>Level 2</th><th>Level 3</th><th>Sources of information</th></tr>
<tr><td rowspan="14">1 Respond to AWS system

Plan 1:
Do 1 to 3 in sequence.

If alarm is associated with authority to proceed, then do 5 in sequence.
If alarm is associated with speed restriction, then do 6.
If alarm associated with Level Crossing, then do 7.
If alarm accompanied by AWS Cancelling Indicator then do 8.</td><td rowspan="5">1.1 Maintain awareness for AWS Audible alarm

Plan 1.1
Do in sequence</td><td>1.1.1 Look out of window</td><td rowspan="14">Sight of AWS magnet
Sound of AWS alert tone
Sight of AWS cancel button
Sight of the AWS sunflower
Sight of AWS cancel board (discard alert)
Sight of AWS associated signal/route feature
Sight of speed restriction board
Haptic feedback from pressing AWS cancel
Knowledge of AWS response appropriate speed</td></tr>
<tr><td>1.1.2 Scan track</td></tr>
<tr><td>1.1.3 Detect AWS magnet on track</td></tr>
<tr><td>1.1.4 Identify (evaluate) magnet as AWS magnet</td></tr>
<tr><td>1.1.5 Anticipate sound</td></tr>
<tr><td>1.2 Hear AWS alarm</td><td>1.2.1 Detect sound</td></tr>
<tr><td rowspan="4">1.3 Observe AWS Cancelling Indicator

Plan 1.3:
Do in sequence</td><td>1.3.1 Look out of window</td></tr>
<tr><td>1.3.2 Scan track</td></tr>
<tr><td>1.3.3 Detect AWS cancelling indicator on track</td></tr>
<tr><td>1.3.4 Identify (evaluate) magnet as AWS cancelling indicator</td></tr>
<tr><td rowspan="4">1.4 Evaluate meaning of AWS alarm

Plan.1.4
Do in sequence</td><td>1.4.1 Discriminate between sounds in cab</td></tr>
<tr><td>1.4.2 Verify Audible alarm as AWS alarm</td></tr>
<tr><td>1.4.3 Recall knowledge of AWS Audible alarm meanings</td></tr>
<tr><td>1.4.4 Discriminate between clear and caution</td></tr>
</table>

Do 9 and 10.		interpretation	
	1.5 Associate AWS warning with authority to proceed *Plan.1.5* Do in sequence	1.5.1 Look at AWS visual "sunflower" display	
		1.5.2 Evaluate whether AWS visual "sunflower" display is black or black-yellow	
	1.6 Associate AWS warning with speed restriction *Plan.1.6* Do in sequence	1.6.1 Recall route knowledge for speed restrictions	
		1.6.2 Look out of window	
		1.6.3 Scan trackside for speed restriction board	
		1.6.4 Detect trackside sign	
		1.6.5 Register shape of trackside sign	
		1.6.6 Evaluate board as speed restriction	
		1.6.7 Detect digits	
		1.6.8 Read digits	
		1.6.9 Evaluate speed restriction	
	1.7 Associate AWS with approaching Level Crossing		
	1.8 Disregard irrelevant AWS alert		
	1.9 Determine requirement to cancel alarm *Plan 1.9* *Do in sequence*	1.9.1 Evaluate signal as clear or cautionary	
		1.9.2 Judge AWS warning as cautionary	
	1.10 Cancel AWS alarm *Plan 1.10* *Do in sequence*	1.10.1 Visually locate AWS reset button	
		1.10.2 Reach for AWS reset button	
		10.3 Press AWS button to clear AWS Audible alarm	
		10.4 Hit AWS response button within 3 seconds (for cautionary signal)	
2 Control Driver Safety Device (DSD) *Plan 2:* Do in sequence	2.1 Hold DSD pedal down with foot	2.1.1 Maintain foot pressure on DSD pedal	Sound of DSD audible alarm Haptic feedback from foot operation of DSD Knowledge of required DSD alarm response
	2.2 Maintain vigilance for Audible signal from vigilance device	2.2.1 Listen for DSD signal	
	2.3 Hear Audible signal	2.3.1 Detect occurrence of signal	
	2.4 Identify signal as vigilance device Audible signal *Plan 2.4* *Do in sequence*	2.4.1 Discriminate between different Audible sounds in cab	
		2.4.2 Recall knowledge of vigilance device characteristics for specific traction type.	
	2.5 Clear DSD warning	2.5.1 Remove foot from DSD pedal	

	Plan 2.5 *Do in sequence*	2.5.2 Replace foot on DSD pedal	
3 Respond to TPWS *Plan 2.3:* *Do 1-3,4,6 to 8 in sequence (unless given authority to proceed beyond signal at danger).* Do 1 to 5 when given authority.	3.1 Monitor authority to move *Plan 2.2.2.2.3.1:* *Do in sequence*	3.1.1 Recall authority to move from previous signal	Sight of Blue TPWS light lit on stop boards Sight of TPWS brake demand indicator Sight of TPWS brake demand tone Knowledge of the responses to TPWS brake demand Haptic feedback from train braking sighting of signal Haptic feedback from pressing TPWS acknowledge button Haptic feedback from pressing TPWS override button
		3.1.2 Look out of window	
		3.1.3 Scan track side	
		3.1.4 Detect signal	
		3.1.5 Detect signal characteristics	
		3.1.6 Discriminate between signal features	
	3.2 Evaluate requirement to stop train *Plan 3.2:* *Do in sequence*	3.2.1 Recall authority given by signaller	
		3.2.2 Judge authority to proceed from signal features	
		3.2.3 Decide to stop (or continue to move)	
	3.3 Attend to TPWS Brake Demand Warning *Plan 3.3:* *Do in sequence*	3.3.1 Hear warning sound	
		3.3.2 Discriminate between warning sounds in cab	
		3.3.3 Identify warning sound as TPWS Brake Demand Warning	
	3.4 Acknowledge TPWS Brake Demand warning within given time limit *Plan 3.4:* *Do in sequence*	3.4.1 Recall procedure for TPWS Brake Demand Warning	
		3.4.2 Scan train operator's desk	
		3.4.3 Detect TPWS Brake Demand Indicator	
		3.4.4 Press TPWS acknowledge button	
		3.4.5 Determine status of TPWS Brake Demand indicator	
	3.5 Activate Train Stop Over Ride *Plan 3.5:* *Do in sequence*	3.5.1 Scan train operator's desk	
		3.5.2 Detect Train Stop Over Ride push button switch	
		3.5.3 Press Over Ride Button	
		3.5.4 Determine status of override button indicator	
	3.6 Ensure train comes to a standstill *Plan 3.6:* *Do in sequence*	3.6.1 Visually scan train operator's desk	Visual perception of speed (egomotion) Visual feedback from speedometer Visual/haptic feedback from brake controller position
		3.6.2 Detect speedometer	
		3.6.3 Detect speedometer needle	
		3.6.4 Align speedometer needle against digits	
		3.6.5 Read digits	
		3.6.6 Monitor movement of pointer against digits	
		3.6.7 Visually locate brake controller	
		3.6.8 Move brake controller	
	3.7 Report circumstances to signaller immediately	3.7.1 Visually locate radio handset	Verbal acknowledgement from signaller via RETB radio
		3.7.2 Lift handset from handset	

	Plan 3.7: Do in sequence	rest	Verbal acknowledgement from signaller via lineside telephone Verbal instruction from signaller via RETB radio Verbal instruction from signaller via lineside telephone
		3.7.3 Press digits	
		3.7.4 Visually locate red "talk" button	
		3.7.5 Listen for signaller to respond	
		3.7.6 Press red "talk button"	
		3.7.7 Give train operator number (Speak)	
		3.7.8 Say "over" at end of each statement	
		3.7.9 Give train number (speak)	
		3.7.10 Say "over" at end of each statement	
		3.7.11 Release red "talk button" to listen to Railway Control Centre's response.	
		3.7.12 Repeat signaller's response	
		3.7.13 Say "over" at end of repeated statements	
		3.7.14 Say "out"	
		3.7.15 Visually locate radio handset rest	
		3.7.16 Replace handset on rest at end of conversation.	
	3.8 Follow the signaller's instructions		

In summary, the main sources of information to respond to the AWS system are the sight of AWS magnet, AWS cancel button, the AWS sunflower, AWS cancel board (discard alert), AWS associated signal/route feature, and speed restriction board; the sound of AWS alert tone; the haptic feedback from pressing AWS to cancel; and the knowledge of AWS response appropriate speed.

For controlling driver's safety devices (DSD), the sources of information are the sound of DSD audible alarm; the haptic feedback from foot operation of DSD; and knowledge of required DSD alarm response.

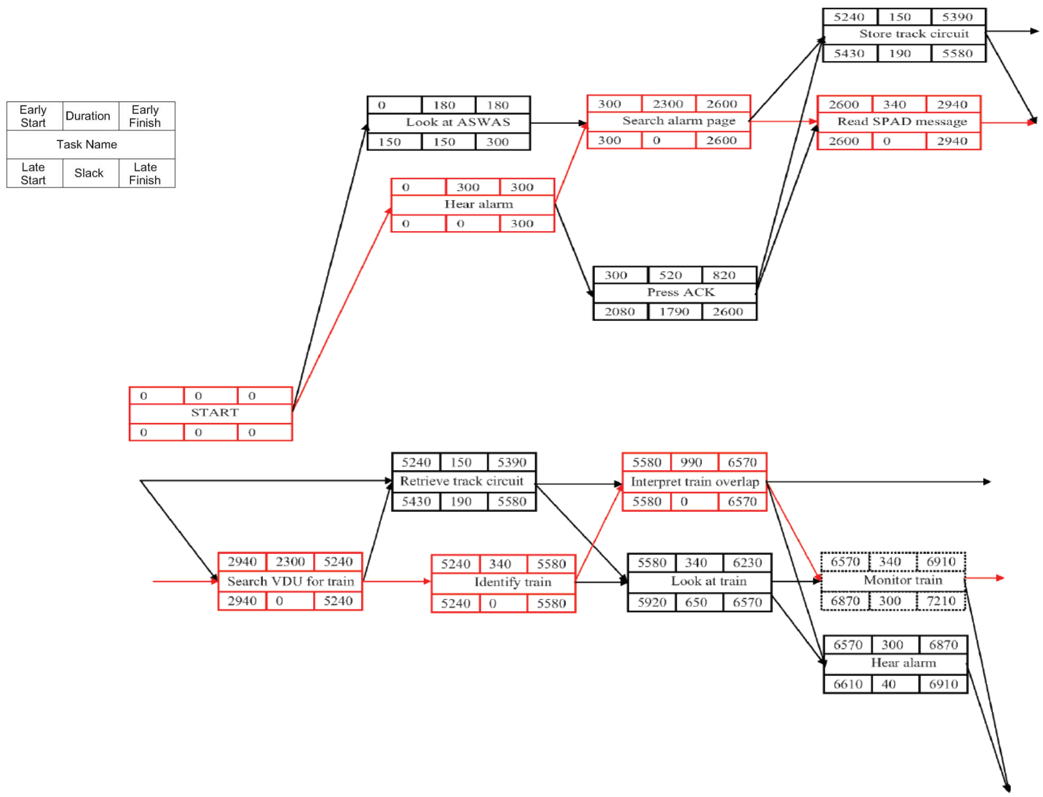
To respond to TPWS, the sources of information are the sight of Blue TPWS light lit on stop boards, TPWS brake demand indicator, TPWS brake demand tone; the knowledge of the responses to TPWS brake demand; and the haptic feedback from train braking Sighting of signal, from pressing TPWS acknowledgment button, and from pressing TPWS override button.

3.2.6 Alarm handling in the Ladbroke Grove rail incident

Stanton and Baber (2008) used CPA to depict how the signaller in the Ladbroke Grove rail incident in the UK could handle the alarms. To do this, they first applied hierarchical task analysis to identify the needed tasks and the initial sequences of tasks based on their order of occurrence.

They then determined the modalities of the tasks (e.g., visual tasks, auditory tasks, central processing tasks, manual tasks, and verbal tasks) and modified their sequence in terms of modality. The sequence modification is based on the fact that tasks with the same modality, e.g., auditory tasks, cannot be performed at the same time. Finally, times were allocated to the tasks, and the critical path was calculated.

The derived alarm handling and the critical path (tasks in red) are mapped in Figure 3-10.



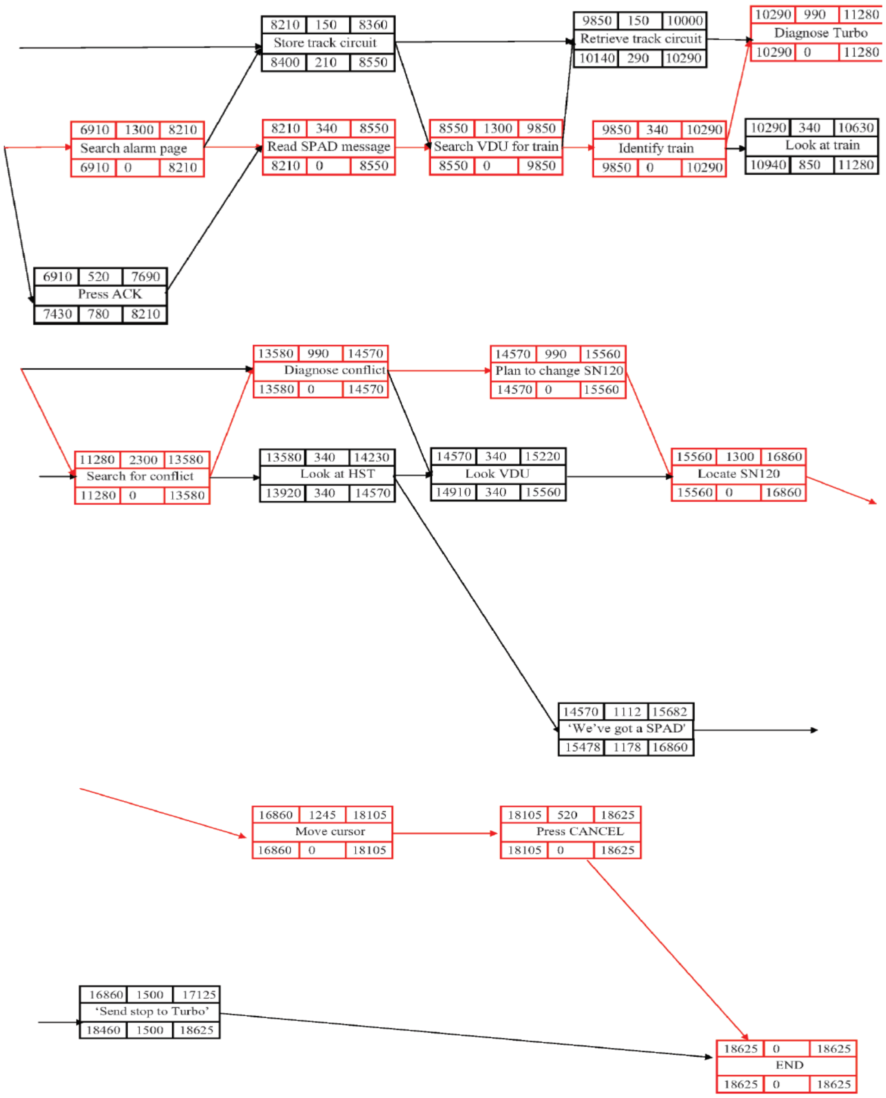


Figure 3-10. Critical path analysis of signaller alarm handling (Stanton and Baber, 2008)

In summary, the critical path of alarm handling during the Ladbroke Grove rail incident consists of Hear alarm, Search alarm page, Read SPAD message, Search VDU (Visual Display Unit) for train, Identify train, Interpret train overlap, Search alarm page, Read SPAD message, Search VDU for train, Identify train, Diagnose Turbo, Search for conflict, Diagnose conflict, Plan to change SN120, Locate SN120, Move cursor, Press cancel. Definitely, any changes in the amount of time spent on carrying out each of these tasks of the critical path directly decrease or increase the total alarm handling time.

4 Alarm management

Alarm management refers to a process by which alarms are designed, implemented, and monitored to ensure safe, reliable, and efficient operations (HPS, 2011; Cebola, 2015). The importance of alarm management can be better understood by acknowledging that ineffective alarm management has contributed to some of the most serious industrial and rail accidents, such as the Texaco refinery explosion at Milford Haven in 1994 and the train collision in the Washington Metropolitan Area in 2009 (Heape, 2015).

An effective alarm design warns users of hazardous conditions early, informs them of the best measures to take, and avoids overloading the user with irrelevant or duplicate alarms, particularly during abnormal situations (RIAC, 2007; Errington et al., 2009). The process industry took the lead in alarm management, and standards and guidelines such as Engineering Equipment and Materials Users Association (EEMUA) 191 (EEMUA 191, 2014), ANSI/ISA 18.2 (ISA, 2016), and IEC 62682 (IEC, 2014), were developed for the management of alarms (Hollifield, 2020). **Table 4-1** depicts the emergence of industry guidelines and standards for alarm management (Goel et al., 2017):

Table 4-1. Evolution of guidelines and standards of alarm management (Goel et al., 2017)

EEMUA 191, 1st edition	YA 711	EEMUA 191, 2nd edition	NAMUR NA 102	ANSI/ISA 18.2	API RP 1167, 1st edition	EEMUA 191, 3rd edition & IEC 62682	ANSI/ISA 18.2, 2nd edition & API RP-1167, 2nd edition
1999	2001	2007	2008	2009	2010	2014	2016

A good alarm design should consider human limitations and task demands. The Railway Industry Advisory Committee (RIAC) of the UK (2007) stated the main properties of a good alarm are as follows:

- Relevant - not spurious or of low operational value
- Unique - not duplicating another alarm
- Timely - not long before any response is needed or too late to do anything
- Prioritized - indicating the importance that the train operator deals with the problem
- Understandable - having a message that is unambiguous and easy to understand
- Diagnostic - identifying the problem that has occurred
- Advisory - indicative of the action to be taken
- Focusing - drawing attention to the most important issues

According to the ISA 18.2 standard, the life cycle of alarm management consists of ten stages (Hollifield, 2010): alarm philosophy, identification, rationalization, detailed design, implementation, operation, maintenance, monitoring and assessment, management of change (MOC), and audit (see Figure 4-1).

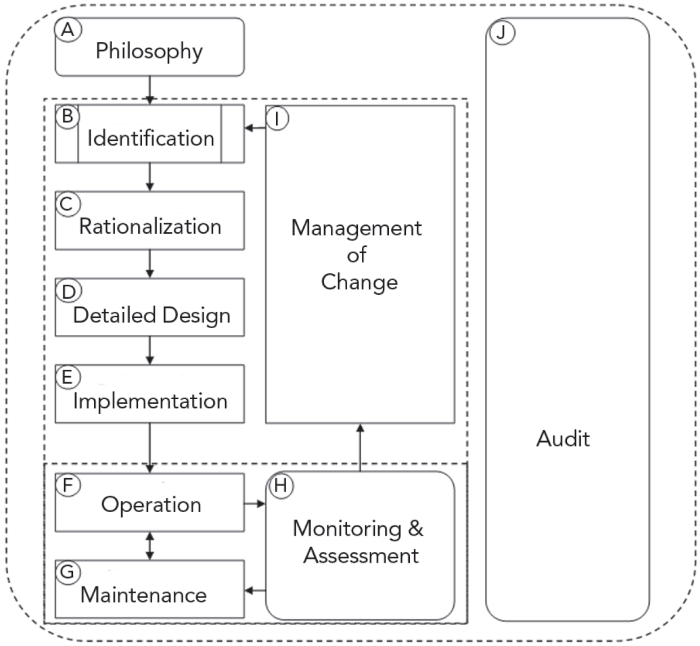


Figure 4-1. The alarm management life cycle based on ISA 18.2 (Hollifield, 2010)

The required tasks, required inputs, and desired outputs of each stage of the alarm management life cycle are summarized in Table 4-2, which shows the outputs of one stage are the inputs for the next stage (Stauffer, 2012).

Table 4-2. Summary of tasks, inputs, and outputs in the alarm management life cycle (Stauffer, 2012; Goel et al., 2017)

Stage	Stage title	Tasks	Inputs	Outputs
A	Philosophy	Define philosophy and requirements for the alarm management	Industry standards and practices, corporate standards, and engineering practices	Alarm philosophy document, alarm system requirement specification (ASRS)
B	Identification	Find and list potential alarms	Alarm database, operating ranges/limits, process hazard analysis (PHA) / layer of protection analysis (LOPA) reports, piping and instrumentation diagrams (P&IDs), operating procedures, safety requirements specification (SRS), etc.	List of all potential alarms for the facility
C	Rationalization	Alarm classification, prioritization, rationalization, and documentation	Alarm philosophy document and list of all potential alarms	Master alarm database (MADB), alarm design requirements
D	Detailed design	Alarm design, human	Master alarm database	Completed alarm

		machine interface (HMI) design	and design requirements	design
E	Implementation	Alarm testing and training	Completed alarm design and alarm database	Operational alarms, alarm response procedures
F	Operation	General plant operation where operators respond to alarms and plant is running in normal condition	Operational alarms and procedures for response to alarms	Alarm history/data
G	Maintenance	Inspection and testing	Alarm reports, alarm philosophy, and inspection and testing procedures	Alarm reliability data
H	Monitoring & assessment	Measure alarm system performance and compare to key performance indicators (KPIs) defined in the alarm philosophy; identify problem alarms (nuisance alarms, frequently occurring alarms, etc.)	Alarm history and alarm philosophy	Alarm monitoring reports and proposed changes
I	Management of change	Process to authorize additions, modifications, and deletions of alarms	Alarm philosophy and changes proposed	Approval for alarm changes
J	Audit	Periodic audits for alarm management processes and update philosophy document if required	Standards, audit protocols, and alarm philosophy documents	Recommendations for improvement

Crampin (2017) benchmarked alarm management in the process industry and provided 28 recommendations for alarm design in the control room:

1. Present attentional directors close to the operator's line of sight within a maximum 15° cone for high priority alerts and 30° cone for all other warnings;
2. Use a master signal within a 15° cone of the line of sight if attentional directors cannot be placed within a 30° cone;
3. Eliminate the possibility of confusing alerts with any other type of display;
4. Ensure alerts are presented until the operator has responded or until the alert state is no longer active;
5. Ensure alerts have at least twice the luminance of other displays in the working environment;
6. Use larger characters for alert text (up to about 60 minutes of arc), especially under adverse viewing conditions;
7. Accepted alerts should be clearly distinguishable from unaccepted alerts;
8. Consider polarity changes of contrast for different alert text and symbols;

9. A sound and flashing light should accompany the onset of an alert;
10. On accepting an alert, any accompanying sound should cease and the flashing resort to a steady light;
11. Add auditory voice signals to high priority alerts;
12. Auditory alerts and warnings should be presented at a sound level above the normal ambient noise of the equipment or control room;
13. A pulsed tone is more likely to be received by an operator than a continuous tone;
14. Female voices are more likely to be obeyed by male operators;
15. Perception of red information is about 75% slower than the perception of other information in peripheral vision because colour perception is poorer peripherally;
16. Signals presented in the bottom of the visual field (about 60 minutes below the line of sight) are detected slightly faster than those at the top;
17. Depending on size and contrast, close alternately flashing stimuli in peripheral vision can appear as one moving stimulus, caused by an effect sometimes referred to as stroboscopic apparent motion. Two alerts may be perceived as only one, hence all flashing indicators should be synchronized;
18. Auditory signals should not be expected to carry the detailed information that is contained in words until attention has been gained. Once attention has been gained by an initial nonverbal signal or attention, it is permissible to add spoken words later;
19. Presentation of alerts should lead the operator through the perceptual (initial detection), decision making and psycho-motor (action required) processes concerned with handling that alert;
20. In the absence of any sophisticated alert handling system, alerts should be listed chronologically. Most recent alerts should appear at the bottom of the list;
21. For listed alerts, the entire background colour, red or amber, should flash. Note that the text should be either white or black to achieve the best contrast ratio for readability;
22. Scrolling up or down needs to be at a speed that enables either rapid access to an alert some distance up or down the list, or fast access while still being able to read each alert as it scrolls by;
23. Inactive alerts should be accessible for training purposes but not as part of normal operating procedures;
24. Alerts that have been accepted should change from flashing to steady. Once dealt with, they should disappear from the list. Should an alert not be accepted and it subsequently resolves itself, for example, by a low pressure resuming its normal state, then this should still flash until accepted, whereupon the alert disappears;
25. A mute should be provided for some alerts. However, this should be confirmed by trials appropriate to the design issue;
26. A separate accept button should be provided for alerts;

27. The first operation of the ‘alert accept’ button should mute all current alerts. Note that each alert has to be accepted individually to stop it flashing. The first operation of the ‘warning accept’ button should mute all current warnings. Warnings can be accepted either individually or as a whole to economize on time;
28. The individual alert that is to be accepted should be separated slightly from the other alerts listed to make it clear which alert is being accepted.

According to ISA 18.2 and IEC 62682 standards, the human machine interface should provide the ability for the operator to:

- silence audible alarm indications (i.e., without acknowledging the alarm);
- acknowledge alarms;
- place alarms out of service through access controlled methods as allowed in the philosophy;
- modify alarm attributes through access controlled methods only;
- initiate an alarm shelving function;
- display alarm messages; and
- assign alarms to operator stations (Hollifield, 2020).

ISA 18.2 lists the alarm states as normal, unacknowledged, acknowledged, return to normal unacknowledged, shelved, suppressed by design, out of service, and latched, and differentiates them by employing a combination of visual and audible indications (see Table 4-3). The last of these is omitted from the IEC list for alarm states (Siemens, 2010; Hollifield, 2020).

Table 4-3. Alarm state indications recommended by ISA 18.2 (Siemens, 2010)

Alarm State	Audible Indication	Visual Indication		
		Colour	Symbol	Blinking
Normal	No	No	No	No
Unacknowledged (new) Alarm	Yes	Yes	Yes	Yes
Acknowledged Alarm	No	Yes	Yes	No
Return to Normal State Indication	No	Optional	Optional	Optional
Unacknowledged Latched Alarm	Yes	Yes	Yes	Yes
Acknowledged Latched Alarm	No	Yes	Yes	No
Shelved Alarm	No	Optional	Optional	No
Designed Suppression Alarm	No	Optional	Optional	No
Out of Service Alarm	No	Optional	Optional	No

In the railway industry, the Ladbroke Grove accident and subsequent Cullen Inquiry are regarded as a turning point in alarm management. After this time, formal requirements for alarm design within signalling control centres were developed and problems related to alarm management were addressed (Traub and Hudson, 2007). Moreover, using the process industry’s standards in the rail industry to manage alarms demonstrated the differences between operations, failures, and deviations of these two industries. Thus, several rail specific alarm management standards and guidance such as the London Underground Library (LUL) S1218 standard (the Human Systems Interaction – Dialogues and Notifications standard of the London Underground; LUL (2014)), the Thameslink Program Strategy Alert/Alarm Strategy (NR, 2013), and the Alarms and Alerts Guidance and Evaluation Toolkit (RSSB, 2009) were generated (Heape, 2015). The Association of American Railroads (AAR) and the Railway Association of Canada (RAC) also cooperatively developed comprehensive guidelines for specifications of positive train control systems in North America. Railway companies including Amtrak, Burlington Northern Railroad (BN), Swedish State Railways, the Japan Rail (JR) companies, Société Nationale des Chemins de Fer Français (SNCF, the French National Railways), and Deutsche Bahn AG (DB, German Railways) individually created their own requirements (Einhorn et al., 2005). A list of alarm management guidelines and standards for industries and railways are provided in Appendix E.

All of these standards and guidance aim to address alarm related issues for railways. In the Alarms and Alerts Guidance and Evaluation Toolkit proposed by the RSSB (2009), for example, general issues (e.g., modality, false alarms, alert philosophy, standardization, and characteristics of users), auditory issues (e.g., number, rate, prioritization, confusability, and loudness), visual issues (e.g., number, visual field, prioritization, colour, flash rates, legibility, luminance, glare and reflectance, and language), and sound design principles were covered.

In research conducted by the FRA to identify contributing factors and possible mitigation measures for SPAD, several good practices for in cab alarm design were offered (Safar et al., 2020), as follows:

- Train operators should be able to control the display of nonsafety critical alarms;
- Train operators should be allowed to acknowledge and silence alarms;
- Only safety critical alarms should be displayed during high workload periods (e.g., in the terminal);
- Nonsafety critical alarms should be shown during times of low or moderate workload;
- The number of nonsafety related alarms should be minimized;
- Noncritical alarms that do not require an immediate response should not occur while the train is operating;
- False alarms should be eliminated or reduced;
- Visual route guidance and upcoming signal indications should be provided in cab to help train operators better anticipate and respond to signals;
- Cab signals, PTC, and other warning systems should be used in both terminals and yards to prevent mode confusion; and
- Train operators should clearly be notified of mode transitions and system failures.

Dadashi et al. (2010) provided design implications intended to improve alarm handling in the railway control room and highlighted the optimum formats of information in each of Rasmussen et al. (1994)'s three cognitive processing modes, i.e., rule based, skill based, and knowledge based behaviour. In skill based mode, the information should be in the format of space-time patterns;

in rule based mode, easily conceivable words and symbols are useful; in knowledge based mode, operators need a semantic form of information. Dadashi et al. (2010) proposed that alarm initiated activities and the area of the interface used during each of these activities should first be determined. Then, knowing the cognitive mode of an activity and its suitable form of information, the designer can determine the optimum information format for each of the areas on the interface.

4.1 Visual alarms

Visual alarms can precisely present the nature of the problem and the required action, and are preferable in situations with a high level of ambient noise. Moreover, their urgency levels can be modified by changing their colours and flash rates (Multer et al., 1998).

The RSSB (2016) outlined location, size, colour, start and end conditions, behaviour, and identification as requirements for the design of driver machine interface indications in the locomotive cab. Furthermore, the difference in preferences for in cab displays must be taken into account during visual warning design. For example, Japanese train operators prefer linear speedometers while American train operators favor circular speedometers (Einhorn et al., 2005).

Research studies carried out by Kuehn (1992), Askey (1995), and Einhorn et al. (2005) demonstrated that providing preview information on the cab display improves safety and performance. Research by the East Japan Railway Company (JR East) to determine the best in cab display of upcoming signals revealed that providing a train operator with more than two blocks of information is too much (where a block is a section of track that can be occupied by only one train at a time (Takashige, 1999)). They also found that displaying the maximum allowed speed instead of showing block signals is more useful because it helps train operators keep the train within the authorized limits for the next block (Einhorn et al., 2005).

Multer et al. (1998) proposed that the principles of developing a dialogue design presented by Schneiderman (1992) should be applied when a display is designed for a locomotive cab. These principles are as follows:

- Support the train operator's need for control. When train operators work with a system, they must feel the system is under their control. The system should avoid actions that surprise the train operator, tedious sequences of data entries, and difficulty in obtaining the necessary information.
- Aim for consistency. Consistency is required for sequences of actions in similar situations, and for terminology used in prompts, menus, and help screens.
- Minimize short term memory load. Displays should be designed in a way that minimizes the train operator's memory load. Humans can generally remember seven plus or minus two chunks of information.
- Facilitate the recovery from errors. The system should be highly reliable to prevent system failure; however, it should be able to detect an occurred error and suggest to the train operator how to handle it.

4.2 Audible alarms

An auditory alarm must distract the operator from the main task and provide them with relevant information. First, it must create a correct perception of the urgency of the situation. Second, it must provide clues about what initiated the alarm, using a customized sound iconography. Third, it should give information to the operator about the location of the hazard (Hermann et al., 2011).

Auditory warnings are categorized into speech and nonspeech (nonverbal). Speech warnings are those that embody human speech, while nonspeech (nonverbal) warnings include tones, mechanical buzzers, klaxons, and bells (Wogalter, 2006; Hermann et al., 2011). While nonspeech alarms attract attention more effectively and cause a faster reaction compared to speech alarms, speech based alarms convey more information but are not suitable for all contexts (Hermann et al., 2011).

Audible alarms have a potential advantage over visual displays because they do not need directional search, operators usually show a faster reaction time to them, they have a higher probability of eliciting a response in emergency conditions, they are not affected by visual noise, and they are flexible in terms of user mobility (Stanton and Edworthy, 1999; Wogalter, 2006; Hermann et al., 2011). Operator reaction to auditory alarms is usually 25 ms quicker than to visual alerts in a quiet environment (Crampin, 2017).

Intensity, frequency, attention getting ability, psychological salience, and noise penetration ability are some features of acoustic warnings that are determined in the context of the background noise environment and the role they are required to play (Stanton and Edworthy, 1999). A range of research illustrates how the 'perceived urgency' of audible alarms can be defined by making changes in the key acoustic variables, i.e., pulse rate, pitch, frequency, harmonic structure, and repetition. Furthermore, operators respond to female voices much faster than male ones (Multer et al., 1998; RSSB, 2010a). Edworthy et al. (2011) reported that the learnability, distinguishability, and audibility of alarms are important factors that should be taken into consideration when in cab warning systems are designed. Learnability of auditory alarms differs regarding the type of sound; abstract alarms are the hardest to learn, verbal sounds the easiest, and auditory icons easier than abstract alarms and almost as easy as speech. A closer semantic relationship between sounds and their meanings increases their learnability (Edworthy et al., 2011).

According to Patterson (1982) guidelines, which were adopted for the design of the TPWS audible alarms, the specifications of auditory alarms are as follows:

- Each alarm should have variation in loudness over the duration of the sound and a gradual onset to reduce startle;
- The suitable pitch for an alarm is between 300 and 600 Hz; and
- It should be taken into consideration that alarms with similar temporal patterns are more likely to be confused with each other.

Nonverbal warnings should be in the range of 200 to 5000 Hz, ideally 500 to 3000 Hz. The loudness of alarm sounds should be higher than the level of ambient sounds, but not so loud that they startle or disrupt the proper response (Multer et al., 1998). Experience from aviation and medical environments has revealed some issues with respect to audible alarms, specifically that there are usually too many of them and that they are too loud, too frequent, and sometimes psychologically inappropriate (Stanton and Edworthy, 1999).

4.3 Common alarm problems

This section describes problems that are usually referred to as “nuisance” or “bad actor” alarms. These types of alarms can cause hazardous situations because operators are susceptible to missing important alarms among a large number of bad actor alarms.

4.3.1 Alarm flooding

Alarm flooding is a situation during which more alarm activations occur than what the operator can effectively handle (Hollifield and Habibi, 2007; Rothenberg, 2009; Hollifield and Habibi, 2010). It starts when the alarming rate reaches at least 10 alarms per 10 minutes and finishes when the alarming rate per 10 min decreases to below 5 (Hollifield and Habibi, 2010). Alarm flooding results in increased workload on the operator, which raises the risk of missing a vital alarm (Goel et al., 2017). During alarm flood conditions, the operator cannot acquire valuable information from alarms, and thus it is highly probable to either select an incorrect alarm to which to respond and misjudge the situation or overlook all alarms and pay no attention (Rothenberg, 2009). Standing alarms, chattering alarms, fleeting alarms, repeating alarms, and stale alarms are classified as the main reasons for alarm flooding (Goel et al., 2017).

4.3.2 Chattering and fleeting alarms

According to the ISA-18.2 standard (ISA, 2016), a chattering alarm “repeatedly transitions between the alarm state and the normal state in a short period of time.” Sub categories of chattering alarms are repeating and fleeting alarms. According to EEMUA 191 guidance (EEMUA 191, 2014), repeating alarms are defined as “the same alarm raising and clearing repeatedly over a period of time” and fleeting alarms as “alarms which are raised and cleared shortly afterward” (but not necessarily repeated). Chattering alarms, also called cyclic alarms, are one of the main causes of nuisance alarms (Goel et al., 2017).

ISA (2016) and Hollifield and Habibi (2007) specified the term “short period of time” in the definition of a chattering alarm as 20 seconds (i.e., more than three times per minute). Rothenberg (2009) considered a period of 6 seconds for a chattering alarm (i.e., 10 or more alarms within 1 minute) and 90 seconds for a repeating alarm (i.e., 10 or more alarms within 15 minutes).

4.3.3 Stale and standing alarms

Stale and standing alarms initially come in, but remain on the alarm page for extended periods (usually more than 24 hours) and the operator cannot clear them (Hollifield and Habibi, 2007). Standing alarms have a shorter term while stale ones are around almost “forever” (Rothenberg, 2009). Rothenberg (2009) defined stale alarms as alarms that are acknowledged but uncleared for between 8 and 12 hours during one shift.

4.3.4 Duplicate (related) alarms

Hollifield and Habibi (2007) classified duplicate alarms into two types: configured duplicate alarms and dynamic duplicate alarms. In definitions provided by Rothenberg (2009), configured duplicate alarms and dynamic duplicate alarms were respectively called consequential alarms and related alarms.

Duplicate (consequential) alarms are one or more alarms that almost always (e.g., 90% of the time) follow a first (initiating) alarm within a short period of time (e.g., 5 minutes). The duplicate alarms are often unnecessary and are the result of interconnections between points in a distributed control system (DCS). In fact, a single abnormal condition produces several alarms that may duplicate each other (Hollifield and Habibi, 2007, 2010; Rothenberg, 2009). Dynamic duplicate alarms occur when different alarms always activate simultaneously based on the configuration (e.g., having identical limits) (Rothenberg, 2009). Rothenberg (2009) called two or more alarms related (duplicate or correlated) if they cooccur within 2 seconds more than 90% of the time. In complex plants, alarms that are placed on several variables may be either redundant or highly overlapping and cause related (duplicate) alarms. Unlike consequential alarms that activate after other specific alarm(s), related alarms occur either before or after other specific alarm(s).

4.4 Alarm performance metrics

Key performance indicators (KPIs) are adopted to measure the performance level of an alarm system. The KPIs illustrate basic usability metrics and benchmarking as described in guidelines and standards including EEMUA 191 and ANSI/ISA 18.2 standards (Goel et al., 2017). For example, “average alarm rate”, “maximum alarm rate”, and “% of time alarm rates are outside of acceptability target” are three main KPIs suggested by the EEMUA to evaluate the performance of an alarm system (HPS, 2011).

Excessive numbers of alarms have a lower probability of response and negative impacts on safety (see Figure 4-2) (Brown, 2003).

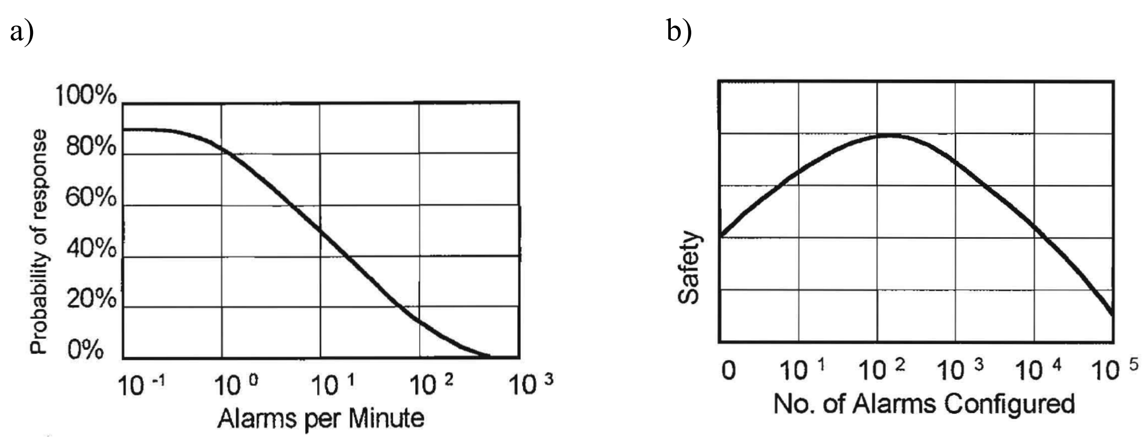


Figure 4-2. Effect of the number of alarms on a) the probability of response and b) safety (Brown, 2003).

Due to the negative consequences that excessive numbers of alarms can have on operators, activation alarm rate is regarded as one of the key aspects of alarm management. The proposed number of all alarms by EEMUA 191 (2014) for steady operation and after plant upset are provided in Table 4-4 and Table 4-5.

Table 4-4. Benchmark for average alarm rates (EEMUA 191, 2014)

Long term average alarm rate in steady operation	Acceptability
More than one per minute	Very likely to be unacceptable
One per 2 minutes	Likely to be overdemanding (industry average in HSE survey)
One per 5 minutes	Manageable
Less than one per 10 minutes	Very likely to be acceptable

Table 4-5. Alarm rates following plant upset (EEMUA 191, 2014)

Number of alarms displayed in 10 minutes after plant upset	Acceptability
More than 100	Unacceptable
20-100*	Overdemanding
10-20*	Manageable (but maybe difficult if several of the alarms require a complex operator response)
Under 10	Acceptable

*The benchmark is applicable to process industries with centralized control rooms.

In addition to rates of alarm activation, the priorities of alarms play an important role in alarm management because excessive numbers of high priority alarms cause extremely tense operations. The proposed priority allocation of all alarms on the system is provided in Table 4-6 (EEMUA 191, 2014).

Table 4-6. Priority allocation of alarms (EEMUA 191, 2014)

Priority	Priority distribution
Low	80%
Medium	15%
High	5%

Benchmarks for target values of the KPIs regarding the ISA 18.2 standard for the process industry are presented in Table 4-7.

Table 4-7. ISA 18.2 alarm performance KPIs (ISA, 2016)

Metric	Target value	
Annunciated alarm per time	**Very likely to be acceptable**	**Maximum manageable**
Annunciated alarms per day per operating position	150	300
Annunciated alarms per hour per operating position	~ 6* (average)	~ 12* (average)
Annunciated alarm per 10 minutes per operating position	~ 1* (average)	~ 2* (average)
Metric	**Target value**	
Percentage of hours containing more	< 1%	

than 30 alarms	
Percentage of 10 minute periods containing more than 5 alarms	< 1%
Maximum numbers of alarms in a 10 minute period	10 or less
Percentage of time the alarm system is in a flood condition	<1%
Percentage contribution of the top 10 most frequent alarms to the overall alarm load	<1% (target), maximum 5%, with action plans to address
Quantity for chattering and fleeting alarms	Zero, action plans to correct any that occur
Stale alarms	Less than 5% on any day, with action plans to address
Annunciated priority distribution	3 priorities: ~80% low, ~15% medium, ~5% high or 4 priorities: ~80% low, ~15% medium, ~5% high, < 1% "highest" other special purpose priorities excluded from the calculation
Unauthorized alarm suppression	Zero alarm suppressed outside of controlled or approved methodologies
Improper alarm attribute change	Zero alarm attribute changes outside of approved methodologies

*For these metrics, averages should be calculated based on at least 30 days' data

Honeywell Process Solutions (2013) benchmarked some key performance indicators in various standards, as shown in Table 4-8.

Table 4-8. Key performance indicator benchmarks (HPS, 2013).

	EEMUA 191	ANSI/ISA 18.2	Oil & Gas	Chemicals	Power	Other
Average alarms per day	<144 (up to 288 may be manageable)	~150 (~300 may be manageable)	1200	1500	2000	900
Average standing alarms	<10	<5 per day	50	100	65	35
Peak alarms per 10 minutes	<10	≤10	220	180	350	180
Average alarms per 10 minute interval	1	~1 (~2 may be manageable)	6	9	8	5
Distribution % (low/med/high)	80/15/5	80/15/5	25/40/35	25/40/35	25/40/35	25/40/35

5 Human factors issues for in cab warning systems

The International Ergonomics Association (IEA) united the terms ergonomics and human factors in human factors/ergonomics (HF/E or E/HF) and defined it as a 'scientific discipline concerned with the understanding of interactions among humans and other elements of a system". IEA further divides HF/E into physical ergonomics (e.g., topics related to working postures and repetitive movements), cognitive ergonomics (e.g., topics related to mental workload, decision-making, human computer interaction, and human reliability), and organizational ergonomics (e.g., topics related to communication, crew resource management, and teamwork). HF/E aims to reduce human error, improve productivity, and enhance safety and comfort with a specific focus on the interaction between a human and the thing of interest (HFES, n.d). This section provides a review of the potential human factors issues that arise from in cab warning systems and investigate rail specific performance shaping factors (PSFs).

5.1 Human factors issues of in cab warning systems

5.1.1 Workload

Wickens et al. (2015) defined workload as the amount of information processing resources used per time unit, for task performance. It can be physical (e.g., pressing a button), visual (e.g., scanning the light on the display), and cognitive (e.g., interpreting a signal) (Halliday et al., 2005).

The NASA-TLX (Task Load Index), SWAT (Subjective Workload Assessment Scale), ISA (Instantaneous Self Assessment), Integrated Workload Scale (IWS), DLR-WAT, and DALI (Driving Activity Load Index) are common subjective scales used to measure workload (Oppenheim et al., 2010; Verstappen et al., 2017; Brandenburger et al., 2018). In addition, the Multiple Resources Model offers the ability to map workload for system aspects that still are under development and have not yet been introduced in the cab; other measuring scales such as the SWAT or NASA-TLX do not offer this possibility (Verstappen et al., 2017). The most widely used scale, i.e., the NASA-TLX, measure workload in six dimensions: mental demand, physical demand, time pressure, performance, effort (both mental and physical), and frustration (Davies et al., 2012). These six dimensions also align with the common sources of stress, which reflects the relationship between workload and stress (FRA, 2014). According to the Workload Assessment Tool (WAT), workload is comprised of the three dimensions of demand, time pressure, and conflicts (Foulkes, 2004).

Workload may be characterized as the reaction to demand or stress, with either positive or negative consequences (Oppenheim et al., 2010). The workload to performance relationship is illustrated in Figure 5-1. The ideal workload situation happens when “homeostasis” is achieved, which can be described as a balance where coping and adaptation to task demands are optimal. Any deviations from the optimal workload level, either an increase or a decrease, can contribute to lower performance (Oppenheim et al., 2010; FRA, 2014). Under-load can result in loss of situational awareness, boredom, fatigue, frustration, and over confidence while over load causes irrational problem solving, loss of situational awareness, exhaustion, and low self esteem (FRA, 2014). Nneji et al. (2019) highlighted that the optimal workload level is between 30% to 70% utilization.

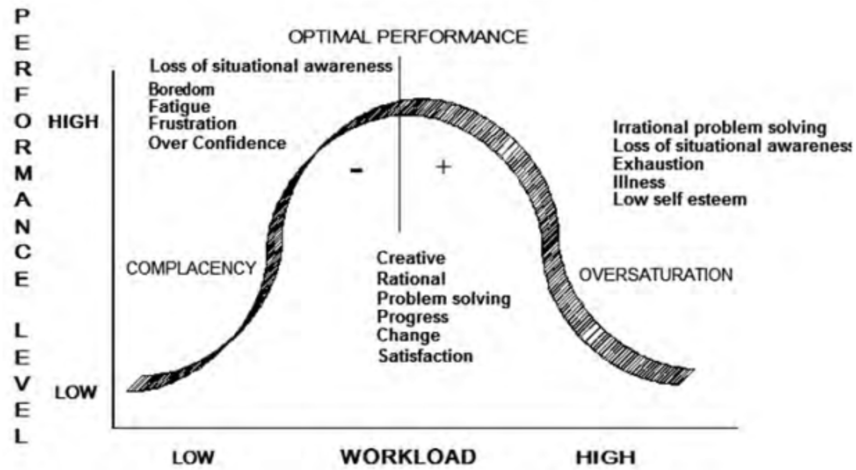


Figure 5-1. Workload versus performance (FRA, 2014)

The NASA-TLX asks the operators to determine their subjective workload levels ranging from zero (very low) to one hundred (very high) on six subscales (Brandenburger et al., 2018). The analysis of more than 1000 global NASA-TLX studies revealed that the definition of low, optimal, and high workload regarding the NASA-TLX score obtained is not unique and differs based on the task type. For example, for an air traffic control task, the lowest workload reported was 6.21 while for monitoring, driving a car, and pilot aircraft tasks, the respective scores were 20, 15, and 16 (Grier, 2015). In contrast to the NASA-TLX, the DLR-WAT measure explicitly indicates the optimal workload level. The DLR-WAT consists of eight workload subscales, namely information acquisition, memory retrieval, decision making for differentiating mental workload, physical workload, temporal workload, effort, frustration, and performance. The first six subscales range from zero (very low) to 200 (very high). The seventh subscale, i.e., frustration, ranges from 100 (no frustration/ optimal) to 200 (very high frustration), and the last subscale, i.e., performance, only ranges from zero (very low performance) to 100 (high performance/ optimal). In the DLR-WAT method, the score of 100 always represents an optimal value (Brandenburger et al., 2018).

It is argued in the literature that the integration of any new technology into a system can, on the one hand, cause an overload of mental workload but can, on the other hand, lead to underload because of the increased automation (Robinson et al., 2015). Robinson et al. (2015) discussed how implementing a mitigation strategy that raises workload during an under load period of train driving has beneficial effects on low workload, low arousal, and fatigue.

Several research studies have been conducted to investigate the impacts of a new device on the workload levels of train operators. For example, the RSSB assessed the effectiveness of an In cab Signal Reminder Device (ICSRD) and concluded it can provide safety advantages over and above the existing AWS system. However, this system has the potential to increase workload by requiring additional cognitive and physical tasks. This can increase train operator stress and thus response time (Halliday et al., 2005). Halliday et al. (2005) described that although semaphore signalling seems effective for the AWS, it may impose an additional cognitive demand on the train operator in the ICSRD system. This is because the train operator would need to first translate the meaning of the semaphore signal to a colour light signal to understand the device and then continuously compare its display with the external semaphore signals as they are approached. They also highlighted that the ICSRD can cause a reduction in the amount of available time to respond and thus place time pressure on the train operator as they need to carry out more tasks compared to the AWS. Canceling an AWS warning requires Simple Reaction Time (SRT) (i.e., the reaction time to respond to one stimulus requiring only one type of response) as it has only one type of response to a stimulus. When it comes to ICSRD with at least five types of stimuli all requiring a different response (i.e., red, single and double yellow, green and speed restriction or "other"), Choice Reaction Time (CRT) (i.e., the time is taken for an individual to make the correct response to two or more possible stimuli requiring different responses), which is longer than the SRT, should be taken into account. Therefore, the current 2.5 second time limit for AWS response may need to be extended to approximately 5 seconds to provide the opportunity for a comfortable CRT, interpretation, and operation of the ICSRD system.

Distributed cognition refers to the theory that cognition and knowledge are not only available "in the head" but also distributed across the individual's social and physical environment (Perry, 2003). The RSSB (2002) compared the imposed workload level of the two types of DRA systems on train operators and concluded that the AWS activated DRA, in which the system is automatically set with regards to the tasks related to AWS, poses a lower workload to the train operator compared to the train operatorset DRA.

Crick et al. (2004b)'s research demonstrated that the visual information provided by the ATP system is too much for some train operators to handle, causing increased workload and distractions. Verstappen et al. (2017) applied multiple resources theory along with the priority, adapt, resource, regulate, and conflict (PARRC) model to determine the workload posed by introducing new devices in Netherlands Railways train cabs. They found that monitoring these innovative devices during driving requires multiple resources (e.g., visual and cognitive resources), which can conflict with the primary driving task. This can cause an increase in workload and influence driving performance. Van Der Weide (2017) found that train operators experienced notably lower workload when driving with ERTMS compared to driving with ATB (i.e., the legacy system in Netherland), and very experienced train operators even reported boredom. Historical data related to head up displays revealed a substantial decrease in train operator workload, but with no appreciable impact on train operator performance (Davies et al., 2012).

Analyses performed by Foulkes (2004) and Buksh et al. (2013) showed the Level 2 ERTMS, in which all signalling indications are shown in cab and there are no lineside signals, contributes to a lower workload than the current train driving task. However, according to studies conducted, a variety of factors including the level of ERTMS implemented, train operator strategy, type of traction, and transitions into and out of ERTMS could impact workload under ERTMS (Robinson et al., 2015). For example, Foulkes (2004) determined that overlaying lineside signals can raise workload compared to the existing GB train driving task. Transition in/out of ERTMS and conflicts between the ERTMS braking profile and the train operator's route knowledge about braking points can cause a higher workload (Porter, 2002; Foulkes, 2004; Buksh et al., 2013).

Transition in/out of a train protection system, particularly in complex areas such as stations and level crossings, can cause an increase in workload (Monk et al., 2017).

A series of studies about the workload level of the PTC system revealed that frequent, often non informative audio alarms of PTC systems and the required data entry during initialization and/or operation are sources of workload (Wreathall et al., 2007a; Roth and Multer, 2009; Roth et al., 2013). Train operators must manually input the required data that are used as parameters for safe operation into the PTC system. This task is carried out at the start of a trip, after a shutdown of the system, and after a penalty brake application and poses not only the risk of data entry errors but also additional workload and distraction. Wreathall et al. (2003) emphasized that train automation systems usually automate the easy parts of a task, reducing workload during times when the workload is already minimal while requiring extensive human involvement in challenging situations when the workload is high. Therefore, during high paced high risk situations where the workload is already very high, there is an increase in workload demands (Wreathall et al., 2003).

During Wreathall et al. (2007a)'s interviews with train operators who have had experience driving with the PTC system, i.e., the incremental train control system (ITCS), expressed concerns regarding high numbers of audio warnings that require to be acknowledged. These can create distractions and high workloads for the train operators. For example, a train location determination system (LDS) of the PTC system sometimes fails to detect the train location. In such a situation, the LDS failure alarm goes off repeatedly and needs the train operator to press the cancelation button several times to acknowledge the alarm, imposing heavy workloads. The train operators recommended that audible alarms should be restricted to alert them to potential issues (e.g., an upcoming speed restriction that might be missed) and should be avoided for positive circumstances (e.g., when a speed restriction is no longer in effect) (Wreathall et al., 2007a).

5.1.2 Distraction

Verstappen et al. (2017) conducted a study about the effects of innovative devices in Dutch train cabs on train operators using the PARRC model. They highlighted that conflicts between the use of these devices (e.g., communication devices or information devices) and train driving tasks, particularly in critical situations, can be a source of distraction for the train operator. However, train operators usually employ driving strategies in a way to adjust these demands and prevent conflicts between tasks. For example, if the train operator uses the route information devices at the correct time, they can show a proactive driving style and effectively manage the primary driving task and secondary tasks by anticipating critical points on the route ahead, leading to distraction risk mitigation. Moreover, adopting in cab warning systems such as AWS and ORBIT can help the train operator to redirect attention towards the primary task in critical situations (e.g., approaching a restricted signal aspect) and reduce the risk of distraction.

Safar et al. (2020)'s interviews with US train operators revealed that nonintegrated in cab displays and alarms can be a contributory factor for distraction and SPAD. The train operators indicated that there are often nonsafety / noncritical alarms that may be distracting. These alarms may sound continuously when activated despite being acknowledged, causing annoyance and distraction to the train operator. Furthermore, a frequent false alarm also raises the risk of ignoring safety critical alarms by the train operator (Safar et al., 2015, 2020). Frequent, often non-informative audio alarms created by PTC systems can be a source of distraction (Wreathall et al., 2007a; Roth and Multer, 2009; Roth et al., 2013). Using devices such as ICSRD and DRA, which need to be used on the move, may distract train operators' attention away from signals ahead while using the device (Halliday et al., 2005).

Vigilance devices, on the one hand, are argued to reduce distraction through an increase in levels of vigilance, arousal, and attention (Halliday et al., 2005). However, on the other hand they can divert the train operator's attention away from the primary task of driving (Wilde and Stinson, 1983). Crick et al. (2004b) found that external noise levels, for example, from opening windows or when passing through tunnels, can also distract train operators from systems and mask alarm sounds.

5.1.3 Loss of situation awareness

Situation awareness (SA) is the ability of a person to correctly interpret, recognize, and anticipate events (Halliday et al., 2005). Endsley (1996) defined SA as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future". Endsley (1995) categorized SA into three levels: level 1 (perception), level 2 (integration and comprehension), and level 3 (projection) (see Figure 5-2). Several empirical studies have shown these levels can differ independently (McBride et al., 2014). The situation awareness global assessment technique (SAGAT) and decision making questionnaire (DMQ) are two metrics applied to measure SA (Park et al., 2020).

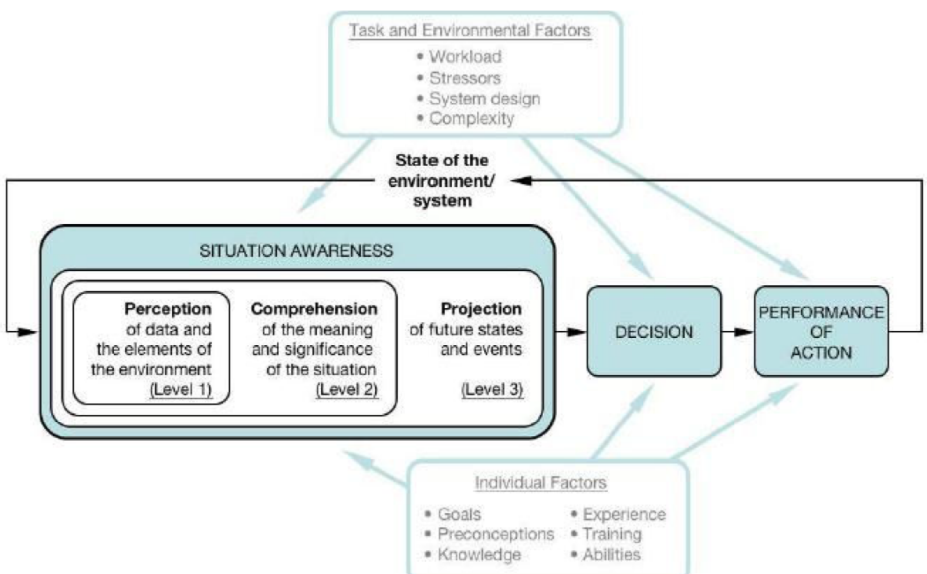


Figure 5-2. Model of situation awareness (Oppenheim et al., 2010)

The inability to properly perceive the situation contributes to a level 1 error. Omission, attentional narrowing, distraction, high workload, unobserved available information, unclear provided information, and wrongly presented information are contributing factors to level 1 SA error (Park et al., 2020). Perception failures represented about 76% of the SA errors in a study of the aviation industry (Endsley, 1995).

In some cases, the information is correctly perceived; however, its cause and meaning are not understood, and hence a level 2 SA error occurs. The causes of this type of error include having an incorrect mental model, being unfamiliar with the situation, and having limited working memory. Moreover, level 2 errors can play a main role in incorrect mental models. In such situations, the driver places overreliance on default values and general expectations despite having a correct mental model about system functions. As an example, a train operator on a new route may drive based on their information and expectations about a previous route they drove (Park et al., 2020). Level 2 errors represented 19% of SA errors in the aviation domain (Endsley, 1995).

A level 3 SA error occurs when the train operator fails to project situations into the future and, consequently, is not able to execute the task by proactive decision making. Inadequate mental resources are the key explanation for why level 3 SA errors occur, wherein the driver has a poor mental model for anticipating the future in spite of having thorough awareness of what is happening in the present (Park et al., 2020). Level 3 errors represented 6% of SA errors in the aviation sector (Endsley, 1995).

SA is reflected in a train operator's actions and response time (Halliday et al., 2005; Park et al., 2020). According to the conscious thinking processes that are needed to attain SA, longer response times are expected in decision making with good SA. When the levels of train operator vigilance (SA) or arousal decrease, their attention may deviate from the task of checking signals and thus increase the risks of making skill based errors. An operator may automatically respond during low arousal despite the loss of SA (Halliday et al., 2005). Furthermore, SA is commonly assumed to improve with experience; thus, novices have low SA and are more dependent on displays of information (Halliday et al., 2005). Crick et al. (2004b) found that more experienced train operators had considerably longer response times to the AWS, possibly reflecting the greater understanding by these individuals of the need to be aware of the signal before responding. Moreover, if ICSRD was used correctly, it would help train operators be aware of signals irrespective of their experience (Halliday et al., 2005).

According to information available, expert judgment, and the simulator experiment, Thomas and Davies (2008) and Davies et al. (2012) proposed that head up display of speed and brake information can help the train operator to maintain situational awareness. Endsley (2016) proposed the principles of Situation Awareness Oriented Design (SAOD) as a design procedure. Later, Park et al. (2020) developed design guidelines for driving SA in smart vehicles to address the limitations of Endsley (2016)'s SA principles for vehicular SA design.

Due to the fact that an occasional response requiring message to the operator can prevent a vigilance decrement (McLeod et al., 2003), Dore (1998) suggested the PRO Active AWS in which the train operator is required to provide an answer about the upcoming signal aspect by pressing either a "clear" button or "caution" button. In Belgium, a relatively similar system was used in which the audible alarms were effectively "switched off" to arouse a more active response from the train operator. Similarly, as the ICSRD requires the train operator to have an active reaction, it could increase SA and reduce automatic responses. Therefore, although the rise in workload induced by using equipment such as the ICSRD can have negative impacts, the need for train operators to make an active decision can result in a benefit by maintaining or even improving the degree of train operator arousal, vigilance, and attention (Halliday et al., 2005).

5.1.4 Mode confusion

Mode confusion (mode error) happens when the user is confused about the system's current mode (i.e., errors in SA) or is unable to recall how the system reacts in the current mode (i.e., slips of action) (Wreathall et al., 2007b). There is a risk that the train operator does not understand or forgets that the mode change has occurred, which can result in mode errors (Sebok et al., 2015). Safar et al. (2020) clarified that train operators accustomed to driving within cab signal territory may forget they are within no cab signal territory and wait for the speed reduction alarm to adjust the speed.

Changes in operating conditions can be the main cause of mode confusion. These kinds of problems may be triggered by frequent switching between trains that have the DRA and those that do not, or switching between trains with train operator set DRA and AWS activated DRA (RSSB, 2002). Crick et al. (2004b) reported that more than half of the interviewed train operators had to switch between driving with and without the vigilance system on a daily basis, requiring changes in driving behavior.

In some cases, train operators correctly acknowledge the AWS alarm but misinterpret the situation (i.e., commit a mode error) and do not respond to the alarm with an appropriate course of action (McLeod et al., 2005a). Several factors contribute to this problem (McLeod et al., 2005a, 2005b; Halliday et al., 2005). First, the AWS alarm and sunflower display are inherently ambiguous because the AWS does not fully discriminate between different sources of alarms and the same alarms can refer to a variety of risks. Furthermore, the sunflower only differentiates between a bell and a horn, not between the origins of the AWS alarm. In fact, the AWS alarm and sunflower display together can refer to four different signal aspects and at least eight other possible states regarding signs, warning boards, emergency, and SPAD indicators. The extension of AWS also provides far more warnings (e.g., emergency speed restriction (ESR), temporary speed restriction (TSR), or permanent speed restriction (PSR) warnings) compared to AWS and exacerbates the problem. Furthermore, some of these warnings may be activated simultaneously. In such situations, the train operator’s memory is the only way to remember how many alarms are current, and the train operator’s correct interpretation is required to determine to which of more than one possible condition the alarm refers. Crick et al. (2004c) reported that 61% of their focus group train operators indicated they are occasionally confused about what triggered an AWS warning.

Two types of mode transitions and their related mode confusion are considered for the PTC system. One type of mode transition is when a train is equipped with a PTC system, but depending on the circumstances, the system could be operating or not. For example, on a PTC equipped train, the system may not be operational because the train is outside of PTC territory or because the PTC system is malfunctioning. The second type of mode transition is related to the situation in which a train operator works on both PTC territory and non PTC territory. The potential issues allied with the first type of mode transition is that the train operator may not recognize that the PTC system is not operating or may notice but fail to adequately enhance vigilance to compensate for the lack of PTC protection. When a train is moving between PTC equipped and unequipped areas, i.e., the second type of mode transition, factors including complacency, skill loss, and primary/backup reversal could contribute to train operator errors. If the train operator has become overreliant on the PTC system and, due to temporary workload or distraction, fails to notice or forgets protection provided by PTC is not available at the moment, it can result in complacency and therefore human errors. Skill loss could occur due to the dependency of the train operator on the PTC system for driving tasks and losing essential knowledge for safe driving (e.g., speed limits and boundary limits). Finally, primary/backup reversal is where the crew depends on the PTC system's information, such as current position, speed limit signs, etc., and hence has more trouble running trains that do not have this sort of information available (Wreathall et al., 2007a, 2007b; Roth et al., 2013).

The increase in the number of transitions in a route/work shift can raise the probability of error (Monk et al., 2017). Hence, an inkblot strategy for rolling out ERTMS imposes less workload on train operators than a patchwork strategy when there are fewer transitions. Notably, in an inkblot strategy, ERTMS is rolled out from one starting track towards adjacent areas, while in a patchwork strategy, the development of ERTMS is distributed across the network, e.g., based on technical urgency (Van Der Weide, 2017). Finally, there is evidence of train operators being puzzled by the various alarms triggered by various devices, as well as the potential conflict between alarms, with one masking another (Crick et al., 2004b).

5.1.5 Complacency and over reliance

Roth and Multer (2009) referred to complacency as a general term that reflects the incapability of a train operator to act as well without a system as they could before the system was installed. Complacency can have various negative consequences, such as train operators not detecting the system failure (or it being off), experiencing delays in identifying and reacting to a system failure, and losing their driving skills and therefore not being able to perform the driving task as well when the system is not available as they previously could have (Roth and Multer, 2009; Roth et al., 2013). Complacency tends to criticize the operator for unreasonably depending on a system and is closely connected to the principles of overreliance and excessive trust (Roth and Multer, 2009; Roth et al., 2013; Wreathall et al., 2007a). Abe et al. (2002) reported that over trust in warning systems can cause substantial delays in responding to hazards when there is a mismatch between what the train operator expects and the actual state of the system. Using ICSRD can increase the train operator’s trust in the system. While increased trust has a potential advantage, it can lead to over reliance. When train operators are over reliant on the system, they are highly prone to accept the displayed information even when it is incorrect (Halliday et al., 2005).

The literature review conducted by McBride et al. (2014) determined that trust and over reliance can detrimentally impact error management processes. The more operators trusted the automation, the more they left it in control without supervision (Muir and Moray, 1996). Therefore, when train operators are passive and observant, they are more prone to perform a task based on system feedback rather than anticipatory, self identified strategies. This could be crucial because anticipation is a required factor for higher level SA and a lack thereof could increase automation errors when the system fails (Giesemann, 2013).

McBride et al. (2014) highlighted that the reliability of a system can play a role in complacency and is a double edged sword. On the one hand, the greater the reliability of an automated system, the better the performance when the system is perfectly operating. On the other hand, the reliable automated system increases the tendency to get complacent, which makes the operator less vigilant and less capable of reacting to system errors or failures. With a highly reliable PTC system, train operator performance may decline if the information provided becomes unavailable (Wreathall et al., 2007a). A degree of complacency in checking all alarms was reported by Carey (2015) for cases containing an excess of noncritical alarm messages. The Complacency Potential Rating Scale (CPRS) is a common method to assess tendencies towards overreliance and complacency (Giesemann, 2013).

5.1.6 Visual attention allocation and visual accommodation

Naweed (2014) investigated the skill levels of modern and traditional train driving. He disclosed that, in spite of the existence of in cab devices and signalling systems, the outside area still needs to be searched for danger. It takes time for the eyes to refocus from one viewing distance to another one (i.e., visual accommodation). Specifically, visual accommodation from infinity to a 25 cm sighting distance takes nearly 2 seconds for a 41 year old and around 0.8 seconds for a 28 year old (Halliday et al., 2005). Hence, the transfer of primary information from outside the cab to inside the cab could negatively affect safety due to the shift in attention and visual accommodation increasing the risk of missing out of cab important events (Wreathall et al., 2007a). Halliday et al. (2005) argued the time taken for visual accommodation may result in a higher required response time of 5 seconds, i.e., even more than needed for CRT.

An exploratory eye tracking field study carried out by Naghiyev et al. (2014) illustrated that some train operators are more dependent on the system and reactively respond to situations, while others rely less on the alerts and alarms and are more proactive. Overall, when train operators used the ERTMS system, they spent considerably more time monitoring the speedometer rather than seeing the out of cab environment in comparison to conventional systems. The results of studies conducted by Van Der Weide (2017) and Hely et al. (2015) also confirmed that train operators direct considerably less attention to out of cab than in cab devices when driving trains equipped with ATP systems (e.g., ERTMS) compared to those with conventional systems. The operators of trains equipped with a PTC system (e.g., CBTM, ASES, ITCS, ETMS) also reported a greater need for focusing on in cab displays, at least initially, thus limiting their ability to check outside the cab (Roth and Multer, 2009; Roth et al., 2013). During an examination of PTC systems (i.e., CBTM, ASES, ITCS), the train operators pointed out that they needed to closely track the in cab display to remain within the braking curve and prevent a penalty brake application. The train operators emphasized that when the train traveled within a time window that allowed no flexibility in schedule variation or approached territories with speed restrictions, attention allocation emerged as an issue. For example, when the operators of trains with the ITCS system entered a block with speed restriction, they monitored the time to brake (TTB) countdown. In ASES, the train operators tried to keep the current speed indicator (a black bar) next to the verge of the green area that graphically shows the instantly changing maximum allowable speed measured from the braking curve (Wreathall et al., 2007a).

When new signalling systems were first introduced, train operators were more focused on the in cab signalling display and were distracted by it, reducing the amount of attention paid to monitoring outside of the cab. However, after a while, they could better balance their attention between inside and outside of the cab (Monk et al., 2017). Some ITCS train operators also mentioned that, after 3 weeks to 1 month of working with the system, they spent less time monitoring the in cab display. However, some train operators indicated no noticeable change in their attention distribution even after they had sufficient experience in running a PTC equipped train and a remaining inability to have a head up driving style (Wreathall et al., 2007a). Wreathall et al. (2007a) proposed that the final design of the PTC system should be checked based on human-in-the-loop evaluations to realize if out of cab monitoring is considerably weakened by the need to fully monitor the in cab display.

Operating ICRSD also means a train operator needs to devote more attention to in cab displays, which can cause head down driving and constant changes in visual distribution (Halliday et al., 2005). Despite some detrimental effects of in cab systems on train operators' visual attention distribution, Merat et al. (2002) discovered that AWS can considerably increase the number of looks at signals as great numbers of the first looks at signals of the train operators studied were taken after AWS had sounded.

5.1.7 Automatic responding

A train operator may read or hear an alarm without understanding its importance and meaning and show a skill based, reactive response to it, called automatic responding (Oppenheim et al., 2010; Carey, 2015). In some cases, the train operator is mentally fatigued but physically awake enough to press the push button or enter data into the train control system because motor reflex actions generally need a lower level of cognitive endeavor. Therefore, the train operator may trigger automatic responses (Stein et al., 2019). The automatic responding shows the warning system has failed in its primary purpose to alert the train operators and attract their attention to threads (Halliday et al., 2005).

The results of a questionnaire survey of 277 UK train operators illustrated that a considerable number (i.e., 56%) have automatically acknowledged an Extended AWS alarm at least once during their driving experience, although only 2% did it on a daily basis. The existence of warnings related to situations that are less important than restrictive signals (e.g., TSR), personal factors, the high number of alarms, and signalling issues were reported as the main reasons for automatic responding (McLeod et al., 2005a). McLeod et al. (2005a) also analyzed OTMR data and found that some train operators started pushing the cancellation button before the alarm had started to sound or they responded to the alarm very quickly. These anticipatory and quick responding behaviours indicate unconscious alarm canceling, with only a physical response and no interpretation (Halliday et al., 2005). Because the AWS neither differentiates between caution and stop signal aspects nor has a mechanism to prevent misperceptions, train operators who are confronted with successive cautionary signals (yellow or double yellow) likely respond to the AWS horn without conscious interpretation about the signal aspect (Lawton and Ward, 2005).

Analyzing SPAD events in Italian railways showed that although the train operators received and acknowledged an in cab alarm relating to an upcoming stop signal, they missed the stop signal and passed it. More analysis revealed that poor alarm management (e.g., excessive, uninformative audible alarms) had reinforced a tendency to an automatic response without completely perceiving the alarm's meaning and thus the system had lost its intended alerting function. As an example of the drawbacks of the warning system, the system set out to anticipate the signal aspect for the next block and alert the train operator for the approach signal aspects, but in many cases the anticipation was incorrect and the signal would change to the clear signal before the train entered the next block. This caused experienced train operators to be ready to press the cancellation button whenever they entered a block and to automatically acknowledge the auditory alarm without checking the in cab display to see if the predicted next signal is the approach or stop aspect. Inasmuch as the alarm sounds for both stop and approach signals were the same and the acknowledge button also was the same in both cases, the train operators acknowledged the alarm without processing the exact predicted signal aspect for the next block. To address this problem, a variety of ideas for effective alarm management were recommended. First and foremost, the warnings must be accurate and informative to reduce the risk of automatic responding. Second, if an audible warning is adopted in a situation that the operator requires to monitor somewhere other than the display screen (in this example, they need to check out the window), it is useful to make distinctions between sounds relating to auditory alarms of different conditions (e.g., a different tone for approach versus stop). Third, using different actions (e.g., a different button push for approach versus stop alerts) for acknowledging different alarms is a good method to mitigate the risk of automatic responding (Wreathall et al., 2007a).

5.1.8 Memory failures

Short term memory, also known as "working memory", is volatile and easily lost or distorted. Not only the passage of time but also interference between the current contents of working memory and newly arriving information can be a reason for information loss (McLeod et al., 2003). Thus, McLeod et al. (2003) recommended that a train operator should never rely on working memory to maintain vital safety data and suggested that external assistance is necessary.

Crick et al. (2004c) reported that 77.1% of their focus group train operators had at least occasionally forgotten the signal aspect after acknowledging the AWS. The evidence showed a possible risk of the train operator being uncertain about what an active alert corresponds to after around 7 seconds (Moray et al., 1983). Based on historical data, expert judgment, and a simulator experiment, Thomas and Davies (2008) and Davies et al. (2012) proposed that repeating the AWS warning on the head up display can reduce the risk of train operators forgetting a cautionary signal was shown on the previous signal.

A memory failure related to the DRA system may include forgetting to set the DRA, pressing a different button (e.g., AWS alarm reset or door release button) instead of the DRA button, resetting the DRA, and starting the trip based on the platform guard's signal without checking whether the signal aspect is clear (this can cause ding ding away SPADs) (RSSB, 2002).

5.1.9 Lack of teamwork

If an in cab display is poorly designed or poorly placed, the ability of teamwork between the train operator and the conductor to catch and recover from errors can be negatively affected (Wreathall et al., 2007a; Roth and Multer, 2009; Roth et al., 2013). When a train has two crew members (e.g., a train operator and a conductor), the conductor is responsible for doing a redundant check/reminder for the train operator. However, if the PTC display is located in a place that only the train operator can see it, the conductor loses the ability to serve as a redundancy check (Wreathall et al., 2007a).

5.1.10 Improved anticipation

Systems that provide preview information, such as upcoming speed restrictions, traffic position and velocity, and upcoming distance data (e.g., mileposts, switches, and stations), help train operators be prepared for track conditions beforehand. Having preview information in in cab displays decreases memory demands on train operators (e.g., decreases the need to recall upcoming temporary speed restrictions), strengthens a more accurate situation model, and enables train operators to create expectations and plan for upcoming conditions (Roth and Multer, 2009; Roth et al., 2013).

5.1.11 Data entry errors

The risk of making an error during data entry tends to be very high (Crick et al., 2004b). Inaccurate data such as wrong ID, wrong train information, or wrong destination code are likely to be input into the automated system, which can negatively affect the reliability of the PTC system (Wreathall et al., 2003, 2007a). Therefore, system designers must implement mechanisms to decrease the probability of data entry errors and promote error detection and correction (Wreathall et al., 2007a).

The complexity of data entry procedure varies with the PTC system used and in some systems, such as ASES, data input is complex, time consuming, and impractical, particularly in the case of restarting the system after a penalty brake application (Wreathall et al., 2007a). Halliday et al. (2005) discussed how if train operators forget to set the safety system (e.g., ICSRD) or fail to set it appropriately, the potential errors will not be omitted and only shifted to another part of the task sequence, i.e., failure to remember the signal would be replaced with failure to set the device.

5.1.12 Impacts on braking style

Train operators have complained that trains were frequently halted by the overspeed functionality of TPWS even though they were sure the train could be stopped before a red signal. This is because the system was designed for trains with poorer braking efficiency. Thus, operators of trains with better braking performance were frustrated by the relatively high number of brake applications (Scott and Gibson, 2012).

PTC systems may also have conservative brake profiles as they consider restrictive assumptions such as a heavy train or slippery track. A conservative brake profile means the train operator must start braking at an earlier point compared to what they were normally used to (Wreathall et al., 2007a; Roth and Multer, 2009; Roth et al., 2013). If the train operator postpones initiating the brake, a visual warning followed by an auditory alarm is activated. After warnings, if the train operator does not show a reaction and does not obey the braking profile, emergency brakes are applied to bring the train to a halt. PTC systems not only require train operators to adjust the braking style to adhere to conservative braking profiles, but may also create conditions where the train must unnecessarily slow down or stop (i.e., spurious PTC enforcement) (Wreathall et al., 2007a).

5.1.13 Skill loss

Skill loss (degradation) is a probable but unpleasant feature of automation (Bainbridge, 1983). As supervisory train control technology increases, train operators have a reduced opportunity to carry out tasks themselves, thus contributing to skill loss. The skill loss issue becomes apparent in a situation that requires the operator to take charge of the train (Wreathall et al., 2003). Therefore, maintaining the required skills of train driving is important and can be achieved either through a frequent application or structured training (Balfe, 2010).

5.1.14 Conflicts with operating rules

With the introduction of new PTC systems, new operating rules must be made to cover procedures required to work with the PTC system and to comply with different contingencies that might occur. To meet new PTC capabilities and restrictions, changes to existing procedures may also be necessary. Train operators of ASES and ITCS indicated that signals of the PTC fault mode can be difficult to recognize, and the procedures for reinitializing PTC after a malfunction can be complicated and time consuming. The operating rules must be straightforward to realize and practical to obey (Wreathall et al., 2007a).

The PTC system and the rulebook must be consistent to not put train operators in a difficult circumstance of making a choice between obeying the rulebook or accepting the PTC enforcement. One example of such a situation was described by an ITCS train operator who indicated that, according to the Northeast Operating Rules Advisory Committee (NORAC) rules, in the case of a dark signal (i.e., when the signal light is out), the train operator must stop the train and contact the dispatcher. ITCS, however, did not enforce this rule because ITCS can infer the signal (Wreathall et al., 2007a).

5.1.15 Violation

Some studies such as RSSB (2002) and Crick et al. (2004b) illustrate some train operators do not make use of DRA at all and others purposely misuse it (e.g., using it on the move); however, most train operators use the DRA as stated within the Railway Safety Rule Book. Compared to those trained as trainees on the DRA, more experienced train operators felt less optimistic about the system and were also less likely to recall using it (RSSB, 2002). The risk of train operator violations with respect to using ICSRD were also reported by Halliday et al. (2005). Einhorn et al. (2005) found that some US train operators turned off the cab signalling and ATP system in low-speed areas to get rid of the distraction of the alarms and better concentrate on controlling the train's speed. This action can pose high risks if the train enters the high speed territory and the train operator forgets to turn on the systems.

5.1.16 Ergonomic issues

The RSSB (2002)'s assessment of the safety aspects of DRA systems demonstrated that the light brightness of the DRA indicator could be an issue. The train operators expressed how it is hard to determine if the DRA indicator is on or off on bright sunny days. On the other hand, the DRA light looks too bright in the darkness of night and causes glare. The same problem was noted regarding the AWS sunflower (Halliday et al., 2005). Some train operators claimed the surface of the AWS acknowledgment button is too slippery so that their fingers could slip off, failing to cancel the AWS warning (Scott, 2008). In some train cabs, TPWS DMIs were poorly positioned so the train operator might not detect that the brake demand indicator is flashing (Scott and Gibson, 2012). The differences in the nature of the foot pedal (Crick et al., 2004b) and position of the AWS reset button (Scott, 2008) from train cab to train cab were other reported issues. A simulator based investigation of human performance in relation to operating with Trip Optimizer (TO; a type of fuel optimization system) in the locomotive cab disclosed no clear, salient displays to warn the train operator about overspeeding. The hands of the speedometer dial change to green and white, which does not clearly reflect a problematic situation of overspeed. More salient indications for overspeed such as a red crosshatched area between two hands or a red flashing hand can support the train operator in realizing the hazard (Sebok et al., 2017).

5.2 Performance shaping factors

According to the human reliability analysis (HRA) methods, performance shaping factors (PSFs) are defined as the context factors that enhannce or degrade human performance, and are used to quantify human error probabilities (HEPs) (Boring et al., 2007). These factors are also known as performance influencing factor (PIF), performance affecting factor (PAF), error producing condition (EPC), and common performance condition (CPC) (Porthin et al., 2020).

Henley and Kumamoto (1996) divided PSFs into extenral factors (including situational characteristics, job and task characteristics, and environmental circumstances) and internal factors which refer to individual characteristics. Later, Kim and Jung (2003) grouped the factors into four main groups namely human, system, task, and environment. Kyriakidis et al., (2015) analyzed 479 railway accident and incident reports from all around the world and developed rail specific performance shaping factors, called railway-performance shaping factors (R-PSFs). They extracted 43 factors and categorized them into the seven main categories of dynamic personal factors, personal factors, task factors, team factors, organizational factors, system and environmental factors (see Table 5-1).

They also reduced the full version of the R-PSFs taxonomy to the R-PSFs lite containing 12 factors or a combination of factors on the basis of their frequencies (i.e., 90% threshold) in the analyzed occurrences as shown in Table 5-2.

Kyriakidis et al. (2018) then identified the dependencies among the R-PSFs according to the railway operational manuals, the accident and incident reports, and Subject Matter Experts (SMEs) opinions as can be seen in Figure 5-3.

Table 5-1. The R-PSFs categories (Kyriakidis et al., 2018).

Category of R- PSFs	Railway Performance Shaping Factors
Personal factors	Experience, Familiarity, Fit to work (health), Individual characteristics, Motivation, Training (competence)
Dynamic personal factors	Decision making skills, Distraction (loss of concentration), Expectation, Fatigue, Interpretation, Perception, Situational awareness, Stress, Vigilance
Organizational factors	Communication within the organization, Fit to work aspect, Incentives for employees, Leadership, Quality of procedures, standards and regulations, Relations within the organization, Safety culture (disregard procedures), Safety Management Systems, Shift pattern (working hours, breaks, manning, Supervision, Training/training methods
Task factors	Monotony, Routine, Task complexity, Task instructions, Time pressure - time to respond, Workload
Team factors	Communication between employees, Relations within the team, Teamwork, Trust in information
System factors	Human Machine Interface (HMI), Railway Communication Means (RCMs), System design, Trust in equipment, Working environment
Environmental factors	Visibility, Weather conditions

Table 5-2. The R-PSFs lite taxonomy (Kyriakidis et al., 2015).

#	R- PSFs lite	Categories
1	Safety culture, SMS	Organizational
2	System design, HMI, RCM	System
3	Fatigue, shift pattern, fit to work	Dynamic personal – organizational
4	Communication, teamwork	Team
5	Distraction, loss of concentration vigilance, situational awareness	Dynamic personal
6	Quality of procedures	Organizational
7	Perception, interpretation	Dynamic personal
8	Training, experience	Personal
9	Expectation, familiarity, routine	Dynamic personal – personal – task
10	Quality of information	Team
11	Supervision	Organizational
12	Workload, time pressure, stress	Task – dynamic personal

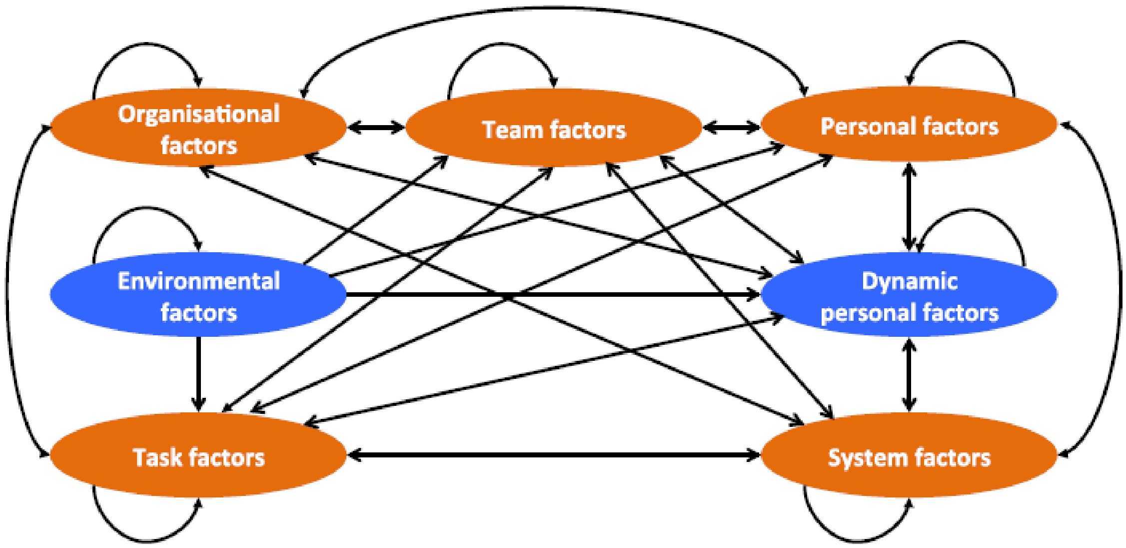


Figure 5-3. The network of interactions between the R-PSFs categories (Kyriakidis et al., 2018).

In this figure, the blue categories reflect the dynamic R-PSFs, meaning factors that are strongly associated with the precise moment of the operation, and the orange ones are the static R-PSFs categories, i.e. the R-PSFs that are less related to the time of the occurrence.

6 An overview of alarm related accidents

This section reviews some of the notable accidents that have happened in relation to warning devices or automated systems.

6.1 Railway accidents

6.1.1 United States of America (USA)

Shady Grove accident

Automation was to blame in the collision between a Washington Metropolitan Area Transit Authority Train and a freight train at Shady Grove Passenger Station in 1996. The braking system of the metro train was automatic and the train operator had no control over the braking force. The automatic braking mechanism was not correctly designed for the icy surface and thus it caused the accident (Traub and Hudson, 2007). On that snowy day, trains were encountering slippery conditions and less traction and in some cases were overrunning stations. Therefore, the train operator of the crashed train asked to turn off the automatic speed control system, a request that was denied. Thereafter, the train entered the station much faster than expected because of poor track friction and collided with a stationary train. It was later debated that the accident could have been prevented if the train operator had been permitted to override the automation (Wreathall et al., 2007a).

Chlorine rail car accident

In 2004, at Macdona, Texas, a Union Pacific (UP) train collided with a Burlington Northern

(BNSF) train causing the derailment of four locomotives and 35 railcars and the release of hazardous material. The train conductor died as a result of the collision. In addition, two people in a nearby house were killed and 43 people were hospitalized due to chlorine inhalation. The accident investigators determined the crew of the UP train did not handle the train in compliance with the operating rules and trackside signal aspect. They failed to make any attempt to bring the train to a stop in response to the red trackside signal, even when the BNSF train came into view (NTSB, 2006). Although the train operator manipulated the throttle and horn, which prevented the Alerter alarm, and also inputted data into the control system, they were in a state of mental fatigue (i.e., were physically awake enough to continue train handling by automatic behaviour) (Stein et al., 2019, NTSB, 2006).

West India Quays derailment

On March 10, 2009, a Docklands Light Railway (DLR) service derailed while travelling through a series of trailing points that were not correctly set for this movement. On the day of the accident, several major signalling system failures occurred and train LEW109 was automatically brought to a halt because an axle counter was broken and incorrectly showed some tracks were closed. The control centre controller asked the train operator to operate in emergency shunt mode instead of automatic train operation (ATO) mode and check the point position indicators while he moved forwards. During communication, the controller had been checking 1125 points and they were displayed in the correct position as they had been set for trains from another direction. Train LEW109 started to move through the 1125 points that were incorrectly set in reverse. The point position indicator remained unlit and did not display a red bar, and the passenger service agent did not identify that the point location indicator was not illuminated and proceeded to move the train through the 1125 points. Meanwhile, a train that was still operating in ATO mode arrived at the station and automatically requested a route through the 1125 points. The controller noticed that the 1125 points were incorrectly set for train LEW109 and made an emergency radio call to the passenger service agent onboard train LEW109 and told him to stop his train. At exactly this moment, the train derailed on the trailing points (Branch, 2010).

Washington Metropolitan Area accident

A metro train-to-train collision occurred in the Washington Metropolitan Area in 2009. This accident, which resulted in nine fatalities and 80 injuries, was attributed to a failure of the train control system. The track circuit malfunction made the control system unable to detect the track was occupied by a stopped train and hence the automatic brake was not initiated to bring the moving train to a halt. The emergency brake was activated by the operator of the moving train after noticing the stopped train, but there was insufficient time to avoid the crash (Li et al., 2017). The NTSB noted that "[o]perators could not have been expected to be aware of the impending collision due to the high number of track circuit failure alarms routinely generated by the system" (Heape, 2015).

6.1.2 United Kingdom (UK)

Although TPWS has reduced SPADs in UK railways, a high rate of improper TPWS interventions (i.e., TPWS alarms when not needed) due to design and operational issues has been reported.

This causes mistrust of the system, and thus train operators to assume that TPWS intervention is either incorrect or inappropriate. For example, in 2002/3, a train operator reset the TPWS and proceeded without contacting the signaler in 15% of correct TPWS interventions (Kinnersley and Roelen, 2007).

Southall train collision

In 1997, a collision happened between a high speed passenger train and a freight train at Southall near Paddington Station. The collision led to seven fatalities and 139 injuries. The train operator of the high speed train passed through three consecutive cautionary signal aspects without slowing down and showed reaction only when the freight train was in his sight distance, but the two trains ultimately collided. The high speed passenger train was equipped with AWS, like most other British trains; however, on the day of the accident, the system failed to warn the train operator. The train operator was also distracted by getting his bag ready to finish his journey at Paddington Station. Therefore, he neither monitored the signal aspects nor received alarms from the failed AWS, which resulted in the accident. In this accident, the complacency of the high speed passenger train operator was identified as the primary cause (Roth and Multer, 2009).

Ladbroke Grove accident

One of the most serious rail accidents in Britain happened at 8:05 a.m. on 5 October 1999 at Ladbroke Grove near Paddington Station in London. The trains and the lines were fitted with an AWS aimed at warning train operators of the presence of a restrictive signal. However, a Turbo train that departed from Paddington failed to stop at a red signal and collided with a high speed train (HST) approaching the station from the opposite direction on the same line. The collision followed by derailment and fires resulted in 31 deaths and more than 400 injuries. The SPAD of the Turbo train was the crucial event for this accident, though investigators did not find any evidence to prove the signal was violated on purpose (Lawton and Ward, 2005).

Lawton and Ward (2005) carried out a systematic accident analysis and categorized five contributing factors: active failures, local working conditions, situational and task factors, inadequate defences, and (latent) organizational failures. The explanations for these factors are provided below.

(a) Active failures: The operator of the Turbo train passed the cautionary signal although they acknowledged the AWS alarm. Moreover, the signaller did not show a timely reaction to the SPAD event and did not send emergency stop signals to the Turbo train as well as the HST.

(b) Local working conditions: inexperience, expectation, distraction, strong motor programs, false perceptions, confirmation bias, and situational unawareness were identified as Subcategories for the local working conditions factor. The operator of the Turbo train was a novice that had passed their training just two weeks before the accident. Moreover, they had never experienced a red signal at this point of the line during their training. The evidence shows the train operator habitually canceled the AWS horn as they had been presented with several successive cautionary signals before this red signal.

(c) Situational and task factors: track layout, poor human system interface, poor feedback from the system, and poor communications were the main situational and task factors that contributed to the accident. The complexity of the layout, multiple signals on the gantry, number of approaches, and obscuration of signals by overhead bridges and electrification equipment caused difficulties in line of sight and poor human system interface. Furthermore, the AWS system sounds the same horn for all restrictive signals and does not distinguish between cautionary (yellow or double yellow) and stop (red) signal aspects, which creates ambiguity about the current condition and no feedback on the action to be taken by the train operator.

(d) Inadequate defences: poorly engineered safety devices, poor signalling, poor policies and standards, and the lack of awareness of hazards were identified as the main accident causes related to inadequate defences. None of the ATP systems or TPWS were installed on the Turbo train.

(e) Organizational failures: although many SPAD incidents had occurred at this location, no safety improvement measures were implemented to mitigate the risk. Furthermore, there were no official standards for train operator training. In addition, in the development of track and signalling at Paddington Station, safety issues and human factors related to the close proximity of the gantry were not taken into account.

The systematic accident model of the Ladbroke Grove crash is summarized in Figure 6-1.

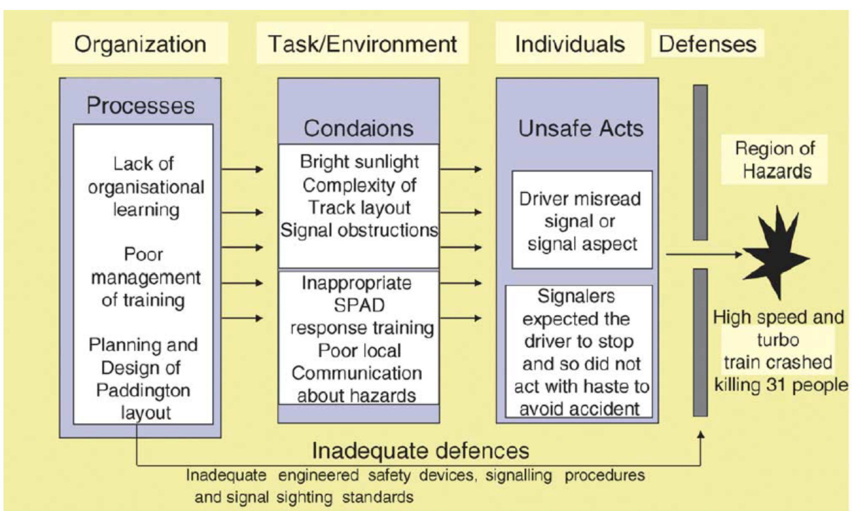


Figure 6-1. Systematic accident analysis of the Ladbroke Grove crash (Lawton and Ward, 2005)

Stanton and Walker (2011) explored the psychological factors involved in the Ladbroke Grove accident. They found five aspects of train operation as contributing factors: (1) custom and practice in the use of the DRA, (2) operation and use of the AWS, (3) the sequence of signaling information, (4) methods of supplying route information, and (5) speed restrictions.

DRA is an additional defence to reduce the likelihood of a driver starting to move when the signal ahead is red. It can be used while the train passes a cautionary signal aspect, though it was designed to be used in stations. The operator of the Turbo train was also trained to activate the DRA at single yellow signal aspects. However, they failed to apply it, which created the conditions for a mode error. This loss of activation may be coupled with a data driven activation error (i.e., the train operator took the triangular speed restriction under the bridge as the cause of the AWS activation) to create a form of local rationality for the train operator).

6.1.3 China

On July 23, 2011, a rail accident occurred on the Yong-Wen high speed railway line at Wenzhou in China that caused 40 fatalities and 172 injuries. At a speed of 99 km/h, the China Railway Highspeed (CRH) train D301 rear ended another CRH train, D3115. As a result of this collision, six cars derailed and two went off the bridge.

Approximately one hour before the accident, severe lightning at this location resulted in a flaw in the control system. Consequently, the signal displaying the track occupancy in the train control centre (TCC) remained red and could not indicate if the track segment was occupied by a train because of the track circuit failure. Maintenance staff were asked to fix the problem, and thus the maintenance engineer checked the machine room of Whenzhou Station. He observed numerous alarm signals related to the track circuit equipment. The engineer tried to replace the defective devices and then the alarm signals disappeared.

Train D3115 was commanded to leave Yongjia station and was notified that the train may brake due to the ATP system in the flawed section of track and, once this occurs, the train must be restarted and continue to travel. As expected, the train automatically stopped, but the train operator failed to restart the train. The train operator contacted the dispatcher and station operator and also was called by them several times; however, all calls were lost. During this period, train D301 departed from Yongjia station as normal. Due to the track circuit breakdown, D301 neither received information about D3115 nor stopped automatically and the two trains then collided (Zhan et al., 2017; Li et al., 2019).

This accident has been analyzed with a range of accident causation models including Systems Theoretic Accident Model and Processes (STAMP) (Song et al., 2012; Dong, 2012; Niu et al., 2014), STAMP combined with Petri net (Dirk et al., 2013), AcciMap (Chen et al., 2015), the Human Factors Analysis and Classification System-Railway Accidents (HFACS-RA) (Zhan and Zheng, 2016; Zhan et al., 2017), HFACS-STAMP (Li et al., 2019), and the Functional Resonance Analysis Method (FRAM) (Liu and Tian, 2017). For example, Zhan et al. (2017) adopted the HFACS-RA method in combination with the Analytic Network Process (ANP) and the Fuzzy Decision Making Trial and Evaluation Laboratory (Fuzzy DEMATEL) techniques to identify the leading causes of this accident. The ranked causal factors were considered in “Unsafe Acts” (showed by “A”), “Preconditions for Unsafe Acts” (showed by “P”), “Unsafe Supervision” (showed by “S”), and “Organizational Influence” (showed by “O”) categories (see Table 6-1).

Table 6-1. Causal factors of Yong-Wen high speed accident (Zhan et al., 2017)

Causal factors	Ranking
A2: Failure to contact train D301 and inform the train operator regarding train D3115	1
A1: Dispatch the train with the red zone of track circuit unclear	2
A4: No follow up instrument to keep a record of equipment failures	3
A3: Substandard troubleshooting operation	4
P1: Lack of teamwork	5
S2: Unqualified follow up inspection for crew training	6
P2: Lack of emergent fault processing experiences	7
S6: Failure to correct wrong maintenance operation	8
P3: Inadequate personnel assignment	9
P5: Substandard implementation of operation standard	10
S3: Lack of qualification examination for the new signal product	11
P4: Negligence of equipment failure, lack of safety meeting	12
S5: Improper train departure plan on the fault train line	13
O1: Negligence of safety corrective actions	14
S4: Unconfirmed fault track circuit equipment downtime registering	15
S1: Lack of effective crew safety training	16
O2: Insufficient training quality and management	17
O3: Purchasing substandard equipment for track circuit	18
O5: Chain of command disorder	19
O7: Insufficient risk assessment of new signal equipment	20
O4: Lack of emergency disposal instructions	21
O6: Lack of safety training program	22

6.1.4 Iran

A good illustration of an alarm related accident is a catastrophic accident involving two trains near Haft-Khan station in Iran in 2016. Two passenger trains collided in a rear end collision followed by a fire, killing 47 passengers and crew and injuring many others. Although different factors such as human error, complex operation process, poor safety management system, and environmental factors contributed to this accident, the faulty ATC system played a pivotal role.

The accident happened when an express train from Tabriz to Mashhad with 432 passengers stopped due to technical problems in its brake system associated with cold weather between Semnan and Damghan and informed the Centralized Traffic Control (CTC). The second express train with 110 passengers travelling from Semnan to Mashhad on the same track controlled by the ATC system stopped after seeing the red signal of the previous block. Meanwhile, the shift for the CTC operator changed and the new operator was replaced before the problem with the first train was resolved. At this point, the operator of the second train asked for instructions from the CTC operator with respect to permission to resume their journey. Verbal approval via radiotelephone giving permission to the operator of the second train to deactivate the ATC system and continue to Haft Khan Station was given. The second train travelled at a speed of 132 km/h and hit the first train, resulting in its derailment and subsequent fire, which affected the last three cars of the first train as well.

While human error may appear to be the key factor in this accident, the underlying reasons for operators to ignore alarms made by the ATC system are worth noting. The accident investigation revealed it was not the first time the CTC operators decided to neglect alarms made by the system. The train control system had reported an error 2000 times from its launch in March 2014 until the accident day. The faulty performance of the ATC system and its frequent incorrect warnings in the past caused the operators of the control unit to distrust the warnings generated by the system. Making such an assumption toward the control system as well as not being aware of the situation, the second operator decided to ignore the warning of the ATC system showing an occupied block ahead and assumed it to be a system fault, as it had been many times in the past, and issued permission for the second train to move, resulting in a fatal accident (Sameni et al., 2018; Eftekhari et al., 2020).

6.1.5 Korea

Korea reported a collision between two trains that were expected to pass each other at a local station. The first train operator continued their trip without noticing the stop signal as well as the ATS system alarm and collided with an approaching train. The ATS warning was triggered when the train reached the stop signal. However, because the train operator acknowledged the alarm, the safety system no longer worked to apply emergency brakes (Lee and Lyou, 2018).

6.1.6 Singapore

In 2017, the train borne signalling system of a Singapore metro train failed to work normally, leading to an interruption in communication between the train and the trackside control. The metro line was partly equipped with the Communications Based Train Control (CBTC) system. Hence, the train was moving on the line with both a new and legacy signalling system.

Train 3535/3536 collided with train 3547/3548 when it was leaving the station and returning to the library at Joo Koon station as planned. The CBTC system did not detect the presence of train 3535/3536 and thus provided the movement authority for train 3547/3548 according to the condition that the track ahead was free. The dispatcher and the operator of train 3535/3536 both supposed the control commands of the CBTC system were correct. Consequently, train 3547/3548 drove towards Joo Koon Station and collided with train 3535/3536 that had stopped ahead (Yan et al., 2018).

6.2 Aviation

Bliss (2003) reviewed the Aviation Safety Reporting System (ASRS) database (between 1991 to 1998), the National Transportation Safety Board (NTSB) database (between 1994 to 1997), and the U.S. Army's Aviation Safety database (between 1995 to 2000) and statistically analyzed the alarm related (involving true, false, and missed alarms) incidents and accidents. The analysis revealed that 1.1% of NTSB reported events were alarm related; the percentages were 3% and 27% for the Army and ASRS databases, respectively. Bliss (2003) stated that the substantially higher percentage of alarm related incidents in the ASRS database is likely because the ASRS database is voluntary with great concern with human factors.

The percentage of alarm related events related to true, false, and missed alarms were 60%, 20%, and 20% within the NTSB database, 58%, 28%, and 13% within the ASRS database, and 5%, 90%, and 4% within the Army database, respectively. The high share of false alarms in the Army database is perhaps because helicopter designers err on the conservative side with respect to the use of warning signals as helicopter pilots encounter a high degree of workload.

The causal analysis highlighted that most false and missed alarm signals were initiated due to component faults or wear, reflecting the high importance of maintenance. This research confirmed that excessive false alarms that may cause pilot mistrust are an issue within the aviation industry. The high number of false alarms could be a result of conservative aircraft design.

6.3 Other industries

The explosion at the Texaco Refinery in Milford Haven, England in 1994 is one of the most referred accidents related to alarm management. The start of the events that resulted in the explosion can be traced to a lightning strike that started a fire in the crude distillation unit. The two operators of this refinery encountered 275 alarms, peaking at three per second in the 10 minutes before the explosion (Heape, 2015). The main issues related to the alarm management that caused the explosion were:

- Alarm floods
- Excessive standing alarms
- Control displays and alarms that did not assist the operators
- No clear process overview to help diagnosis
- Alarms that activated faster than they could be responded to
- 87% of the 2040 alarms displayed as "high" priority, despite many being informative only
- Safety critical alarms were not understandably distinguishable

The key lesson learned from this accident was that alarm management is not only a technical issue, and must be considered in connection with the safety management system (SMS). The SMS shortcomings found in the Texaco accident included:

- Inadequate plant improvement procedure
- An insufficient device maintenance system
- Lack of training and competence of operators
- A lack of a clear guideline on handling unexpected events and when to start emergency plant shutdown
- A lack of clear authority to initiate shutdown (Wilkinson and Lucas, 2002).

The incident at Three Mile Island in 1979 that led to the release of radioactive materials is another alarm induced incident. In this incident, a relatively minor fault in the secondary cooling circuit caused the primary coolant to overheat, and finally the reactor automatic shutdown for one second. The operators were unable to diagnose the reason for the alarm and shutdown and thus responded to it improperly (i.e., turning the emergency cooling systems off). The operators were overloaded with numerous alarms, and some vital alarms were misleading (Rothenberg, 2009). In summary, inappropriate operator action aligns with contributory factors such as deficiencies in their training, lack of clarity in their operating procedures, failure of organizations to learn the proper lessons from previous incidents, and deficiencies in the design of the control room were considered as factors that caused this accident (Kemeny, 1979). This incident provoked politicians to limit nuclear power reactors in the US for the next four decades. The following alarm management concerns linked to this incident were an impetus for the development of the majority of today's alarm management strategies(Rothenberg, 2009):

- Alarms were not applied properly due to a misunderstanding of the purpose of alarms and a failure to appreciate the implications of using them without careful consideration.
- The alarms were not adequately understood by the operators leading to incorrect action.
- An alarm system is profoundly interconnected with the existing infrastructure, and thus, the alarms must be coordinated with the plant design and culture.
- Alarm redesign is not simply an addon and requires significant change management.

Table 6-2 summarizes some of the major alarm related incidents in industries (Goel et al., 2017).

Table 6-2. Major alarm related incidents in industries (Goel et al., 2017)

Incident	Year	Root cause related to alarms	Effect	Injuries/ Fatalities
Three Mile Island	1979	Operators were loaded with numerous alarms; several key alarms were misleading	Radioactive material released	0/0
Piper Alpha Oil rig	1988	Inadequate shift handovers; issues with false alarms	Fire	0/167
Texaco Milford Haven refinery, UK	1994	Poorly prioritized alarms & design of displays; alarm flood	Explosion	26/0
Channel tunnel fire, UK	1996	Rail control centres were flooded with alarms	Fire	0/0
Tosco Avon Accident, Martinez, California	1997	No alarm on temperature indication and control system with high priority alarms	Autoignition of flammable hydrocarbon and hydrogen	46/1
Longford gas explosion, Australia	1998	Inappropriate response for critical alarms	Fire and explosion	8/2
Grangemouth refinery Scotland	2000	Significant alarm floods	Steam leakage	0/0
First chemical corporation, Pascagoula, Mississippi	2002	No action taken for alarm; system was not protected with enough layers of protection including alarms; safety interlocks; and overpressure protection	Steam leakage	3/0
BP Texas refinery incident	2005	Failed management of instruments and alarms	Fire and explosion	180/15
Bunce field oil storage, Hemel, Hemstead	2005	Shortcomings in design, provision, and operation of the protection alarms and shutdown systems	Fire and explosion	40/0
Kalamazoo River oil spill	2010	Numerous alarms from the affected Line 6B, but controllers thought the alarms were from phase separation, and the leak was not reported	Crude oil leakage into environment and nearby	326/0

			creek	
Columbia gas transmission corporation pipeline rupture, Sissonville, West Virginia	2012	Controller did not recognize the alert of the leak	Explosion	0/0

6.4 Lesson learned from accidents

The following lessons can be learned from the analyzed accidents:

- False alarms result in a perceived low system reliability resulting in the train operator losing confidence. As a result, alarms may be ignored, disabled or responded to slowly as in the Haft Khan accident.
- Highly reliable systems can cause complacency and over reliance. A train operator loses situational awareness and cannot identify automation errors. The Shady Grove accident, Southall train collision, Washington Metropolitan Area accident, and Ladbroke Grove accident are examples where overreliance on the systems and complacency were significant contributory factors.
- The warning system should provide unambiguous feedback and convey the degree of risk and urgency. In the Ladbroke Grove accident, the train was only equipped with the AWS system which activates the same horn for all restrictive signal aspects (i.e., yellow, double yellow, and red signal aspects), the result was that the train operator misinterpreted the alarm related to the red signal (stop) for the yellow signal aspect.
- The alarm management stages should be implemented during the design and adoption of warning systems to prevent ambiguous alarms, nuisance and irrelevant alarms, alarm overload, poorly prioritized alarms, etc.
- In accidents such as the Ladbroke Grove accident and Korean accident, the automation systems did not stop the trains as a result of habitual response to warnings by the train operator which overrode the automatic brake system. Thus, automated braking should be a result of the emergence of an unsafe situation not on a failure of the train operator to respond.
- Train operators should be trained in procedures to follow when the in cab warning system malfunctions and unexpected events occur. They also should also be trained as to higher risk portions of routes and mitigation measures.
- Alarm systems should be analyzed not only from technical points of view but also in connection with the safety management system.

7 Conclusions & Recommendations

The purpose of this report is to provide a better understanding of in cab warning system technology, characterize potential cognitive impacts, and as a step towards the creation of strategies to mitigate negative potential cognitive impacts. To achieve these objectives, train warning and safety protection systems and their functions were reviewed; and, the nature and sequence of provided alarms, the acknowledgment procedures, and the risk controls were summarized. Second, samples of alarm initiated activities and alarm handling techniques in the railway domain were investigated. Third, alarm management and its life cycle, common problems, and performance metrics were considered. Fourth, the negative effects of in cab warning devices and train protection systems on train crews were reviewed, and performance shaping factors were investigated. Finally, alarm related accidents in railways, as well as other industries, were explored.

The main findings of this review are as follows:

From **§2**, the prevention of signal passed at danger, overspeed, collisions, and train operators' vigilance are the primary focus of in-cab warning systems. These systems commonly use visual and auditory alarms sequentially or concurrently to warn the train operators of a hazardous situation. Systems can be categorized into three generations: first generation, consists of a warning only system without the requirement for train operator acknowledgment or automatic brake intervention; second generation, consists of a warning system which requires the train operator to acknowledge warnings and an automated application of brakes to stop the train upon failure to acknowledge; and third generation, which enhances second generation capabilities with monitoring of train speed and an application of brakes in the event of over speed. Within the reviewed literature concerns were raised that upgrading of systems through generations has resulted in the confusing array of controls and displays, and recommend a consolidated control system and interface when possible.

From **§3** and **§4**, the ability of a train operator to handle (i.e., alarm notification, acceptance, analysis, and clearance) and cope (i.e., filtering, queuing, categorizing, similarity matching, and extrapolation) with alarms differs between persons (e.g., affected by their experience, route knowledge, and mental state) and situations (e.g., expected versus unexpected situations). Thus, both the train operator, and the context in which warning and alarms are issues need to be addressed through alarm management to ensure the intended response by the train operator.

From **§5**, most negative cognitive impacts of in cab warning and train protection systems on train operators are a result of workload; with an under-load of the train operator resulting in boredom, fatigue, over confidence and complacency; and, an over load resulting in irrational reactions, confusion, exhaustion and low self-esteem. And, due to the potential for negative cognitive impacts, automated braking should be a result of the emergence of an unsafe situation not reliant on a failure of the train operator to acknowledge.

From **§6**, automation related accidents in the railway industry, including the Ladbroke Grove accident in the UK, the Yong-Wen rail accident in China, and the Haft-Khan collision in Iran demonstrate that automated system failure, complacency of the train operator, inconsistency of alarm performance with user expectations, and poor alarm design and management were common reasons for most of these accidents.

From the literature review, the authors recommend the following two streams of future research: human reliability analysis (HRA); and, alarm management. The recommendations for each stream of research are provided in the order of the steps to be taken, and are thus prioritized.

Within the first stream it is recommended that a human reliability analysis (HRA) be performed to evaluate the train operator's contribution to risk. This can be accomplished by:

- Conducting hierarchical task analysis (HTA) and cognitive task analysis (CTA)/ cognitive work analysis (CWA) to identify tasks that train operators should perform and the cognitive activities they utilize to do these tasks.
- Extracting railway-performance shaping factors (R-PSFs) for Canadian railways and identify how these factors are dependent and how they impact the performance of train operators by using fuzzy multicriteria decision making (MCDM), Bayesian network (BN), expert knowledge elicitation, and/or machine learning methods.
- Applying text mining and machine learning methods on rail accident/incident reports and safety data to categorize Canada's rail accidents by causal factors and the role of human errors in the Canadian rail accidents. And, employ a BN based human reliability analysis method to examine the human risks associated with implementing an in cab warning system in the Canadian railway industry.
- Performing analyses of the USA rail accident or incident data related to before/during/after PTC transition to get a better understanding of the effects of the PTC system on the probabilities and causes of rail accidents/incidents, particularly those associated with train operator errors.

In the second stream it is recommended that an alarm management life cycle analysis be conducted to develop alarm management best practices for the Canadian railway industry. This can be accomplished by:

- Reviewing alarm management standards and best practices from other jurisdictions to identify alarm performance metrics and their target values for alarm philosophy, alarm monitoring and assessment.
- Developing specific alarm management best practices for the Canadian railway industry accounting for operational and regulatory environment.
- Performing a gap analysis between the performance of currently available alarm systems and the developed best practices to identify issues and areas for improvement.

Appendix A. An overview of in cab warning systems

Different types of in cab warning systems are adopted in trains to warn Train Operators of risks ahead and to support them in handling abnormal and hazardous situations. This appendix presents the most common systems.

A.1 I-ETMS (Interoperable Electronic Train Management System)

I-ETMS offered by Wabtec is an overlay train system that displays warnings to the Train Operator of track authority violations, speed limit violations, unauthorized entry into work zones, and train movement through an improperly set switch. If the Train Operator does not take corrective action, it triggers a brake application to stop the train (Hartong et al., 2006). It also provides warning and enforcement in the case of a highway-rail grade crossing warning device malfunction and broken rails.

Figure A-1 show that if a train locates within warning distance of a speed restriction and the system predicts the train will exceed the speed by at least 5 mph, a “Speed Reduction to XX mph” message will be displayed accompanied by the time remaining to brake application (black messages and numbers on the yellow bar). The brake will be applied to bring the train to a stop if the Train Operator takes no action.

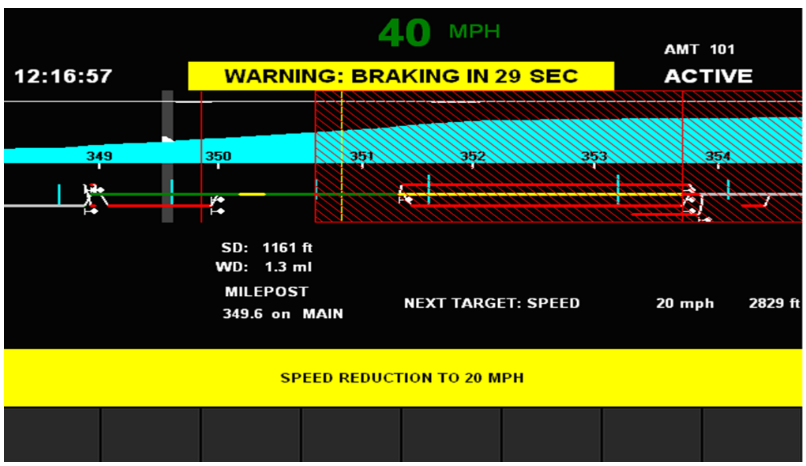


Figure A-1. I-ETMS predictive speed enforcement (Hayward-Williams and Stonecypher, 2019)

Furthermore, in cases when the train exceeds the maximum speed allowed for the track by 3 mph and/or exceeds the maximum speed allowed for the current location by at least 5 mph, the speed reduction, as well as the “Braking in Progress” message (in red), will be displayed and the enforcement brake will be applied (see Figure A-2).

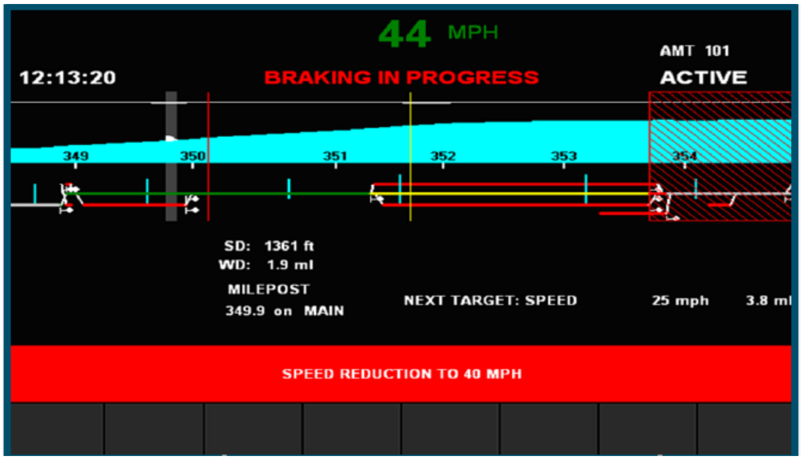


Figure A-2. I-ETMS reactive speed enforcement (Hayward-Williams and Stonecypher, 2019)

In addition, the brake profile and the distance to target are displayed, and nonconformity with mandatory directives such as movement authorities, speed restrictions, and work authority are also highlighted along with audible alarms (Collins, 2015).

A.2 ACSES (Advanced Civil Speed Enforcement System)

ACSES (latest version named ACES II) is an overlay positive train control system supplied by Alstom and implemented by Amtrak (Roth and Multer, 2009; FRA, 2019). ACSES was integrated into cab signal systems to enforce permanent/temporary speed limits and stops at red signals to prevent train to train collisions, overspeed, and wrong entry to foreman's work authority. The ACSES aspect display unit (ADU) shows the signal aspect and enforcement with indicators as well as the cab signal speed limit and civil speed limit (i.e., the maximum track speed) in numbers (see Figure A-3) (Amtrak, 2000; Hoelscher, 2001b).

Figure A-3. ACSES aspect display unit (Hoelscher, 2001a)

In ASCES, as long as the train speed is less than or equal to the warning curve speed, the system takes no action. If the train speed exceeds the warning profile, the locomotive engineer is given an audible warning and the speed restriction is displayed as a changed speed in the track speed display. If the engineer does not reduce speed before the braking profile is passed, the system enforces the penalty brake (Hoelscher, 2001b; Sheehan et al., 2015). On passenger trains only, the release of the penalty brake is permitted after the train speed is below the target speed. Once the train reaches the end of the speed restriction, the system displays the new speed limit and removes the speed restriction enforcement (Hoelscher, 2001b).

A.3 ASES (Advanced Speed Enforcement System)

ASES is an interoperable system of ASCES and implemented on NJ Transit (Amtrak, 2000). The ASES display shows current speed, target speed at the upcoming speed restriction, and instantaneous maximum authorized speed as calculated from the braking curve on the colour coded circular speedometer. The distance to the target is shown as a bar, and the text messages are presented in the centre of the speedometer gauge in red (see Figure A-4) (Roth and Multer, 2009).

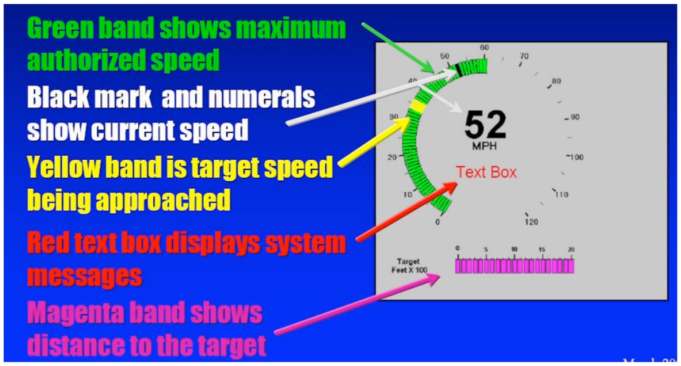


Figure A-4. ASES in cab display (Roth and Multer, 2009)

A.4 ITCS (Incremental Train Control System)

ITCS is a PTC system built by GE Harris-Harmon Electronics for passenger and freight trains (Einhorn et al., 2005). An extended version of ITCS operating without trackside signals was also developed in China (Hann, 2010). The ITCS in cab display shows the actual speed, current speed limit, target speed limit, distance to the target, and a countdown time to brake (TTB). Moreover, the ITCS mode, overspeed, and penalty are represented by indicators (see Figure A-5) (Roth and Multer, 2009). The system provides warning and enforcement of speed restrictions (permanent and temporary), work zone boundaries, and route integrity of monitored switches and absolute signal integrity (Hartong et al., 2006).

ITCS continuously displays the allowed speed limit to the Train Operator and warns the Train Operator when a speed reduction is needed. If the Train Operator violates the speed limit or required speed reduction, a warning is displayed followed by a penalty brake application (Hann, 2010). ITCS shows TTB countdown 30 s prior to applying the brakes. If the locomotive engineer does not obey the braking curve in the first 20 s of the TTB, the system sounds an audio alarm. When the countdown reaches zero, the brakes are activated. The TTB is adjustable with the train speed and increases when the speed decreases. It disappears if the train reaches the target speed or the TTB is sufficiently large (Roth and Multer, 2009). Status mode, overspeed, and brake application are also presented by indicators.

Figure A-5. ITCS in cab display (Roth and Multer, 2009)

A.5 EJTCS (East Japan Train Control system)

The cab warning devices in Japanese railways were adopted to alert the Train Operator that the train is approaching a red signal. Later, automatic train stop (ATS) systems were connected to the cab warning devices to automatically bring the train to a stop whenever the Train Operator does not acknowledge the warnings (usually by pressing a confirm button). In the ATS-S system, which evolved from the AWS, a bell or chime sound as well as a red display warn the Train Operator that the train is approaching a red signal. The Train Operator has 5 s to confirm the alert; otherwise, the automatic brakes are triggered. One drawback of ATS is that Train Operators could continue driving if they acknowledged the warning but took no action. Therefore, ATC systems were installed that intermittently or continuously show permitted speeds on an in cab monitor and automatically trigger the brakes whenever the train speed exceeds the speed pattern. The ATS-P is an example of a system developed to address weaknesses of the ATS-S. It sounds an alarm whenever the train is approaching at a dangerous speed pattern. It does not need the Train Operator's confirmation and applies the brakes if the Train Operator does not reduce the speed to a safe level. Enforcing stop signal aspects, speed restrictions, and level crossing control has become possible using the ATS-P (Matsumoto, 2005, 2006; Nakamura, 2016).

Matsumoto (2006) provided an overview of train control evolution for Japanese railways (see Figure A-6).

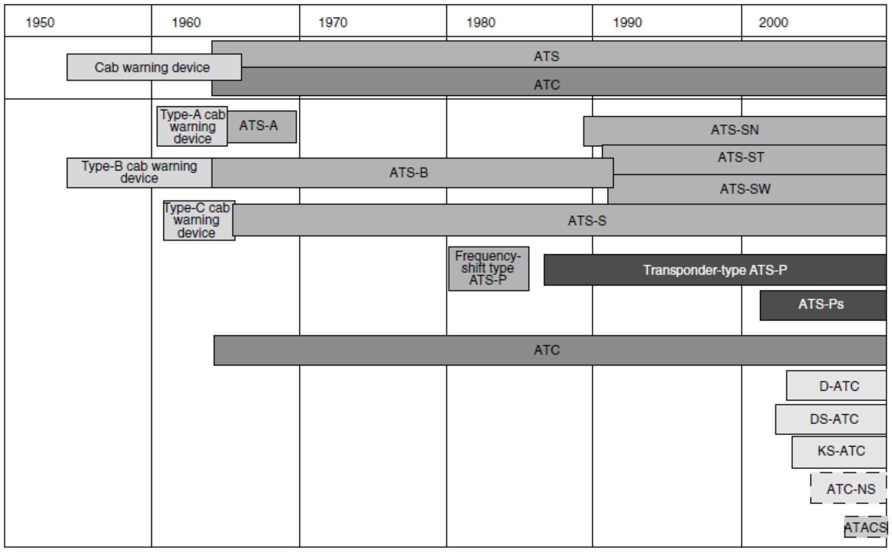


Figure A-6. Evolution of train control systems for Japanese railways (Matsumoto, 2006)

A.6 ETCS (European Train Control System)

The ETCS refers to the train signalling and control component of the European Rail Traffic Management System (ERTMS). It is a replacement for legacy train protection systems in European railways including EBI cab, Anuncio de Señales y Frenado Automático (ASFA), Automatische Trein Beïnvloeding (ATB), Contrôle de Vitesse par Balises (KVB), and Transmission Balise Locomotive (TBL) (Figure A-7 illustrates the diverse train control systems in Europe), with the main aim of improving interoperability.

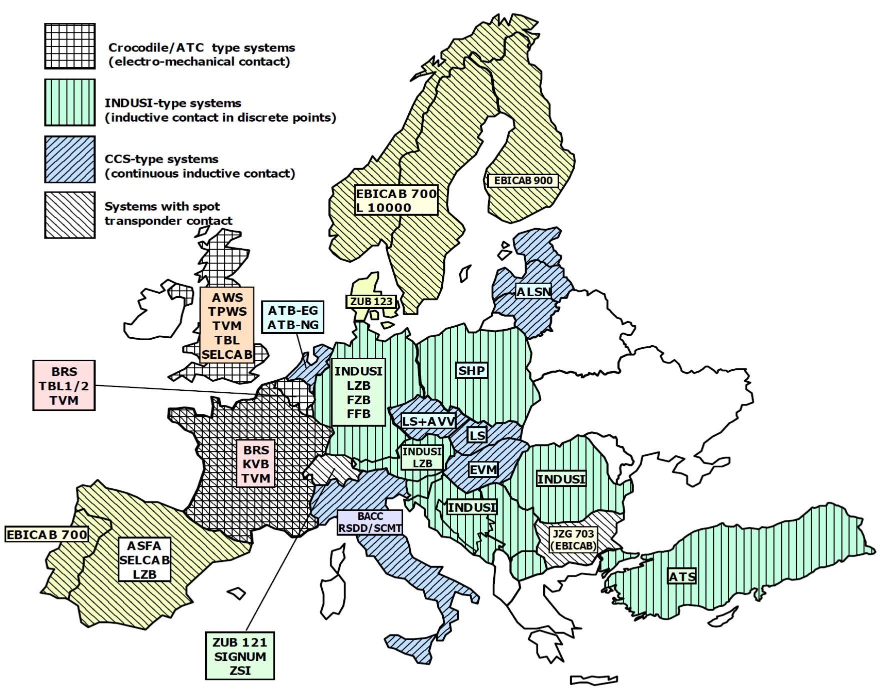


Figure A-7. Train control systems in Europe (Vincze and Tarnai, 2006).

ETCS is being employed by European railways instead of incompatible national safety systems, and many non-European countries such as Australia, China, Israel, Russia, Saudi Arabia, and South Korea are also adopting ETCS or very similar systems. The ETCS system was introduced at different levels of technological development (levels 0 to 3), ranging from overlaid equipment on conventional signalling to the full ATC implementation (AG, 2018).

The ETCS driver machine interface (DMI) is the main means of interaction between the Train Operator and the system. It is used to display visual signals such as analog and digital values, target distance bars, symbols, and system status text messages; to play audible signals, i.e., S1, S2, Click, and Sinfo sounds; to enter data; and to acknowledge situations by the Train Operator. Figure A-8 is a sample of the ETCS DMI in which speed control area, brake details area, auxiliary driving information area, and planning area are the main parts.

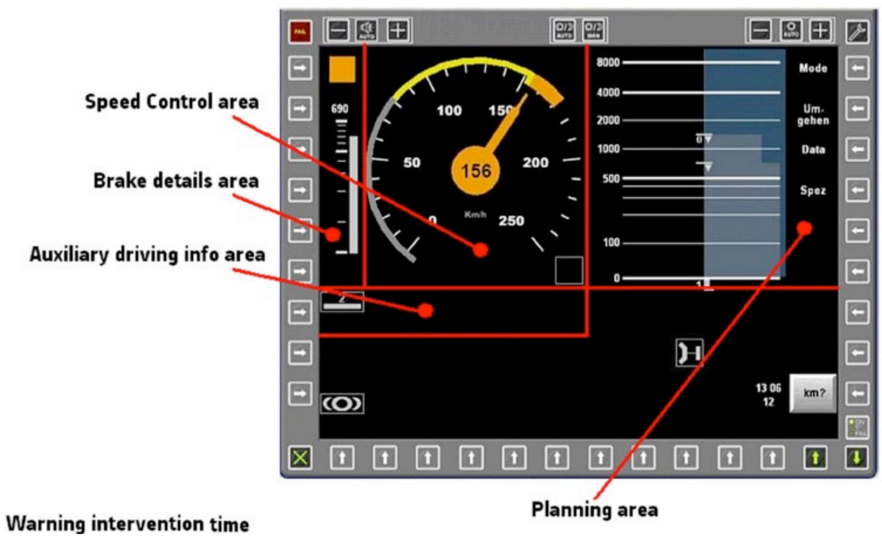


Figure A-8. Sample of the ETCS DMI (Railwaysignalling.eu, 2014)

The following text describes each area of the DMI (Railwaysignalling.eu, 2014; Cervenka, 2017; ERA, 2019,):

The speed control area consists of the speed dial, train speed digital value in the centre of the circular dial, and circular speed gauge (CSG) located around the speed dial. In this area, the permitted speed, target speed, release speed (speed value to allow a train to reach the end of authority (EOA)), and service brake intervention limit are displayed. Furthermore, the used colour reflects the degree of urgency for the Train Operator's action. The colours from lower to higher priority are respectively white, grey, yellow, orange, and red. White means no action is required. Grey means no need for immediate action. Yellow shows that appropriate action (i.e., train braking) is required. Orange reflects the need for immediate corrective action (i.e., increased braking). Finally, red is displayed to show the required action has not been performed.

- The brake details area contains the distance to target display and service/emergency brake intervention indication. Distance to target is displayed digitally and by a bar.
- The auxiliary driving information area provides information about the current level and supervision mode of ERTMS/ETCS, track conditions including free track ahead, tunnel

stopping area, and level crossing, as well as text messages.

- The planning area displays the gradient profile, indication marker, speed profile, and orders and announcements of track conditions to inform the Train Operator of conditions ahead. Uphill and downhill gradients are presented with gray and dark gray colours, respectively, along with their numeric values. The indication marker shows the location on the track where the target speed monitoring to the next target starts. The speed profile is displayed by graphical symbols with numeric values (see Figure A-9).

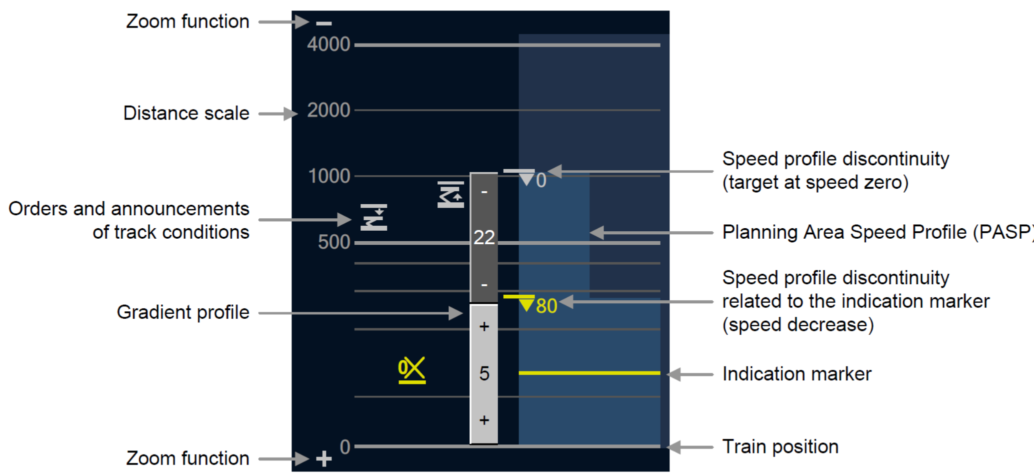


Figure A-9. Main items of the planning information area (ERA, 2019)

According to the ETCS drivers' handbook (ERA, 2019), different types of symbols represented on the DMI include the ETCS level, mode, status, track condition, planning information, Train Operator request, level crossing, and limited supervision.

In addition to the abovementioned visual displays, the ETCS DMI uses four different audio signals to interact with the Train Operator: two are for the speed monitoring function (i.e., S1 & S2 sounds), one for the general notification (i.e., Sinfo), and one as a button click feedback (Cervenka, 2017). The 'S1' sound is sounded once if the current train speed exceeds the permitted speed. The 'S2' audible alarm is played if the current train speed is close to or overpasses the brake intervention speed limit. The 'Sinfo' sound reflects that there is new visual information on the DMI. Finally, the 'click' sound is feedback for when the Train Operator presses a button (ERA, 2019).

Regarding the ETCS level and the situation, various combinations of visual and audible signals are used to convey useful information to the Train Operator. As an example, in ETCS level 1, "when the train approaches a target where a brake command is needed, the CSG and the pointer are coloured in yellow from the permitted speed to the target speed and in grey from 0 to the target speed. If the current train speed exceeds the permitted speed, the CSG and the pointer are coloured in orange from the permitted speed to the braking intervention speed limit. As soon as the current train speed exceeds the permitted speed, the S1 sound is played. If the current train speed overpasses the warning limit, the audible information S2 is played. If the current train speed exceeds the brake intervention speed limit the ETCS onboard equipment commands the service brake. In this case, the CSG and the pointer are coloured in red from the permitted speed to the brake intervention speed limit". These three explained situations for the examples of permitted speed, target speed, and target distance of 140 km/h, 60 km/h, and 760 m are shown in Figure A-10 (ERA, 2019).

Figure A-10. ETCs level 1 speed and supervision information for target with braking needed (ERA, 2019)

In total, the ETCS DMI has three types of buttons—"up type", "down type", and "delay type"—that can be in states of "enabled", "disabled", or "pressed". The Train Operator gets visual and tactile/audible feedback with the activation of a button. In a situation that needs the Train Operator's acknowledgment, an up-type button (e.g., acknowledgment button Ack) is pressed. If two or more acknowledgments are simultaneously required, they are displayed with a first in, first out (FIFO) order after 1 s of each acknowledgment (Cervenka, 2017; ERA, 2019). In the DMI with soft key technology, the Train Operator can acknowledge a text message shown by pressing the message. Note that the displayed text messages or symbols requiring Train Operator acknowledgment are usually shown with a flashing frame and/or by the Sinfo sound. In most cases, the brake is triggered if the Train Operator does not acknowledge before the end condition is reached or within a certain time (e.g., 5 s). Conditions that require the Train Operator's acknowledgment includes level transition, mode transition (e.g., Shunting (SH), Trip, On Sight (OS; ETCS mode that gives the Train Operator partial responsibility for the safe control of his train), Staff Responsible (SR), Reversing (RV), Unfitted (UN), National System (SN), Limited Supervision (LS)), brake command, brake intervention, and system status message about failure (ERA, 2019).

A.7 AWS (Automatic Warning System)

AWS was introduced to UK railways in the 1950s following a SPAD accident in which 112 people were killed (Scott and Gibson, 2012; Connor and Schmid, 2019). AWS was originally created to support semaphore signalling and later deployed in three and four aspects of colour light signalling. However, it only discriminates between two signal aspects: clear (green) and restrictive (red, single yellow, or double yellow).

AWS provides in cab warnings for the Train Operator about the aspect of the upcoming signal in the form of an audible alarm as well as a yellow and black visual indicator, known as the 'sunflower' (see Figure A-11). When a train is approaching a green signal, the audible bell will sound and the sunflower will remain all black. In this situation, there is no need for physical acknowledgment from the Train Operator. If the signal being approached is a restrictive aspect (red, single yellow, or double yellow), a warning horn will sound until the Train Operator presses the AWS acknowledgment button on the Train Operators' desk within the time limit. Then, the sunflower indicator changes to yellow and black segmented to remind the Train Operator they have just received a cautionary warning and acknowledged it. If the Train Operator fails to acknowledge the AWS horn within 2 s (high speed trains) or 2.7 s (lower speed trains), an automatic emergency brake is applied (Crick et al., 2004b; McLeod et al., 2005a; Scott and Gibson, 2012; RSSB, 2016; Van Gulijk et al., 2018). Therefore, in AWS, safety is structurally tied to the reliability of the Train Operator (McLeod et al., 2005a).

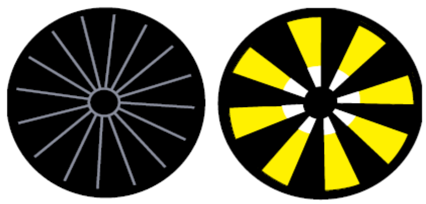


Figure A-11. Visual indications (sunflower) in the AWS system (McLeod et al., 2005a)

A.8 Extended AWS

Later, the AWS warning was extended and used to warn Train Operators of other hazardous situations including speed restrictions (permanent, temporary, emergency) and open level crossings. In this case, the system is referred to as "Extended AWS" (Crick et al., 2004b; McLeod et al., 2005a; RSSB, 2016).

A.9 ICSRD (In cab Signal Reminder Device)

ICSRD was introduced to enhance memory of signal aspects and the AWS system. It is an in cab device requiring the Train Operator to press a button regarding the aspect of the displayed signal. The visual indication, which is a sample and constant reminder of the signal aspect, is then displayed on the Train Operator's desk (see Figure A-12).

For yellow signals, a single press for single yellow and a double press for double yellow is needed. If the double press is not executed within a specified length of time, the system reverts to the more restrictive single yellow. An additional button labeled 'other' can be depressed to indicate the emergency speed restriction (ESR), temporary speed restriction (TSR), or permanent speed restriction (PSR) as well as other operating conditions that use AWS magnets. In this case, a double white illumination is lit up, which be cancelled by the 'Reset' button (Halliday et al., 2005).

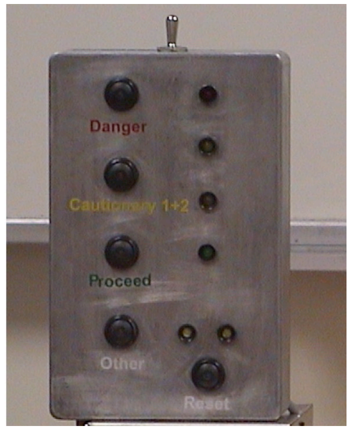


Figure A-12. ICSRD human-machine interface (HMI) (Halliday et al., 2005)

A.10 TPWS (Train Protection Warning System)

TPWS was first introduced to a segment of the Thameslink route in 1996 and then was widely implemented in most parts of the UK railway (Connor and Schmid, 2019). It is a safety intervention system designed to apply the brakes of a train in case of SPAD, overspeeding at PSRs, and overspeeding on the approach to buffer stops (Scott and Gibson, 2012; RSSB, 2016). It consists of an overspeed sensor (OSS) and a train stop (TS) component. The OSS will automatically initiate the brakes if the train approaches a signal at danger at excessive speed. The OSS may also be applied at locations without signals, such as spots with PSRs. The TS will automatically start a brake application on a train that passes a signal at danger without authority (Crick et al., 2004b; RSSB, 2007; Scott and Gibson, 2012).

Unlike AWS, TPWS does not give any warnings to the Train Operator (RSSB, 2016) and is activated whenever AWS is initiated (Crick et al., 2004a; RSSB, 2016). If AWS activates the brake, the brake demand indicator on the TPWS DMI flashes in the same way it does when TPWS applies the brakes (Scott and Gibson, 2012).

The TPWS system was not installed on all signals, with specific locations selected based on a risk assessment to avoid unnecessary interventions (Crick et al., 2004b). According to European directives, TPWS systems will be replaced with ERTMS to provide a higher level of train protection.

The TPWS DMI cannot distinguish between reasons for brake applications, i.e., a SPAD, an overspeed, or a “late to cancel” AWS event. To address this safety issue, several aspects of the TPWS DMI, i.e., ‘variant’, ‘2 indicators’, and ‘3 indicators’, were designed and tested by the RSSB (see Figure A-13). In the new designs, unique visual and audible indications are allocated to different causes of brake executions. For example, in the ‘variant’ and ‘2 indicators’ designs, the AWS horn sounding intermittently warns the Train Operator of a SPAD, while the ‘3 indicators’ design uses speech warnings for both SPAD and overspeed events (Scott and Gibson, 2012). Simulation experiments revealed that all new TPWS interfaces outperformed the existing DMI, and the ‘3 indicators’ interface was the best among those proposed. Audible alerts incorporated in the ‘3 indicators’ TPWS DMI were three verbal messages, with the first two preceded by the same, short, ‘priming tone’ (RSSB, 2010b):

- ‘SPAD alert, contact the signaller’;
- ‘Overspeed, contact the signaller’; and
- ‘TPWS and AWS operational’.

a) b) c)

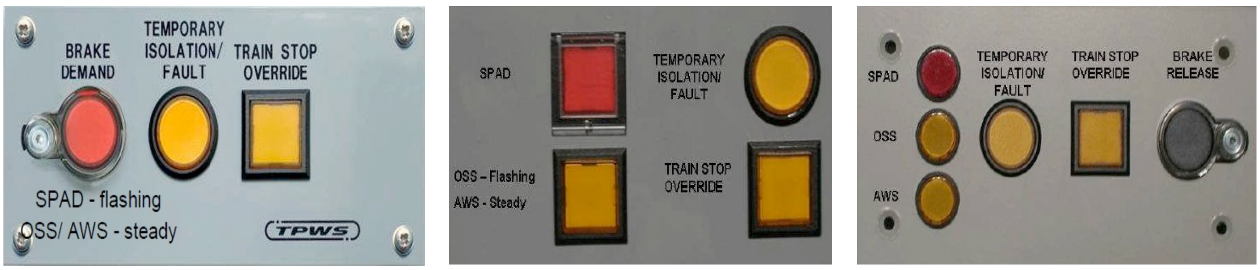


Figure A-13. TPWS DMI for a) ‘variant’; b) ‘2 indicators”; c) “3 indicators” designs (Scott and Gibson, 2012)

Figure A-13a shows the ‘variant’ design for the TPWS DMI. In this DMI, Brake Demand is a push brake reset button as well as an indicator. In a SPAD case it flashes accompanied by an intermittent audible alarm, while in an overspeed or ‘late to cancel’ AWS situations it remains steady. In the ‘2 indicators’ DMI (Figure A-13b), a flashing red SPAD indicator is accompanied by an intermittent sound and a yellow indicator that flashes for an overspeed and is steady for a ‘late to cancel’ AWS. Finally, in the ‘3 indicators’ DMI (Figure A-13c), separate flashing indicators are provided for each SPAD, overspeed, and ‘late to cancel’ AWS event followed by audible warnings (both Nonverbal and verbal warnings) for SPAD and overspeed (Scott and Gibson, 2012).

The RSSB (2016) investigated the integration of AWS and TPWS displays with the ETCS DMI and proposed a final design (see Figure A-14).

a) b) c)

Figure A-14. DMI design for: a) SPAD; b) TPWS overspeed; and c) AWS failure to cancel (RSSB, 2016)

A.11 TASS (Tilt Authorization and Speed Supervision)

TASS is an overlay to train protection systems allowing the control the speeds of tilting trains.

The first introduction of the TASS technology to UK railways was in the West Coast Main Line (WCML) in 2003. TASS, which is based on ETCS components, authorizes tilt operation wherever permitted and controls the speeds of tilting trains during tilt operation (Crick et al., 2004a; Fenner, 2006; Connor and Schmid, 2019). Tilting trains are those that have a mechanism enabling them to tilt cars inwards around curves to mitigate the centrifugal force felt by passengers and reduce wear and tear on rails and wheels (Persson, 2010).

Unlike AWS and TPWS, TASS cannot warn the Train Operator of signal aspects and only controls train speed. In the case of overspeed during tilt operation, the intervention lamp will be illuminated and the Train Operator will hear an audible alarm (Crick et al., 2004a). If speed is not reduced, the train brakes are automatically applied; if speed is reduced to that permitted, the brakes are released and the alarm is reset (Crick et al., 2004a; Connor and Schmid, 2019).

A.12 CAWS (Continuous Automatic Warning System)

CAWS is a type of cab signalling and train protection system deployed in Ireland. CAWS provides the Train Operator with a signal aspect on the in cab ADU until it is updated about 350 m before the next signal. If the signal is changed to a less restrictive aspect, e.g., double yellow to green, a momentary audible ‘warble’ will sound. If there is a change to a more restrictive aspect, e.g., single yellow to red, a continuous audible tone accompanied by the Acknowledge Switch illumination will be activated. In such a situation, the Train Operator must acknowledge the alarm within 7 s to prevent automatic emergency brake application. However, after acknowledgment, the Train Operator overrides the system and can continue the trip without reducing speed (Connor and Schmid, 2019).

A.13 EBI Cab

EBI Cab is a trademark registered by Bombardier for onboard equipment of an ATP system. It is used in Sweden, Norway, Finland, Portugal, and Bulgaria (Vincze and Tarnai, 2006; Ghazel, 2014). In Portugal, it is called Convel (a contraction of Controlo de Velocidade, meaning speed control) (Connor and Schmid, 2019). Two versions are prevalent: EBI Cab 700 and EBI Cab 900 (EC, 2002). Recently, EBI Cab 2000, an onboard ETCS, was approved to be employed by the Spanish National Rail Operator, i.e., RENFE (Bombardier, n.d.).

Train characteristics such as maximum train speed, train length, and train braking characteristics should be inputted by the Train Operator. EBI Cab then provides Train Operators with information including the distance to the next target, target speed, maximum permitted speed, current speed, time to service brake intervention, and faults in wayside or vehicle equipment (EC, 2002; Bombardier, n.d.). EBI Cab can supervise permanent, temporary, and emergency speed restrictions, dynamic brake profile, level crossing, landslide detector status, slip compensation, stopping point, and authorized passing signal at the stop (EC, 2002).

An audible warning is activated when the train speed is more than 5 km/h for EBI Cab 700 (3 km/h for EBI Cab 900) above the speed limit. If the train speed exceeds the permitted speed by 10 km/h (5 km/h for EBI Cab 900), service braking is initiated and the TTB application is shown. The service brake can be released by the Train Operator when the speed is within the limits. EBI Cab will brake sufficiently regardless of Train Operator’s action. The emergency brake is only used in a real emergency, e.g., when service braking is not sufficient. The release of the emergency brake can occur when the train is stationary (EC, 2002; Connor and Schmid, 2019).

A.14 VDD (Vigilance Driver Device)

VDDs were developed to ensure that Train Operators are vigilant during train journeys. They address the risks associated with Train Operator sleepiness, fatigue, faintness, and death. They give audio and visual indications to Train Operators, and if they fail to respond to the alarms within a certain time then an automatic brake is applied (Multer et al., 1998).

A dead man's switch was the first version of a VDD and makes an emergency brake application after a predetermined delay (usually 2 to 3 s) in depressing the food pedal or handle. It stimulates the Train Operator to react through visual and auditory alarms. Since the 1920s, most passenger locomotive cabs in the US and Europe have been equipped with a dead man's switch (Crick et al., 2004b; Oman and Liu, 2007).

Later, additional vigilance control devices were incorporated due to the fact Train Operators sometimes do not release dead man switches during the early stages of sleep. These systems, also known as Alerters in the US, have different types, but generally provide visual and audible alerts with increasing frequency and/or intensity after a specific time. They then give the Train Operator a predefined time for acknowledgment, and an emergency brake is initiated if the Train Operator fails to push an acknowledgment button within this time frame. Note that the time intervals between alerts (usually between 25 and 120 s) as well as time to acknowledgment (usually 3-15 s) are sometimes functions of speed and required braking distance. Furthermore, visual and auditory indications can be synchronous or asynchronous. In asynchronous form, the first visual alert, which is sometimes accompanied by a numeric display of TTB, is activated. An audible alarm is then sounded with delay only if the Train Operator does not respond to the visual alert. In the early 1960s, another generation of Alerters, called activity based Alerters, was introduced. In this type of Alerter, the timers were altered in relation to the Train Operator's activities including changes in throttle or brake settings, horn, bell, and lights (Oman and Liu, 2007).

In the proposed Next Generation Locomotive Cab (NGLC) by FRA, the Alerter warning bar is a large horizontal bar that lights up to notify the Train Operator of the Alerter warning. It will have three levels of warnings. The first level occurs 20 to 10 s before a penalty brake application, and features a yellow flashing bar accompanied by black font TTB and no audible alarm. The second level occurs 10 to 5 seconds before the brake and shows the red flashing bar with TTB in white font followed by a slow audible warbling alarm. Finally, from 5 to 0 s before the penalty brake application, the flashes of Alerter bar and the audible warbling alarm become faster. If the Train Operator interacts with other controls, the Alerter counter will be reset (DiFiore et al., 2012).

Although the existing Alerter systems play an important role in keeping Train Operators conscious, they are deficient in terms of revealing a lack of mental engagement of the Train Operator in the case that the person is physically able to press the acknowledgment button. When a Train Operator is neither fully asleep nor fully awake, it is probable to interact with the system while suffering from a lack of situational awareness. Thus, Monitoring Engineer Fatigue (MEFA), a modified version of Aurora's Aircrew Labor In cockpit Automation System (ALIAS), is being developed by FRA to fill this gap. MEFA activates alerts to warn the Train Operator of potential hazards based on the situation. A comparison between the Alerter system and MEFA is shown in Table A-1 (Stein et al., 2019).

Table A-1. Alerter System vs. MEFA (Stein et al., 2019)

		Technology	
		Alerter	*MEFA*
Mentally Engaged	*Physically Engaged* ***AWAKE***	× Obtrusive	✓ No action
	Physically Disengaged ***FATIGUED***	✓ Detects	✓ Detects
Mentally Disengaged	*Physically Engaged* ***FATIGUED WITH AUTOMATIC BEHAVIOR***	× Cannot Detect	✓ Detects
	Physically Disengaged ***FULLY ASLEEP***	✓ Detects	✓ Detects

The Driver Vigilance Telematic Control System (DVTCS) is a wearable vigilance device developed by the Russian vendor Neurocom and works based on the driver's electrodermal activity (EDA). EDVTCS (Engine DVTCS) is a specific version modified to the locomotive cab and is used by Russian, Australian, and UK railways. This is a wrist and/or finger worn device illuminating a vigilance indicator and countdown display whenever it detects Train Operators are losing their alertness. If the alertness reaches a predefined lower limit, a sound alarm is activated that must be acknowledged by pressing a response button before the activation of automatic brakes (Dorrian et al., 2008; Stein et al., 2019).

In Australia, the Vigilance Alerter system generates an oscillating tone alarm sound as well as text. If a Train Operator control remains inactive for 17 s (Dash-9) or 26 s (Acella Express), the alarms will go off. Unless a reset button is pressed or a driving control action is made, the emergency brakes will be triggered (Spring et al., 2009).

In the UK railway, driver safety devices (DSDs) and driver vigilance systems (DVSs) are closely integrated and available in basic or multi resettable forms. In the basic version, the DVS alarm periodically sounds and resets by releasing and repressing the DSD pedal or canceling the AWS warning. Activation of alarms regardless of the activities the Train Operator is performing can cause distraction. Therefore, a multi resettable version was developed that is automatically reset by pressing the AWS acknowledgment button or moving the brake controller, power handle, or warning horn (Crick et al., 2004b).

A list of railway vigilance devices was reviewed by the RSSB in 2002 (see

Table **A-2**) (Whitlock, 2002). No other review papers of vigilance systems for railways were found, but Wang et al. (2006), Barr et al. (2009), Dawson et al. (2014), and Sikander and Anwar (2018) are some reviews of fatigue detection systems for automobile and truck applications.

Table A-2. Overview of driver vigilance devices (DVDs) (Whitlock, 2002)

Device	Device Company	Country	Measure of readiness
Engine Driver Vigilance Telemetric Control System (EDVTCS), 3rd Generation	J-S Co. NEUROCOM	Russia (contact details are for Luxembourg)	EDA and EDR
MicroNod Detection System (MINDStm)	Advanced Safety Concepts, Inc (ASCI)	USA	Head movements
Eye Tracking Alertness monitor	Future of Technology and Health	USA	Eyelid droop, pupil occlusion, eyelid closure
ABM Drowsiness Monitoring Device (DMD)	Advanced Brain Monitoring Inc	USA	EEG
Photo Driven Alert System	Michael Myronko	UK	Blink Rate
Device for monitoring haul truck operator alertness	Australian Coal Association Research Programme (ACARP)	Australia	Reaction time
ETS-PC Eye tracking system	Applied Science Laboratories	USA (UK contact details)	Eye closure
Face LAB™ 2.0	Seeing Machines	Australia	Eye blinks, eye closure
Vehicle Driver's Anti-Dozing Aid (VDADA)	BRTRC Technology Research Corporation	USA	Head movements and eye closure
Co-pilot PERCLOS Monitor	Driving Research Centre	USA	PERCLOS
Alertness Monitor ambulatory eye blink monitor	MTI Research Corp.	USA	Eye blink
Eye tracker and steering wheel sensor	Bristol University	UK	Uses ASL's eye tracking technology
Hypo vigilance Diagnosis Module (HDM) and Driver Warning System	Part of the EU's Information Society Technologies (IST) research programme	Greece	Not available

A.15 ORBIT

ORBIT is a warning system that provides the Train Operator with a verbal warning whenever the train approaches a signal at danger with exceeded brake curve and speed. It does not apply the brakes automatically to reduce the speed (Verstappen et al., 2017).

A.16 ExPL (External Perception for Locomotives)

ExPL is a current R&D project being undertaken by the FRA with the cooperation of Aurora Flight Sciences and the MIT Human Systems Laboratory (see Figure A-15). It is a real time, automated second set of eyes based on machine vision/machine learning technologies. ExPL detects railway signal lights, detects and reads railway signs, observes rail track and merging conditions, and detects long-distance objects in day/night conditions. It provides visual alerts and improves crew situational awareness. The feasibility and proof of concept of ExPL were confirmed in the Volpe Centre Cab Technology Integration Laboratory (FRA, 2020).

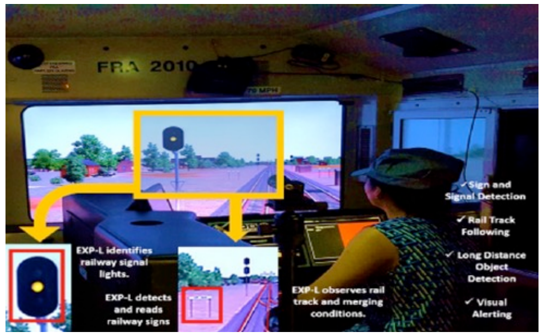


Figure A-15. An overview of ExPL (FRA, 2020)

A.17 De novo

De novo is a recently-proposed internet-of-things (IOT) based system to warn the Train Operator of the existence of an object at a grade crossing. It will have an in cab electronic display to illuminate a warning to the Train Operator about obstructions on the track (Minoli and Occhiogrosso, 2017).

A.18 Anticollision Devices

Train collision early warning system (TCEWS), which is proposed as an addition to train control systems in China, uses a global navigation satellite system (GNSS) and Global System for Mobile Communications-Railway (GSM-R) to addresses the problem of train-to-train collisions (Jiang et al., 2016). It monitors the train position and movement vector and provides the Train Operator with warning signals whenever the potential for collision arises. The system should compute the time to potential collision by considering factors such as Train Operator reaction time, wireless communication, train position, and train braking, and then send the Train Operator different alarms depending on how imminent the collision will be. Furthermore, it utilizes a colour based system combined with some common vocabulary to convey the level of danger for warnings and provides advisory measures for the Train Operator to follow to avoid a collision. According to collision risk, a four tier colour coded system was designed, with red representing the most severe collision risk, followed by orange, yellow, and blue (Jiang et al., 2016; Li et al., 2018). In principle, the TCEWS does not involve in train control and only provides the information of the preceding train and warnings for collision avoidance. The Train Operator who received the warnings decides the safety responses (slow down or stop) (Li et al., 2018).

A similar train avoidance system to TCEWS is currently being investigated by the German Aerospace Centre (DLR) is named Railway Collision Avoidance System (RCAS). This system can consider other sources of threats such as road vehicles or obstacles in addition to advancing trains (García et al., 2007; Lehner et al., 2009; Li et al., 2018). RCAS was inspired from the aeronautical Traffic Alert and Collision Avoidance System (TCAS) as well as the maritime Automatic Identification System (AIS)(Strang et al., 2006). The Collision Avoidance System (CAS) developed by the Alaska Railroad Corporation (ARRC) is another collision avoidance device that is a vital part of the PTC system (Li et al., 2018). The system was designed to prevent train-to-train collisions, enforce speed limits, and protect roadway workers and equipment (Tse, 2009).

A.19 DRA (Driver's Reminder Appliance)

Passenger Train Operators are more likely to be distracted by their station duties and forget that the next signal is at danger. To overcome this problem, the DRA was introduced in 1997. The last action the Train Operator will undertake before powering away from the station is resetting the DRA. It is a reminder for the signal ahead is red. When the Train Operator pushes the DRA button, a prominent red light in the cab is displayed that prevents power from being drawn from the engine until it has been disengaged.

This system developed has two types, i.e., the Train Operator set (passive) DRA and the AWS activated (or active) DRA. The Train Operator set DRA is set by the Train Operator pushing down a button (sometimes a rotary selector) on the driving cab after coming to stand and is reset by pulling out the button, which then allows the Train Operator to proceed. When the DRA is in set mode, the button shows red and disables the traction power. In the AWS activated DRA, the system is automatically set when the train passes an AWS magnet and then its doors are opened (RSSB, 2002; Crick et al., 2004b).

A.20 Roadway Worker Warning System (RWWS)

Although the PTC system prevents a train from entering a work authority, all track locations are not equipped with PTC and so an alternative worker protection device is required. RWWS is a proposed device that sends indications to both Train Operators and track workers and warns them of the presence of a train or a worker. In this system, a protection zone, which follows the workers as they walk the track, is first identified with modern sensor and communication technology. When a train enters the boundaries of the protection zone, a warning alert will then be sent to all workers. The train crew will also receive either an in cab or wayside visual indication. In the case of a worker on the track, the train will automatically slow down or stop until the track is cleared (Smith, 2016).

A.21 Earthquake Early Warning (EEW)

EEW is an alert system that quickly detects significant earthquakes and sends an alert before EEW shaking begins. In the US, Caltrans is examining the integration of EEW with PTC to protect rail infrastructure and operations from earthquakes and seismic activity. In China, the development of a new EEW alarm tool for use in a high speed rail system is under investigation. This system decelerates the train whenever it receives the first seismic wave, i.e., P wave. The EEW system adopted by France is designed to “automatically slow down or if necessary stop the train a few seconds after the detection of an earth tremor liable to deform the tracks, to avoid it reaching the damaged areas at full speed.” The use of an EEW alert by East Japan Railway Company (JR East) during the Great East Japan Earthquake of 2011 is reviewed in the literature (Riding, 2019).

A.22 HUD (Head up Display)

HUD provides a virtual image in the line of the Train Operator's sight (see Figure A-16). It was first developed by the aviation industry for fighter aircrafts, and then civil airplanes, to reduce the need for in cab attention. The main advantages of HUD are enhanced situation awareness, task performance, and detection of outside events (Thomas and Davies, 2008; Davies et al., 2012; FRA, 2020).

FRA, with the cooperation of the MIT Human Systems Laboratory and General Electric Global Research, started a HUD development project in 2018 (FRA, 2020). Another relevant project was also conducted by the RSSB in the UK (Thomas and Davies, 2008; Davies et al., 2012). The HUD used in Australia shows train system status information including train speed, brake pressures, throttle, and brake lever positions. It also displays overspeed and Vigilance Alerter text alarms (Spring et al., 2009).

Figure A-16. An example of head up display (FRA, 2020)

A.23 NGLC (Next Generation Locomotive Cab)

The FRA program for NGLC proposed redesigning the cab to have an integrated locomotive control system and to end the hodgepodge of controls and displays added to the cab over time. The NGLC cab consists of three LCD touch screen displays in front of the engineer (see Figure A-17) and a redundant LCD display mounted on the electrical cabinet wall opposite the back of the locomotive engineer's workstation.

a) b) c)

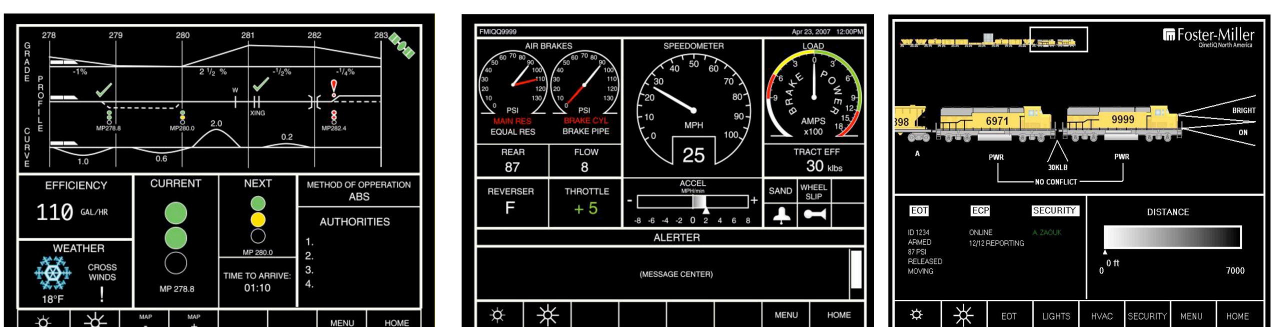


Figure A-17. NGLC displays: a) left auxiliary; b) centre; and c) right auxiliary (DiFiore et al., 2012)

The centre display includes air brake information, speed and acceleration information, load information and tractive effort, reverser and power information, icon block, Alerter warning bar, message centre, locomotive ID, date and local time, PTC, route guidance, track authority information, fuel consumption information, and rail condition information (current and forecasted) soft keys. The left hand auxiliary display shows weather conditions; route guidance, PTC, and track authority information; and operating efficiency information. The right hand auxiliary display contains locomotive and train security and condition monitoring information. Failures and other problems that are detected are conveyed to the engineer via graphical alerts (DiFiore et al., 2012).

Appendix B. Modality and source of Cambrian in cab information

Table B-1. Modality and source of Cambrian in cab information (Blanchard and Hill, 2004):

Modality	Source
Auditory	Absence of handset tone
Auditory	Acknowledgement from conductor (via in cab phone)
Auditory	Acknowledgement from signaller (via radio)
Auditory	Audible feedback from cab display unit (CDU)
Auditory	Audible feedback from operation of AWS
Auditory	Audible feedback from operation of driver safety device (DSD)
Auditory	Audible feedback from test of fire bell
Auditory	Audible feedback from the operation of public address (PA) system
Auditory	Audible feedback from train buzzer codes
Auditory	Communication with conductor via cab to cab phone/intercom
Auditory	Conductor's codes
Auditory	Feedback from operation of PA system
Auditory	Feedback from radio electric token block signalling (RETB) radio test
Auditory	Hear AWS bell/buzzer
Auditory	Hearing shunter (radio or voice) communication (radio or direct voice)
Auditory	Hearing signaller communication (verbal)
Auditory	Information from signaller via RETB radio
Auditory	Sound of AWS alert tone
Auditory	Sound of conductor communication via cab to cab phone
Auditory	Sound of conductor's codes
Auditory	Sound of DSD audible alarm
Auditory	Verbal acknowledgment from signaller via RETB radio
Auditory	Verbal communication with signaller via RETB radio
Auditory	Verbal confirmation from the signaller
Auditory	Verbal instruction from signaller via RETB radio
Psychomotor	Feedback from power brake controller
Psychomotor	Gradient from feedback during driving
Psychomotor	Haptic feedback from application of brake controller
Psychomotor	Haptic feedback from contact with buffers
Psychomotor	Haptic feedback from engine
Psychomotor	Haptic feedback from foot operation of DSD
Psychomotor	Haptic feedback from pressing AWS cancel
Psychomotor	Haptic feedback from pressing TPWS acknowledge button
Psychomotor	Haptic feedback from pressing TPWS override button
Psychomotor	Haptic feedback from the braking controller
Psychomotor	Haptic feedback from the train
Psychomotor	Haptic feedback from train braking
Psychomotor	Haptic perception of brake position
Psychomotor	Haptic perception of deceleration
Psychomotor	Haptic perception of position of brake
Psychomotor	Perception of acceleration during track deviations
Psychomotor	Perception of deceleration
Psychomotor	Perception of vertical acceleration during track gradients
Psychomotor	Train loading from feedback during driving
Psychomotor	Train faults from diagnostic train activity
Visual	Brake controller position
Visual	Brake isolation light

Modality	Source
Visual	Brake pressure gauge indication
Visual	Cab indicators showing status of lights
Visual	CDU visual display
Visual	Train Operator notices
Visual	Train Operator slips
Visual	Equipment in Train Operator's bag, e.g., torch, watch, rulebook
Visual	Extent on RETB token (can be long or short)
Visual	Feedback from all in cab fault indicators
Visual	Indication of TPWS system status
Visual	Journey diagram
Visual	POIS documentation
Visual	Possession of correct RETB token on CDU
Visual	Possession of correctly filled out RETB form
Visual	RETB CDU visual display
Visual	Sight of AWS cancel button
Visual	Sight of AWS fault indicator
Visual	Sight of AWS sunflower
Visual	Sight of brake gauge
Visual	Sight of brake pressure gauge
Visual	Sight of brake setting
Visual	Sight of cab controls
Visual	Sight of cab instruments - blue interlock light
Visual	Sight of cab instruments
Visual	Sight of CDU
Visual	Sight of CDU display
Visual	Sight of CDU display screen
Visual	Sight of CDU display screen (token granted displayed)
Visual	Sight of CDU unique number
Visual	Sight of CDU unit
Visual	Sight of circuit breaker settings
Visual	Sight of communication handset
Visual	Sight of detonators
Visual	Sight of diagram
Visual	Sight of diagram/Train Operator notices
Visual	Sight of DRA setting
Visual	Sight of Train Operator notices/diagram
Visual	Sight of Train Operator's daily sheets
Visual	Sight of Train Operator's slips
Visual	Sight of Train Operator's watch
Visual	Sight of driving diagram in cab
Visual	Sight of emergency brake
Visual	Sight of fault book
Visual	Sight of fault indicators
Visual	Sight of fault log book
Visual	Sight of fire extinguisher
Visual	Sight of gradient from view
Visual	Sight of horn/whistle control
Visual	Sight of isolator switch settings
Visual	Sight of journey diagram
Visual	Sight of late operating notices
Visual	Sight of master switch position

Modality	Source
Visual	Sight of personal equipment on person, e.g., keys and Hi Vis jacket
Visual	Sight of rear cab external (tail) light switch positions
Visual	Sight of red flags
Visual	Sight of sectional appendix
Visual	Sight of spare lamp
Visual	Sight of speedometer
Visual	Sight of TOPS sheet
Visual	Sight of TPWS brake demand indicator
Visual	Sight of TPWS brake demand tone
Visual	Sight of TPWS fault indication
Visual	Sight of TPWS indicator
Visual	Sight of TPWS system indicator
Visual	Sight of track circuit clips
Visual	Sight of train fault log book
Visual	Sight of train loading form
Visual	Sight of train windows
Visual	Sight of wheelspin indicator
Visual	Sight of windscreen condition
Visual	Sight of wiper movement
Visual	Status of DRA indication
Visual	Status of Signal Line Working Ticket
Visual	Status of Special Authority Card
Visual	TOPS sheets
Visual	Train faults from cab instruments
Visual	Train faults from train log book
Visual	Train loading from official form
Visual	Train loading from official TOPS form
Visual	Visual feedback from brake pressure gauge
Visual	Visual feedback from position of the circuit breakers
Visual	Visual feedback from position of the isolator switches
Visual	Visual feedback from speedometer
Visual	Visual feedback through train window
Visual	Visual perception of changing speed
Visual	Weekly notices
Visual	Wheelspin cab indicators
Visual / Auditory	Visual/audible feedback from door lock operation
Visual / Cognitive	Train number from memory/record card
Visual / Psychomotor	Visual/haptic feedback from brake controller position

Appendix C. Factors influencing Train Operator response to consecutive caution signals

Table B-2 shows a complete list of the factors influencing Train Operator response to consecutive caution signals, derived by the RSSB (2015). Note that shaded cells in this table show the relevant service types, Train Operator experience level, and task steps relevant to each influential factor.

Table B-2. Factors influencing a Train Operator's response to consecutive caution signals (RSSB, 2015)

		Service type			Train Operator experience		Task step	
Category	**Influencing Factor**	**Suburban / Metro**	**Passenger - Long distance**	**Freight**	**Novice/ Inexperienced**	**Experienced**	**Planning response to signal aspect**	**Initiate and execute response to signal aspect**
Train Operator	Expectation - incorrectly attributes reason for delay to traffic							
Train Operator	Expectation - traffic related cautionary sequence							
Train Operator	Train Operator fatigue							
Train Operator	Train Operator level of expertise	N/A	N/A	N/A				
Train Operator	Expectation - of approach release from red							
Train Operator	Expectation - signals held at danger for no reason							
Train Operator	Expectation - of a particular signalling sequence (location dependent)							
Train Operator	Train Operator desensitized to cautionary signals through							

Category	Influencing Factor	Service type			Train Operator experience		Task step	
		Suburban / Metro	Passenge r - Long distance	Freigh t	Novice/ Inexperience d	Experience d	Plannin g respons e to signal aspect	Initiate and execute respons e to signal aspect
	familiarity							
Train Operator	Avoidance of coming to a standstill (passenger expectations)							
Train Operator	Passenger comfort							
Train Operator	Platform - departing at caution							
Train Operator	Platform - distracted by passengers/PTI							
Train Operator	Knowledge of train position ahead (seen or inferred from aspect changes)							
Train Operator	Knowledge of proximity to terminus station							
Train Operator	Train Operator inexperience							
Train Operator	Route knowledge - expectation of distance to next signal							
Train Operator	Route knowledge - expectation of distance to next station							
Train Operator	Route knowledge - unaware of location of braking trigger points							
Train Operator	Shift patterns/Time into shift							

Category	Influencing Factor	Service type			Train Operator experience		Task step	
		Suburban / Metro	Passenger - Long distance	Freight	Novice/ Inexperienced	Experienced	Planning response to signal aspect	Initiate and execute response to signal aspect
Train Operator	Speed judgement							
Train Operator	Train Operator focus on train ahead rather than signal aspects							
Train Operator	Knowledge - Train Operator unfamiliar with stopping at particular signal							
Train Operator	Vigilance - decrement over time							
Train Operator	Vigilance - in cab distraction							
Train Operator	Vigilance - microsleeps, driving without attention mode							
Train Operator	Expectation - other traffic movements in the area							
Train Operator	Expectation - traffic density (e.g., in peak hours)							
Train Operator	Pressure to meet scheduled station booking times							
Train Operator	High Train Operator workload or distraction							
Train Operator	Low Train Operator workload (boredom, switching-off)							

Category	Influencing Factor	Service type			Train Operator experience		Task step	
		Suburban / Metro	Passenger - Long distance	Freight	Novice/ Inexperienced	Experienced	Planning response to signal aspect	Initiate and execute response to signal aspect
Train Operator	Expectation of PSR, ESR, TSR ahead							
Train Operator	Train Operator has false understanding of reason for signal aspect							
Train Operator	Train Operator frustration at delays							
External environment	Adhesion problems - leaf fall, ice, pollutants, snow, rain problems							
Infrastructure	AWS used as a stopping marker							
Infrastructure	AWS positioned too close to signal							
Infrastructure	AWS positioned too far from signal							
Infrastructure	Signal sighting time - specifically on curved approaches							
Infrastructure	Wrong signal illusion (curved approach)							
Infrastructure	Falling gradient							
Infrastructure	Flashing yellow aspect sequences							
Infrastructure	Read through - intensity of signal beam							
Infrastructur	Signal							

Category	Influencing Factor	Service type			Train Operator experience		Task step	
		Suburban / Metro	Passenger - Long distance	Freight	Novice/ Inexperienced	Experienced	Planning response to signal aspect	Initiate and execute response to signal aspect
e	conspicuity - intensity of signal beam							
Infrastructure	Other light sources							
Infrastructure	Platform curvature							
Infrastructure	Rising gradient							
Infrastructure	Sighting of signals ahead							
Infrastructure	Signal sighting time							
Infrastructure	Spacing of signals/section length (i.e., short signal sections)							
Infrastructure	"Wrong side" signals							
Infrastructure	Signals for other lines							
Infrastructure	Density of signals (high density) in area							
Infrastructure	Double blocking used in area							
Operations	Train Operator training and assessment							
Operations	Route Knowledge - information share with other Train Operators/trainers							
Operations	Company driving policy							
Operations	Company							

Category	Influencing Factor	Service type			Train Operator experience		Task step	
		Suburban / Metro	Passenger - Long distance	Freight	Novice/ Inexperienced	Experienced	Planning response to signal aspect	Initiate and execute response to signal aspect
	ecodriving policy							
Operations	Signal sighting committee competence & fitness							
Operations	Service stopping pattern							
Operations	Timetable							
Operations	Service is not in timetable, e.g., ECS							
Operations	Missing a timetabled/booked path for service							
Operations	Service regulation issue/inefficiency							
Operations	Signaller prioritizes faster service							
Train	Looped train/long rolling stock							
Train	Spacing of signals - braking distance							
Train	Train stock is difficult to control at low speeds							
Train	Power and braking characteristics of stock							

Appendix D. Design guidance for alarm systems in the railway domain

Dadashi (2012) proposed the following design guidance for alarm systems in the railway domain according to an analysis of alarm handling in the railway control room.

Table D-1. Design guidance for supporting alarm handling (Dadashi, 2012)

Activity	Main artifacts	Strategies	Design guidance
Notification	Alarm banner	Filtering, Categorizing	● The information presented on the alarm banner should be coded so that it is easy to filter. ● Codify the types of alarms to facilitate categorizing.
Acceptance	Alarm banner, Display area	Categorizing, Similarity matching	● On the alarm banner, mark the alarm to tell the operator that there are similar previous cases. ● On the display area, provide information about similar previous cases. This is to ensure that operators have a clear overview of the alarm and do not automatically accept it because of some similarities between this alarm and some previous cases.
Analysis	Display area, Menu, Overview	Extrapolation, Similarity matching	● On the display area provide details of previous cases and also facilitate playing back the alarm situation.
Clearance	Menu, Display area, Overview	Extrapolation, Similarity matching	● Provide clearance options and ultimately potential outcomes of these courses of action according to previous cases (e.g., their delay contribution, etc.).

Appendix E. List of alarm management resources

Industries:

- ANSI/ISA 18.2- Management of Alarm Systems for the Process Industries (ISA, 2009, 2016)
- API RP-1167- Pipeline SCADA Alarm Management (API, 2010, 2016)
- EEMUA 191- Alarm systems- a guide to design, management and procurement (EEMUA, 2007, 2014)
- IEC 62682- Management of alarm systems for the process industries (IEC, 2014)
- NAMUR NA-102- Alarm management (NAMUR, 2013)
- YA-711- Principles for alarm system design (Norwegian petroleum directorate) (NPD, 2001)

Railway:

- Alarms and Alerts Guidance and Evaluation Toolkit (RSSB, 2009)
- Thameslink Program Strategy Alert/Alarm Strategy (NR, 2013)
- LUL S1218- the Human Systems Interaction – Dialogues and Notifications standard of the London Underground (LUL, 2014)
- The developed guidelines by:

➢ The Association of American Railroads (AAR) and the Railway Association of Canada (RAC) for specifications of positive train control systems in North America.

➢ Amtrak

➢ Burlington Northern Railroad (BN)

➢ Swedish State Railways

➢ Japan Rail (JR) companies

➢ Société Nationale des Chemins de Fer Français (SNCF, the French National Railways)

➢ Deutsche Bahn AG (DB AG, German Railways)

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