The Contribution of Automation to Resilience in Rail Traffic Control

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Abstract. This paper addresses the challenges of high system complexity within rail traffic control. Based on resilience engineering principles, the different types of traffic control technology are analysed in order to identify either their contributions or hindering factors towards system resilience. Throughout four main generations of technology in traffic control, whilst there is a clear path towards increased automation, evidence from recent research in this domain suggests that the introduction of automation does not necessarily contribute to enhanced resilience. Despite its contributions to efficiency by placing larger areas under the supervision of each control post, it has introduced many new complexities in traffic control decision making. In many cases, automation has created a gap between rail operations and those in charge of their control. Beyond basing their decisions on operational needs and priorities, Traffic Controllers must take into account the possible responses that automated systems might initiate. So far, traffic control technologies are unable to deal with disruptions and much of the variability inherent to complex operations such as the railway but future generations of rail signalling systems may be able to better support resilience if appropriately designed.

Keywords: Complexity, decision making, flexibility versus rigidity, ETTO, automation, resilience, rail human factors.

1 Introduction

Technology is today profoundly embedded in every aspect of our social and economic activities. In a few decades, it has produced major transformations across all industry domains, both at management and operational levels. Within a safety management context dominated by human error concerns, automation has been a source of increased efficiency and quality (higher outputs and standardisation), whilst shifting human action away from the "sharp end" towards progressively higher and more complex levels of systems control and supervision.

More recently, in the domain of traffic control, the widespread application of information and communication technologies has tackled some of the challenges resulting from the highly distributed decision making processes, on which such control and

D. Harris (Ed.): EPCE 2014, LNAI 8532, pp. 458–469, 2014.

supervision tasks are grounded. Within rail traffic control, there is evidence to suggest that, in addition to coping with increasingly dynamic and large scale operations, new system complexity related factors are emerging as a result of heightened automation, which may significantly hinder the ability of humans to cope with traffic control demands (Balfe et al., 2012). For example, the need for the operator to consider which factors have been accounted for by the automation and which have not. While discussing the impacts of complexity within most currently existing systems, Leveson (2004) points out that the increasing presence of software at all levels of management and operation gave way to "more integrated, multi-loop controls in systems with dynamically interacting components". This generates system interactions increasingly difficult to understand and control.

Based on the concept of resilience and in particular on resilience engineering as a framework for coping with high complexity in sociotechnical systems, this paper develops an overview of the evolution of automation in rail traffic control and investigates its impacts on decision making and overall system performance. After briefly introducing the key aspects of resilience engineering, a description of rail traffic control is developed, highlighting the main generations of systems, which over the years, have supported it. The impacts of automation on decision making processes are then discussed in light of resilience engineering literature, with particular interest on aspects which may hinder or enhance system resilience.

2 Resilience

Resilience has become a widely used concept across many different domains. Within the scope of resilience engineering, it is defined as the "intrinsic ability of a system to adjust its functioning prior to, during or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions" (Hollnagel 2011, pp xxxvi). Based on this concept, resilience engineering consists of the development and implementation of the tools necessary to enhance resilience across all system operations (Wreathall, 2006). Although it has been described as an approach to safety management, resilience engineering acknowledges that operations in most industrial sectors rely on highly interdependent sociotechnical systems, and that within such contexts, an effective integration of safety into every aspect of system performance (both at management and operations level) becomes increasingly critical.

As often discussed by Hollnagel *et al* (2006), one of the aims of resilience engineering is the ability to cope with variability of system operations and uncertainty about possible outcomes. Managing variability and uncertainty should be built around four main system capabilities towards resilience (Hollnagel, 2011):

- **Knowing what to do** corresponds to the ability to address the "actual" and respond to regular or irregular disruptions by adjusting function to existing conditions.
- **Knowing what to look for** corresponds to the ability to address the "critical" by monitoring both the system and the environment for what could become a threat in the immediate time frame.

- **Knowing what to expect** corresponds to the ability to address the "potential" longer term threats, anticipate opportunities for changes in the system and identify sources of disruption and pressure and their consequences for system operations.
- **Knowing what has happened** corresponds to the ability to address the "factual" by learning from experiences of both successes and failures.

Enhancing system resilience relies on managing a dynamic balance between these four capabilities. At any given time and place, operational demands may vary considerably and thus system capabilities (resources) must be managed in order to adjust functioning to such changing operational demands.

3 Automation

Automation is defined as when a machine (usually a computer) assumes a task usually performed by humans (Parasuraman & Riley, 1997). Automation is often introduced in order to achieve tasks more efficiently and reliably than humans and the benefits are perceived to be a reduction in human error, a saving on labour costs and a reduction in human workload. However, in complex systems such as rail traffic control, automation lacks the flexibility of human operators in the face of novel situations. Technology is the driving force behind automation, coupled with the desire of organisations to operate systems more economically. However, full automation of complex systems is rare and most automated systems have at least one operator to monitor their performance. Wickens (1992) lists three circumstances when it is appropriate to introduce automation; automation which is employed to perform a function that is beyond the capabilities of a human operator, for example performing complex calculations at high speed; automation which performs functions at which human operators are poor, for example monitoring a system for a single failure event; and automation which provides assistance to human performance, for example augmenting information on display systems.

Issues regarding human interaction with automation are well documented in the human factors literature (e.g. Woods, 1997). Bainbridge (1983) highlighted a number of ironies of automation that included the tendency of designers to automate the tasks that are simple to automate and leave the operator with the tasks that are comparatively more difficult. Thus, automation is often implemented to support operations during normal working, but the operator must take over when conditions move outside the normal operating envelope. The removal of routine tasks from operators may have a resulting effect on their long term skill level (Bainbridge, 1983) and also on their short term situation awareness or a phenomenon associated with automation known as out-of-the-loop unfamiliarity (Endsley, 1996). These effects mean that operators are less equipped to handle disruption efficiently when it occurs.

Balfe et al (2012) discuss the importance of rail traffic control systems providing feedback from the automated system to the operator in order to overcome the issues associated with out-of-the-loop unfamiliarity and Lenoir et al (2006) suggest that feedback may be particularly important in rail traffic control due to the lack of precision in the information available. Kauppi et al (2006) argue that train graphs (a graph presentation of the timetable) represent a powerful method of presenting information to the operator in a useful format allowing them to proactively identify and manage potential threats.

4 Rail Traffic Control

The purpose of rail traffic control is to ensure separation between trains and to efficiently route trains along the rail network to their destination. For instance, in the British rail network, traffic control is typically achieved through three types of control interface. The first, and oldest, is the lever frame technology dating from the 1800s (Figure 1). These use levers physically attached to the points or signal they control to move the position of the points or signals. The system is operated under the Absolute Block principle, which states that one train may be in one section of the railway on one line at one time. A mechanical interlocking system prevents the signaller from pulling a lever that would set a 'conflicting move', i.e. a route two trains in to the same section of the railway. Signallers communicate the movements of trains by means of a telegraph system which uses bell codes to send messages between signal boxes. This type of control is only suitable for very small areas due to the physical link between the lever and the points/signals.

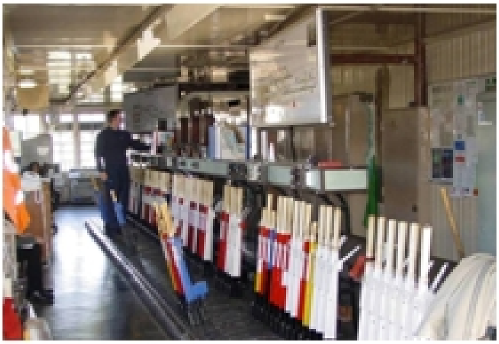

Fig. 1. Lever frame

The next generation of rail traffic control system, the eNtry-eXit (NX) panel, was introduced in the 1950s (Figure 2). NX panels were introduced in conjunction with technologies to operate points and signals remotely and to provide the signalling system with an indication of train positions. This system allowed signallers to control much larger areas and the development of Track Circuit Block (TCB) also allowed trains to run closer together whilst still ensuring separation, supported by a relay interlocking. The final generation of signalling systems also use TCB and are run similarly to NX panels.

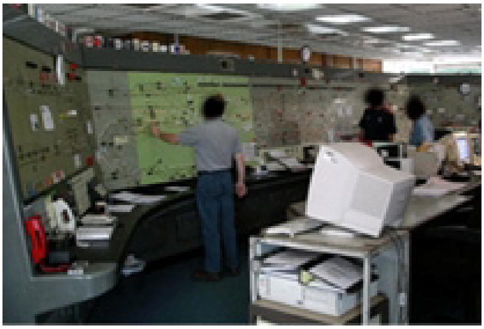

Fig. 2. NX panel

The major change was in the format of the interface, with the control system moving from panel technology to VDU technology (Figure 3). This change facilitated the introduction of automated signalling systems which set the routes for trains according to the timetable. A number of forms of automation are possible, from simple systems which set the priority for trains according to the order in which they appear on the workstation through to advanced forms which attempt to calculate the minimum delay for all trains approaching the area. In the GB network, an advanced form of automation known as Automatic Route Setting (ARS) is used. This system works alongside the signaller and uses complex algorithms to determine which trains to prioritise.

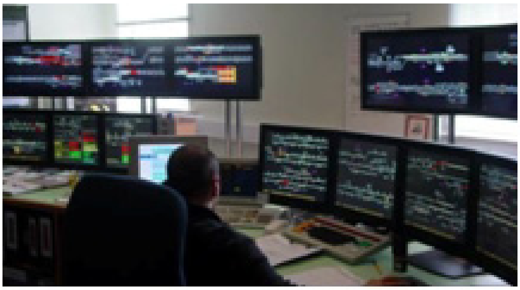

Fig. 3. VDU workstation

In rail traffic control systems, the system works smoothly when running to the predetermined timetable. However, if any disruption occurs due to late running trains or the unavailability of a piece of infrastructure, the signalling task becomes more complex as decisions are required on the routing of trains over a common piece of track. Signallers make a series of decisions on the running order of trains in these circumstances in order to attempt to minimise the effects of the disruption, whilst maintaining safety.

The generation of signalling systems currently under development in GB are Traffic Management systems. These aim to move beyond the traditional control interface of a schematic view of the railway under control towards a train graph (Figure 4) allowing direct manipulation of the timetable. This system can highlight potential conflicts between trains ahead of time, allowing operators to adjust the timetable to resolve the conflict, in contrast with the current situation where the conflict can only be resolved as it occurs.

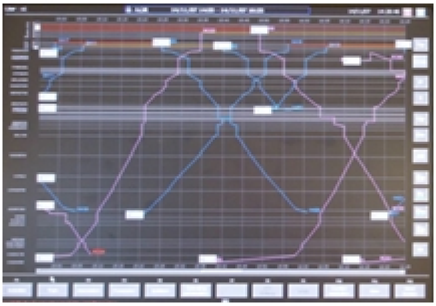

Fig. 4. Train graph

5 Resilience in the Context of Traffic Control

Regardless of the transport sector considered, traffic control is today recognised as a safety critical and complex domain. One of the main repercussions of high complexity is the underspecified nature of systems operations (Wilson *et al* 2009). The large number of human, organisational and technical elements that must be accounted for, together with their fast pace changing behaviour, imposes serious limitations to the ability to fully understand and monitor system operations. Thus, maintaining operational (traffic) control must recognise high variability and uncertainty as constant challenges.

Traffic control is constantly dealing with decisions critical to the safety and efficiency of rail operations as whole. It is inherently built on highly distributed and complex decision making processes. The inevitable finite nature of resources requires the constant making of choices regarding their allocation. At the heart of each of these choices is a decision that must be made. Within the context of rail traffic control, while resource limitation manifests itself through the available access to the rail infrastructure for both the running of trains and the response to any engineering needs, decision making addresses any choices that must be made to safely run as many trains as possible, whilst ensuring the safety of those having to work on the line and reliability of the work they deliver.

Within the scope of resilience engineering, the choices and the decisions that shape them have been expressed through the concept of Efficiency-Thoroughness Trade-Off (ETTO - Hollnagel 2009). In this frame of mind, efficiency generically means achieving a given purpose with minimum expenditure of resources (time, human, technical, financial...) and thoroughness represents a hypothetical ability to accomplish an objective with total disregards to any such resource limitations. It should be kept in mind that actions or devices contributing to safety, because they always consume a certain amount of resources, they constitute a trade-off in favour of thoroughness (although in the future, they may come to contribute to efficiency in some way). For instance, if nothing else, at least time must be invested to develop a safety check (i.e. pre-flight checklists), and thus, efficiency is sacrificed in some measure.

As resources are always limited, a trade-off between efficiency and thoroughness is inevitably generated throughout every decision making, regardless of the fact that it may often assume a very diffuse nature, rather than an explicit form. Hence, keeping in mind the critical role of decision making earlier described, two capabilities are fundamental for trade-offs to contribute to resilience in traffic control:

- People require information to support their decisions. Safety relies on providing operations and management with information about changing vulnerabilities (Woods & Hollnagel, 2006). Only such information can support an adequate level of awareness regarding how much pressure for efficiency the system can sustain and when it is time to ponder with more thoroughness on the information available, or even to search for additional information (sacrifice decisions).
- Organisations need to develop ways of monitoring safety boundaries. As pointed out by Woods (2006), systems need to maintain awareness and responsiveness to evidence of any potential shifting of decision criteria, which might lead the system across safety limits.

5.1 Analysis of Resilience in Rail Traffic Control Technologies

The four generations of signalling system are analysed here in terms of Hollnagel's (2011) four main system capabilities for resilience of knowing what to do (actual), knowing what to look for (critical), knowing what to expect (potential), and knowing what has happened (factual). The analysis is based on ethnographic observations of signalling operations over a seven-year period as well as a detailed set of interviews conducted with signallers regarding their use and opinions of signalling automation (Balfe et al., 2012). The projections for TM are drawn from experience of TM design philosophies. The outcome of this analysis process is summarised in Table 1.

In terms of the 'actual', the table shows the potential for automation to degrade the signallers' ability to know what to do during disruption situations. The reasons for this are threefold; first, the size of the area controlled by one operator is greatly increased by automation so the decisions required during disruption from one operator are more wide-ranging and complex. Second, as discussed earlier, a long-term consequence of automation is the de-skilling of operators as they are no longer routinely involved in traffic control. Finally, the automation itself will be making decisions and/or suggestions and management pressure to use the costly automation systems mean that the operator must attempt to incorporate the actions of the automation with their own actions.

Table 1. Summary of results drawn from rail traffic control analysis

	Actual	Critical	Potential	Factual
Lever Frame	Small span of control; Limited decision consequences; High degree of control.	Limited span of control; Direct control of all elements; Immediate problems obvious to operator.	Very limited visibility beyond control area; Very limited forewarning of approaching issues.	Factual recording; Opportunity to learn limited to the individual learning from their experiences.
NX Panel	Larger span of control; Larger decision consequences; High degree of control.	Direct control; Large control areas; Problems can go undetected in the short term	Limited visibility beyond control area; Limited forewarning of approaching issues.	Factual recording; Learning is limited to handovers and reports.
ARS	Large span of control; Large decision consequences. Automation may act outside the understood boundaries making it difficult to anticipate.	Indirect control (via automation); Problems can occur without operator knowledge until after the event.	Limited visibility beyond control area; Limited forewarning of approaching issues.	Factual recording; Learning is limited to handovers and reports.
TM	Large and complex span of control; Advanced automation may result in the system becoming beyond the ability of the operator to fully understand and control.	Direct control of the automation via the plan. Visibility of approaching issues via the train graph.	Visibility beyond control area is hugely extended via the train graph.	Potential for replay of events to facilitate organisational learning.

In contrast, the ‘critical’ dimension has the potential for improvements with the introduction of more advanced automation. This dimension has become progressively more difficult for the signaller to date as the size of their control area has increased (a relatively minor effect) and as comparatively obtuse automation has been introduced. In particular, ARS does not give any indication of its planned actions before implementing those actions meaning the signallers are reliant on their experience to know what the automation will do in a particular situation. However, TM features an improved interface which explicitly displays how the timetable has been modified and gives the key information in a more concise format as well as holding the possibility of highlighting conflicts between trains to operators. This advancement holds the potential to improve the signaller's ability to identify and control threats in the immediate timeframe.

Knowing what to expect in rail traffic control is very dependent on the ability of the operator to see beyond their own area of control in order to identify disruption which may later affect their area. In lever frame boxes, this is extremely limited and the situation is not much improved by the NX and VDU technologies although separate information systems have been implemented to attempt to improve this and the larger area of control means that there is more opportunity to identify issues before they reach the key regulating locations in the area. However, TM does address this by providing operators with visibility of the current and planned train running in adjacent areas and a prediction of the knock-on effects on their own area of control.

Knowing what has happened, 'factual', is not well supported in any of the current systems and organisational learning is haphazard at best. Systems are in place to record the actions taken and the delays to individual trains, but these are primarily used for investigative purposes, not for learning. Again, TM holds the potential for improvement through replay functionality, allowing operators to assess the actions taken for a given scenario and identify more effective solutions. However, this is not core functionality and the efficiency pressures on the organisation may prevent the time and operational staff being made available to take advantage of this opportunity.

6 Discussion

Rail traffic control is a complex system that relies on the decisions of signallers and automated signalling systems to deliver trains to their destination as efficiently as possible, whilst ensuring safety. A key effect of automation has been to increase the area of control of a single operator with consequent effects on their ability to fully understand and correctly control that area. This is compounded by the complexity of the ARS automation system which requires signallers to predict its actions ahead of time in order to fully control it. Although it may be appropriate to automate to allow routes to be set fast and more reliably (Wickens, 1992), some of the pitfalls of automation, such as leaving difficult tasks to the operator (Bainbridge, 1983) have been realised. The result has been the reduction in the overall resilience of the system as failure to correctly control the automation can result in significant additional delays.

In simple terms, although they are still considered traffic controllers, people are more often in the position of overseeing the behaviour of technology, rather than in fact controlling traffic. This contrasts with other domains of control tasks such as air traffic control, where people remain fully responsible for every decision and only rely on technology as a source of information on which to base their decisions. Enhanced feedback from the automated systems is critical for improving overall system performance and resilience by allowing the automation and the human operator to work more closely together and capitalise on the strengths of each. Access to real time data and information on overall system performance can increase the ability to adjust and adapt to high dynamics operational environments and appropriately designed automation systems can provide this in a format that is accessible and easily processed by the operator.

Traditional automation systems have reinforced rigidity through their basis on the timetable and the comparatively limited approach to prioritisation of trains. Automation towards resilience must support adequate levels of system flexibility and adaptability to cope with dynamics of rail operations and unexpected events, and this can be best achieved by supporting the human operator's decision making process. Currently, railway operations have a very rigid design. They are still based on the principle of blocks (in between two block signals and at any given time, only one train is allowed) and whenever something goes wrong, the system is stopped. From an ETTO perspective, this means that efficiency is always sacrificed in favour of safety. Hence, although the railway can be considered an ultra-safe system, it is not necessarily a resilient one. The integration of new technologies such as those linked to the European Rail Traffic Management System (ERTMS) will introduce new forms of automation and important sources of flexibility into rail systems. Because more flexible operational modes will most likely result in higher degrees of performance variability, in order for such new technologies to contribute to enhanced system resilience, careful consideration must be given to the way in which they will come to support traffic control decision making. The challenge is for the resilience and human factors research community to collect and present clear evidence to guide the design of future traffic control systems and ensure that potential improvements in system resilience are achieved.

On the basis of the analysis presented in this paper, we propose that the attributes of rail traffic automation that can enhance resilience include facilitating a high degree of control over train movements, the ability to anticipate the automation through provision of suitable feedback via intuitive interfaces, increasing the visibility of events in the control area and the boundary areas, and the facilitation of organisational learning through event replay and simulations. The first three attributes address the requirement to provide information to support operator decision-making and the final attribute is proposed as a potential manner in which system safety boundaries can be monitored while also identifying possible improvements in performance.

7 Conclusions

Traffic control is clearly a critical railway component and developments in terms of resilience must take this into account. Thus, increased flexibility in railway systems must be based on the integration of traffic control technology that adequately supports human decision making, which will ultimately be responsible for system ETTOs.

Managing a balance between safety and efficiency under high variability and uncertainty conditions relies on the information available at all hierarchical levels and organisational areas, and how this information supports decision making with an adequate visibility of operational conditions (Ferreira 2011). As stated by Woods & Hollnagel (2006), progress on safety ultimately depends on providing workers and managers with information about changing vulnerabilities and the ability to develop new means for meeting these.

This paper has discussed resilience only in terms of train routing. Integration of other rail operational domains, including engineering work delivery, electrification, planning, emergency response mechanisms, etc., are not discussed in this paper but are critical to overall levels of system performance. In particular, engineering delivery is not well supported by any generation of signalling system and can be hugely disruptive. This is a key area for future research towards improving resilience in traffic control and in the rail sector as a whole. To this end, further research is needed on rail technology that contributes to a higher integration of various operational domains and needs, aiming to enhance an efficient and safe allocation of critical resources such as access to the rail infrastructure.

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