Use of simulators to investigate complex issues relating to human factors

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Abstract. Developments in rail automation have not been the same throughout the industry. Train dispatchers mostly work in centralised control centres today, while train drivers have only been completely replaced by technology in exceptional cases. This situation has resulted in new challenges for operations management. With the automation of many operational processes, system knowledge has been lost by both train drivers and train dispatchers.

Linear methods are not useful for analysing the course of complex events, which is why human factors are included in the analysis (particularly in aviation) as they can be measured and assessed using qualitative methods. As part of a railway research project, test drives were simulated on a driving simulator, to measure situation awareness among train drivers and test the impact of time pressure.

Simulators are useful tools for studying complex issues involving factors that cannot be measured using quantitative methods. The tests with train drivers mentioned above clearly show the need for integrated driving and signalling simulators. But no such integrated simulators currently exist. They would, however, permit studying the work of train drivers and train dispatchers simultaneously.

Modelling train tracks for use in simulators requires much effort and expense and is thus a major cost factor. Using video-based data collection instead can considerably reduce this cost burden. No standards have been established to date for the modelling of signal boxes, but the electronic Π-Tool [5] can be used for this purpose. This generates Petri net-based models for simulations.

With the use of integrated simulators, new insights into the impact of human factors on rail operations can be gained, which will contribute to rail safety.

Keywords: railway system, operations management, simulators, modelling of signal box logic, human-machine interface (HMI), human factors, complexity

1 Introduction

Automation has brought about fundamental changes in the Swiss railway system, especially in the past 20 years. With the introduction of large operations control centres and remote control centres, signal boxes have been automated and train dispatchers no longer operate locally. Today, only few stations have staff who control and ensure the safety of rail operations. Developments have been completely different in rail vehicle automation, where state-of-the-art driver assistance systems are used. Automatically operated trains are technically feasible, but they are still the exception today.

These developments in the automation of signal boxes and rail vehicles have resulted in considerable changes in the duties of train drivers and train dispatchers. Whereas personal contact between the two staff groups used to be essential for the smooth running of operations, today, each group works independently. For communication, they normally rely entirely on technical appliances such as signals and train control systems. Only in exceptional cases or in emergencies do train drivers and train dispatchers come into personal contact, usually via the telephone. In both jobs, a marked shift from operating to monitoring can also be observed.

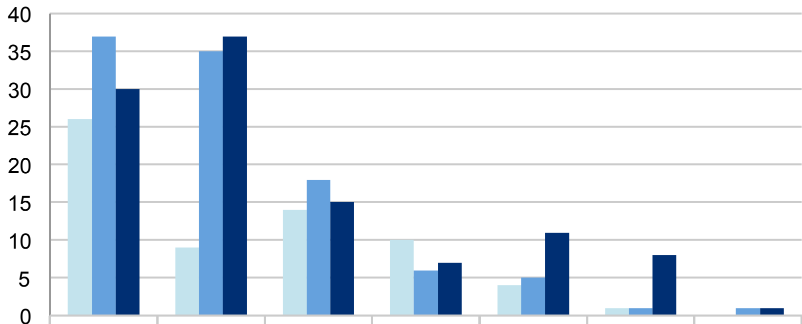
These changed duties have resulted in new challenges for the railway at the system level. The shift away from manual tasks has to some extent resulted in a loss of system knowledge among the staff concerned. Such losses will only have an impact when requirements are higher, such as in the event of a failure of technical components or when handling incidents. Since professional experience in the railway system involves a high level of multitasking, it is difficult to measure using quantitative or linear methods. It is, for instance, not possible to quantify the safety-critical impact of a train driver's driving experience. However, in the event of brake failure, this driving experience will have a crucial impact on the handling of the incident.

This paper presents ways of studying such issues using simulators, and specifies the requirements that these tools would therefore have to meet. It discusses the complexity of issues in the context of rail automation based on the following research questions:

- How can situation awareness be measured?
- Does time pressure have a negative effect on the situation awareness of train drivers?
- What are the requirements for simulators used to investigate complex issues?

2 Complexity in the railway system

A complex system is defined as a whole of independent but interrelated elements whose interactions are not fully or not at all predictable. Causes of complexity in the railway system are typically found at the human-machine interfaces (HMI). Analysis shows that human error is very often one of the major causes of accidents and incidents. In two train crashes that occurred in Switzerland in 2013, the train drivers had passed a stop signal instead of waiting for a crossing train. Such errors are the result of a number of factors that can often not be unambiguously quantified and thus cannot be analysed using linear methods. Incident analysis shows that the number of SPAD cases (signal passed at danger) in Switzerland is on the increase (2010: 118 cases; 2011: 124 cases; 2012: 136 cases) [2]. This development reflects not only the increase in traffic as such, but also the resulting requirements for train drivers. A differentiated analysis of the development shows that particularly causes such as the misinterpretation of instructions, errors, misreadings and inattention have a strong impact. Figure 1 shows an analysis of SPAD cases in the Swiss rail network, grouped into categories of causes.



	Departure at danger Q4	Error, mistake Q5	Distraction Q3	Confusion of signals Q2	Confusion train and shunting itinerary Q6	Misinter-pretation of order Q1	Communi-cation Q7
2010	26	9	14	10	4	1	0
2011	37	35	18	6	5	1	1
2012	30	37	15	7	11	8	1

Fig. 1. Analysis of SPAD cases in the Swiss rail network, 2010 to 2012, by categories of causes [2].

Simulators that have to date been used for training purposes only could be useful tools for analysing such incidents. Based on measurements and qualitative methods, driving and signalling simulators can help gain new insights into the perceptions, decision-making processes and actions of both train drivers and train dispatchers. With a sufficiently large group of test subjects, such simulator tests can yield new findings regarding the behaviour of train drivers and train dispatchers in specific situations.

Measurability of situation awareness

In the railway sector, there have so far been few studies of topics such as human-machine interactions or mental information processing and their impacts [3]. In aviation in particular, the situation awareness (SA) model by Endsley [1] is considered very important. It is relevant for decision-making and can be seen as a 3-level structure: perception, comprehension and projection. Studies of pilots have shown that errors occur most frequently at the first level, as a result of information not being perceived. Possible underlying causes are a lack of attention, distractions, workload and other stress factors [6].

3 Method

To understand complex issues, both quantitative and qualitative methods are needed. On the one hand, formal models serve to describe the system; on the other hand, simulators are used for human-machine investigations.

As part of a research project, 20 train drivers participated in test drives on a Swiss driving simulator of a Re 460 type locomotive. The test subjects had to drive two passenger trains, one from Olten to Brugg, the other from Baden to Zurich. The two test drives were designed to have as many similarities as possible, though without a learning curve between them for the test subjects. Each test drive contained 11 so-called SA-relevant tasks or dilemmas. Observations focused on specific actions by the test subjects after each dilemma. Based on previously specified criteria, points were awarded for the observed behaviour and so-called *SA performance scores* calculated (see Table 1). Parts of this methodology were based on the research project *Enhanced Safety through Situation Awareness Integration in Training*, which tested pilots' SA-related skills [4].

Table 1. *Dilemmas* and *criteria* in test drive B. The *SA performance score* is calculated by adding the points obtained for handling of the eleven dilemmas. The score ranges from 0 to 22.

Dilemmas in test drive B		**Criteria**	**Yes=2 No=0**
1	Only upper light of shunting signal working	Has dispatcher been advised?	
2	Traction loss	Start breaking before advance signal?	
3	Speed restriction section 80 km/h	VIST 80 km/h entry signal?	
4	Neutral section	Correct process for neutral section?	
5	Exit signal closed (neighbouring signal open)	Correct process?	
6	Advance signal 60 km/h	Main signal 60 km/h?	
7	Extra stop at Zurich-Altstetten	Has train stopped at Zurich-Altstetten?	
8	Incoming emergency call/ distorted sound	Line-of-sight driving (V max 40 km/h)?	
9		Has dispatcher been advised?	
10	Only one lower light of shunting signal working	Has train been stopped?	
11		Has dispatcher been advised?	
		SA performance score	

In addition, the Situation Awareness Rating Technique (SART) was used, which permitted the subjects to rate their own situation awareness [10]. This validated questionnaire consists of ten items concerning *Demand from Attentional Resources (D)*, *Supply of Attentional Resources (S)* and *Understanding of the Situation (U)*. The total score was obtained using this formula:

$$\text{SART total score} = U + S - D$$

Whereas SA performance and SA self-rating represented the dependent variables, time pressure was added as a stress factor, representing the independent variable. Each of the 20 train drivers had to complete one test drive under time pressure and one without time pressure. This resulted in test scenarios with the parameters in Table 2.

Table 2. Test subjects divided into Groups 1 and 2 to measure SA performance and for use of the Situation Awareness Rating Technique (SART)

	Test drive A (Olten - Brugg)	**Test drive B (Baden–Zürich)**
Group 1: 10 test subjects	No time pressure	Time pressure
Group 2: 10 test subjects	Time pressure	No time pressure

The influence of the factor Time pressure on SA performance and SA self-rating was calculated by analysis of variance with repeated measurement.

Finally, for the design and construction of an integrated simulation toolkit, the use of efficient and cost-effective methods is desirable. With this in mind, it made sense to collect the data required for track modelling using the video-based tool QRailScan [11]. For the modelling of signal box logic, a standard is aimed for that can be applied universally and irrespective of the signal box type. The functions of signal box logic basically consist of cyclical processes, which is why it made sense to rely on Petri nets for modelling this logic.

4 Results

An overview of the results of the test drives is shown in Figure 2, comparing all test drives with time pressure to all test drives without time pressure.

Effect of time pressure on SA performance. Considering the entire journey, time pressure had a significant influence within the groups. However, the simultaneous significant interaction between the factors Time pressure and Group would indicate that the different performance averages result not only from time pressure, but also depend on group membership. This might in fact show clearly the difficulty of creating two similar and comparable test drives and the need to further improve the methodology. However, a significant negative effect on SA performance was found in the final section of the test drive, where the subjects were presented with more difficult dilemmas. Here there was no significant interaction between time pressure and group. This result suggests that, in combination with an increased workload, time pressure makes it more difficult for the train drivers to show a good SA performance.

Effect of time pressure on SA self-rating. Time pressure showed only a numeric but no significant effect on the SA self-rating, which was performed only for the entire journey.

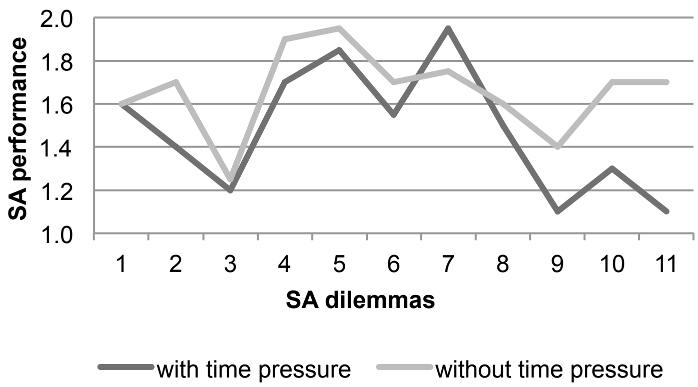


Fig. 2. Overview of the results of the test drives, showing overall mean of *SA performance* for each *SA dilemma*, divided into lines with and without time pressure

The results of this study and the relevant literature both show that increasing stress factors such as a higher workload, a lack of system knowledge, monotony, and poorly identifiable signalling make it harder to develop an appropriate level of situation awareness. However, in railway systems as in aviation, such a level of situation awareness is one of the key requirements of safe operations.

Requirement criteria for the simulation toolkit

The analysis of an incident at the station of Thun in Switzerland [9] shows among other things that the interaction between train dispatchers and train drivers has a causal effect on the course of events. For instance, information that is not safety-critical, such as the scheduled time of departure, can lead to serious mix-ups. Failure to observe communication rules or language problems may also have an impact on safety. In their collaboration, train drivers and train dispatchers do not normally have personal contact nowadays. Instead, they communicate via signals, control technology and train control systems. Only in exceptional cases is there oral communication, such as in the event of faults in the protection systems or vehicles. Where safety-critical components fail, clarity and a lack of ambiguity in the communication of instructions may be crucial.

There are very few simulation tools today that take into account both the train driver's and the train dispatcher's perspectives. To study complex issues arising at human-machine interfaces in the railway system requires integrated driving and signalling simulators. These would provide an experimental platform to help detect vulnerability issues at the system level, such as ambiguous passages in regulations and sets of rules, or the lack of fallback levels in technology. Resolving such vulnerability issues could help prevent accidents.

Based on these findings and using existing driving simulators, an integrated simulation toolkit can be developed for both train drivers and train dispatchers. The middleware permits integrating an almost indefinite number of signal box and driving simulators, thus allowing the realistic modelling of a complete timetable scenario on any train route or in any monitoring area that a train dispatcher in an operations control centre is in charge of. Figure 5 shows the principle of connection between driving and interlocking simulators via DESM middleware with the data flows.

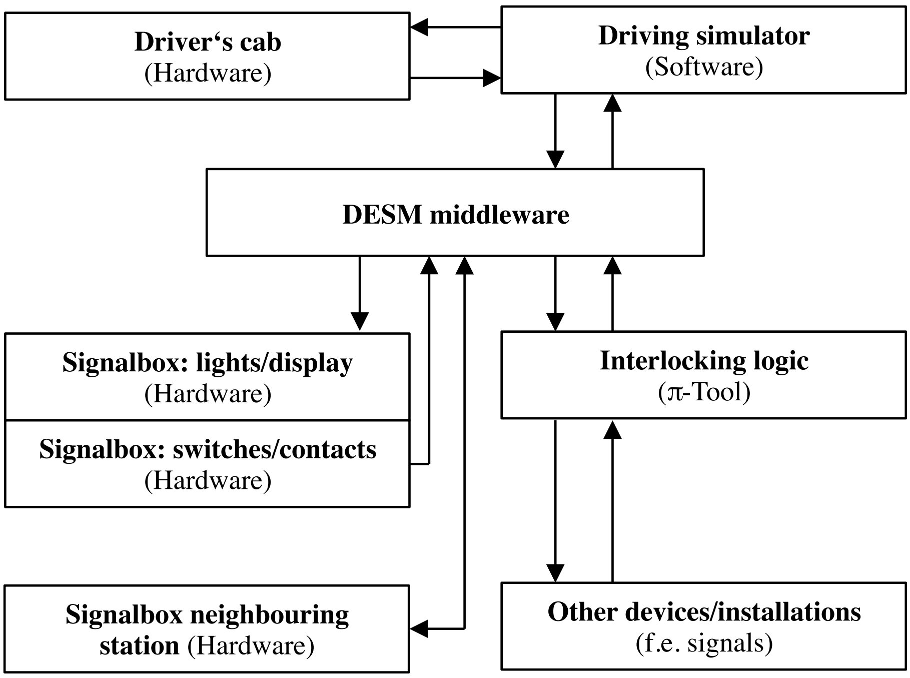


Fig. 3. Principle of the integrated simulation toolkit

There are no known technical standards for the modelling of signal boxes and control technology for use in simulators. However, for some years, the railML initiative [7] has been working on the development of a standard format for the management and exchange of data for railway applications. The railML schemas are developed in an open project, through discussion forums and conferences. Use of the railML data format is a major requirement for efficient and cost-effective data exchange, which would also have a positive effect on the costs of modelling for simulators.

The test drives mentioned earlier show that the simulator workplaces of both train drivers and train dispatchers must be designed with a high level of detail and as faithful representations of the test subjects' familiar work environment. Another basic requirement is that the driver's cabs and signal boxes in the simulators are enclosed. These factors are vital to ensure that the subjects can become sufficiently absorbed in their work to display natural behaviour in terms of their habits and routines. In fact, driving simulators that are equipped with a motion base, which simulates the vehicle dynamics, have found greater acceptance.

The video-based tool QRailScan collects data about the route and infrastructure components semi-automatically in geo-referenced video clips [11]. Figure 3 shows the general function of QRailScan with the flow of data. Using photogrammetric methods, easily identifiable objects can also be detected automatically [8]. With this data collection method, there is no need for the acquisition of infrastructure data or the laborious conversion of existing data to another format.

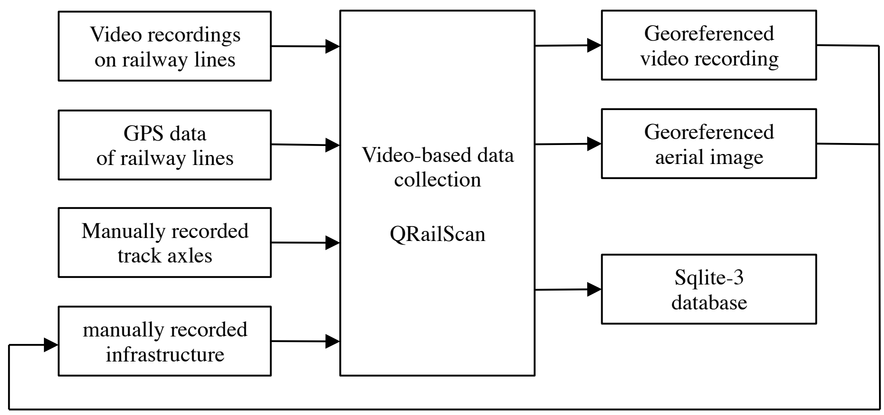


Fig. 4. Principle of video-based collection of infrastructure data [11]

The basic functions of a signal box – such as the point controllers, clear track signalling systems, pre-set routes, blocks, or level crossing protection systems – can be modelled in subnets and visualised. The Petri net-based simulation tool Π-Tool [5] can create and interconnect such subnets. To permit external information exchange, Π-Tool is able to export the model as Java code, which can be used in the middleware. Ultimately, this tool enables simulation of the signal box logic.

With the help of this toolkit, it will be possible to analyse and study the importance of human factors for rail operations. As automation progresses, new findings relating to the perception, decision-making and actions of train drivers and train dispatchers will help to continuously improve the safety and reliability of rail operations.

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