THE WHOLE KIT AND CABOODLE: APPLYING A SYSTEMS ANALYSIS AND DESIGN FRAMEWORK ACROSS THE RAIL LEVEL CROSSING DESIGN LIFECYCLE

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The continued incidence of trauma at rail level crossings is unacceptable, and provides a clear indication that the current approach to rail level crossing safety is failing. It has been suggested that this may be, in part, attributed to the fact that a systems thinking approach has not been adopted when attempting to improve rail level crossing designs. As a response, this paper presents an overview of a rail level crossing design lifecycle process that involved applying Cognitive Work Analysis to analyze existing rail level crossing systems, and then to generate, evaluate, and refine new rail level crossing design concepts underpinned by systems thinking. An overview of the process adopted is provided and selected outputs from the following phases are discussed: systems analysis; generation of design concepts, evaluation of design concepts, and refinement of design concepts. In closing, the implications for future rail level crossing design activities are discussed.

Introduction

The continued incidence of rail level crossing collisions across the world demonstrates that the longstanding problem is not being solved by current interventions. In Australia, between 2000 and 2009, there were 695 collisions between road vehicles and trains at rail level crossings, resulting in 97 fatalities (Independent Transport Safety Regulator, 2011). Despite various safety initiatives, in 2011 there were 49 collisions between trains and road vehicles (ATSB, 2012). Moreover, the problem is not only limited to collisions between
trains and vehicles; between 2002 and 2012 there were 92 collisions between trains and pedestrians at rail level crossings (ATSB, 2012).

Recently, researchers have suggested that one reason for which existing approaches have not fully solved the safety issues at rail level crossings is the fact that a systems thinking approach has not been adopted (e.g. Read et al., 2013; Salmon et al., 2013). Specifically, it is argued that a focus on parts of the system alone (such as road users or warnings) has led to incremental design changes that can have only a limited impact. Moreover, the emergent behaviours brought about by different rail level crossing interventions have not been fully considered. An absence of systems thinking in system and countermeasure design is now widely acknowledged to represent a key issue in safety critical systems (e.g. Dekker, 2011; Reason, 1997). Despite this, there appears to be a research and practice gap whereby a systems thinking approach to rail safety is gaining traction in academic circles (e.g. Read et al., 2015; Salmon et al., In Press) but not in practice.

The application of new thinking in practice requires practical and usable methodologies – a gap that has been noted in relation to systems thinking and sociotechnical systems (Salmon et al., In Press). This paper argues that the rail level crossing research practice gap can only be closed through the development, demonstration, and communication of appropriate methods and frameworks underpinned by systems thinking. Accordingly, we present an overview of a rail level crossing design lifecycle process that involved applying a systems analysis and design framework, Cognitive Work Analysis (CWA) (Vicente, 1999) first to analyse existing rail level crossing systems, and then to generate, evaluate, and refine new rail level crossing design concepts. The process was adopted as part of a major research program currently being undertaken in Victoria, Australia. The overall aim of the research program is to develop and evaluate new rail level crossing system designs underpinned by systems thinking.

To demonstrate, we provide an overview of the process and discuss selected outputs from each of the following phases: systems analysis, generation of design concepts, evaluation of design concepts and refinement of design concepts.

Cognitive Work Analysis

CWA (Vicente, 1999) is a systems analysis and design framework that has previously been used both to analyse complex sociotechnical systems and to inform design or re-design activities. The framework is underpinned by a focus on identifying the constraints imposed on behaviour and the resulting impacts on sociotechnical system performance. It comprises five separate analysis phases. In the present research the first four of these phases were used. A brief description of each of the phases employed is given below. For a full description of the framework the reader is referred to Vicente (1999) or Jenkins et al. (2008).
Work Domain Analysis
The first CWA phase, Work Domain Analysis (WDA), is used to provide an event and actor independent description of the system under analysis: in this case the rail level crossing 'system'. The aim is to describe the purposes of the system and the constraints imposed on the actions of actors performing activities within it (Vicente, 1999). Using the Abstraction Hierarchy (AH) the system under analysis is described across five levels: the functional purposes level (purpose of the system); values and priority measures (the measures that are used to assess system performance); generalised functions (the functions that are required to achieve the functional purposes); the physical objects comprising the system, and their associated physical functions or affordances.

Control Task Analysis
The second phase, Control Task Analysis (ConTA), focuses on the activity necessary to achieve the purposes, priorities and values and functions of a work domain (Naikar et al., 2006). Rasmussen’s decision ladder (Rasmussen, 1976; cited in Vicente, 1999) and Naikar et al.’s (2006) contextual activity template are used for the ConTA phase. The decision ladder is used to examine the decision making process adopted during control tasks along with the short cuts that are typically made by experts. The contextual activity template is used to examine how functions currently are and potentially could be achieved during different situations.

Strategies Analysis
The strategies analysis is used to identify specifically the different ways in which functions can be achieved, providing a process description of how activity can be undertaken (Vicente, 1999) The Strategies Analysis Diagram (SAD) (Cornelissen, 2013) was recently developed to support conduct of the strategies analysis phase. This builds on the WDA outputs to examine the range of strategies available within a given system.

Social Organisation and Co-operation Analysis
The Social Organisation and Co-Operation Analysis (SOCA) phase is used to identify how activity is distributed amongst human operators and technological artefacts. SOCA involves using the outputs from the first three phases to identify which human and non-human actors currently perform which functions, decisions, and strategies. A formative component then enables analysts to consider what human and non-human actors could potentially perform required functions, decisions, and strategies.

The Cognitive Work Analysis-based design process
The CWA-based design process is presented in Figure 1. It describes four phases beginning with data collection, followed by the application of CWA, the development of design concepts and the evaluation and refinement of those concepts.
In addition to the CWA framework, the design process utilized the recently developed CWA-Design Toolkit (CWA-DT, Read et al., In Press). The CWA-DT was developed to assist CWA users in identifying design insights from CWA outputs and to use these insights within a participatory design paradigm. It promotes the collaborative involvement of experts (i.e. ergonomics professionals, designers and engineers), stakeholders (i.e. company representatives, supervisors, unions) and end users (i.e. workers or consumers) to solve design problems, based on insights gained through CWA.

Underlying the CWA-DT is both the design philosophy of CWA (i.e. ‘let the worker finish the design’) and the related sociotechnical systems theory approach which aims to design organisations and systems that have the capacity to adapt and respond to changes and disturbances in the environment (Trist & Bamforth, 1951; Clegg, 2000; Walker et al., 2009). Consequently, the CWA-DT includes design tools and methods that encourage consideration of the values underlying the sociotechnical systems approach (and indeed underpinning ergonomics more generally). These include the notion of humans as assets or adaptive decision makers, rather than error-prone liabilities, of technology being designed as a tool to assist humans to achieve their goals, rather than implemented because of assumed efficiency or cost-savings; and design to promote the quality of life or end users. Furthermore, the consideration of sociotechnical design principles, such as minimal critical specification, boundary management and joint design of social and technical elements, intends to achieve the design of systems that can operate within their safety and performance boundaries both on implementation and in an on-going fashion through continual monitoring and re-design.

**Data Collection & Cognitive Work Analysis of Rail Level Crossings**

Phases 1 and 2 culminated in a CWA of rail level crossings in Victoria, Australia. The analysis focused on both ‘active’ and ‘passive’ rail level crossings. Active crossings are so-called because they have ‘active’ warning devices that provide a warning of an approaching train, including flashing lights,
boomgates and warning bells. Passive crossings, on the other hand, do not have active warnings and rely on static warnings of the presence of rail level crossing only (e.g. road signs, road markings, rail level crossing markers).

The CWA was informed by data collected through a range of activities undertaken during phase 1 (see Salmon et al., In Press). These included on-road studies of driver behaviour at level crossings, cognitive task analysis interviews with drivers, a diary study of road user behaviour at rail level crossings, subject matter expert workshops, documentation review, and in-cab train rides. For example purposes a summary of the active rail level crossing WDA is presented in Figure 2 (see Salmon et al., In Press) for examples CWA outputs from all four phases).

Figure 2: Summary of WDA (AH) of active rail level crossings

Once the CWA outputs were finalized through subject matter expert review, the analysis team engaged in a workshop to generate a series of insights that would support the development of rail level crossing designs. This involved using a series of prompts from the CWA-DT in conjunction with the CWA outputs. Initially, each analyst presented the outputs and key findings from each of the CWA phases to the group. Following this, the CWA-DT prompts were used to interrogate the analysis outputs in order to generate key design insights.

**Development of design concepts**

A series of initial rail level crossing design concepts were developed through a workshop which was designed through the application of the CWA-DT. Eighteen participants participated in the design workshop. Participants were invited as representatives of rail level crossing stakeholder organisations (i.e. government departments, regulators, road authorities, road user peak bodies,
transport investigators, etc.) or as interested persons with a professional interest in the research (i.e. HFE professionals, researchers, designers, etc.).

The design workshop was delivered over two days and involved participants generating design concepts and solutions for improving behaviour and safety at rail level crossings. Workshop activities included an idea generation phase (using targeted approaches such as assumption crushing, metaphor-based design, etc.), concept design, and concept prioritisation. The workshop culminated in 11 rail level crossing design concepts prioritised by the workshop participants in order of those thought likely to be most effective in improving safety.

**Evaluation of design concepts**
The highest ranked 7 design concepts of the 11 created were selected by the research team for evaluation. The 4 remaining design concepts were not selected for further evaluation based on the research teams’ judgements regarding alliance with systems thinking, practicality, and likelihood of implementation.

The initial evaluation process involved three core activities: insertion of concepts into the AH, identification of user errors, and evaluation against sociotechnical systems values and principles. This enabled the evaluation to consider the extent to which the designs aligned with systems thinking along with the likely impact and emergent behaviours associated with each design concept.

Insertion of the concepts into the rail level crossing AH involved adding the features of each design concept (e.g. in-vehicle display, new road markings, rumble strips) into the physical object level of the AH presented in Figure 2, removing any nodes as appropriate, and then remodelling the means-ends relationships. Following this, the impact of each new object was assessed by summing the following at each level of the AH:

- **New nodes** e.g. the new physical object ‘optimal speed to avoid train in-vehicle display’ would ‘communicate optimal speed’ and ‘provide distance to rail level crossing’ notification;
- **Support for existing nodes** e.g. the new physical object ‘in-vehicle warning display’ would provide support for the existing function of ‘Alert user to the presence of train’;
- **Appropriate restriction** e.g. the new physical object ‘default closed pedestrian gates’ would appropriately restrict (pedestrian) traffic flow which in turn would support the function of ‘maintain road and rail user separation’; and
- **Negative influence** e.g. the new physical object ‘speed limit reduction signs’ would have the effect of slowing traffic through rail level crossings which in turn may negatively influence the ‘maximise efficiency’ value and priority measure.
Identification of user errors for each design concept was achieved by applying the Systematic Human Error Reduction and Prediction Approach (SHERPA) (Embrey, 1986) to predict the likely errors that would arise when users interacted with the new rail level crossing. Initially, one analyst applied SHERPA to rail level crossings generally, and then to each design concept. The output was a series of likely errors for each concept, including a description of each error and the associated consequences, ratings of likelihood (low, medium, high) and probability (low, medium, high) and potential remedial measures. Metrics such as number of existing potential errors reduced by the new design concept as well as new errors introduced were calculated.

The evaluation against sociotechnical systems theory values and principles involved the research team considering each design concept and providing a rating of 1 to 3 (low, medium, high) in relation to the following values and principles:

- Tasks are allocated appropriately between and amongst humans and technology;
- Useful, meaningful and whole tasks are designed;
- Boundary locations are appropriate;
- Boundaries are managed;
- Problems are controlled at their source;
- Design incorporates the needs of the business, users and managers;
- Intimate units and environments are designed;
- Design is appropriate to the particular context;
- Adaptability is achieved through multifunctionalism;
- Adaptability is achieved through flexible structures and mechanisms;
- Information is provided where action is needed;
- Means for undertaking tasks are flexibly specified;
- Authority and responsibility are allocated appropriately; and
- System elements are congruent.

The ratings were then aggregated giving each design concept a total score out of 42. Based on the three evaluation activities five concepts were selected as the most likely to be effective in reducing collisions at rail level crossings.

Refinement of design concepts
Following the evaluation process a second workshop was held to further refine the design concepts. Ten participants attended the design refinement workshop which was held approximately six months after the initial design workshop. Prior to the workshop, participants were provided with a written summary of the top five ranked design concepts and a summary of the overall evaluation findings. A detailed overview of each concept was provided, following which participants engaged in a series of CWA-DT activities designed to refine each concept. This included reviewing suggested design improvements identified during the evaluation process, identifying additional design improvements, and conducting
an evaluation and final ranking of concepts following the inclusion of design improvements deemed to be practical and appropriate. The output of the concept refinement workshop was four refined design concepts (two of the original five concepts were integrated through the refinement process).

**Representation of concepts**

A 3D representation of each refined design concept was subsequently modelled using the Sketch Up 3D imaging software. Two of the design concepts are presented in Figure 3 (one urban active rail level crossing and one rural passive rail level crossing).

![Figure 3: Example rail level crossing design concepts produced from CWA-based design process (Mercedes active urban crossing at the top of Figure, Simple but strong passive rural crossing at the bottom of Figure).](image)

Driver behaviour in response to the proposed design concepts is currently being tested using driving simulation.

**Discussion**

There are increasing calls for a systems thinking approach to transport system design and evaluation (Salmon and Lenné, 2015). Translation of systems
thinking in practice requires that appropriate design methodologies be developed to support systems thinking in design and evaluation processes. This paper has provided an overview of a rail level crossing analysis and design process underpinned by systems thinking. Specifically, the CWA framework and its accompanying design tool, the CWA-DT, were used to analyze existing rail level crossing systems and develop a series of new rail level crossing design concepts underpinned by systems thinking principles. The application presented demonstrates how the approach can be applied in transport system design activities.

A key strength of CWA when applied to analyse existing systems as part of a design process is its depth and explanatory power. In the present program of research CWA was useful in that it examined the behaviour of multiple end users (e.g. drivers, pedestrians, cyclists, motorcyclists) and the factors influencing their behaviour. As a result new design concepts tended to consider all end-users, rather than one group in isolation. In addition, it identified factors outside of end users and the rail level crossings themselves that influence safety, such as design standards, risk assessment processes, and incident reporting systems. A second important strength of the process adopted was the utilisation of CWA outputs throughout the design concept development and evaluation process. This enabled a significant level of consistency in that insights derived from the CWA were used to drive the design process, and then design concepts were evaluated through consideration within the original CWA outputs. This ensured that systems thinking was adopted through all design stages and that the impact of proposed design changes on system performance was considered.

Some weaknesses were encountered. These include the high level of resources required to collect appropriate data and undertake each of the phases and the high requirement for subject matter expert involvement throughout the process. Overall, it is our opinion that the utility of the outputs produced in this case justify the high level of resources invested.

In closing, it is recommended that further systems analysis and design applications adopting approaches such as the one described in this paper be undertaken. A key challenge for safety critical systems generally is to embed sociotechnical systems analysis and design methodologies within design processes (Eason, 2014). To this end, articles describing applications involving systems thinking-based design studies are desirable. Following this, empirical testing of designs developed through such studies are required. The current phase of the research program from which this work derives involves the use of driving simulation to test the RLX design concepts produced. This will provide data to better understand the potential effectiveness of the designs which will in turn support implementation in practice.
References


Cornelissen, M., Salmon, P. M., McClure, R. & Stanton, N. A. (2013). Using cognitive work analysis and the strategies analysis diagram to understand variability in road user behaviour at intersections, Ergonomics, 56:5, 764-780


Read, G. J. M., Salmon, P. M. Lenné, M. G. and Jenkins, D. P. (In press). Designing a ticket to ride with the cognitive work analysis design toolkit. Ergonomics.


Salmon, P. M., Lenné, M. G. (2015). Miles away or just around the corner: systems thinking in road safety research and practice. Accident Analysis and Prevention, 74, 243-249.

