Who does what, where and why? Optimising allocation of functions in rail level crossing systems

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Abstract

Level crossings represent one of the key strategic risks on railways across the world. Recent research has indicated that collisions at rail level crossings (RLXs) may be better prevented through more sophisticated allocation of functions within these environments. The aim of the research described here was to explore this further and to identify potential design remedies. Cognitive Work Analysis (CWA) is a systems analysis framework that has been successfully used to identify how social and technical components within systems can be configured to enhance overall performance. Two CWA techniques were used to identify design options related to how functions are allocated within RLX systems. Based on an analysis of nine RLXs in metropolitan Melbourne, the findings highlighted an uneven spread of activity across the situations in which train detection and safety can occur and across the actors involved in these functions. The majority of activity currently occurs when users are closest to the RLX. However, there are instances where important activities could occur away from the RLX but typically do not. In addition, the analysis showed that the RLX infrastructure is currently responsible for most functions relating to safety, and there are parts of the system that could be better exploited to support and/or improve behaviour, including humans, in-vehicle systems and the surrounding infrastructure.

Introduction

Level crossings represent one of the key strategic risks on railways across the world. In Australia an average of 37 people are killed at RLXs each year (Australian Transport Council, 2010), incurring an estimated annual cost of around $24.8 million (Cairney, 2003). Similar estimates have been reported in other developed countries including Europe and the US (RSSB, 2014; Federal Railroad Administration, 2014). Recent research in Melbourne, Australia, has indicated that collisions at RLXs may be better prevented through a more sophisticated allocation of functions within these environments. For example, the recent Kerang RLX tragedy would likely have been prevented through the provision of warnings by other parts of the system such as the truck driver's vehicle (through in-vehicle warnings) or active early warning signage (Salmon et al., 2013). Cognitive Work Analysis, a popular systems analysis and design framework, focuses on optimising social (i.e., human) and technical (i.e., non-human) components within systems. The study described in this paper involved using methods from CWA to examine current and potential allocation of functions to optimise safety at RLXs.

According to some researchers (e.g., Salmon et al., 2015; Read et al., 2013), progress towards improving safety at RLXs has been hampered by a continued focus on system components and countermeasures (i.e., road users, warnings, signage, enforcement etc.) in isolation. However, this 'broken component' mentality does not fully take account of the interactions between users and the RLX infrastructure which give rise to unsafe behaviours (Salmon et al., in press). A new line of inquiry is needed to address these types of interactions. Although not commonly applied to the study of RLX safety, (Read et al., 2013; Wilson & Norris, 2005), a systems approach is likely to have the greatest potential for understanding the interactions between humans and technology (Salmon & Lenné, 2015) from which potential design solutions can then be identified.

CWA is a five-phase systems analysis framework that aims to improve design in complex sociotechnical systems (Vicente, 1999), of which RLXs are an example (Salmon & Lenné, 2015). It has been used indirectly to inform various design or redesign activities (e.g., Cornelissen, Salmon, Stanton & McClure, 2015; Jenkins, Stanton, Salmon & Walker, 2011; Stanton & Bessell, 2014; Stanton & McIlroy, 2012) and more directly in a range of design applications including large scale military operations (e.g., Bisantz et al., 2003), teams (Gualiteri, Roth & Eggleston, 2000; Naikar, Pearce, Drumm & Sanderson, 2003), interfaces (e.g., Burns, 2000; Vicente, 1992) and cognitive artefacts (Jenkins, Salmon, Stanton & Walker, 2010). While few designs based on CWA have been formally evaluated, there is evidence that system design can be improved using this framework. For example, task performance, as measured in empirical studies, has been found to improve using designs based on CWA (Reising & Sanderson, 2002; Sharp & Helmicki, 1998). When these designs were evaluated by subject matter experts they were judged to be superior to those using non-CWA methods (Naikar et al., 2003).

All five phases of CWA can be used to inform system design, however this paper focuses only on the second and fourth phases, known as Control Task Analysis (ConTA) and Social Organisation and Cooperation Analysis (SOCA) respectively. ConTA and SOCA were used here to examine how functions are, and could be, allocated within RLX environments in Victoria, Australia as the train driver and the road user approach an actively controlled RLX in a typical metropolitan environment.

Control Task Analysis

Control Task Analysis (ConTA) focuses on recurring activities within systems and examines what is to be achieved independent of how the activity is to be carried out (Vicente, 1999). The Contextual Activity Template (CAT), developed by Naikar, Moylan and Pearce (2006), is used within this phase of CWA. The CAT is a representation of a system's activity in terms of both work functions and work situations. Work situations can be broken down on the basis of recurring work schedules or specific locations (or both). The CAT examines how tasks currently do and could occur in different situations and locations.

An extract of the CAT showing a sub-set of RLX functions and situations is shown in Figure 1. The functions, displayed on the vertical axis, include some of the known functions afforded by the various components of the system. The situations, shown on the horizontal axis, represent the five temporally and spatially separated stages within which the driver could be when the rail user is at the pre-whistle board stage on approach to the RLX. Cells surrounded by dashed lines indicate the situations or stages of approach where a function is able to occur but typically does not, while the cells in which box and whisker diagrams are displayed indicate where functions can and typically do occur. Empty cells indicate that the function is not possible in that situation. For example, the first function shown on the vertical axis, 'visual warning of RLX', can be provided in the earliest approach zone situation 'road user pre-approach', but typically is not (because the road user is too far from the RLX to receive the warning or to see the crossing). However, it typically does occur in the latter four approach zone phases, 'road user on approach', 'road user pre-boom gates', 'road user at boom gates', 'road user on RLX (because the road user is close enough to receive the warning and/or to see the crossing).

Social Organisation and Cooperation Analysis

Social Organisation and Cooperation Analysis (SOCA) is used to examine actual and potential allocation of functions within sociotechnical systems. When applied to the CAT SOCA examines the constraints imposed by allocation of specific actor (both human and non-human) roles to functions in any given situation (Stanton & Bessell, 2014). Different actors are allocated to different

functions and the analysis examines who currently does what and who could do what given the constraints of the system (Salmon et al., 2015). This provides useful information about how activity is dispersed within the system, including the balance between activities completed by humans and by technology. In addition, it shows how activities could be allocated differently given design modifications. Within the RLXs examined, the key actors and their related coding are shown in Figure 2. For example, the function 'visual warning of RLX' is currently only performed by the warning/detection systems except when the train passes through the crossing (in this situation the train itself also provides a visual warning). The analyst then asks whether other actors within the system (such as the vehicle through an in-vehicle display) could also perform this function, and also whether this function could be provided in situations where it is currently not but in which the CAT shows that it could be (namely when the driver is in the 'pre-approach' and 'on RLX' situations).

Unlike other human factors methods, the unique contribution offered by CWA for design lies in the identification of constraints imposed by the system on behaviour. This formative type of analysis focuses on modelling how a system could perform given its constraints as opposed to how it should perform or currently performs (Stanton, McIllroy, Harvey et al., 2013). This can provide an optimal allocation of functions analysis which can be useful for prompting system re-design (McIlroy & Stanton, 2011). The aim of the current study then, was to use CAT and SOCA-CAT to examine current and potential allocation of functions within RLX systems as the basis for identifying design options. The analysis focussed on active RLXs (controlled by boom gates, flashing lights and bells) in metropolitan Melbourne.

Method

A CAT was developed to represent a typical metropolitan actively controlled RLX as approached by both the train driver (referred to as the rail user) and a driver (referred to as the vehicle user). Pedestrians and cyclists, passively controlled RLXs, and actively controlled RLXs in rural areas were excluded due to space constraints but have been examined elsewhere as part of the larger research program from which this analysis is derived.

The first step in constructing the CAT involved identifying the situations and functions within the RLX system and how these should best be represented. The situations, as shown along the horizontal axis in Figure 1, depict the spatially and temporally distinct approach phases that the road and rail user will progress through on approach to the RLX. For the rail user these phases are: pre whistle board, at whistle board, at track magnet, at station pre-RLX, traversing RLX, and pre-RLX. (Due to space constraints, only the 'pre-whistle board' approach phase is shown in Figures 1 and 2). For the road user, these phases are: pre-approach, on-approach, pre boom gates, at boom gates/boom gates closing, and on RLX. The functions, as shown along the vertical axis, represent 11 of the 43 different functions provided by the physical objects within the RLX system, such as 'visual warning of approaching train', 'prompt stop/go decision' and 'dissemination of incident data'. For example, physical objects including the flashing light assembly and the boom barriers afford the function 'visual warning of approaching train'. Due to space constraints, this paper focuses only on the functions directly associated with safety and train detection.

The situations and functions were derived by the research team using existing documents and literature from the rail design and rail safety literature as well as inputs from earlier phases of CWA reported elsewhere (Salmon et al., in press). The relationships between each of the functions and the situations in which they occur or could potentially occur were then mapped onto the CAT following the method outlined in the Introduction.

The next step was to construct the SOCA-CAT. This phase involved populating the CAT with the various human and non-human actors to show who carries out the work in the system in which

situation. Five groups of actors were identified, namely, the rail user, the vehicle user, warning/detection systems, regulators/authorities, and the physical infrastructure. The rail user comprises the train driver and the train itself. The vehicle user comprises the driver and the driver's vehicle. The warning/detection systems include the flashing light assembly (including the bells and the boom gates), the track magnet (which sets the warning systems in operation once it has been triggered by the train), and static signage and road markings associated with the RLX. The physical infrastructure includes road signage and markings within the vicinity of the RLX as well as the road itself. Regulators/authorities include the personnel responsible for the higher level operation and management of the rail system including the road regulator, the rail regulator, the road infrastructure owner, the rail infrastructure owner, the government and the police. The shaded CAT (SOCA-CAT) with the key for the different actors is shown in Figure 2.

SITUATIONS / FUNCTIONS	ROAD USER PRE APPROACH / RAIL USER PRE WHISTLE BOARD	ROAD USER ON APPROACH / RAIL USER PRE WHISTLE BOARD	ROAD USER PRE BOOM GATES / RAIL USER PRE WHISTLE BOARD	ROAD USER AT BOOM GATES / RAIL USER PRE WHISTLE BOARD	ROAD USER ON RLX / RAIL USER PRE WHISTLE BOARD
VISUAL WARNING OF RLX		├───────────────────	───────────◯───────────	───────────┤	
AUDIBLE WARNING OF RLX					
VISUAL WARNING OF APPROACHING TRAIN					
AUDIBLE WARNING OF APPROACHING TRAIN					
ATTRACT ATTENTION		├───────────────────	───────────◯───────────	───────────┤	
SPEED REDUCTION				├──────◯──────┤	
DETECT TRAIN					
ASSESSMENT OF RISK					
PROMPT STOP / GO DECISION	├─────────────	──────◯──────	─────────────────	───────────┤	
FAULT DETECTION	├─────────────	──────◯──────	─────────────────	───────────┤	
DIRECT ROAD USERS	├─────────────	──────◯──────	─────────────────	───────────┤	

Figure 1. Extract of CAT for approaching an actively controlled metropolitan RLX

SITUATIONS / FUNCTIONS	ROAD USER PRE APPROACH / RAIL USER PRE WHISTLE BOARD	ROAD USER ON APPROACH / RAIL USER PRE WHISTLE BOARD	ROAD USER PRE BOOM GATES / RAIL USER PRE WHISTLE BOARD	ROAD USER AT BOOM GATES / RAIL USER PRE WHISTLE BOARD	ROAD USER ON RLX / RAIL USER PRE WHISTLE BOARD
VISUAL WARNING OF RLX					
AUDIBLE WARNING OF RLX					
VISUAL WARNING OF APPROACHING TRAIN					
AUDIBLE WARNING OF APPROACHING TRAIN					
ATTRACT ATTENTION					
SPEED REDUCTION					
DETECT TRAIN					
ASSESSMENT OF RISK					
PROMPT STOP / GO DECISION					
FAULT DETECTION					
DIRECT ROAD USERS					

Legend:
- WARNING / DETECTION SYSTEMS
- VEHICLE USER
- REGULATORS / AUTHORITIES
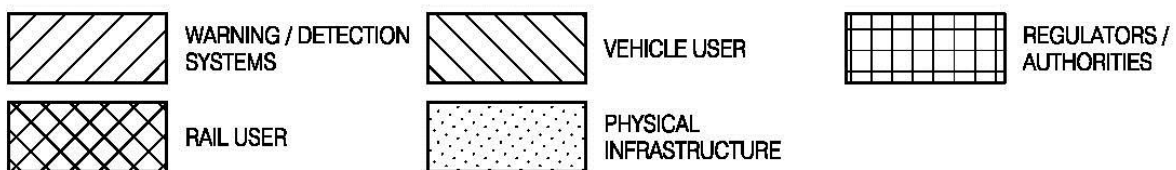- RAIL USER
- PHYSICAL INFRASTRUCTURE

Figure 2. Extract of SOCA-CAT for approaching an actively controlled metropolitan RLX

The CAT and SOCA-CAT were refined on the basis of the data collection activities outlined below, and the formative SOCA analysis was conducted following the approach outlined in the Introduction.

On-road studies of driver behaviour

An on-road study of driver behaviour at RLXs was undertaken. The study focussed on metropolitan active RLXs in Melbourne's south eastern suburbs. Twenty-nine drivers aged 18 – 55 years (M=30.5, SD = 11.1) drove a pre-defined route incorporating nine actively controlled RLXs. Participants provided 'think aloud' verbal protocols as they negotiated the route. The on-road study was particularly useful for verifying the road user situations on approach to the RLX.

Train driver focus group and in-cab familiarisation

A focus group was held with two train drivers and one rail subject matter expert to gather information regarding train driver behaviour at RLXs. Participants were asked to describe their behaviour on approach to the RLX along with the constraints influencing behaviour. In addition, three of the co-authors participated in train cab rides through urban and regional areas to gain familiarisation with the train-driving task and to understand the train driver perspective on approach to RLXs. These activities were particularly useful for verifying the situations on approach to the RLX for the train driver.

Subject Matter Expert workshop

A subject matter expert workshop was conducted with 11 stakeholders from rail and road safety organisations (including representatives from the state road authority, the rail regulator, relevant state government departments, train service providers and transport safety investigators). The workshop was particularly useful for refining the functions within the RLX system.

Results

Contextual Activity Template

A number of observations can be made on the basis of the CAT. First, there are only a very small number of functions (16%) that are not able to be supported across all of the situations on approach to the RLX (as indicated by the empty cells). In most cases this is of little concern since these functions are typically not relevant to the situations in which they do not occur. For example, 'exit from track' which provides a safe means for exiting the crossing for road users trapped on the RLX is only possible when the road user is actually on the tracks. 'Optimise warning time' which provides the required minimum amount of time to inform the road user that a train is approaching can only occur once the train has activated the track magnet to trigger the active warning signals; therefore it cannot occur in any situation prior to this.

Second, more of the activity within the system occurs in those situations where both the road user and the rail user are closer to the RLX. For example, 17 (73%) of functions occur when the road user is at the boom gates and the rail user is at the track magnet compared to only 5 (21%) of functions when the road user is in the pre-approach zone and the rail user is pre-whistle board. Across all six rail user approach zone phases, the distribution of functions is similar, with the most functions occurring when the road users is at the boom gates, and the least occurring when the road user is in the pre-approach zone.

Third, in all situations, there are a number of functions that could occur but typically do not (as indicated by the dashed boxes). These potentially represent opportunities for redesign. Most of

these functions could occur in situations when the RLX is inactive and/or when the road and rail user are furthest from the RLX. For example, when the rail user is pre-whistle board (i.e., crossing inactive), 47% of functions are possible when the road user is in the pre-approach zone compared to 34% of functions when the road user is at the boom gates. When the rail user is at the track magnet (crossing active), 39% of functions are possible in the road user pre-approach zone compared to 13% when the road user is at the boom gates.

Most of these functions are associated with warnings of the RLX or the train's approach (or related functions including attract attention, speed reduction, detect train and assessment of risk), and do not typically occur in situations when the rail and road user are farthest from the RLX. For example, the only situation in which visual warning of the RLX is not currently provided to road users but potentially could be is when the road user is in each of the pre-approach situations. This is because the road user typically cannot yet see the RLX or the warning signs on this early phase of approach due to the presence of visual clutter and heavy traffic in the metropolitan environment which obscures the driver's view. For similar reasons, audible warning of the RLX is not typically afforded in situations other than when the road user is on approach or just prior to the boom gates because the road user will typically not be able to hear the warning bells and/or the train's approach. Assessment of risk and detect train could but typically do not occur before the train has reached the track magnet because the road user will not yet know that a train is approaching and the rail user will not yet be approaching the RLX.

Social Organisation and Cooperation Analysis Contextual Activity Template

The SOCA CAT found that almost 60% of the activity within the system is carried out by the warning systems, followed by the vehicle user (29%) and then the rail user (23%). The physical infrastructure performs almost 13% of the work, while the regulators/authorities perform about nine percent. The share of activities carried out by the driver and the vehicle is about even for the rail user group, but the driver carries out a larger proportion of the work within the vehicle user category (56% driver versus 43% vehicle). Overall, the majority of functions within the metropolitan RLX system are currently being performed by technology, with relatively fewer functions carried out by humans.

SOCA-CAT formative analysis

The formative SOCA-CAT analysis involved making an assessment as to whether the workload within the system could be redistributed across situations and/or reassigned to different actors and artefacts to optimise system functioning. To summarise, a number of possible re-design options were identified.

First, the CAT showed that most of the activity for key system functions associated with safety and train detection occurred when both the road user and the rail user were at the RLX. Although these functions were able to take place earlier in time and place, they typically do not. This raises the question as to whether more of the activity that normally occurs at the RLX could take place earlier. For example, visual and audible warning of the RLX could be provided to road users during the pre-approach zone phase via active signage or an in-vehicle warning. This would potentially overcome the problem of visual and audible clutter that is typical in metropolitan environments, and re-assign some of the workload from the warning systems to the vehicle itself. Road users would then be prompted to look out for the RLX earlier and prepare to stop if necessary. This would also assist drivers to prepare for, or carry out, other related functions earlier including speed reduction, assessment of risk, and prompt stop/go decision, all of which can only happen when the RLX is within the driver's line of sight. The in-vehicle warning device would have a similar effect when used to warn of the train's approach. In this case it would permit the occurrence of functions

including 'detect train', 'visual warning of approaching train' and 'auditory warning of approaching train' earlier than in the situations in which they typically occur (i.e., before the train has reached the track magnet and triggered the active warnings).

Second, there is potentially scope for actors not directly responsible for functions related to safety and train detection at the RLX itself to play more of a role in optimising system performance. These actors include the physical infrastructure and environment which currently account for only 13% of the system's activity, and the regulators/authorities which currently account for less than ten percent of it. For example, a pedestrian shelter and hub area with amenities close to the RLX may increase the likelihood that pedestrians will gather there to wait for the train (rather than hurry across the RLX), which in turn could have benefits for approaching motorists including slowing down and being alerted to the presence of the RLX. The presence of a person to act as a representative from the regulators/authorities group such as a crossing supervisor during peak periods would provide similar benefits. Both of these actors would potentially shift the allocation of train detection and safety functions from the RLX infrastructure, the vehicle and the driver alone.

Discussion

The study described in this paper involved using methods from CWA to examine current and potential allocation of functions within metropolitan actively controlled RLXs. The outcomes give pointers to improve safety at RLXs by identifying how social (i.e., human) and technical (i.e., non-human) components within the system can be optimally configured. A number of important findings emerged from the analysis.

First, the results highlighted an uneven spread of activity across the situations in which train detection and safety can occur and, second, across the actors involved in these functions. Specifically, the CAT showed that the majority of activity related to train detection and safety currently occurs when the rail user and the road user are closest to the RLX. Conversely, the majority of situations where this type of activity could occur but typically does not are those in which the road user and the rail user are farthest from the RLX. An in-vehicle system designed to provide advanced warning of the RLX and/or the approaching train was suggested as a potential design option for re-allocating some of the functions relating to train detection and safety earlier than when they would normally occur. The intention of the design is to provide more time for road users to prepare for the RLX, with the overall goal that they will be more likely to notice the crossing and stop safely if necessary.

The SOCA-CAT showed that the RLX infrastructure is currently responsible for most functions relating to safety, and there are parts of the system that could be doing more to support and/or improve behaviour, such as humans, in-vehicle systems and the surrounding physical infrastructure. An in-vehicle warning system would potentially help re-distribute some of the workload from the RLX infrastructure, thus providing another layer of protection for those users who might otherwise overlook the RLX by relying on the active warning systems alone. Implementation of a crossing supervisor and pedestrian hub/waiting area could potentially provide similar benefits.

This study is not the first to call for new designs to improve safety at RLXs, and a number of researchers (e.g., Larue et al., 2014; Tey, Wallis, Cloete, Ferreira & Zhu, 2012) have already tested a range of emerging intelligent transport systems, including visual and auditory in-vehicle warning systems. The results of these simulator studies generally showed increased compliance and earlier reduced approach speeds at passive RLXs, although only marginal improvements in behaviour at active RLXs were found when compared to baseline conditions (i.e., no in-vehicle warning). Overall, drivers found the in-vehicle warning systems to be useful, easy to use, and socially acceptable (Larue, Rakatonirainy, Haworth & Darvell, 2015). The designs proposed in the current

study are currently being refined through discussions with subject matter experts and will then be tested in a simulator as part of the larger project from which this study is derived. It is planned that the in-vehicle warning system will be examined both alone and in combination with other re-designs including the crossing supervisor and pedestrian hub/waiting area.

Although CAT and SOCA-CAT have been useful for mapping out the problem space in an explicit manner, it will be important to examine any potential threats to safety that might arise from allocating functions to situations where they are not currently afforded. For example, in busy metropolitan environments, provision of an early in-vehicle warning could compete with other driving tasks that take a higher priority for the driver's attention during the pre-approach zone, such as a pedestrian darting out in between parked cars or traffic lights changing from green to red. Aside from the issue of distraction, drivers may also become desensitised to a warning if it is given too early such that they fail to pay attention to the RLX at the time when it becomes critical to do so. Larue et al. (2014) did not identify any issues associated with the in-vehicle devices in terms of driver distraction or increases in driver workload, although at actively controlled crossings these effects were examined only when the active warnings had commenced activation and the driver was within the vicinity of the RLX. The simulation studies to be conducted as part of the larger research program will examine driver behaviour at all stages on approach to the RLX.

Due to space constraints, the current analysis was restricted to metropolitan actively controlled RLXs and focussed on drivers only. The wider research program also examined the distribution of activity in a sample of ten passive RLXs, and both motorised and non-motorised road users were included in the analysis for active and passive RLXs. New designs incorporating the outputs of these analyses will also be examined in the simulator as part of the larger research program.

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