Integrating Human Factors and Systems Thinking for Transport Design: Rail level Crossing Case Study

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Abstract

Rail level crossings (RLXs) represent an intractable problem. Safety gains achieved through existing approaches appear to have plateaued. We describe a multi-year program of research that took an innovative approach to this longstanding problem. This involved integrating human factors and systems thinking methods to provide a whole of design lifecycle approach to analyse the performance of existing RLXs, design novel RLX environments, and evaluate and test these designs. The research program culminated in a series of empirically tested design concepts, recommendations for further research into promising infrastructure changes, and systemic recommendations for improving management of RLXs more generally.

Background

Collisions at rail level crossings (RLXs) are a longstanding transportation safety issue. They represent a persistent source of trauma, accounting for nearly half of Australian rail fatalities, excluding suicide and attempted suicide cases (ONRSR, 2015). Worryingly, safety gains at RLXs appear to have plateaued, in line with broader road safety trends, such as increases in the road toll in several states (BITRE, 2016).

To improve RLX safety, it has been argued that new approaches are required (Read et al, 2013). Specifically, there is a need to depart from traditional reductionist approaches which focus on improving individual parts of the system (e.g., preventing driver errors, making a warning more conspicuous), to approaches that consider how these components interact, and how the functioning of the overall transport system can be optimized.

This paper describes a program of research that took a new systems thinking approach to RLX safety. The intention was to generate a series of design concepts that ostensibly would enhance behaviour and safety at RLXs. Systems thinking involves taking the overall system as the unit of analysis, looking beyond the individual, and considering the interactions between humans and between humans and technology within a system. This view also considers factors relating to the wider organisational, social and political environment. Taking this perspective, safety emerges not from the decisions or actions of an individual, but from interactions between humans and technology across the wider system (Dekker, 2011; Leveson, 2004; Salmon & Lenné, 2015).

To demonstrate some of the complexity of the RLX system, an ‘Actormap’ (Rasmussen, 1997) is shown in Figure 1. The Actormap illustrates how the RLX system is made up of a hierarchy of levels, from government / parliament down to the operating environment, with actors at each level who share responsibility for rail level crossing safety. This shows that there are a great number of actors / agents (both human and non-human) involved, all of whom make decisions and actions that can affect behaviour in this context. An important implication here is that any RLX collision is effectively created by a network of interacting decisions and actions made by multiple actors across all levels of the sociotechnical system.

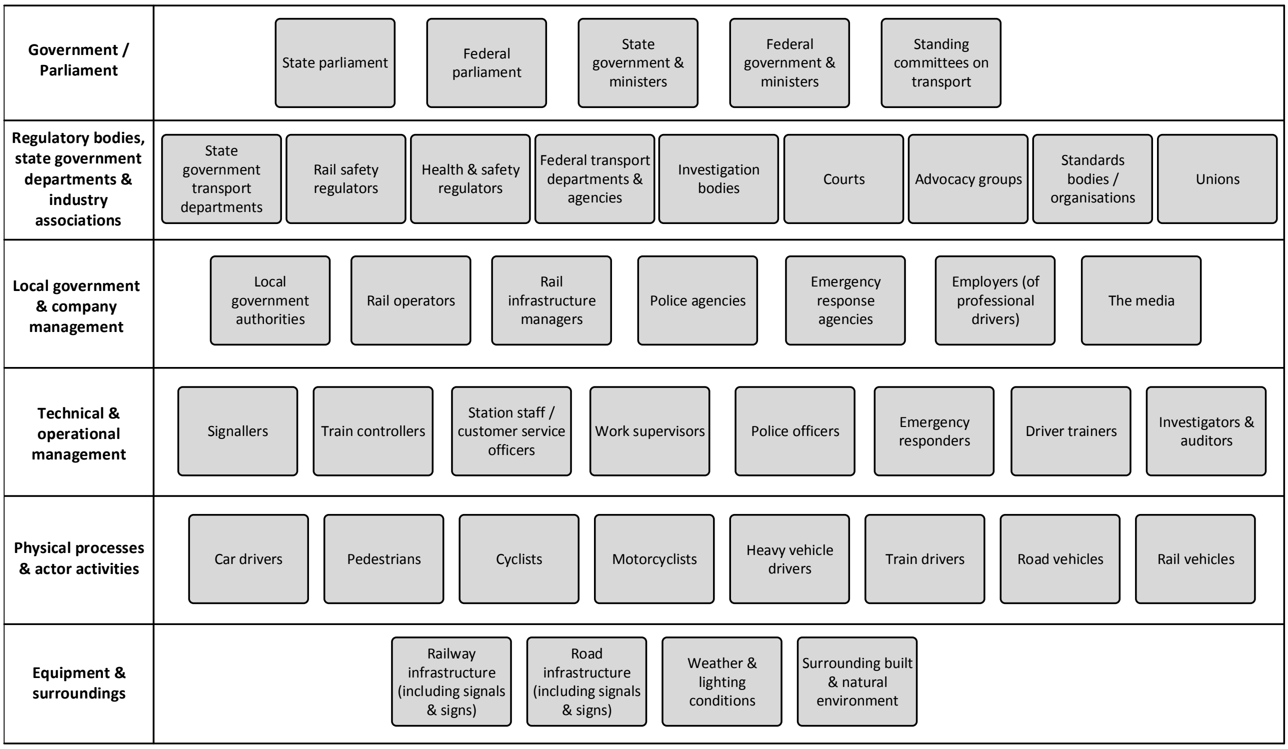

Figure 1. Rail level crossing Actormap (adapted from Read, Beanland, Lenné, Stanton, & Salmon, 2017).

The aim of this paper is to outline how human factors and systems thinking approaches were integrated and applied to understand this complex system and to develop recommendations for improving its safety performance.

Method

The research program comprised the four phases. A brief overview of each phase is provided below.

Data collection

Data were collected on system functioning and user behaviour at both 'active' and 'passive' RLXs. Active crossings have warning devices that activate based on detection of an approaching train (e.g. flashing lights, boom gates and warning bells). Passive crossings instead rely on static warnings of the presence of RLX only (e.g. road signs, road markings, RLX markers).

A range of data collection activities were undertaken including on-road and questionnaire-based studies of road user and pedestrian behaviour at RLXs, in addition to document review and interviews with subject matter experts (e.g. Beanland, Lenné, Salmon, & Stanton, 2016; Salmon, Lenné, Young, & Walker, 2013).

Systems analysis

The data were used to build models of the RLX system using Cognitive Work Analysis (CWA; Vicente, 1999) and Hierarchical Task Analysis (HTA; Annett et al., 1971). CWA is a systems analysis and design framework. An important feature of CWA is that it provides analysis tools that identify the constraints present within a system and how these constraints restrict behaviour. The identification and understanding of constraints allows the exploration of the possibilities for changing behaviour through the removal of existing constraints, addition of new constraints, or through changing the nature of constraints. For examples of the CWA outputs see Salmon et al. (2016), Mulvihill et al. (2016) and Read et al. (2017).

HTA was used in addition to CWA to understand how activity is undertaken within the RLX system in terms of the goals, sub-goals and operations of the key actors including road users, train drivers, the train and the rail level crossing infrastructure.

Generation of innovative design concepts

Insights from the systems analyses were extracted and used in a participatory design workshop involving stakeholders from the road and rail industries. The design process used the CWA Design Toolkit to generate a set of novel designs for RLXs (Read, Salmon, & Lenné, 2016).

Eighteen participants attended the design workshop. Participants were invited as representatives of RLX 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. human factors professionals, researchers, and designers).

The design workshop was delivered over two days and involved participants generating a series of design concepts and solutions for improving behaviour and safety at RLXs. 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 produced 11 RLX design concepts prioritised by the workshop participants in order of those thought likely to be most effective in improving safety. The seven most highly ranked concepts were subject to a desktop evaluation using the CWA models of the existing system to understand the positive and negative impacts of introducing the new designs, and to assess the extent to which the designs aligned with systems thinking. In addition, the Systematic Human Error Reduction and Prediction Approach (SHERPA; Embrey, 1986) was used to predict the likely errors that would arise when users negotiated each of the proposed rail level crossing environments.

A refinement process was then undertaken to enhance the initial designs and address any potential negative effects or new errors introduced. In addition, a workshop with human factors experts was undertaken whereby two more designs were generated for further testing and evaluation.

Evaluation of designs

The design concepts were formally tested through studies in a driving simulator and a questionnaire-based study.

Three driving simulator studies were undertaken to evaluate the RLX design concepts based on their impacts on driver behaviour and other key concepts such as situation awareness (Stanton et al., 2017), subjective workload (Hart & Staveland, 1988), usability (Nielsen, 1993) and preference for the designs. Drivers responses to the new designs were compared to 'baseline' conditions which were simulated environments representing standard RLX designs for urban or rural areas in the state of Victoria, Australia. The first study tested the urban RLX design concepts (Read et al., 2016), the second tested the rural RLX design concepts and the third investigated specific high-risk scenarios in the rural context (specifically driver distraction and failures of the crossing infrastructure / technology).

An online questionnaire-based study was also conducted to ensure that the views and preferences of all road users (e.g. drivers, heavy vehicle drivers, pedestrians, motorcyclists, cyclists) were considered in the evaluation process. The survey was distributed with recordings of the simulations, taken from the perspectives of different road users. Participants viewed the video simulations, provided comments on the strengths and weaknesses of the designs from the perspective of their road user group, and compared the designs in relation to four criteria: safety, efficiency, compliance and ease of use.

Integration of the methods throughout the research program

An important aspect of the research program was that throughout the four phases of research, several human factors and systems thinking methods were applied (see Figure 2). Many of the methods were used across multiple phases. For example, vehicle measures were collected at the beginning of the research program during on-road studies to understand driving behaviour at existing crossings and again in the final phase during driving simulator studies to understand responses to the innovative RLX designs.

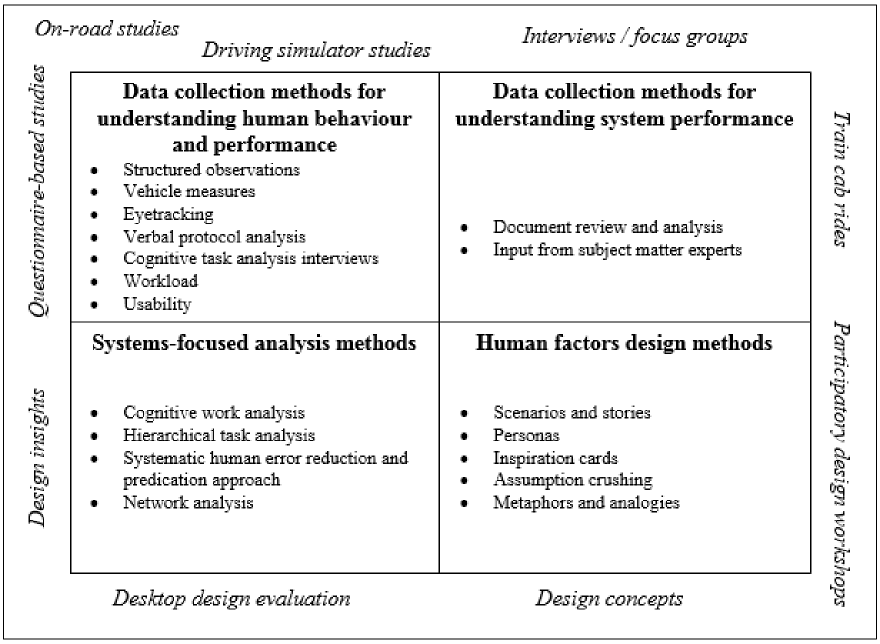

Figure 2. Human factors and systems thinking methods and approaches applied in the research program.

Results

Key findings from the systems analyses

The CWA analysis revealed a number of systemic issues that influence the effectiveness of the RLX system. First, there are multiple competing purposes that the system is attempting to achieve simultaneously. For example, the system is set up to give priority access to rail traffic, yet especially in busy urban areas, there is pressure to minimise delays to the road network. This challenge is likely to intensify with both train frequency and traffic volumes continuing to increase. Second, although safety data are collected around collisions and near misses at RLXs, there are opportunities to improve the way that risk and safety is monitored, for example through collection of new types of data around behaviours and non-compliances.

An additional key finding from the systems analysis that shaped the design concepts was that different types of road users (e.g. drivers, pedestrians, cyclists, motorcyclists) use different information and cues when making decisions to stop or go at level crossings, and use different behavioural strategies when encountering these environments. Thus, there is not a ‘one size fits all’ solution that will be appropriate for all types of users.

Key findings from the testing of design concepts

The key findings from testing of the design concepts are shown in Tables 1 and 2. Table 1 provides the combined results of studies into the effectiveness of the urban RLX design concepts while Table 2 presents the results of studies into the rural RLX design concepts.

The testing process was beneficial as it highlighted the positive and negative aspects of each design, and how they were perceived by different road user groups. This provided insight into which design features showed promise in improving behaviour and which features would be acceptable to users. Given the novelty of all designs, further trialling and testing would be needed prior to being implemented in the real world.

Table 1. Results for urban RLX design concepts, note that apart from rankings, all comparisons are to baseline / standard RLXs

Design	Design philosophy	Key findings
Comprehensive risk control crossing 	A combination of safety risk controls and aspects to improve amenity and user experience, especially for pedestrians. Focuses on drawing road user attention to the presence of the RLX and trains. Also aims to prevent queuing on the RLX or to mitigate its consequences.	• No difference in driving performance to baseline. • Highly rated for safety and compliance. • Drivers reported liking the traffic lights. • Heavy vehicle drivers liked the additional safety features, and separation of vehicles, cyclists and pedestrians. • Most highly preferred concept by pedestrians.
Intelligent level crossing 	Use of new and emerging intelligent transport system (ITS) technologies to optimise the functioning of the transport system by improving communication and coordination between road and rail. Provides decision support systems to road users (in-vehicle interfaces, smartphones or dynamic displays) and enforcement of stopping when collisions are predicted. In-vehicle display based on field of safe travel theory (Gibson & Crooks, 1938).	• Decreased mean and maximum speed on approach to the RLX compared to baseline. • Reduced mean braking pressure and time spent traversing the RLX than baseline. • Provided earliest awareness of train approach. • Most preferred design for drivers.
Community courtyard crossing 	Underpinned by the notion of shared space and prioritisation of active transport in the roadway. Intended for specific urban environments, it provides a space to enhance social interaction and inclusion while providing a focus of transit orientated economic and community activity. Provides opportunity for recovery from failures as train speed slowed and RLX is supervised by railway attendants.	• Lower speeds on approach and more gradual deceleration, leading to longer travel time. • Significantly higher levels of mental demand and frustration. Rated as less usable/less pleasant to use. • Concerns that not recognizable as an RLX. • Pedestrians and cyclists rated as most efficient, drivers and motorcyclists rated as least efficient and least preferred.

Table 2. Results for rural RLX design concepts, note that apart from rankings, all comparisons are to baseline / standard RLXs

Design	Design philosophy	Key findings
Simple but strong 	Uses simple and low-cost features to draw attention to the upcoming RLX and the danger posed, and to provide warning of train approach. Approach speed is reduced over the approach beyond the standard Victorian reduction of 80km/h down to 60km/h, then 40km/h just prior to the crossing to provide more time for error recovery.	• Produced greatest speed reduction, especially when no train was approaching and longer travel time through the RLX when train was present. • Considered complex to use. • Cyclists and drivers rated it as most likely to engender compliant behaviour. • Cyclists and heavy vehicle drivers rated as safest, and was most efficient and preferred concept for cyclists. • Drivers and motorcyclists reported not liking the speed reductions.
Ecological interface design 	Applied the principles of ecological interface design to enhance road user awareness of key constraints. Emphasises the danger zone, the train as the key hazard and assists both road users and train drivers to judge speed and distance. Slows both the road user and train to enable the system to better recover from errors.	• Simulator participants slowed significantly compared to baseline when a train was approaching (leading to longer travel times), but maintained travel speeds when there was no train. • Reported the design was complex to use. • Reported train more conspicuous, some liked road markings and roadside poles, some were confused about mirrors that reflected the image of the approaching train. • Ranked most preferred of the rural design concepts by simulator participants, but not preferred by any road user group in the questionnaire study.
GPS average speed to avoid a train 	Underpinned by time-based separation, promotes efficiency and traffic flow as a means to also improve safety. Uses new and emerging technologies to provide drivers with speed guidance to avoid needing to stop for an approaching train.	• Drivers slowed sooner, and to a lesser extent, maintaining more constant pace with less variability in approach speed over the last 250m before the crossing. • Most efficient travel time of the new rural designs. • Participants liked that they could use it to avoid stopping for a train; however, not all participants intuitively understood the interface; some found it distracting. • Ranked most preferred by heavy vehicle drivers.

Recommendations for improving RLX safety

Based on the findings from the research program, several recommendations were made for improving safety at RLXs. As can be seen in Figure 3, while a number of recommendations are associated with changes to physical infrastructure at the crossing, with the intent of facilitating safe interactions between road users and trains at the site of the crossing, recommendations were also proposed in response to systemic issues such as coordination amongst agencies, risk assessment methodologies and design standards.

The recommendations included:

- *Recommendations for the introduction of in-vehicle warning devices.* In general, the in-vehicle warning devices tested demonstrated considerable benefit and appeared to have acceptance from users. Therefore, a number of recommendations are associated with supporting the appropriate introduction of ITS technologies for improving RLX safety.

- *Recommendations for changes to RLXs in urban environments.* Based on the evaluation of the urban design concepts, recommendations were made regarding aspects of the designs that performed well or were well-received by users. These included consideration of implementing traffic lights at higher risk urban locations to improve compliance with flashing lights, trialling of pedestrian amenities (such as shelters at the RLX waiting area), trialling of RLX attendants at high risk locations during peak times, addition of cycle lanes and/or cycle boxes where feasible, and trialling of adapted shared space areas at specific locations, encompassing traditional RLX warnings (boom barriers, flashing lights, audible warnings).

- *Recommendations for changes to RLXs in rural environments.* Based on the evaluation of the rural design concepts, recommendations were made regarding aspects of the designs that performed well or were well-received by users. These included trialling of road markings to emphasise the ‘danger zone’ on approach to and across the RLX, further investigation into the use of mirrors at RLXs including engineering feasibility and human factors research to ensure the design will not introduce new risks, and further investigation / field trials of improved train conspicuity, particularly focusing on drawing attention to the front of the train.

- *Recommendations for RLX management.* This set of recommendations focused on optimising the overall RLX system. The first recommendation was to continue efforts already commencing by RLX stakeholders to increase the scope of data collection to include normal performance at RLXs, rather than collection of near miss and collision data only. Another recommendation was for consideration to be given to amending engineering standards to promote a process that is more focused on risk management in the context of individual crossings (e.g., factoring in risks that arise from adjacent side roads, vehicular and pedestrian traffic to/from local businesses, and other unique attributes of the crossing), rather than achieving consistency without reference to local conditions. In addition, it was recommended that the findings from the systems analyses be integrated into risk management processes, evaluation processes for new RLX technologies, investigation methodologies and data collection tools, and design standards. For example, risk management processes could be augmented by incorporating some of the factors influencing behaviour identified in the data collection and systems analysis phases of the research program. Finally, it was recommended that RLX stakeholders continue to build a culture of shared responsibility for RLX safety through coordinated efforts and the implementation of appropriate performance measures and incentives on all agencies, focused on reducing risk.

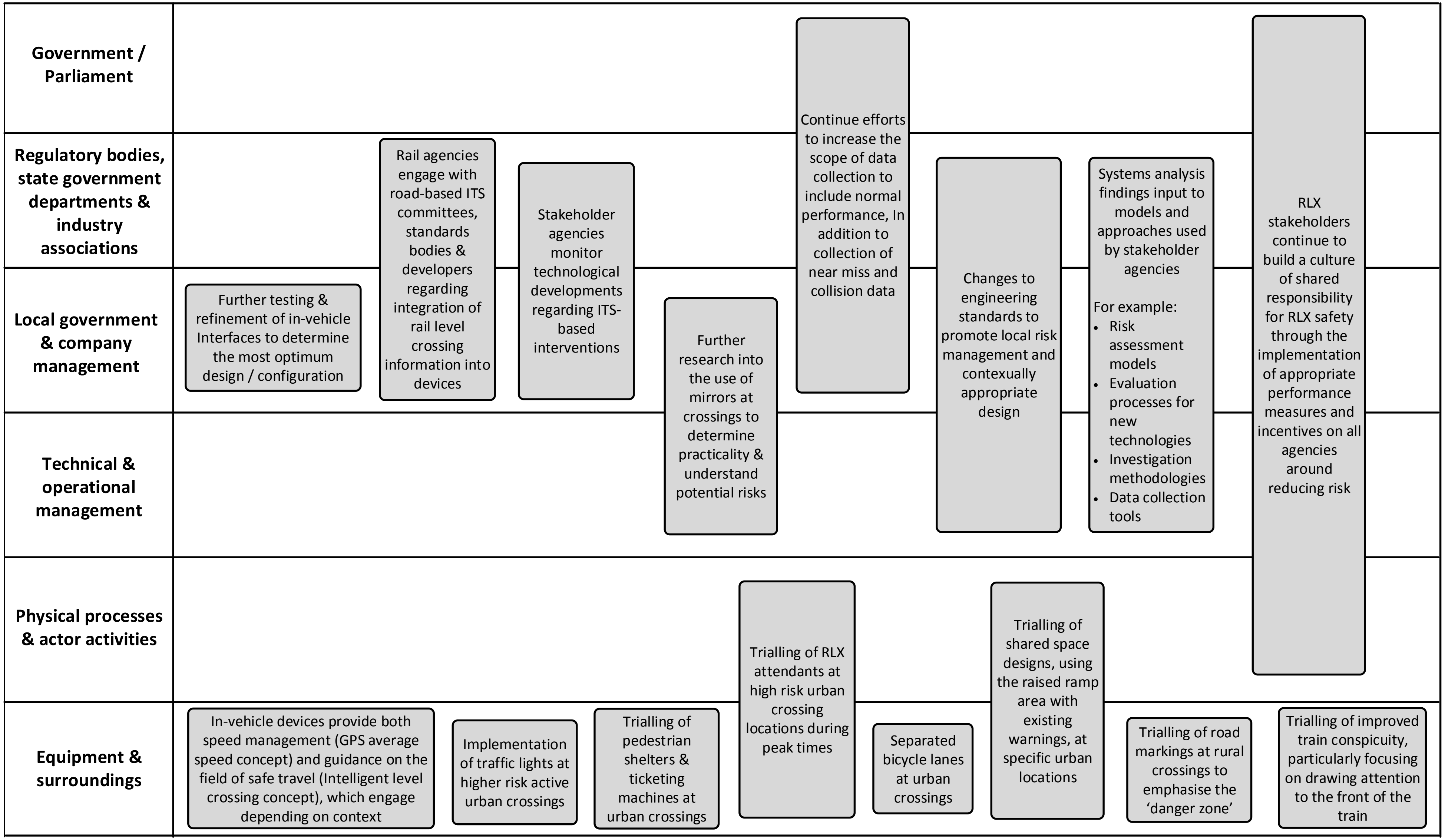

Figure 3. Recommendations from the research, indicating where they sit across the RLX system (adapted from Read et al., 2017).

Conclusions

A key challenge for safety critical systems generally is to integrate systems thinking into design and evaluation processes. The research program described here demonstrated the utility of applying multiple methods and perspectives on the problem of risk at RLXs. It produced novel findings about user behaviour at RLXs, generated innovative design concepts for RLXs and provided initial evidence of the likely effectiveness of the designs. These activities led to the provision of a range of recommendations for improving safety.

There are increasing calls for a systems thinking approach to transport system design and evaluation (Salmon & Lenné, 2015). Translation of systems thinking in practice requires that appropriate methodologies be developed to support systems thinking in design and evaluation processes. We encourage others to consider adopting similar approaches to address other key risks in the transport industries.

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