Through a different lens: applying contemporary systems analysis methods in road safety

Paul M. Salmon*, Gemma J. M. Read, Michael G. Lenné

Human Factors Group, Monash University Accident Research Centre

*corresponding author: paul.salmon@monash.edu

Abstract

There is growing consensus that increased understanding of, and reductions in, road trauma, can be achieved through a systems theory driven approach to road safety. To test this assertion, this paper presents an application of three contemporary systems analysis methods in the road and rail transport context: Accimap, Cognitive Work Analysis and STAMP. The methods were used to describe the Kerang tragedy in which a loaded semi-trailer truck struck a passenger train on a railway level crossing in Northern Victoria, Australia, killing eleven train passengers. The analyses indicate that a more exhaustive insight into the causes of road trauma can be achieved through the application of such methods. Notable outcomes include that the role of factors beyond road users (e.g. government, road rules, road designers) in road trauma is elucidated, that issues influencing road system efficiency are identified, and that countermeasures derived from this approach are likely to be more holistic, treating conditions across the entire transportation system.

Key words: Human Factors, Systems theory, Kerang

1. Introduction

Road transport-related trauma remains a leading cause of death and disability throughout the world (WHO, 2009). Although significant reductions in death and injury have been achieved, persistent issues remain and reductions appear to be slowing. Despite this, current road safety strategies have significant fatality and injury reduction targets. For example, the Australian National Road Safety Strategy 2011-2020 has the target of reducing annual road fatalities and serious road injuries by 30% (ATC, 2011). This paper argues that future road safety targets can only be achieved through a paradigm shift, both in the way in which current road safety problems are described and understood and in the nature of the solutions used to remove them. Specifically, it is argued that a systems theory-driven approach to road safety problems will enhance our understanding of them and will produce more appropriate, holistic, and efficient solutions.

To test the utility of the systems theory driven approach, the recent Kerang rail level crossing (RLX) collision is described using three contemporary systems analysis methods: Accimap (Rasmussen, 1997), Cognitive Work Analysis (CWA; Vicente, 1999) and STAMP (Leveson, 2004). It is argued that the outputs provide a holistic, systems-based understanding of the incident, shedding light on the factors across the road and rail systems that contributed to the incident. This paper begins by describing the Kerang incident, following which an overview of the three analysis methods is given. The results are then presented and discussed with regard to their implications for future road safety research efforts.

2. Kerang

2.1. Rail level crossing Y2943

Within Australia, RLXs are typically classified as one of two types based on the warnings provided to road users: *passive* and *active* RLXs. Passive RLXs have only ‘passive’ warnings that alert road users to the RLX itself, such as road signage and road markings. Active crossings have passive warnings and also ‘active’ warning devices that alert road users to the presence of a train, such as flashing lights, boom gates, and warning bells. At the time of the Kerang incident, the RLX involved (officially known as crossing number Y2943) was considered to be an active RLX, having the following active and passive warning devices: width marker assembly, flashing lights, warning bells, approach warning signage, and road markings.

2.2. The Kerang incident

The following description of events is adapted from the Victorian Office of the Chief Investigator's (OCI) report describing their investigation into the Kerang incident (OCI, 2007). On the morning of Tuesday 5th June 2007 a semi-trailer truck departed its depot in Wangaratta, Victoria, embarking on a weekly freight run to Adelaide in South Australia. The driver was a professional truck driver with over 25 years experience of truck and van driving and no infringements (OCI, 2007). He had been driving the same route around once a week for approximately seven years and had returned to work on the 5th June following a period of four weeks leave (OCI, 2007).

At around 13:00 the same day, a regional passenger train departed Swan Hill station en-route to Melbourne. Around 25 seconds before the train encountered RLX Y2943, it passed over a track circuit, activating RLX Y2943's flashing lights and warning bells. Shortly after, upon seeing the whistleboard for RLX Y2943, the train driver activated the train's air horn.

Travelling at around 100km/h, the truck passed 'RAIL' and 'X' road markings (approximately 267 and 253 metres from the RLX respectively) and an RLX warning sign (approximately 260 metres from the RLX) and approached the RLX along a curve in the road, apparently not noticing the train or the RLX's flashing lights. The truck driver stated that, upon noticing the warning sign, he looked at the RLX's flashing light assembly, but did not see the lights flashing (R v Scholl, 2009). Around 140 metres before the crossing, the train driver noticed that the truck was continuing toward the RLX at speed, despite being only 70-100 metres short of it. He subsequently sounded the train horn for several seconds. Upon finally becoming aware of the train, the truck driver applied the brakes and attempted to steer the truck into a gully to the left of the train tracks. The truck struck the passenger train as it crossed the highway, killing 11 train passengers and injuring a further 14 (the truck driver was also severely injured).

The official investigation into the incident concluded that the train and train crew, the truck, the road and rail infrastructure, and the RLX warning devices all played no causal role in the incident (OCI, 2007). The truck driver, however, refused to be interviewed by investigators and did not provide any information to them (OCI, 2007). As a result, following an exhaustive investigation, the OCI was only able to conclude that the primary causal factor of the incident was that "for reasons not determined the truck driver did not respond in an adequate time and manner to the level crossing warning devices" (OCI, p. 72). The truck driver was prosecuted following the incident on the basis that he had failed to keep a proper lookout. He pleaded not guilty to eleven counts of culpable driving causing death and eight counts of negligently causing serious injury and was acquitted by a jury (R v Scholl, 2009).

3. A systems analysis of the Kerang incident

The present analysis is not concerned with the psychological mechanisms underlying the truck driver's failure to see the RLX's flashing lights or the train in a timely manner. A separate analysis of the incident (See Salmon et al, under review) concluded that the truck driver's failure to respond in a timely manner to the crossing warning devices was caused by activation of the wrong mental schema in the mind of the truck driver, namely a schema for the level crossing in a non-activated state (i.e. no train approaching), which, through shaping the truck driver's expectations and perception, then caused a look but failed to see error in which the driver scanned the RLX's warning lights, but did not perceive their flashing state. The present analysis instead focuses on the factors across the road and rail systems that enabled such an incident to occur. The paper thus proceeds by presenting a systems analysis of the incident. The aims were to identify the factors outside of the truck driver that played a part in the incident and to explore the utility of systems analysis methods for understanding and responding to road safety problems.

The systems approach to safety in complex sociotechnical systems centres on the notion that safety is an emergent property arising from non-linear interactions between a system's components. With regard to accident causation, accidents are viewed as emergent phenomena that result from the interactions between multiple components across complex sociotechnical systems (e.g. Leveson, 2004). Moreover, behaviours implicated in accidents often represent normal, everyday behaviour and in themselves offer little indication of impending accidents; it is the interaction between behaviours and the ensuing emergent properties that create accidents as opposed to the behaviours alone. Consequently the systems approach argues that, in order to understand performance in a way that supports appropriate safety interventions, it is the interactions between components of the system that are of interest, not the individual components themselves. The overall system, therefore, represents the most appropriate unit of analysis (Ottino, 2003)

Various safety and risk management models have emerged from the systems approach paradigm (e.g. Leveson, 2004; Rasmussen, 1997). To support systems analyses, various methods underpinned by the systems philosophy are now available. The present analysis involved the use of three currently popular systems analysis methods: Accimap, CWA, and STAMP. A brief overview of each approach is given below.

Accimap

Rasmussen (1997) developed the Accimap approach to support systems analyses of accidents in complex sociotechnical systems. Accimap graphically represents the actions, decisions, etc involved in producing the system in which a particular accident was allowed to occur. The 'system' considered by Accimap typically includes the following six organisational levels: government policy and budgeting; regulatory bodies and associations; local area government planning & budgeting (including company management); technical and operational management; physical processes and actor activities; and equipment and surroundings. Factors at each of the levels are identified and linked between and across levels based on relations (e.g. cause-effect relations).

Cognitive Work Analysis

CWA is a systems evaluation and design framework comprising five analysis phases. The present analysis involved the application of the first analysis phase: Work Domain Analysis (WDA). WDA is used to describe or model the purposive and physical constraints imposed on activity within a particular system. This involves constructing an Abstraction Hierarchy (AH), which describes the system in question across the following five levels of abstraction:

- *Functional purpose* – The overall purpose(s) or raison d'être of the system and the external constraints on its operation;
- *Values and priority measures* – The criteria that the system uses for measuring progress towards its functional purpose;
- *Generalised functions* – The general functions of the work system that are necessary for achieving the functional purposes;
- *Physical functions* – The functional capabilities and limitations of the physical objects within the system that enable the generalised functions; and
- *Physical objects* – the physical objects within the work system that afford the physical functions.

Items at each of the levels are linked using means end relations. The output therefore provides a constraints-based model of the system, addressing not only what activities can be performed within a particular system, but also how and why they are performed and with what.

STAMP

STAMP (Leveson, 2004) is a systems analysis approach that views accidents arising from control failures at different levels of the system in question. STAMP views systems as comprising hierarchical levels of controls and constraints, with each level in the hierarchy imposing constraints on the level below. Conversely, information at the lower levels about the appropriateness and condition of the controls and constraints is communicated upwards in the hierarchy to inform the upper levels controls and constraints. According to the STAMP philosophy, accidents occur due to the inadequate control of safety-related constraints (Leveson, 2004), that is, when component failures, external disturbances, and/or inappropriate interactions between systems components are not controlled (Leveson, 2009). Leveson (2009) describes various forms of control, including managerial, organisational, physical, operational and manufacturing-based controls. STAMP analyses involve describing the control structure in place for the system in question and then identifying the system wide control failures involved in the accident.

Accimap, CWA and STAMP analyses were conducted for the Kerang incident. The purpose of these analyses was to identify the systemic factors involved in the incident as viewed by each approach. The primary data source was the OCI investigation report (OCI, 2007); however, other data, such as court transcripts (R v Scholl, 2009) were used to support the analysis. Initially three Human Factors analysts met to discuss the data. Following this, one analyst with significant experience in all three methods conducted the analyses. This was then reviewed by the other two analysts with any disagreements being resolved through further discussion. The Accimap output was also reviewed and verified by two Human Factors rail safety experts and also the leader of the OCI investigation team. Again, any disagreements were resolved through discussion and modification where appropriate.

4. Results

ACCIMAP

An Accimap for the Kerang incident is presented in Figure 1. The Accimap depicts the factors across the road and rail systems that played a role in shaping the RLX system in which the incident occurred. At the equipment and surroundings level there are various factors that potentially contributed to driver's failure to notice the activated RLX and approaching train. The crossing had flashing lights and sign- and road-based warnings but was not fitted with boom gates. Boom gates would have provided a stronger, more conspicuous visual cue to the driver and would have represented a physical barrier. It is likely that, had boom gates been in place, the driver would have been alerted to the presence of a train earlier. This is evidenced by the fact that, according to accident data, crossings with boom gate barriers achieve the best safety performance (e.g. Saccomanno, Park & Fu, 2007).

The weather on the day was fine with visibility estimated to be around 50km (OCI, 2007); however, the sun was directly in front of the truck throughout its approach to the RLX and a post incident test run in similar conditions reported considerable sun glare from the road surface (OCI, 2007). The sun glare may have influenced the drivers' visibility of the crossing warning signage and controls (OCI, 2007); however, court transcripts show that the truck driver reported that the glare was not a problem. The OCI reports that the contrast between the train and its background is likely to have been reduced as a result of the truck-facing side of the train being shadowed. Trees in close proximity to the left hand side of RLX may have obscured the truck driver's vision of the approaching train while the A-pillar of the truck also provided a potential momentary obscurement of a stationary vehicle located on the opposite side of the RLX.

The train driver sounded the train horn twice on approach to the RLX, first at the whistle board, and second, continuously for 7 seconds from the point at which the train was 140 metres from the RLX. It is unlikely that the first horn sounding would have alerted the truck driver to the presence of the train (OCI, 2007). It may be that the sound from the train horn was not of sufficient intensity to be detectable in the cabin of the truck, or it may be that the driver's low expectation of a train approaching led to the driver being biased against detecting this stimulus, as proposed by Rapoza and colleagues in their signal detection theory analysis of the audibility of train horns (Rapoza, Raslear & Rickley, 1999). Finally, the road speed limit at the time of the collision was 100km/h. Ostensibly a lower speed limit could have provided more time for error recovery or evasive action.

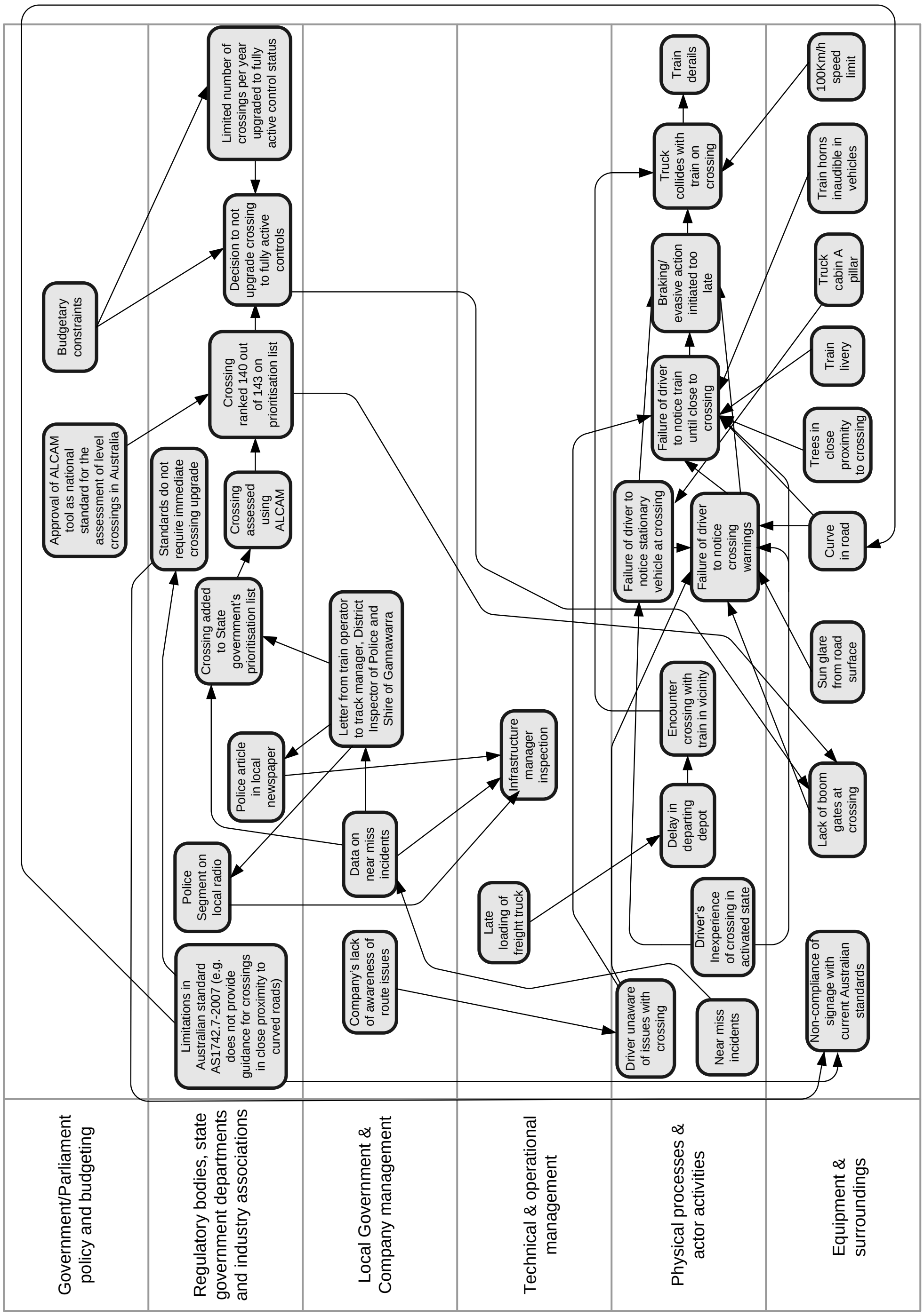

Figure 1. Kerang incident Accimap

The physical processes and actor activities level describes the chain of events that led to the truck colliding with the train. Also included at this level is the truck driver's lack of experience of RLX Y2943 in an activated state (i.e. train approaching). He had driven trucks along the same route, for the same carrying company, approximately once a week for seven years prior to the incident (OCI, 2007) and yet had never previously experienced a train at RLX Y2943 (R v Scholl, 2009). On the day of the incident the driver was delayed in departing the depot due to freight loading issues. This ensured that the truck encountered the RLX at the same time as the train. Potentially influenced by his extensive experience of the RLX with no train approaching and by environmental, meteorological, and vehicle factors (e.g. sun glare, trees in close proximity to crossing, truck A pillar), the driver failed to notice the approaching train, and the active RLX warnings. Upon noticing stationary vehicles located on the opposite side of the RLX and then the train itself, the driver took evasive action but at this stage it was too late, and the truck collided with the train on the RLX, leading to the train derailment.

The delayed loading of the truck is placed at the technical and operational management level, as is an inspection of the RLX conducted by an infrastructure manager in response to a series of near miss incidents and a letter from the train operator to the track manager expressing concern over road user behaviour at the RLX. The haulage organisations lack of awareness of near miss incidents at the RLX is placed at the local government and company management level; had they been aware of the issues and subsequent Police radio and newspaper pieces on this it is highly likely that they would have made some communication with their drivers. Unfortunately these attempts to educate road users on the risks associated with the RLX do not appear to have reached the trucking company or truck driver involved.

At the regulatory bodies, state government and industry level various factors combined to ensure that the RLX was not upgraded to fully active status via the addition of boom gates. Notably, since the incident, the crossing has been modified to include boom gates, Light Emitting Diode (LED) lights, rumble strips, active advanced warning signs and the approach road speed limit has been reduced to 80km/h. On the basis of near miss data detailing six incidents at the crossing during 2005 and 2006 and a subsequent letter from the train operator to various authorities outlining concerns over motorist behaviour at RLXs in and around Kerang (OCI, 2007), various activities were initiated, including public education efforts (article in local newspaper and police segment on local radio) and the addition of the RLX to the state government's RLX prioritisation list (OCI, 2007). As a result, the RLX was assessed in 2006 using the Australian Level Crossing Assessment Model (ALCAM). The RLX was assigned a risk score and was ranked 140 out of 143 RLXs on the prioritisation list (OCI, 2007). This meant that it was not upgraded at the time of the incident and nor would it be for some time to come, since budgetary constraints enable only a limited number of upgrades each year.

At the Government/Parliament policy and budgeting level the Australian standards were limited in that they did not consider RLXs with a curved road on approach. The risk assessment tool used to assess RLXs in Australia is also placed at this level. Although it does offer a risk assessment, currently it does not take into account accident or near miss incident data or human factors and is heavily weighted towards exposure data (i.e. the volume of road and rail traffic passing through the RLX under assessment). Finally, financial and budgetary constraints are placed at this level since annual funding allocations limit the number of RLXs that can be upgraded to full active controls.

Work Domain Analysis

A WDA for the Kerang RLX system is presented in Figure 2. The shaded nodes within the WDA represent objects, functions and purposes that failed or were not fulfilled during the incident. Although the analysis is useful as it provides a description of the different components within the system and the relationships between components, in the present paper its utility lies in identifying which objects, functions and purposes failed or were not fulfilled during the incident. Notably the failed/unfulfilled items are either *functions* or *purposes*, which indicates that the physical components (e.g. technology such as flashing lights, track sensors) within the RLX system all worked as they should have done.

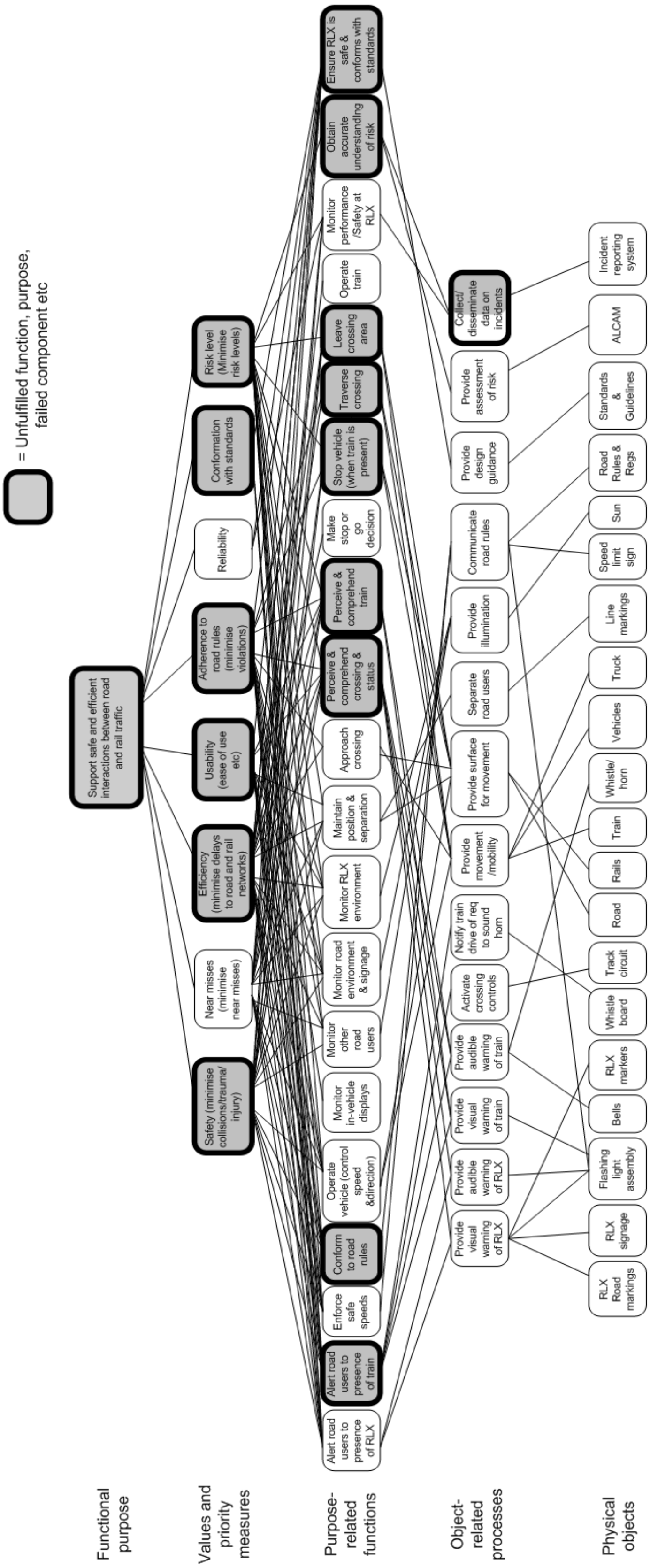

Figure 2. Kerang WDA

Starting at the top of the WDA, the RLX's overall functional purpose of 'Support safe and efficient interactions between road and rail traffic' was not fulfilled as there was a collision between the truck and train causing multiple fatalities and injuries. At the next level down, the following values and priority measures were not fulfilled: safety (minimise collisions/trauma/injury), efficiency (minimise delays to road and rail networks), usability (e.g. ease of use, efficacy of RLX), adherence to road rules, conformation with standards, and minimise risk levels. At the functional purpose level various functions were unfulfilled. Most importantly the functional purposes ‘alert road user to presence of train’, ‘perceive and comprehend status of RLX’, ‘perceive and comprehend train’, and ‘stop vehicle’ were not achieved. When this is coupled with the fact that the physical objects within the system all operated as required, the requirement to investigate factors residing outside of the RLX involved is strengthened.

STAMP

A simplified version of the basic RLX system control structure at the time of the incident is presented in Figure 3. Control failures deemed to be involved in the incident are overlaid on the control structure.

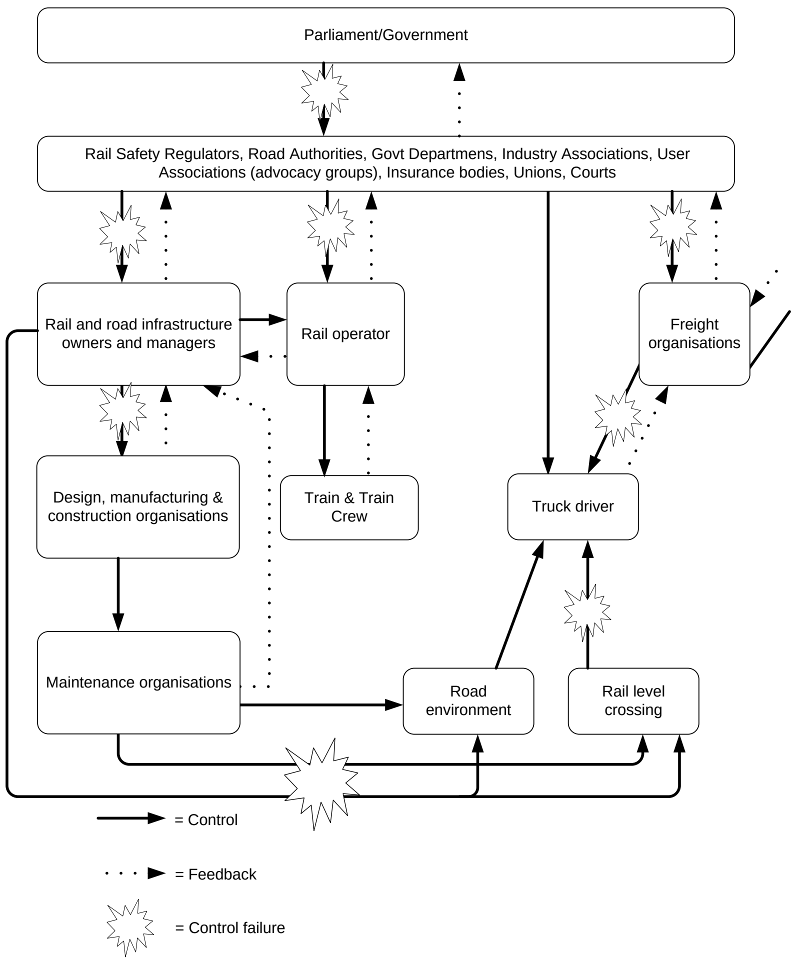

Figure 3. Rail level crossing control structure with control failures.

As depicted in Figure 3, various control failures across the overall RLX system played a role in the incident. The STAMP method classifies control failures into either inadequate execution of control actions, inadequate enforcement of constraints, or feedback failures. The majority of control failures involved in this case can be classified as inadequate enforcement of constraints (e.g. failure to identify hazards, inappropriate, ineffective or missing control actions) or inadequate execution of control actions (e.g. communications failures). For example, the failure of the RLX to control the truck driver’s behaviour can be classified as ‘ineffective control actions’ since, although the RLX warnings performed as required, they were ultimately ineffective. The control failure between the freight organisation and the truck driver represents the freight organisations failure to communicate issues with, and near miss incidents involving, RLX Y2943, to the truck driver and in turn the control failure between the road authorities/Govt departments represents the failure to make the freight organisation aware of these issues and near miss incidents. Examples of control failures at the higher levels include the ALCAM risk assessment of the RLX, since it failed to adequately identify the hazards associated with RLX Y2943, and also the budgetary and standards issues described in the Accimap section. Space limitations prevent a full discussion of the control failures identified; however, the key finding from the STAMP analysis is that control failures across multiple levels of RLX system played a part in the incident, as opposed to only control failures at only the individual truck driver level.

5. Discussion

The aim of this paper was to test the utility of three currently popular systems analysis methodologies for use in the description and analysis of road safety incidents and issues. In conclusion, the systems analyses identified the factors across the road and rail systems that had prevented RLX Y2943 from being upgraded to fully active controls (e.g. budgetary constraints, low risk assessment ranking), along with the factors on the day which conspired to place the truck and train at the RLX together at the same time (e.g. delayed loading and departure of truck) and which facilitated the truck drivers failure to see and perceive the flashing warning lights and the approaching train (e.g. truck drivers inexperience of the RLX in activated state, sun glare from road, trees in close proximity to RLX). In relation to the specific methods applied, Accimap identified the factors across the overall RLX system that played a role in the incident, along with the relationships between them. The WDA component of CWA described the system in terms of functions, purposes and physical objects and in turn identified the purposes that were not fulfilled, and also the functions and physical objects that failed during the incident. Finally, STAMP described the control structure in relation to RLX systems and identified the control failures, whereby parts of the RLX system did not control other components, involved in the incident.

It is concluded that systems analysis methods are appropriate for use in the road safety context. They provide an exhaustive account of road safety incidents, and one that is consistent with the safe systems approach to road safety. That is, if the entire road transport system shares the responsibility for safety, then it is imperative that the system continually monitors itself to identify where it is contributing to road crash incidents and road safety issues. Under the safe systems philosophy, it is vital that investigators go beyond road users to uncover the wider system factors involved in road safety incidents and remove these through targeted interventions. In other safety critical domains, it has long been acknowledged that countermeasures based on systems analyses, rather than individualistic analyses, are more appropriate for safety efforts (e.g. Reason, 1997; Dekker, 2002). This is because the factors influencing behaviour across the overall system are dealt with, rather than just the behaviour itself. A shift away from individual blame and culpability to a learning culture for system improvement is therefore needed in road transport. This can only occur when the complexities of human behaviour and the impact of the system on behaviour is understood. The need for systems analyses approaches is therefore pressing, particularly if the shared responsibility philosophy is to be realised.

It is these authors view that the use of systems theory and systems analyses methods in road transport will trigger the paradigm shift that is needed to achieve future road safety targets. A further implication of the analysis presented is that the issue of crash culpability within road transport remains ill-defined; in the Kerang incident, although the truck driver made ‘errors’, factors across the road and rail systems played a part. The extent to which drivers can be blamed in the context of wider system failures requires examination.

What then is required to move toward implementation of systems analysis methods in road transport? Although various shifts are required, such as a paradigm shift from reductionist to systems thinking with regard to road user behaviour (Salmon et al, 2012), a central requirement is the need for new data systems that support systems analyses. The legacy of the successful reductionist philosophy is that the whole approach to understanding and enhancing behaviour and safety in road transport is entrenched within a reductionist paradigm (Salmon et al, 2012). The data systems and methods used to understand behaviour and evaluate safety interventions are thus reductionist in nature, which in turn means the data required to support systems analyses is not typically available (apart from high profile, high fatality incidents that are subject to detailed investigation such as Kerang). Appropriate crash data collection and analysis systems thus represent the first step in moving toward systems analysis efforts in road transport.

Acknowledgement

This research was funded through the Australian National Health and Medical Research Council (NHMRC) post doctoral training fellowship scheme. The analyses presented are based on the OCI investigation report and selected court transcripts.

References

Australian Transport Council (2011). The National Road Safety Strategy 2011 – 2020. http://www.atcouncil.gov.au/documents/files/NRSS_2011_2020_15Aug11.pdf, accessed 21st November 2011.

Dekker, S. W. A. (2002). Reconstructing human contributions to accidents: the new view on human error and performance. *Journal of Safety Research*, 33, 371-385.

Leveson, N. G. (2004). A new accident model for engineering safer systems. *Safety Science*, 42:4, pp. 237—270.

Leveson, N. G. (2009). The need for new paradigms in safety engineering. Safety-Critical Systems: Problems, Process and Practice, *Proceedings of the Seventeenth Safety-Critical Systems Symposium*, Brighton, UK, 3–5 February 2009

Office of Chief Investigator. (2007). Level crossing collision V/Line passenger Train 8042 and a truck near Kerang, Victoria, 5th June 2007. Rail safety investigation Report No. 2007/09

Ottino, J. (2003) Complex systems, *AIChE Journal*, Vol. 49 No. 2, pp. 292-299.

Rapoza, A. S., et al. (1999). Railroad Horn Systems Research Safety of Highway-Railroad Grade Crossings Series. Washington DC: Federal Railroad Administration.

Rasmussen, J. (1997). Risk management in a dynamic society: A modelling problem. *Safety Science*, 27:2/3, pp. 183-213.

R v Scholl. (2009). Transcript of Proceedings (Supreme Court of Victoria, Kaye J, 25 May to 13 June 2009)

Reason, J. (1997). Managing the risks of organisational accidents. Burlington, VT: Ashgate Publishing Ltd

Saccomanno, F. F., Park, P. Y.-J., & Fu, L. (2007). Estimating countermeasure effects for reducing collisions at highway-railway grade crossings. *Accident Analysis & Prevention*, 39, 406-416.

Salmon, P. M., et al. (2012). Road transport in drift? Applying contemporary systems thinking to road safety. *Safety Science*, 50:9, pp. 1829-1838

Salmon, P. M., et al. (Under review). The Crash at Kerang: Investigating systemic and psychological factors leading to unintentional non-compliance at rail level crossings. *Accident Analysis and Prevention*.

Vicente, K. J. (1999). Cognitive work analysis: Toward safe, productive, and healthy computer-based work. Mahwah, NJ: Lawrence Erlbaum Associates.

World Health Organisation (2009). Global status report on road safety: time for action. Geneva, World Health Organization, 2009 (www.who.int/violence_injury_prevention/road_safety_status/2009).