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Using the abstraction hierarchy to identify how the purpose and structure of road transport systems contributes to road trauma

Paul M. Salmon [a,*], Gemma J.M. Read [a], Nicholas Stevens [a], Guy H. Walker [b], Vanessa Beanland [c], Rod McClure [d], Brett Hughes [e], Ian R. Johnston [f], Neville A. Stanton [g]

[a] Centre for Human Factors and Sociotechnical Systems, Faculty of Arts, Business and Law, University of the Sunshine Coast, QLD 4558, Australia
[b] School of the Built Environment, Heriot-Watt University, Edinburgh EH14 4AS, UK
[c] Department of Psychology, University of Otago, Dunedin, New Zealand
[d] University of New England, Faculty of Medicine and Health, New South Wales, Australia
[e] Department of Transport, Government of Western Australia, Perth, Australia
[f] Ian Johnston Transport Safety Pty Ltd, Australia
[g] Transportation Research Group, University of Southampton, Boldrewood, Southampton SO16 7QF, UK

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ABSTRACT

Research is beginning to demonstrate the merits of considering the broader road transport system when attempting to understand and prevent road trauma. This study involved the use of Work Domain Analysis, a systems analysis method, to develop a model of a road transport system based on Queensland, Australia. The model was subsequently used to identify the system wide contributory factors that play a role in road crashes, and to identify aspects of road transport systems that could be exploited when developing road safety interventions. The findings show that there are a set of crash contributory factors relating to the raison d'etre, values, and functions of road transport systems. This suggests that further significant reductions in road trauma will only be achieved through fundamental changes to the road transport system itself. Examples discussed include reducing the emphasis on the use of road transport for economic growth, reducing motor vehicle use and increasing active transport modes, and overhauling road safety strategies.

1. Introduction

The term ‘systems thinking’ describes a philosophy currently prevalent within safety science. There are various tenets, with contemporary models underpinned by the notion that safety and accidents are emergent properties arising from interactions between multiple components across entire systems (e.g. Dekker, 2011; Leveson, 2004; Rasmussen, 1997). This has a number of implications for safety management. These include incident investigation activities which consider the overall system, and strategies designed to prevent adverse events which focus on all levels of the system rather than individual components in isolation (Dekker, 2011). In the road safety context, this approach suggests that as well as focussing on road users, vehicles, and the road environment, road safety interventions should also consider components of the broader road and societal system such as road safety strategies, design standards, work systems, and land use planning and urban design (Salmon et al., 2019). It has been noted that current road safety strategies, whilst incorporating terminology and elements of systems thinking, do not fully align with systems thinking principles (Hughes et al., 2016; Salmon and Lenné, 2015).

The utility of fully applying systems thinking principles and methods in road safety research and practice has been recognised, and such approaches are gaining traction (Hughes et al., 2016; Larsson et al., 2010; Read et al., 2017; Salmon et al., 2012; Young and Salmon, 2015; McIlroy et al., 2018). Proponents have argued that ambitious road safety targets can only be achieved through such an approach (Hughes et al., 2016; Larsson et al., 2010; Salmon et al., 2012; Salmon and Lenné, 2015). It has been suggested that the recent plateauing of fatality and injury reductions in many jurisdictions reflects the fact that the highly successful ‘3 Es’ approach of education, enforcement, and engineering is now experiencing diminishing returns (Salmon et al., 2019). Contemporary road safety strategies such as Vision Zero (Johansson, 2009), the Dutch sustainable safety strategy (Wegman et al., 2008), the Australian Safe Systems approach (Australian Transport Council, 2011), and the UN Decade of Action for Road Safety (World Health Organization, 2011), have gone beyond the three Es to

* Corresponding author.
E-mail address: psalmon@usc.edu.au. (P.M. Salmon).

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consider a broader set of road transport components and their interrelations. As mentioned above, though, it has been noted they do not fully embrace the tenets of systems thinking (Hughes et al., 2015; Salmon and Lenné, 2015). It is argued, therefore, that systems thinking can operationalise an even broader systems approach that can facilitate new reductions in road trauma (Hughes et al., 2016; Salmon et al., 2019).

Researchers have subsequently applied systems theory-based methods to investigate the causes of road trauma (e.g. Cornelissen et al., 2013; Hughes et al., 2016; Newnam et al., 2017; Newnam and Goode, 2015; Parnell et al., 2017; Salmon et al., 2014, 2016a). This body of work shows that there is a complex web of interacting contributory factors underpinning road trauma (Newnam et al., 2017; Salmon et al., 2016a, 2019). Although some of these factors relate to individual road users (e.g. personality, risk tolerance, complacency, education), others relate to the structure and dynamics of road transport systems (e.g. governance, policy, regulation, design). Consequently, it is hypothesised that, although traditional road safety interventions such as education, enforcement and engineering will have some impact, other factors will not be dealt with and road crashes will continue to occur. With accident reductions now plateauing in many jurisdictions, the need to search for bolder strategies is becoming greater. A critical direction for road safety research is therefore the application of systems thinking-based methods to: a) understand the structure and composition of road transport systems and; b) identify what factors across road transport systems play a role in road crashes and road trauma. In particular, identifying road transport system 'leverage points' (Meadows, 1999) where modifications can have a significant and postive safety effects represents a critical need for road safety research.

One systems analysis framework which has been used in this manner in other safety-critical domains is Cognitive Work Analysis (CWA; Vicente, 1999). To date there have been only a small number of applications of CWA in road transport, and these have not involved modelling entire road transport systems. Rather, they have focussed on specific contexts, such as intersections (Cornelissen et al., 2013), eco-driving (Birrell et al., 2012), railway level crossings (Salmon et al., 2016b) and motorcyclist safety (Regan et al., 2015). Despite the benefits of using CWA to describe and understand overall systems (e.g. Naikar, 2013), CWA has not yet been used to develop a model of an entire road transport system.

The present study involved the use of Work Domain Analysis (WDA), the first phase of CWA, to develop a model of a road transport system. This was undertaken as part of a program of research involving the application of systems thinking methods to road transport system analysis and design. Whilst the developed model was based on the characteristics of the road transport system in the state of Queensland (Qld), Australia, it is generic and applies to road transport systems across Australia and internationally. The model was subsequently used to:

a. identify road transport system factors that play a role in road crashes and trauma; and
b. identify road transport system components that could be exploited to develop new interventions designed to prevent road trauma.

2. Method

2.1. Cognitive work analysis

CWA (Vicente, 1999) is a systems analysis and design framework that has become a popular method for understanding and optimising complex systems (Bisantz and Burns, 2008; Stanton et al., 2017). The framework provides a series of modelling approaches that focus on identifying the constraints imposed on behaviour within the system under analysis (Vicente, 1999). It was originally developed at the Risø National Laboratory based on a need to design systems that could cope with emergent and non-routine situations as these had been implicated in process control system failures. CWA's theoretical roots lie in general and adaptive control system theory and also Gibson's ecological psychology theory (Fidel and Pejtersen, 2005).

CWA provides a series of analytical and formative methods that focus on identifying the constraints present within a system and the resulting impacts on behaviour. This enables the identification of a. what constraints exist, b. what impact different constraints have on behaviour, and c. how different constraints can be modified to support safe and efficient performance. The formative nature of CWA allows analysts to explore possibilities for changing behaviour through the removal or modification of existing constraints or the addition of new constraints. CWA has been used across a wide range of domains for various purposes (Bisantz and Burns, 2008; Stanton et al., 2017). Example design applications include railway level crossings (Read et al., 2017), road intersections (Salmon et al., 2018), air traffic control displays (Ahlstrom, 2005), disaster management processes (Jenkins et al., 2010), training systems (Naikar and Sanderson, 1999), and in-vehicle displays (Birrell et al., 2012).

The CWA framework comprises five phases, each modelling constraints and behaviour from a different perspective: work domain analysis (WDA); control task analysis; strategies analysis; social organisation and cooperation analysis; and worker competencies analysis. In the present study, WDA was applied to develop a model of the Qld road transport system.

WDA is used to construct an event- and actor-independent model of the system under analysis, known as an abstraction hierarchy (Naikar, 2013). This means it is not focussed specifically on any event (e.g. a road crash) and does not include actors who operate within the system (e.g. road users, vehicle designers, road safety stakeholders). The aim is to describe the functional structure of the system as well as the purposes of the system and the function, process and object-related constraints imposed on the actions of any actor performing activities within that system (Vicente, 1999). The abstraction hierarchy method is used to describe systems according to the following five conceptual levels:

1. *Functional purpose* – The overall purposes of the system;
2. *Values and priority measures* – The values that are assessed and used to measure the system's progress towards the functional purposes;
3. *Purpose-related functions* – The general functions of the system that have to be undertaken within the system so that the functional purposes are achieved;
4. *Object-related processes* – The functional capabilities of the physical objects within the system that enable the purpose-related functions; and
5. *Physical objects* – The physical objects within the system that are used to undertake object-related processes.

Abstraction hierarchy models use means-ends links to show the relationships between nodes across the five levels of abstraction. Linked nodes above a node in the hierarchy delineate 'why' that node is required, and linked nodes below the node show to 'how' the node is achieved. For example, in a road transport system model the function 'Enforce and regulate road user behaviour' has links to values and priorities above it such as preventing crashes and injuries and fatalities (Salmon & Read, 2019). This is because enforcement and regulation of road user behaviour is used to help prevent crashes, injuries and fatalities (the 'why'). At the level below 'Enforce and regulate road user behaviour' has links to the object-related processes that are used to achieve it such as 'educate and inform users' and 'enforcement' (the 'how') (Salmon & Read, 2019).

2.2. Abstraction hierarchy development

Naikar's (2013) nine-step WDA methodology was applied across an initial draft abstraction hierarchy development phase and a subsequent expert workshop.

Initially the aims and purpose of the analysis were established (as expressed earlier) and any relevant project constraints were identified. Next, the analysis boundary was defined as the road transport system incorporating the activities of the actors and organisations described by Salmon et al. (2016a) in their Qld road transport system control structure model. Salmon et al.'s (2016a) control structure model included all of the actors and organisations who play a role in the design and operation of the road transport system in Qld. This included actors across the following levels: International context; Parliament and Legislatures, Government agencies, industry associations, use groups, insurance companies, courts and universities; Operational delivery and management; Local management and supervision; and the Operating process and environment.

The draft road transport system abstraction hierarchy was then developed by four of the authors (PS, GR, NS, GW), all of which have extensive experience in applying WDA in a range of domains including defence, aviation, rail, disaster management, sport, and process control (e.g. Read et al., 2017; Salmon et al., 2016b; Stanton et al., 2017; Stanton and Bessell, 2014). Development of the abstraction hierarchy involved systematically working through each abstraction hierarchy level using Naikar's (2013) prompts to identify relevant nodes (see Fig. 1 for examples of the prompts used). Nodes were identified based on the authors own knowledge of the Qld road transport system which is based on the conduct of various road safety research projects in Qld over the previous decade. Publically available documentation regarding the Qld road transport system (e.g. National and state road safety strategies, road rules and regulations, standards) and existing analyses previously undertaken by the authors (e.g. Salmon et al., 2016a) were used to support this process. Discussion continued until the four authors were in agreement regarding the nodes identified. Once the nodes were finalised the authors discussed the means-ends links, again agreeing on appropriate means-ends links to include in the abstraction hierarchy.

The abstraction hierarchy was then reviewed and refined in a subject matter expert workshop involving seven of the authors (PS, GR, NS, VB, RM, BH, IJ). The group comprised researchers with extensive experience in road safety research as well as applied systems thinking research across a range of domains. In the workshop participants systematically reviewed and verified the nodes at each level followed by the means-ends links. Nodes and means-ends links were either agreed upon, modified, or removed if all authors did not agree that they should be included. In addition, where new nodes or means-ends links were identified, they were discussed and if agreed upon, were added to the model. The workshop continued until there was agreement regarding the abstraction hierarchy's content.

2.2.1. *Using the abstraction hierarchy to identify contributory factors and interventions*

Once the abstraction hierarchy was finalised, two of the authors (PS, GR) worked through each level and identified which nodes are either currently known to play a role in road trauma or could potentially play role in road trauma. For example, the physical object 'Car' was identified as playing a role in road trauma as vehicle defects are a known crash contributory factor (Stanton and Salmon, 2009; Wierwille et al., 2002). At the object-related processes level, 'driving' was identified as playing a role in road trauma as inappropriate or erroneous driver behaviour is a known crash contributory factor (Reason et al., 1990; Sabey and Staughton, 1975; Stanton and Salmon, 2009; Wierwille et al., 2002). At the generalised function level, 'Manage throughput' was identified as a playing a role in road trauma as prioritising vehicle throughput can lead to the design of intersections that may not support safe interactions between vehicles and vulnerable road users (Salmon et al., 2014).

Following this process, the same two authors worked through each level of the abstraction hierarchy and made a judgement as to whether nodes could potentially be used as part of an intervention to prevent road crashes and road trauma. The scope here was deliberately broad, including any modifications that could potentially prevent crashes and/or trauma. For example, the physical object 'Car' was identified as modifications such as advanced automation and enhancing crashworthiness could be used to prevent road crashes and trauma. At the object-related processes level, 'Educate and inform users' was identified as education campaigns can be used in attempts to prevent drivers from engaging in behaviours known to lead to road crashes such as drink and drug driving, speeding, and driving while distracted. At the generalised function level, 'Develop and implement policy and strategy' was identified as new road safety strategy could be used to drive new forms of intervention.

Both the contributory factor and interventions analyses were subsequently reviewed by all authors and any disagreements were resolved through discussion until group consensus was achieved.

Functional Purpose	For what reasons does the road transport system exist? What are the highest level objectives or ultimate purposes of the road transport system?
Values and Priority Measures	What criteria can be used to judge whether the road transport system is achieving its purposes? How is the performance of various functions within road transport systems evaluated?
Purpose-related functions	What functions are required to achieve the purposes of the road transport system? What are the functions of individuals, teams, and departments?
Object-related processes	What can the physical objects in the road transport system do or afford? What processes are the physical objects in the road transport system used for?
Physical Objects	What are the physical objects or physical resources in the road transport system – both man made and natural? What physical objects or physical resources are necessary to enable the processes and functions of the road transport system?

Fig. 1. Abstraction hierarchy prompts.

3. Results

In Fig. 2, a summarised version of the abstraction hierarchy is presented (for the full abstraction hierarchy see Salmon & Read, 2019).

3.1. Functional purposes level

Two functional purposes were identified: to provide economic growth and to provide access (Headicar, 2009; Preston, 2001). Transport plays a key role in economic activity and many studies have discussed or demonstrated the impact of transport on economic growth (e.g. Saidi et al., 2018). Beyond its economic role, the road transport system provides the population with access to employment, education, social and leisure activities, shopping, and public and health services.

3.2. Values and priorities level

The values and priorities level encompass the criteria and measures that road transport system stakeholders use to determine the extent to which the system is achieving its functional purposes. Fifteen values and priorities were identified. The first group is safety-related, and includes minimising the number of crashes, injuries and fatalities incurred per year, as well as the costs of trauma (both financial and social). The next group of values relates to the efficiency of the road transport system, and includes efficiency, journey times, and reliability of infrastructure. A third group of values relate more specifically to the end-user experience, and include modal choice, individual choice, and user experience. The impact that the road transport system has on the broader environment is considered via the environmental impact value, and the extent to which components of the system comply with relevant safety, environmental or economic regulations is considered through the compliance with regulations value. Social and political capital were also deemed to be important values, as was the economic capacity of the road transport system.

3.3. Purpose-related functions

The purpose-related functions encompass the general functions that are necessary for the road transport system to achieve its functional purposes. The following sixteen purpose-related functions were identified:

1. *Mobility*. The mobility function refers to the need for the road transport system to provide the ability for users to independently move around (Alsnih and Hensher, 2003). Mobility enables people to access employment, education, social and leisure activities, shopping, and public and health services and is closely linked to wellbeing, independence and quality of life (e.g. Spinney et al., 2009; Stanley et al., 2011). It also includes transport to support economic activities such as the movement of goods and services (Headicar, 2009; Preston, 2001).
2. *Control traffic behaviour*. The control traffic behaviour function encompasses various activities that are undertaken to ensure that road users behave safely in accordance with the road rules and in a manner that optimises traffic flow. This includes informing and directing road users, enforcing road rules (e.g. controlling speed), and controlling traffic in different contexts such as intersections.
3. *Manage throughput*. Managing throughput relates to the need to minimise congestion and optimise traffic flow by maintaining infrastructure and operations to provide appropriate levels of traffic throughput across the road transport network.
4. *Manage incidents*. The manage incidents functions relates to the need to rapidly respond to and manage traffic incidents across the road transport network.
5. *Enforce and regulate road user behaviour*. The enforce and regulate road user behaviour function includes all enforcement activities that are undertaken to ensure that road users act safely and in compliance with the road rules.
6. *Design, maintenance and upgrade (Infrastructure)*. The design, maintenance and upgrade (Infrastructure) function incorporates the activities that are undertaken to ensure that the road infrastructure is at a suitable standard and in a serviceable condition.
7. *Design, maintenance and upgrade (Vehicles)*. The design, maintenance and upgrade function (Vehicles) incorporates activities that are undertaken to ensure that vehicles are at a suitable standard and are kept roadworthy, as well as the activities undertaken by vehicle manufacturers around design and upgrade of vehicles.
8. *Development and implementation of policy and strategy*. Road transport policy and strategy plays an integral role in the functioning of road transport systems. The development and implementation of policy and strategy encompasses the activities undertaken by road transport system stakeholders to develop and implement relevant overarching policies and strategies such as the Australian National Road Safety Strategy (Australian Transport Commission, 2011).
9. *System performance monitoring and improvement*. The system performance monitoring and improvement function relates to the activities undertaken by stakeholders to monitor key aspects of road transport system outcomes such as crashes, injuries and fatalities, throughput and congestion levels.
10. *Training and education*. Training and education incorporate road user training (e.g. driver training) as well as education campaigns and other more methods to improve driver performance. For example, pre- and post-license driver training focuses on the development of the procedural and higher order cognitive skill sets required to drive safely (Beanland et al., 2013a). Education is broader and typically focuses on the acquisition of knowledge about driving and road safety (Beanland et al., 2013a). Examples include the education campaigns that are used in attempts to prevent drivers from engaging in behaviours such as drink and drug driving, speeding, and driving without a seatbelt.
11. *Insurance and compensation*. The insurance and compensation function includes the activities required to ensure that road users are appropriately insured and are compensated when required. For example, in Qld the Motor Accident Insurance Commission (MAIC) operates the mandatory motor vehicle accident and personal injury insurance scheme.
12. *Research and development*. The research and development function includes the activities undertaken by various groups to conduct research and development regarding aspects of road transport such as vehicle and infrastructure design, road safety, and road user behaviour.
13. *Licensing*. The licensing function incorporates the activities undertaken to ensure that all road users hold the appropriate license to drive. This includes licensing for all stages of the graduated driver licensing system as well as the licensing required for other vehicles such as motorcycles and heavy goods vehicles.
14. *Registration*. All vehicles driven on the roads in Qld must be registered, including cars, motorcycles and mopeds, caravans and light trailers, and heavy vehicles. The registration function covers the activities undertaken to ensure vehicles are at a suitable standard and in a serviceable condition, including registration and transfers of registration following vehicles sales.
15. *Investment and funding*. Investment and funding is required to ensure infrastructure meets a suitable standard and is kept in a serviceable condition, including maintaining and upgrading key components of the road transport system such as roads and infrastructure, training and education, road safety interventions, and enforcement activities. This function encompasses the processes around determining investment and managing funding.
16. *Litigation*. The litigation functions encompass the activities undertaken when legal action is taken following road crashes, road trauma, or other adverse events occurring within the road system that lead to personal injury or economic loss.

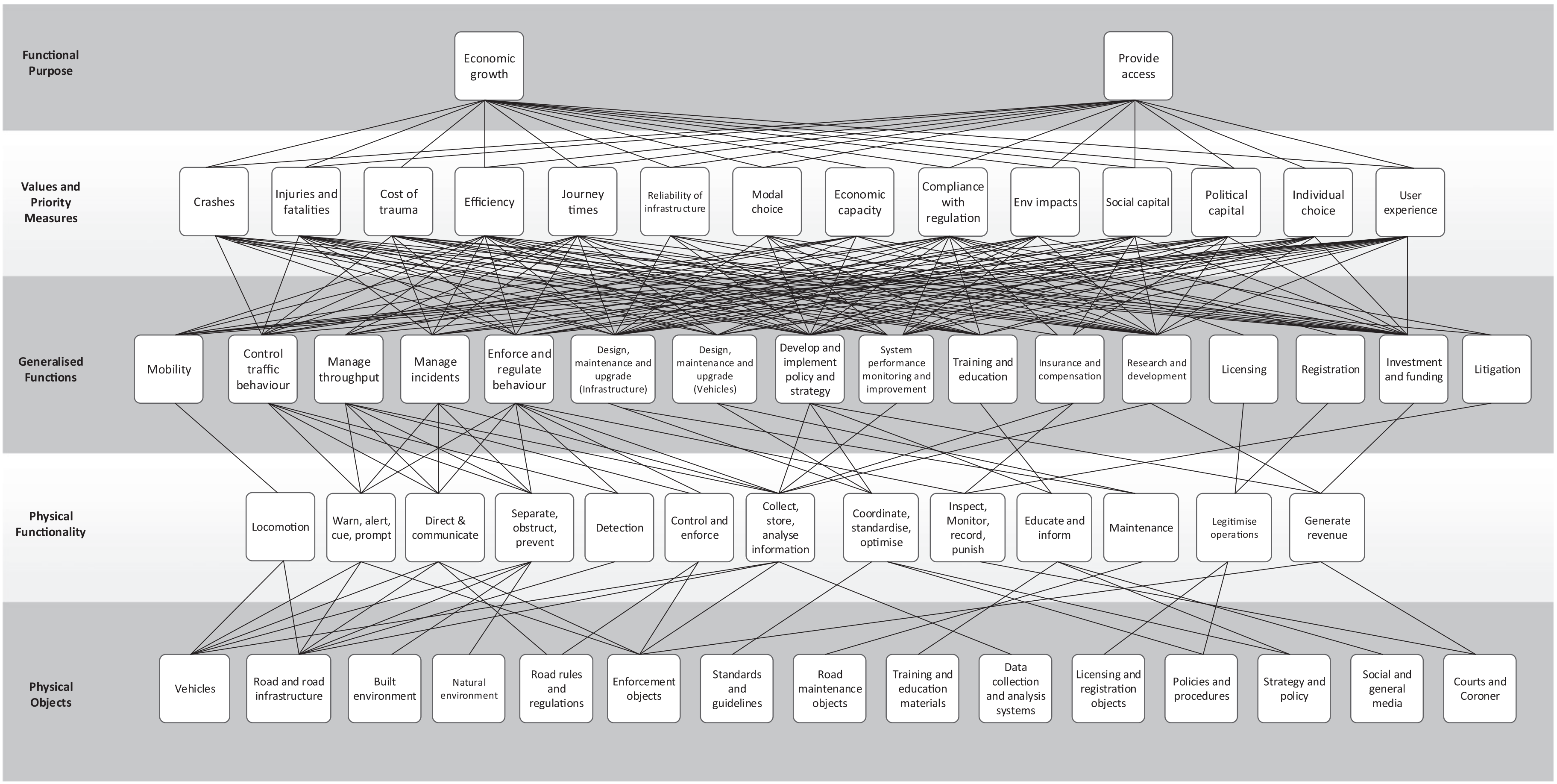

Fig. 2. Simplified road transport system abstraction hierarchy. Note, only a summary of the bottom two level nodes is presented.

3.4. Physical objects and object-related process

Fifty-seven physical objects and 35 object-related processes were identified. Broadly the physical objects relate to the vehicles used within the road transport system (e.g. cars, motorcycles, heavy goods vehicles, bicycles, buses), road infrastructure objects (e.g. roads, kerbs, traffic lights, signage, lighting), objects in the surrounding built environment, objects relating to road rules and regulations, design standards, training and education, and licensing, registration, and insurance. The object-related processes reflect the processes that the objects are used for and that are required to achieve the functions (e.g. the object-related process of 'Driving' a 'Car' enables the function of 'Mobility').

3.5. Contributory factors and potential interventions

Table 1 presents each of the nodes from the top 3 levels of the abstraction hierarchy along with examples of where they have or may play a contributory role in road crashes and trauma causes. Examples of where the nodes could be used as part of road safety interventions are also included. The analysis of the bottom two levels of the abstraction hierarchy are not presented as this mainly included crash contributory factors and interventions that are already widely discussed across the road safety literature (e.g. contributory factors and solutions relating to and vehicles and road infrastructure).

4. Discussion

The aim of this study was to develop an abstraction hierarchy model of the road transport system, based on Qld, Australia. The model was subsequently used to identify factors within the wider road transport system that play a role in road trauma. It was also used to identify components that could be exploited to develop road safety interventions.

4.1. Contributory factors

The abstraction hierarchy shows that there are a range of contributory factors across the road transport system that potentially play a role in crashes and road trauma. As the model is actor- and event-independent, few of the factors identified relate to individual road users and their engagement in adverse behaviours such as drink driving, speeding, driving while fatigued, and driving while distracted. Rather, the majority relate to the functional purposes of the road transport system (e.g. Economic growth), its values and priority measures (e.g. Economic capacity, Efficiency, User experience), requisite functions (e.g. Manage throughput), physical objects (e.g. Vehicles, Road infrastructure, Billboards) and object-related processes (e.g. Entertainment, Advertising). The factors identified at the functional purpose and values and priorities level are not typically reported in road crash analysis studies and are not typically included in road crash classification schemes (Beanland et al., 2013b; Mussone et al., 2017; Stanton and Salmon, 2009). The findings therefore suggest that, outside of factors relating to road users, their vehicles, and the road infrastructure, there are a broader set of crash contributory factors that relate to the functional purposes and structure of the road transport system as well as the activities undertaken in pursuit of stakeholder values and priorities. These contributory factors have generally been neglected in the study of road safety (Salmon et al., 2019).

At the lower levels of the abstraction hierarchy, many of the physical objects and object-related processes judged to play a role in road crashes and trauma are unsurprising. For example, the role of vehicles, the road environment and infrastructure, and weather in road crashes and trauma is well known and has been for some time (e.g. Treat et al., 1979). More interesting are the functional purposes and values and priority measures identified. For example, the functional purpose of 'Economic growth' and its associated value and priority measure of 'Economic capacity'. This suggests that activities undertaken to strengthen the road transport system's capacity to facilitate economic growth can in fact have the concomitant effect of creating road crashes and trauma. An example is freight transportation, which plays a significant role in economic growth (Beyzatlar et al., 2014; Saidi and Hammami, 2017), but also makes a significant contribution to the road injury and death toll. In Australia, for example, 787 drivers were killed in truck-related incidents between 2002 and 2012, and 1119 people were involved in heavy vehicle fatal road crashes (SafeWork Australia, 2014). As the economy expands and production increases, the demand for freight transportation increases, and in turn, road crashes and road trauma increase (Gaudry and de Lapparent, 2013; Hughes, 2017; Scuffham and Langley, 2002). So long as the road transport system acts as a primary facilitator for economic growth, there will be crashes, fatalities and injuries. Examination of the abstraction hierarchy's means-ends links also suggests that the structure of the road transport system may better facilitate the functional purpose of 'Economic growth' than it does the functional purpose of 'Provide access'. This highlights the importance of economic factors in decision making around the design and operation of the road transport system, and the importance of finding safety solutions that take account of economic factors and consequences (Salmon & Read, 2019).

4.2. Road safety interventions

Opportunities for intervention were found across all levels of the abstraction hierarchy. For example, instances where new objects could be introduced (e.g. appropriately designed automation), where functions could be strengthened (e.g. integrate human factors approaches in road infrastructure design) and where values and priorities and functional purposes could be modified to encourage behavioural change (e.g. increasing active transport) (Salmon & Read, 2019). An implication is that there is significant scope to develop new innovative road safety interventions that target different aspects of road transport systems' functional structure (e.g. at the objects level, as well as further up at the values and priority measures level, or functional purposes level). This should complement the traditional '3 Es' road safety approach of education, enforcement, and engineering.

Many of the potential interventions identified already form part of road safety practice, particularly those identified at the object, object-related processes, and purpose-related function levels. For example, modifications to the road infrastructure, enforcement, and education campaigns have long been used in road safety efforts, and have had a significant impact in terms of reduced crashes and fatalities. Opportunities for novel and wide-reaching interventions reside at the top two levels of the abstraction hierarchy. The majority of these interventions require fundamental change to the nature or structure of the road transport system and beyond, however, it is likely that most of them would have a significant impact on the road toll. Examples of these interventions include shifting freight transport to other transport modes, reducing motor vehicle use, maximising modal choice through increasing active transport and optimising public transport, and using land use and urban planning to reduce journey times and the requirement to drive in the first place. An important feature of these interventions is that they would also likely have benefits over and above the resulting reduction in road crashes and trauma.

For example, attempting to maximise the value and priority measure of 'Modal choice' provides an opportunity to reduce road crashes and trauma levels, whilst at the same time optimising the population's health and wellbeing. Maximising modal choice includes reducing motor vehicle use by reducing the need to drive (e.g. through improved land use design and urban planning) and increasing and optimising alternative forms of transport including public transport (e.g. trains, trams, buses) and active transport (e.g. cycling and walking). The benefits of active transport modes are well known (Woodcock et al., 2007). Further, various studies have demonstrated the kinds of reductions in road trauma and improvements in health that can be achieved by reducing motor vehicle use and increasing active transport. Woodcock et al. (2009)), for example, estimated the health impacts of modal shift in London, UK and Delhi, India. In

Table 1
Abstraction hierarchy nodes and example associated road trauma causes and interventions.

Abstraction hierarchy node	Example contributory role in road trauma	Example intervention
Functional purposes		
Economic growth	An overemphasis on using transport as a means for economic growth can lead to increased levels of on-road freight and an associated increase in freight-related crashes.	Shift freight from the road onto other transport modes such as rail, maritime, and aviation.
Provide access	Increasing access through building more roads (rather than alternative transport modes) leads to increases in traffic levels and an associated increase in crashes.	Encourage/provide access through other modes of transport such as public transport and active transport modes. In some contexts, access may be facilitated through non-transport means, such as digital technologies (e.g. e-learning).
Values and priority measures		
Crashes	N/A	Use education programs to increase public awareness of road toll, contributory factors and to gain support for road safety initiatives.
Injuries and fatalities	N/A	Use education programs to increase public awareness of the injury toll and the long-term impacts of crash-related injuries.
Cost of trauma	N/A	Use education programs/awareness campaigns to raise employer awareness of the costs associated with road trauma.
Efficiency	An overemphasis on efficiency in road design can lead to road environments that are focussed on maximising the throughput of motorised vehicles whilst not fully considering the needs of other transport modes.	View and optimise efficiency at a whole of transport network level, rather than on a site-by-site basis. Include other modes of transport in efficiency measures and interventions.
Journey times	If users, employers etc. value short journey times too strongly they may engage in adverse behaviours such as speeding.	Improve land use planning and urban design so that journey times are reduced and alternative transport and access options are more attractive
Reliability of infrastructure	Unreliable infrastructure can lead to crashes (e.g. failed traffic lights).	Ensure reliability of infrastructure via improvements in monitoring and maintenance of infrastructure.
Modal choice	Prioritisation of private motor vehicles over other modes can lead to more motorised traffic and road environments, rules, regulations etc. that do not fully consider the needs of other modes. In turn, this can lead to crashes between motorised vehicles and other modes.	Improve access to other transport modes Providing safe and appropriate infrastructure for active transport modes such as cycling and walking
Economic capacity	An overemphasis on using transport as a means for economic growth can lead to increased levels of on-road freight and an associated increase in freight-related crashes.	N/A
Compliance with regulation	Non-compliance with infrastructure and vehicle design standards can lead to unsafe road environments and unsafe vehicles.	Improving compliance checking mechanisms Independent road safety regulator
Environmental impacts	N/A	Reduce motor vehicle use e.g. through improved land use planning and urban design and increasing access to active transport modes
Social capital	N/A	Community ownership and control of local roads
Political capital	Projects designed to gain support from voters may be suboptimal safety wise.	Lobbying and advocacy at the political level
Individual choice	Inappropriate behaviours driven through individual choice e.g. speeding, mobile phone use, failure to wear a seatbelt.	Understanding the population's individual desires and designing transport system to cater for them
User experience	Introducing in-vehicle systems designed to enhance user experience can lead to increased potential for driver distraction.	Improve human factors Integration in the design of vehicles, road infrastructure, road safety strategy and policy etc.
Purpose-related functions		
Mobility	Attempting to maintain mobility via private motor vehicle use increases traffic levels and can keep unsafe/risky drivers on the road.	Increase access to people, places goods and services via increasing access to alternative modes of transport such as active transport and public transport.
Control traffic behaviour	If traffic behaviour is not controlled appropriately adverse behaviours will occur resulting in crashes e.g. non-compliance with the road rules.	Automated monitoring and enforcement through telematics.
Manage throughput	An overemphasis on throughput in road design can lead road environments that do not fully support other transport modes e.g. intersection design	Manage throughput from a whole of network, multi-modal perspective.
Manage incidents	Poor management of incidents may lead to secondary crashes and risk to emergency responders.	Optimise incident management e.g. use of smarter technologies such as variable message signs.
Enforce and regulate behaviour	Lack of enforcement due to limited resources allows road users to engage in adverse behaviours known to cause road crashes e.g. drink and drug driving, speeding.	When designing vehicles incorporate features that prevent adverse behaviours such as intelligent speed adaptation and alcohol interlocks.
Design, maintenance and upgrade (Infrastructure)	Lack of maintenance/upgrade can lead to road infrastructure becoming unsafe	Improved maintenance and upgrade processes along with better infrastructure monitoring systems.
Design, maintenance and upgrade (Vehicles)	Lack of maintenance/upgrade of vehicles can leads to them becoming unsafe and not fit for use	Improved maintenance and upgrade processes along with better vehicle monitoring systems.
Develop and implement policy and strategy	Sub-optimal road safety policy and strategy, or implementation of it, does not prevent crashes and trauma	Develop flexible road safety strategies and policies that focus on outcomes in line with systems theory. Improve implementation via state and national coordination
System performance monitoring and improvement	Lack of feedback regarding systemic contributory factors leads to a lack of learning and the design of road safety interventions that do not address wider issues across the road transport system	Enhance crash reporting and investigation systems Improve linkage across data systems e.g. Police, hospital, insurance data Use of crash data to inform policies, standards, interventions
Training and education	Inadequate training and education programs lead to unskilled and uneducated road users	Develop and apply more sophisticated driver training and education programs. Improve road safety and transport professional capability.
Insurance and compensation	N/A	Insurance schemes use telematics to incentivise safe driving via monitoring behaviour and providing discounts where appropriate.
Research and development	N/A	More research, higher quality research, better research translation Independent transport safety investigator
Licensing	Licensing system may allow risky motorised road users to enter or remain in the road system.	Improve relicensing processes and increase the number of regular or targeted licensing checks.

(continued on next page)

Table 1 (*continued*)

Abstraction hierarchy node	Example contributory role in road trauma	Example intervention
		Prepare for and apply future road safety technologies e.g. autonomous vehicles.
Registration	Registration system may allow risky vehicles to remain on the road.	Improve registration processes and increase the number of regular or targeted licensing checks
Investment and funding	Inappropriate allocation of funding may lead to key safety-related issues not being addressed.	Increase amount of road safety-related funding and improve allocation of funding
Litigation	Litigious system creates a focus on blame which prevents learning from incidents and the design of road safety interventions that do not address key issues.	Adopt a no-blame culture in crash reporting and investigation

both cities, a combination of active transport and lower-emission motor vehicles yielded the greatest benefits in terms of disability adjusted life years. Woodcock et al. (2009) recommended new policies designed to increase the acceptability and safety of active transport, and to reduce private motor vehicle travel. Similarly, based on system dynamics modelling of different road safety and public health policies in 9 major cities, McClure et al. (2015) found optimal reductions in vehicle crash related deaths and disability adjusted life years were achieved through policies that aimed to reduce motor vehicle use and increase active transport. Notably, the modelling demonstrated that these policies need to be accompanied by appropriate infrastructure modifications designed to improve interactions between motorised and non-motorised forms of transport (McClure et al., 2015). Many of the interventions identified in the present study support these findings.

The connectivity of nodes in terms of the number of means-ends links within the abstraction hierarchy also highlights the relative importance of the road safety policy and strategy function. Within the abstraction hierarchy this function is connected to all nodes above it, suggesting that it plays a critical role in achieving all road transport values and priorities and functional purposes. This is an important finding given Hughes et al.'s (2016) assertion that existing road safety strategies fail to encompass the complexity of road transport systems and the impact that societal issues have on road safety (Hughes et al., 2016). An implication is that new forms of road safety strategy and policy may be required to cater for increasingly complex transport sysems and to facilitate new reductions in road trauma. Indeed, modifications to road safety strategy and policy may provide an opportunity to facilitate some of the fundamental changes discussed above.

4.3. Study limitations and areas for further research

There are some study limitations worth noting. First, while the abstraction hierarchy was developed based on subject matter expert opinion and documentation describing key features of the Qld road transport system, it was not subject to any further validation through avenues such as a Delphi study (e.g. Salmon et al., 2016a). Whilst the author team includes members with extensive experience in road safety, we acknowledge that further validation with a larger set of subject matter experts would strengthen the model. This represents a potential future study, particularly if the model is to be used further by road safety stakeholders. Of course, the act of publishing the work and placing it in the public domain opens it to wider scrutiny, use and modification. Second, the abstraction hierarchy was developed based on the Qld road transport system only, and not the overall Australian road transport system. This boundary was necessary to ensure that the analysis was achievable given finite project resources. Further, it is the authors opinion that the similarities across Australian states mean that the findings are generalizable to other Australian road transport systems and indeed to other road transport systems in the developed world. An interesting area of future research would be to use WDA to develop abstraction hierarchies of road transport systems in lower middle-income countries such as India, Kenya, or Indonesia. This would enable identification of any differences across countries which in turn may impact the generalisability of road safety research beyond high-income countries.

5. Conclusion

This study has added to the growing consensus that road trauma is created by a web of interacting factors that span all levels of road transport systems. The contribution has been to identify a set of system-wide factors that contribute to road trauma, many of which sit outside the most often considered tripartite of road users, vehicles, and the road environment. Consideration of these factors, as well as related societal issues, is strongly urged when developing road safety strategy, policy, and interventions. It is concluded from the present study that further reductions in road trauma will likely only be achieved through fundamental change to the nature and structure of road transport systems. This includes reducing the emphasis on using transport for economic growth, increasing active transport modes and reducing motor vehicle use, and overhauling road safety strategies.

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Erratum

Erratum regarding missing Declaration of Competing Interest statements in previously published articles

A **Declaration of Competing Interest** statements were not included in the published version of the following articles that appeared in previous issues of Transportation Research Interdisciplinary Perspectives. The appropriate Declaration/Competing Interest statements, provided by the Authors, are included below.

1. "The challenges impeding traffic safety improvements in the Kurdistan Region of Iraq" [Transportation Research Interdisciplinary Perspectives, 2019; 2: 100029] https://doi.org/10.1016/j.trip.2019.100029
2. "Facilitating practices for sustainable car sharing policies – An integrated approach utilizing user data, urban form variables and mobility patterns" [Transportation Research Interdisciplinary Perspectives, 2019; 2: 100055] https://doi.org/10.1016/j.trip.2019.100055
3. "Factors associated with physical, psychological and functional outcomes in adult trauma patients following Road Traffic Crash: A scoping literature review" [Transportation Research Interdisciplinary Perspectives, 2019; 3: 100061] https://doi.org/10.1016/j.trip.2019.100061
4. "Computing optimum traffic signal cycle length considering vehicle delay and fuel consumption" [Transportation Research Interdisciplinary Perspectives, 2019; 3: 100021] https://doi.org/10.1016/j.trip.2019.100021
5. "Link-level travel time measures-based level of service thresholds by the posted speed limit" [Transportation Research Interdisciplinary Perspectives, 2019; 3: 100068] https://doi.org/10.1016/j.trip.2019.100068
6. "Using the abstraction hierarchy to identify how the purpose and structure of road transport systems contributes to road trauma" [Transportation Research Interdisciplinary Perspectives, 2019; 3: 100067] https://doi.org/10.1016/j.trip.2019.100067
7. "Factors influencing Pedestrian Speed in Level of Service (LOS) of pedestrian facilities" [Transportation Research Interdisciplinary Perspectives, 2019; 3: 100066] https://doi.org/10.1016/j.trip.2019.100066
8. "Embedding aircraft system modeling to ATM safety assessment techniques" [Transportation Research Interdisciplinary Perspectives, 2019; 3: 100026] https://doi.org/10.1016/j.trip.2019.100026
9. "The impact on neighbourhood residential property valuations of a newly proposed public transport project: The Sydney Northwest Metro case study" [Transportation Research Interdisciplinary Perspectives, 2019; 3: 100070] https://doi.org/10.1016/j.trip.2019.100070
10. "Creating a prediction model of passenger preference between low cost and legacy airlines" [Transportation Research Interdisciplinary Perspectives, 2019; 3: 100075] https://doi.org/10.1016/j.trip.2019.100075
11. "Using social media to evaluate associations between parking supply and parking sentiment" [Transportation Research Interdisciplinary Perspectives, 2020; 4: 100085] https://doi.org/10.1016/j.trip.2019.100085
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13. "Adolescents' attitudes and intentions to use a smartphone app to promote safe driving" [Transportation Research Interdisciplinary Perspectives, 2020; 4: 100090] https://doi.org/10.1016/j.trip.2020.100090
14. "Perceived safety and experienced incidents between pedestrians and cyclists in a high-volume non-motorized shared space" [Transportation Research Interdisciplinary Perspectives, 2020; 4: 100094] https://doi.org/10.1016/j.trip.2020.100094
15. "Pathways to sustainable urban mobility planning: A case study applied in São Luís, Brazil" [Transportation Research Interdisciplinary Perspectives, 2020; 4: 100102] https://doi.org/10.1016/j.trip.2020.100102

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