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Review

Road transport in drift? Applying contemporary systems thinking to road safety

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ABSTRACT

Despite the extent to which the proximal causes of road traffic injury are known, road trauma remains a substantial and growing component of the global health burden. Application of contemporary sociotechnical systems theory to the problem of traffic injury suggests that the lack of progress globally may be a consequence of "drift into failure". This article considers the new systems perspective on safety, explores the utility of this approach for road safety efforts, and specifically examines the 'drift into failure' hypothesis. It is argued that road transport systems do currently display characteristics of complex systems in drift and that greater understanding of complexity theory-based models will support improved road safety efforts. However, the extent to which such models can support road safety practitioners appears to be limited by the lack of practical tools for translating theory to practice. The article concludes by drawing attention to similarities between complex systems theory and the contexts in which the discipline of Human Factors has been developed, and suggests that Human Factors methodologies could be usefully used to facilitate further research in this field.

Contents

1. Introduction

Road transport-related trauma is a leading cause of death and disability throughout the world (WHO, 2009). In Australia, 1509

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people were killed during 2009 as a result of road crashes (Australian Government, 2010) and transport-related trauma leads to approximately 50,000 hospital admissions a year (Bradley & Harrison, 2008). Worldwide, the World Health Organisation estimates annual road deaths of approximately 1.2 million, with between 20 and 50 million more people sustaining non-fatal injuries. Significant reductions in death and injury have been made over the last four decades in most motorised countries (Elvik, 2010); however, persistent problems remain and reductions in injury and fatality rates appear to be slowing. Further, in lower and middle income countries the number of fatal and non-fatal road traffic injuries is increasing. By 2030 road traffic injury is expected to be the 5th leading cause of global deaths (WHO, 2009).

Despite the apparent failure of the global response to the public health problem of road traffic injury, aggressive reduction targets continue to be set in contemporary road safety strategies. For example, the Australian National Road Safety Strategy 2011–2020 has the target of reducing the annual number of road fatalities and serious road injuries by 30% (ATC, 2011). The Swedish Vision Zero strategy (Johansson, 2009), widely touted as one of the most forward thinking and effective road safety strategies across the world, is underpinned by the aim that eventually no one will be killed or seriously injured on Sweden's roads (Johansson, 2009). The UN Decade of Action for Road Safety (WHO, 2011) aims to save five million lives on the world's roads in the next 10 years. These reduction targets reflect a confidence on the part of road safety experts in their understanding of the causation of road crash injury.

Following from work recently published by Dekker (2011) failure to meet national road safety targets and to contain the growing global road safety epidemic could be explained by limitations of the Newtonian Kinetic Energy paradigm within which our current understanding of road traffic injury causation has been developed. Arguably, if contemporary complexity and systems thinking (e.g. Dekker, 2011; Walker et al., 2010) were applied to road safety, a better understanding of the reasons for road safety's lack of success would lead to the development of more appropriate solutions for redressing the problem.

In this paper, the current model of road safety is compared with a recently proposed complex sociotechnical systems model. The postulation that under certain conditions systems can drift into failure (Dekker, 2011) is examined in the context of road safety. On this basis it is suggested that current road safety problems are a consequence of complex system drift to failure and that the use of complexity and systems theory-based models is the paradigm shift needed to manage this drift and achieve greater safety gains. A series of challenges faced by road safety practitioners in order to move toward practical implementation of such approaches are articulated. The paper concludes by noting that the discipline of Human Factors has some of the tools to overcome these challenges and elucidate the characteristics of the complex road safety system in a way that facilitates research and practice.

2. The kinetic energy model

Kinetic energy is a function of the mass of an object and its speed at any instant in time (Corben et al., 2010). Under the kinetic energy model road safety is achieved by separating sources of kinetic energy and, if this is not possible, controlling the energy inherent in moving vehicles so that it is not transferred to road users at levels exceeding human biomechanical tolerance (Corben et al., 2010). The kinetic energy model of road traffic injury prevention underpins contemporary national and international policies. These include, Vision Zero (passed by the Swedish Parliament in 1997) and derivatives of Vision Zero, i.e. the Netherlands Sustainably safety strategy (Wegman et al., 2008), the Australian Safe Systems strategy (ATC, 2001) and the UN Decade of Action for road Safety (WHO, 2011). Although the expression of these contemporary road safety strategies contain some of the language of systems thinking, the approach currently adopted by road safety researchers and practitioners is not underpinned by complexity theory-based systems models (Larsson et al., 2010; Salmon and Lenné, 2009). In fact, it is argued here that it is a failure to understand the way in which complex sociotechnical systems function that leads to these ineffective strategies.

3. The systems approach

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 multiple components across complex sociotechnical systems (e.g. Leveson, 2004; Walker et al., 2009). 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 themselves. Consequently the systems approach argues that, in order to understand performance in a way that supports appropriate safety interventions, it is the relationships between components of the system that are of interest, not the individual components themselves. Ottino (2003) puts it succinctly by arguing:

> "Complex systems cannot be understood by studying parts in isolation. The very essence of the system lies in the interaction between parts and the overall behaviour that emerges from the interactions. The system must be analysed as a whole" (Ottino, 2003, p. 293).

Various systems-based safety and risk management models have emerged over the past two decades (e.g. Leveson, 2004; Rasmussen, 1997; Reason, 1990). Rasmussen's risk management framework (Rasmussen, 1997, see Fig. 1), for example, describes the various 'systems' levels (e.g. government, regulators, company, company management, staff, and work) involved in production and safety management. According to the model each level is involved in safety management via the control of hazardous processes through laws, rules, and instructions. For systems to function safely, decisions made at the higher governmental, regulatory, and managerial levels of the system should propagate down and be reflected in the decisions and actions occurring at the lower levels. Conversely, information at the lower levels regarding the system's status needs to transfer up the hierarchy to inform the decisions and actions occurring at the higher levels (Cassano-Piche et al., 2009). Without this so called 'vertical integration', systems can lose control of the processes that they are designed to control (Cassano-Piche et al., 2009).

According to Rasmussen (1997), accidents are typically 'waiting for release', the stage being set by the routine work practices of various actors working within the system. Normal variation in behaviour then serves to release accidents. A second component of Rasmussen's model, represented on the right hand side of Fig. 1, describes how work practices are malleable and evolve over time as a result of economic and production pressures. Under certain conditions, evolution of work practices can evolve in a manner that leads to safety boundaries being traversed. This 'migration of safe work practices' occurs at all levels of the system and not just on the front line. The importance of monitoring migration of work practices, and addressing inappropriate migration, is thus paramount.

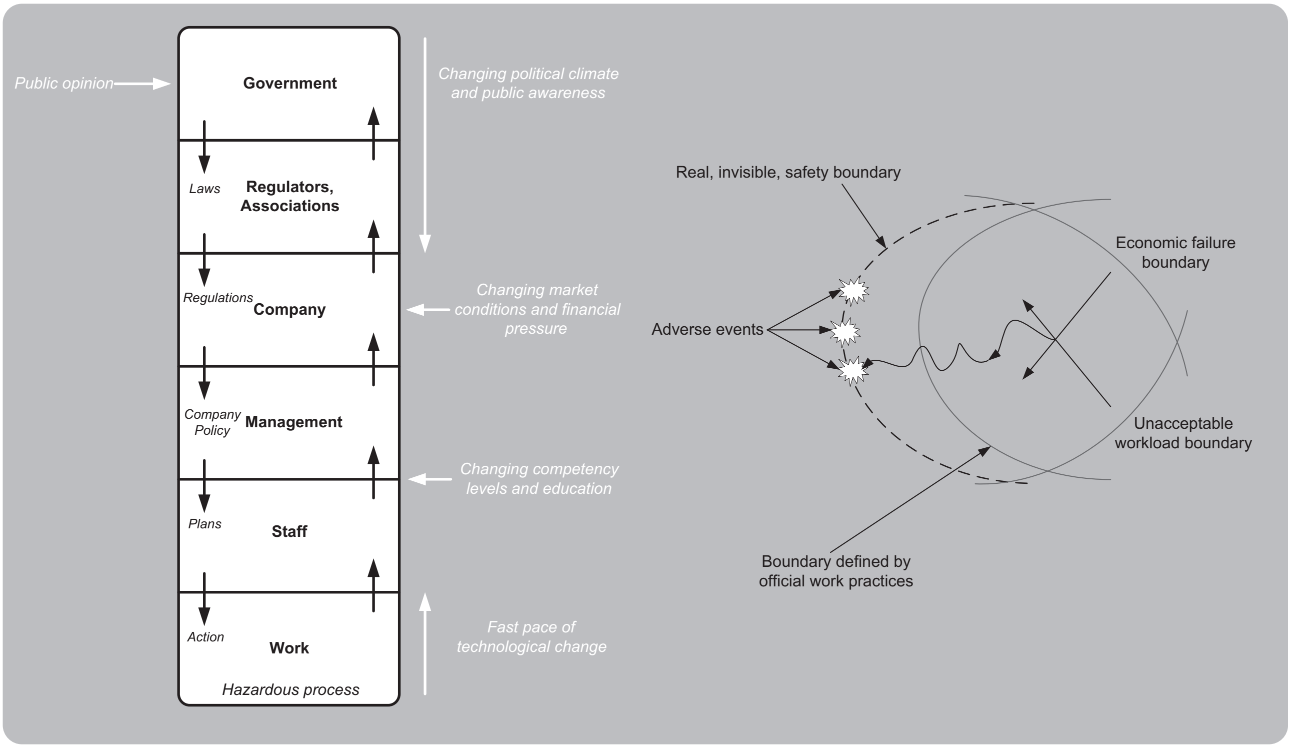

Fig. 1. Rasmussen's risk management framework (adapted from Rasmussen, 1997).

4. Dekker's drift into failure model

Underpinned by systems and complexity theory, and building on systems models (e.g. Leveson, 2004; Rasmussen, 1997), Dekker (2011) recently proposed the drift into failure (DIF) model as a way of describing how complex system performance gradually shifts, unchecked and often unrecognised, to a point at which safety is compromised. According to the DIF model, far from being predictable events resulting from failures and adverse behaviours, accidents in complex systems often result from the non-linear interactions between what often seem locally to be very normal behaviours. Multiple decisions and actions, occurring over time, in different contexts, under different constraints, and with only limited knowledge of effects, gradually lead the system towards adverse events. Systems slowly but steadily adapt in unforseen ways, eventually leading them across the boundary of safe performance. In presenting the DIF model, Dekker (2011) also asserts that modern day systems are now so complex that our understanding of them has not been able to keep pace; the typical reductionist approach to understanding the world simply cannot cope with complex, emergent, non-linear systems (Dekker, 2011).

The DIF model outlines five key characteristics of drift: scarcity and competition, decrementalism, sensitive dependence on initial conditions, unruly technologies, and contribution of the protective structure.

4.1. Scarcity and competition

Scarcity and competition reflects the limited availability of resources and the competition between organisations present in most complex systems. Operations are impacted by various resource constraints (e.g. financial, personnel, organisational and regulatory constraints) and strong competition exists between organisations operating in similar contexts. As a result, multiple trade offs are made in order to remove or balance resource limitations and production pressures; often this leads to a steady adaptation of processes and technologies toward unsafe practices (Dekker, 2011).

4.2. Decrementalism

Decrementalism, or small steps as Dekker puts it, refers to the gradual, step-by-step slide of safe operational practices to unsafe ones; continuous minute modifications to practise, driven by different system components under various constraints, can eventually lead to large failures (Dekker, 2011). Each small step is accepted as it is only a minor departure from the previously accepted norm, and safe, successful performance following each step is taken as an indicator that the adaptation is unlikely to effect safety (Dekker, 2011). In reality, each small step is another step away from safe operations towards unsafe ones.

4.3. Sensitive dependence on initial conditions

Sensitive dependence on initial conditions, also known as the butterfly effect (see Hilborn, 2004), refers to the notion that even miniscule changes in initial conditions can lead to dramatic changes in system behaviour (Hilborn, 2004). This essentially means that small decisions or actions made some time ago, at the onset of a complex system, can propagate through the system, interacting with other components, to create catastrophic events down the track.

4.4. Unruly technology

Unruly technology reflects the lack of control held over the technologies that are introduced into complex systems; despite

Table 1
Complex system characteristics and their presence in road transport systems.

Complex system characteristic	Present/reflected in road transport	Example
Complex systems are open systems	✓	– Road transport systems are open to influences from environment but also influence the environment in return – Fuel pricing, for example, is dependent upon plethora of factors (e.g. demand, price of crude oil, refining costs, global events). The price of fuel influences behaviour of the road system in terms of vehicle usage, routes taken, driver behaviour etc, in turn, demand for fuel (high and low) influences the pricing of fuel, which also has wider effects itself, such as its influence on inflation and the economy
Ignorance of components	✓	– Each of the components that make up the road system are ignorant of the behaviour of the road system as a whole – The average driver, for example, would be incapable of describing what the entire road transport system actually comprises, let alone of understanding the effects of their behaviour on the overall system. Road users are most likely limited to understanding the local effects of their behaviours on their own activities and on proximal road users as opposed to effects on the overall system
System complexity versus component complexity	✓	– None of the components present in road transport can achieve the level of complexity of the overall road transport system – If a system can be described fully and taken apart and put together again, it may be complicated but it is not complex (Dekker et al., 2011). The modern day car, for example, is an intricate and complicated machine; however, it can be taken apart and put back together relatively easily and further all of its potential states can be described. The overall road system; however, cannot be taken apart nor described fully. It is the overall system in which the car operates that is complex
Continuous inputs from components	✓	– Road transport systems are dependent upon continuous inputs from component parts in order to keep functioning – If, for example, road user inputs were stable and non-dynamic, the system would grind to a halt. Road users would not be able to operate together on the road
Path dependence	✓	– Road transport systems have path dependence: decisions and actions made previously influence the here and now – Take, for example, the problem of rail level crossing crashes between vehicles and trains. In Australia, for example, there were 58 collisions between trains and vehicles at rail level crossings during 2008 (ATSB, 2009). Instances of unintentional compliance, where drivers fail to perceive warnings and continue across crossings, account for almost half of all rail level crossing crashes (ATSB, 2002). Past decisions surrounding how to cope with the intersection of the road and rail networks have created and subsequently facilitated these behaviours. Unintentional non-compliance with rail level crossings cannot occur if the rail level crossing does not exist; grade separation, whereby the road and rail tracks are aligned at different heights would remove the issue completely. Upon first instance of the problem, had a decision been made to deal with the intersect of the road and rail networks through grade separation, then the potential for non-compliance would have been removed completely; however, influenced by factors such as economic and resource constraints, rail level crossings with different cost driven levels of sophistication were put forward as the solution. The past is co-responsible for present behaviour at rail level crossings
Non-linear interactions	✓	– The interactions taking place within road transport systems are non-linear – For example, on the road itself, a driver taking their eyes off the road for a matter of seconds to check a text message or change the radio station can lead to a multiple vehicle crash involving injury and fatalities, road closures, traffic jams etc with various other knock-on effects – A slightly more benign example is traffic flow, a topic that has been investigated for over 50 years leading to the discovery of non-linear traffic phenomena such as hysteresis and capacity drop (Ngoduy and Liu, 2007)

the best efforts of designers, certification, regulators and so on new technologies often behave in unexpected ways when introduced into complex systems (Dekker, 2011). Due to unforeseen interactions with other components, how a piece of technology is envisaged to operate is often very different to how it actually operates in different contexts.

4.5. Contribution of the protective structure

Finally, contribution of the protective structure refers to the many dispersed and detached structures that are designed to ensure that systems, technologies and operations stay safe. These include regulatory arrangements, safety committees and teams, and quality review and certification boards to name only a few. According to Dekker (2011) in addition to failing to intervene when it should, the protective structure can actively contribute to drift through poor knowledge, lack of access and information, conflicting goals, and decisions that make only local sense. Control measures brought in to solve one problem may introduce new problems into systems, pushing it closer toward failure.

5. Road transport as a complex sociotechnical system?

According to Vicente (1999) a system that comprises technical, psychological and social elements is a sociotechnical one. Similarly, Walker et al. (2009) suggest that ‘any practical instantiation of socio and technical elements engaged in purposeful goal directed behaviour’ represents a sociotechnical system. In this sense road transport represents a sociotechnical system; social, technical and psychological elements combine for the purpose of transportation of people, goods etc from one point to another. Road transport is therefore sociotechnical in nature, but is it complex?

Based on Cilliers (1998; cited in Dekker, 2011) presents a summary of the main characteristics of complex systems. First, complex systems are *open systems* in that they are open to influences from the environment in which they operate and also influence the environment in return. Second, each of the components that make up the system are ignorant of the behaviour of the system as a whole and do not comprehend the effects of their actions on the behaviour of the overall system. Third, it is the system that is complex rather than the components themselves. Fourth, complex systems do not operate in a state of equilibrium; inputs need to be made by components at all times in order to keep the system functioning. Fifth, complex systems have a history or *path dependence* (Dekker, 2011). Their past is co-responsible for their present behaviour. Sixth and finally, the interactions taking place within complex systems are non-linear. There is asymmetry between input and output, and small events can produce large results (Dekker, 2011). These characteristics point to a system in constant conflict and change, forever evolving in an unpredictable manner, moving in and out of safe boundaries randomly. This does not bode well for the idea of safety management and control.

Confirmation that road transport systems are representative of complex systems is given in Table 1, which presents road transport specific examples of the complex system characteristics outlined above.

There is also support in the literature for deeming road transport as complex system. For example, Using Skyttner's (2005; cited in Larsson et al., 2010) slightly different conception of complex systems, Larsson and colleagues (2010) have previously made this case. Specifically, they argue that road transport comprises a large number of elements (e.g. road users, vehicles, road components) subject to literally millions of random interactions daily. They argue also that the attributes of components are only partly predetermined, that the system is open to the environment (in fact the environment is part of the system itself) and that safety is largely subject to the behaviours of road users.

6. Road transport as a system in drift?

6.1. Scarcity and competition

Scarcity and competition is present throughout road transport across its many components; for example, it exists in the context of government agencies and road safety authorities, transportation companies, local government agencies and so on involved in activities such as road safety, roadway design and maintenance, update of transport infrastructure and goods haulage. Road safety authorities, for example, compete with other authorities for funding, and the level of funding available dictates what they can and cannot do within road safety programs. Scarcity of resources and competition effectively dictates what safety interventions are delivered; going back to the rail level crossing example described Table 1, the amount of funding allocated to the authority responsible for upgrading rail level crossings from *passive* controls (e.g. warning signage only) to *active* controls (e.g. flashing lights and boom gate controls) dictates how many crossings can be upgraded in a given year. Cuts in funding, driven by competition from other organisations, means less crossings are upgraded, which leaves more passive crossings on the road that do not effectively control road user violations; the result of this is the continued presence of inherently unsafe level crossings. Scarcity and competition also influences organisations involved in vehicle design, manufacturing and maintenance, oil production and distribution, driver training etc. Finally, it also applies to road users; vehicle choice and maintenance is driven by financial constraints and behaviour on the road is impacted by competition for space from road users. All entities across road transport systems are thus influenced by resource constraints (e.g. financial, personnel) and competition from other organisations vying for the same resources. Productivity and efficiency driven decisions and trade offs, made in the face of scarcity and competition, can potentially amalgamate together in a way that safety becomes compromised.

6.2. Decrementalism

Instances of decrementalism are evident throughout road transport, but one notable exemplar is the evolution of in-vehicle infotainment systems and what systems permitted by legislation within road vehicles. In-vehicle infotainment systems, for example, first emerged in the 1930s in the form of the car radio, and have evolved to such an extent that modern day vehicles can potentially provide internet connectivity, televisions, route guidance systems, phones, and DVD, CD and MP3 players. Further, mobile phones and music playing devices such as the IPod can now be used within vehicles and also integrated with other in-vehicle systems. The devices themselves are also now more sophisticated, incorporating touch screen interfaces, speech recognition and voice controls.

Many studies have identified various driving performance decrements associated with the use of IVIS systems (e.g. Bayly et al., 2008; Stanton and Salmon, 2009) and also their role in road traffic accidents (e.g. McEvoy et al., 2007). Decrementalism here relates to the step-by-step advances in the systems that are permitted within vehicles. Standards and guidelines fail to keep pace with the new and improved technology, meaning more and more sophisticated systems are allowed into the vehicle and drivers are permitted to use them. Presumably the idea that a driver could engage with a touch screen route navigation system along with a hands free mobile phone whilst operating a touch screen music playing device connected to the car radio would have been preposterous in the 1930s; however, each system gradually became slightly more advanced, requiring slightly more physical and cognitive resources from the driver, and legislation failed to keep pace.

6.3. Sensitive dependence on initial conditions

Motorisation has occurred throughout the world at different stages of each country's economic, cultural, and social development. Thus in each society currently exposed to the challenges of road traffic trauma, the current complex road safety systems have developed in radically different directions, and display radically different properties. The characteristics of the road system in the United Arab Emirates and Malaysia depend not so much on the nature or timing of national development of motorised transport, but on the differences existent in nature of the transport system at the time rapid motorisation began. Different conventions have also developed in different road systems, bringing about their own unique safety issues. For example, permitting drivers to turn right through a red light in United States road systems (known as right turn on red; Preusser et al., 1982) is one example of how minute changes in conditions can lead to safety problems. For example, Preusser et al. (1982) report significant increases in pedestrian and bicyclist accidents involving right-turning vehicles at signalised intersections post introduction of right turns on red in New York and New Orleans. Minute changes in conditions (e.g. new road rules) resulted in large changes in system behaviour (right turn crashes between different road users).

6.4. Unruly technologies

Unruly technologies refer to the general lack of control that is held over technologies with regard to the way in which they actually behave when introduced into complex systems; the idea that technologies behave quite differently to the way in which designers, regulators etc think they will (Dekker, 2011). Since road transport is subject to the constant advancement of technologies and continual introduction of new and sophisticated technologies, it is littered with examples. Airbags, for example, were first introduced in the late 1970s to provide protection to drivers and passengers during crashes. Although early estimates found that passenger airbags reduced *adult* fatalities by 18% in frontal crashes and 11% across all crash types, the same data showed that they actually increased the risk of death for children under 10 years old (Braver et al., 1997; cited in Durbin et al., 2003). This happened because non-usage of restraints and the effects of pre-impact breaking led to children being positioned inappropriately in the deployment path of the airbag (Durbin et al., 2003). Unforseen interactions between different components of the system led to a technology, designed and introduced to prevent fatalities and serious injuries, actually causing fatalities and serious injuries in children and even small adults. This has since been rectified via the depowering of air bags and the introduction of advanced air bags that use information on crash severity and occupant characteristics to determine deployment force (MacLennan et al., 2008); the extent to which this reduces their effectiveness, however, requires further investigation (MacLennan et al., 2008). Other examples of unruly technologies include the introduction of anti-lock braking systems, mobile phones, road side advertising, and so on.

6.5. Contribution of the protective structure

Protective structures embody terms such as regulation, compliance, oversight and inspection and comprise a complex web of different entities (Dekker, 2011). Road systems worldwide possess complex intricate protective structures. In Victoria, Australia, for example, there are multiple organisations, committees, working groups, standards and guidelines etc involved in road safety including the Minister for Infrastructure and Transport, the Minister for Public Transport, the Australian Transport Council, the National Road Safety Council, the Department of Transport, the Department of Justice, the Victorian road safety authority (VicRoads), the Transport Accident Commission (TAC), and Victoria Police to name only a few.

Based on identifying road transport-related examples of the five characteristics of DIF outlined by Dekker (2011), it is concluded that road transport systems generally fit into the DIF philosophy. Two remaining questions now drive this paper: first, do models such as DIF provide a useful framework for driving road safety efforts? and second, what are the fundamental steps required to initiate the application of these models in road safety.

7. The utility of complexity and systems theory-based models versus the Newtonian models for road safety

This section focuses on the utility of models such as DIF in the road transport context, that is, will complexity and systems theory-based models aid practitioners in understanding and enhancing road safety? In attempting to answer this question the current approach to accident analysis in road transport is focussed on. In outlining the DIF model, Dekker (2011) is highly critical of the reductionist approach whereby things are broken into parts that can be understood and fixed if needed. This approach is said to fall short in complex sociotechnical systems, not least because it is the overall system and the interactions between parts, rather than the parts themselves, that are of interest. Examination of the road safety literature clearly indicates that this approach is currently prevalent in road safety research; the ‘hunt for the broken component’ as Dekker puts it, is currently alive and well in road safety. Road safety research typically looks at problems in isolation, investigates components in isolation, and assumes that inserting a new component into the system will produce a safety benefit. For example, recent articles from within this journal reflect this, with studies focussing on components such as drivers (e.g. Young and Salmon, 2012), pedestrians (Walker et al., 2012), in-vehicle systems (Merat et al., 2011) and road design (Fu et al., 2011).

A clear example of how the reductionist philosophy limits road safety efforts lies in the current approach to road traffic accident analysis. From other safety critical domains, such as aviation, it is well known that a systems approach to accident analysis is highly useful for safety efforts (e.g. Leveson, 2004; 2011). In Victoria, Australia, currently the data collected on road traffic crashes is reductionist in nature and lacks sufficient detail to support anything close to systems-based analyses. In a recent study attempts to apply systems theory-based accident analysis models and methods to road traffic crash data failed due to the paucity of data regarding factors outside of the drivers and vehicles involved and the inability to identify relationships between causal factors (Salmon et al., 2010). Driven by a blame culture and reductionist thinking, crash data typically focuses on driver culpability, ignoring causal factors across the wider road system. In addition, were such data to exist there are currently no appropriate road specific systems-based accident analysis methods available; road safety professionals simply do not have access to, or experience in, methodologies that could cope with systems data (Salmon et al., 2010). Simply put, accidents are viewed as a driver, vehicle and/or roadway environment problem; the notion that interactions between components other than these might play a role in road accidents is not considered by the current approach. As a corollary our understanding of road traffic accidents is currently limited to driver, vehicle and a limited set of roadway factors and consequently interventions are restricted to individual components (e.g. driver focussed training and educational campaigns). As Dekker puts it, we currently go ‘down and in’ rather than ‘up and out’ to understand and rectify road traffic crashes.

In this sense then there is a clear utility in applying models such as the DIF model in road transport. In the case of road traffic crashes, such an approach would shed light on the factors outside of the driver, vehicle and road environment that play a role in road traffic crashes. Evidence on causal factors at the higher levels of the road system (e.g. Government, road authorities, road designers, societal norms, road design, road rules etc) would be forthcoming. This would allow treatment of the failures across the system that influence the way in which the road system behaves. Many have argued that treatment of wider systems failures, identified through systems-based accident analysis, is more appropriate than the treatment of local factors at the sharp end of system operation, since the factors creating the front line behaviours are removed following accident analysis efforts (e.g. Reason, 1990; Dekker, 2002; Leveson, 2004; Rasmussen, 1997). Ignorance of the role of these other components in accidents leads to inappropriate countermeasure which merely treat front line behaviours (e.g. in this case driver-focussed countermeasures). Application of models such as the DIF model would therefore move road traffic crash analysis from a ‘hunt for the broken component’ to a ‘hunt for the interacting system components’ mentality. Further, such models force a departure from the notion that components are ‘fixed’ toward the continual vigilance of complex system drift. Identification of interacting systems components and continued monitoring of drift are examples of where further road safety gains could be made through consideration of complexity and systems-based models.

If models such as DIF are likely to be useful, then the next question is can they be applied given current thinking and practice in road safety? Whilst it is these authors’ opinions that a movement toward models such as the drift philosophy could yield greater insight and potentially greater reductions in trauma, it is also apparent that embracing these models may not be possible. The inescapable conclusion is that the DIF model, although enlightening in itself, does not equip practitioners with the tools to apply it. Entrenched within the reductionist paradigm, road safety practitioners simply do not possess the methodologies or data systems to ‘go up and out’ nor is complex systems thinking sufficiently embedded in road safety circles to initiate such a paradigm shift. Moreover, in what is its biggest weakness, the DIF model does not specify in any detail the methodologies, approaches, or practical steps required to implement its own philosophies.

Driven for some time now by systems thinking, the discipline of Human Factors, offers some the practical methods required to initiate this paradigm shift. A movement towards the thinking behind the DIF model, driven by the application of systems-based Human Factors methods, is advocated by these authors. For example, in the context of road crashes, systems-based accident analysis approaches which consider factors across the entire system of work have been applied for many years now. Accimap (Rasmussen, 1997) and STAMP (Leveson, 2004), for example, both have a long history of applications across the safety critical domains in which system-wide failures have been identified (e.g. Johnson and de Almeida, 2008; Leveson, 2011; Salmon et al., 2012). Whilst not going ‘up and out’ to the extent that the DIF model advocates, such approaches do shed light on factors across the complex sociotechnical system involved in accident causation, going up and out to even the level of government legislation and practice. Further, systems-modelling approaches such as the Cognitive Work Analysis framework (CWA; Vicente, 1999) allow systems to be modelled in their entirety based on their reason for being, functions and purposes, and the components making up the system, allowing the interactions between parts to be identified along with the resulting effects on system functioning. The point to make is that these methods are tried and tested across the safety critical domains, and offer more than the current reductionist approach. Application of these methods in a safety context will initiate a movement towards the application of DIF type models.

Two applications are recommended by these authors. First, complexity and systems theory-based accident analysis methods, such as Accimap and STAMP, should be applied to road traffic crashes. This involves not only applying these methods for road crash analyses but also the development of the crash data collection systems required to generate systems data for road crashes. Second, systems modelling approaches such as CWA and STAMP should be used to describe the overall road transport ‘system’, including its components and the interactions between them. The former will shed light on crash causal factors across the entire complex sociotechnical system of road transport, whereas the latter will enable description of the road transport system in a manner that allows identification of the many components along with the interactions between them. Without both applications, DIF in a road transport context will remain an attractive concept, but one that is not able to be described meaningfully or applied practically.

It is worth elaborating on the practicalities and potential benefits of both lines of inquiry, as well as identifying instances of where the approaches mentioned have already been applied in this context. The use of systems-based accident analysis methods such as Accimap in the road transport context is feasible given provision of the appropriate data systems. In fact, in first presenting the method in this journal, Rasmussen (1997) used a road traffic accident in which a truck carrying oil crashed, causing an oil leak into a nearby water reservoir. The Accimap presented by Rasmussen (1997) shows how factors across six road transport system levels interacted to create the system in which the accident occurred. These included government policy (e.g. National transport policy, road building requirements), regulatory body (e.g. road regulations, design regulations), local area government (e.g. regional development plans, road maintenance), company planning (e.g. company policy and practice, competition and priorities, transport schedules), physical processes (e.g. weather and road conditions, speed, loss of control) and equipment and surroundings factors (e.g. road topography, road side boulders). This analysis demonstrates how factors other than the road user are considered under such an approach and gives an indication of how future road transport applications could produce more system-focused crash analyses. To demonstrate, a representation of some of the potential factors that could be identified through road transport Accimap applications is presented in Fig. 2.

The benefits of applying such methods to the analysis of road traffic crashes are clear: interactions between factors across the overall road transport system that shape performance and lead to crashes will be identified. Not only will the role of road users in road traffic crashes be identified, but also the role of policy, road

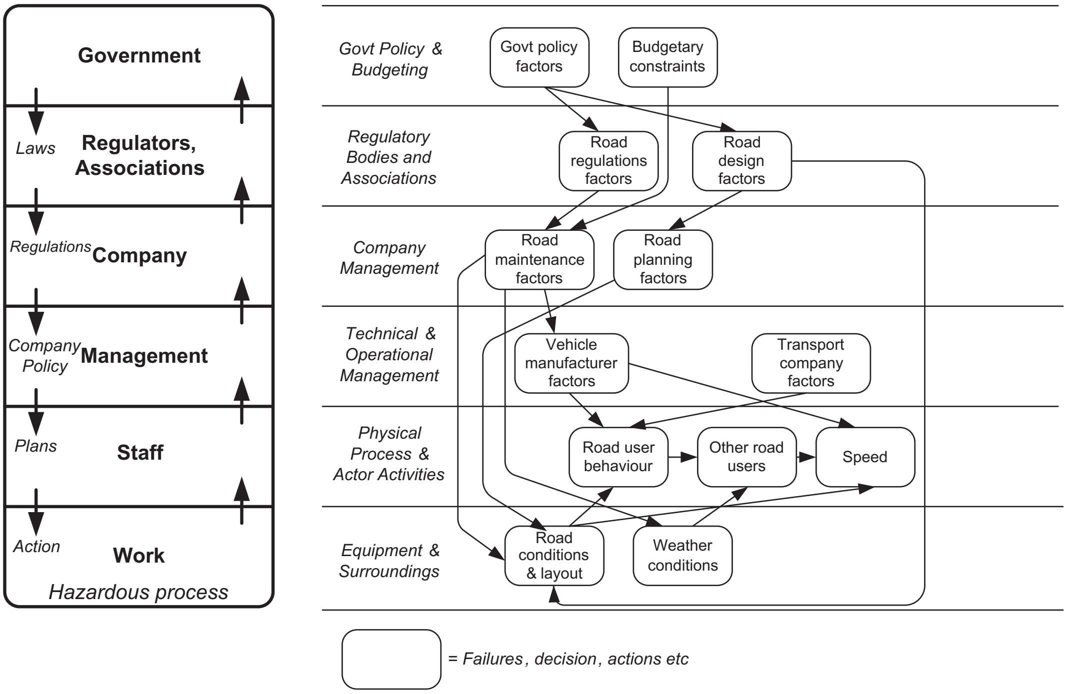

Fig. 2. Accimap showing potential road transport crash factors.

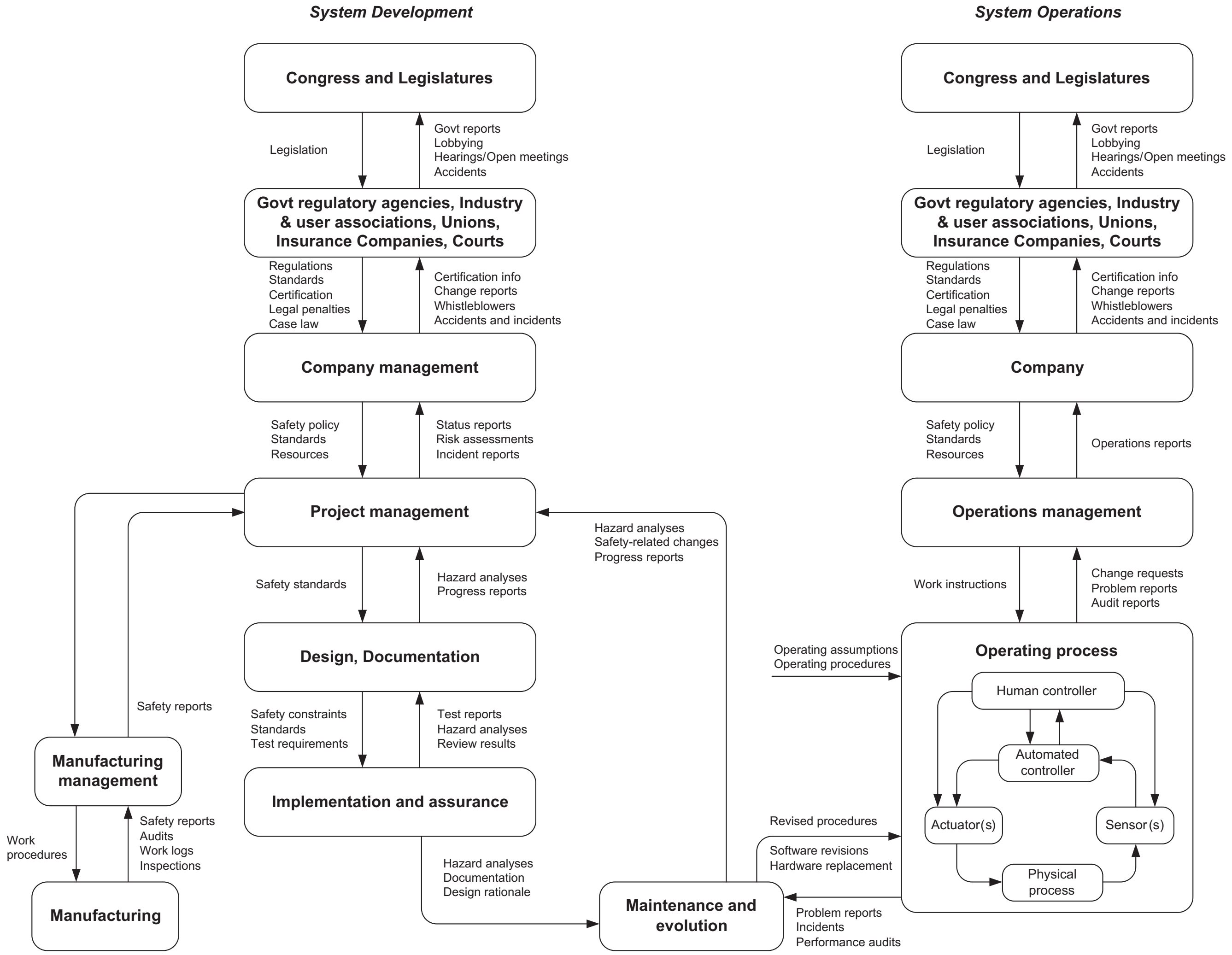

Fig. 3. STAMP generic control structure diagram (adapted from Leveson, 2004).

engineering and design, budgetary constraints, road maintenance etc. Most importantly, how factors across the road transport system interact with one another to shape performance will be revealed through such analyses. This in line with the DIF philosophy that it is the interactions between system components that is of interest for safety research in complex systems. Further impetus for applying methods such as Accimap in road transport is that previous applications across the safety critical domains tend to show that higher systems levels factors (e.g. government policy, local government, regulatory factors) are similar across domains (e.g. Jenkins et al., 2010). It may be that the factors shaping behaviour in road transport are similar to other domains, which in turn enables system reforms and accident countermeasures from other domains to be considered in the road transport context.

The main barrier to road transport applications of systems-based accident analysis methods such as Accimap is the data on which road traffic crash investigations are currently built. As discussed earlier, current crash data systems are underpinned by a reductionist, blame culture, and are thus heavily focused on the road users involved. During the road traffic crash analysis research project described earlier (Salmon et al., 2010), test applications of the Accimap methodology revealed that only the bottom two levels (equipment and surroundings and physical processes and actor activities) can be validly populated when using data from existing road traffic crash data systems. It is notable that Accimap analyses typically occur in domains with more exhaustive data systems (e.g. space exploration, Johnson and de Almeida, 2008) or focus on large scale catastrophes in which significant resources are invested in collecting in-depth data regarding the incident (e.g. the Stockwell Charles De Menezes incident, Jenkins et al., 2010). Exhaustive data of this type is not typically available for road traffic crashes. Applying the DIF philosophy in road transport crash analyses is thus contingent upon the development of appropriate data systems underpinned by the same philosophy.

The use of approaches such as STAMP to describe road transport systems is also both important and feasible. Larsson et al. (2010) discuss how this is often thought to be inappropriate given that road transport systems are characterised as ‘open’ rather than ‘closed’ systems, the kind of which STAMP appears to be more suited to. Larsson et al. (2010) go on to discuss how this is not be the case, and that the open nature of road transport systems actually makes applications of this type more important, since system components are likely to be more variable as there is more latitude for behaviour. To these authors knowledge, however, there are no published road transport applications of STAMP. Examining other STAMP analyses, however, clearly demonstrates its potential utility. Applying the method entails developing a description of a system’s control structure and identifying failures in this control structure contributed to sub-optimal performance (see Fig. 3 for generic control structure diagram).

Leveson (2004), for example, describes how systems comprise hierarchical structures, with each level imposing constraints on the activities of the level beneath them. A description of road transport system control structure will thus provide the first steps to enabling future systems thinking in road safety. This will depict the control structures in place across road transport systems, including descriptions of the different levels and entities (e.g. government, road safety bodies, vehicle manufacturers, insurers, advocacy groups, road user community) and the control loop relationships and communications between them. Such a description of road transport systems has not yet been produced and would be extremely powerful, initially to describe the road transport 'system', but also to understand how behaviour is influenced by different entities. Since STAMP views accidents as resulting from the inadequate control of safety-related constraints (Leveson, 2004), investigation of these control loops and failures within them will shed further light on how different levels of the road system interact to shape performance and also on the factors across the system that have an influence on road safety. Leveson (2004), for example, describes various forms of control, including managerial, organisational, physical, operational and manufacturing-based controls.

Whilst applications of STAMP for accident analysis purposes are constrained by the same data-related issues currently preventing Accimap applications (discussed above), in the short term construction of a road transport control structure is entirely feasible (Larsson et al., 2010). The barriers in this case are more down to the complexity of the analysis and the effort required. Such an analysis is not a simple endeavour, requiring significant analyst effort, and access to various road safety subject matter experts (e.g. researchers, personnel from government, road safety bodies, car manufacturers). Based on our experiences in other domains (e.g. Salmon et al., 2012), the analysis itself is also likely to be highly complex, requiring many iterations. Despite this, it is these authors view that the benefits of representing and understanding a particular road transport system in this manner far outweigh the difficulty and resource intensiveness of the analysis.

8. What is needed to actualise the consideration of road safety as a complex system?

What then is required to move toward implementation of complexity and systems-based theory models in road transport? First and foremost, a paradigm shift toward complexity and systems thinking is required. The current reductionist approach is borne, in part, out of its success and also road safety professionals' lack of willingness to apply complex systems thinking to road safety problems. Although many have made the call for a systems approach it has not penetrated road safety research, practice or policy in any meaningful manner. Only when this paradigm shift occurs can models such as DIF be even considered by road safety professionals. Second, Dekker's idea of 'going up and out' needs to be clarified in the road transport context. What does 'going up and out' entail exactly? How is it achieved? What methods are required? What data systems (e.g. for road crashes) are required? The problem for road safety professionals is that, as Dekker asserts, complex systems are indescribable, and our knowledge of them is limited. This means that there is no guidance for 'going up and out'. Third, the legacy of reductionist thinking is that the whole approach to understanding and enhancing behaviour and safety in road transport is entrenched within the reductionist philosophy. For example, the data systems and methods used to understand behaviour and evaluate safety interventions are reductionist in nature and safety interventions involve component parts only. Application of contemporary Human Factors methods, such as systems-based accident analysis and modelling approaches will be useful here, particularly when used in a complimentary manner with reductionist approaches. An example of this entails using existing reductionist approaches to examine the driver-related causes of road traffic crashes, but also applying systems-based accident analysis methods to identify how factors across the road transport system interacted with one another to create the conditions which in turn influenced driver behaviour.

In closing, this paper has confirmed that complexity and systems theory-based models, such as Dekker's DIF model, apply in a road transport context. Stagnation of road fatality and injury reductions, along with aggressive new road safety targets, suggest that a new approach is required. Models such as the DIF philosophy could potentially provide this new approach; however, to keep road transport drifting toward safety and not to failure, further clarification of the practical nature of these models, along with significant paradigm shifts both in the thinking and methods underpinning road safety efforts, are required. The first steps in this regard include the promulgation of complexity theory and sociotechnical systems thinking throughout road safety circles, a clarification of DIF in the road transport context, and the application of systems-based Human Factors approaches to road safety problems.

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