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Assessing the 'system' in safe systems-based road designs: Using cognitive work analysis to evaluate intersection designs

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ABSTRACT

While a safe systems approach has long been acknowledged as the underlying philosophy of contemporary road safety strategies, systemic applications are sparse. This article argues that systems-based methods from the discipline of Ergonomics have a key role to play in road transport design and evaluation. To demonstrate, the Cognitive Work Analysis framework was used to evaluate two road designs – a traditional Melbourne intersection and a cut-through design for future intersections based on road safety safe systems principles. The results demonstrate that, although the cut-through intersection appears different in layout from the traditional intersection, system constraints are not markedly different. Furthermore, the analyses demonstrated that redistribution of constraints in the cut-through intersection resulted in emergent behaviour, which was not anticipated and could prove problematic. Further, based on the lack of understanding of emergent behaviour, similar design induced problems are apparent across both intersections. Specifically, incompatibilities between infrastructure, vehicles and different road users were not dealt with by the proposed design changes. The importance of applying systems methods in the design and evaluation of road transport systems is discussed.

1. Introduction

Intersections are complex and dangerous parts of the road transport system because they represent a point where two or more roads cross and road user activities include turning left, right and crossing over. This presents many potential conflict points between road users (Federal Highway Administration, 2000). This level of complexity and risk is exemplified in road crash statistics, where intersections are over-represented. For example, in Victoria, a jurisdiction in Australia, approximately 50% of all road crashes occur at intersections (VicRoads, 2011a) and similar figures are reported worldwide (c.f. Kuciemba and Cirillo, 1992; The Highways Agency, 1995).

Despite interventions (c.f. Archer and Young, 2009; Chiou and Chang, 2010; Shin and Washington, 2007), there has been little reduction in casualties and serious injuries at intersections over the past decade (Hoareau et al., 2011). From a systemic viewpoint (Emmerik van, 2001; Larsson et al., 2010; Salmon and Lenné, 2009; Salmon et al., 2012) it is argued that the high crash rate at intersections is a product of a reductionist approach being adopted during the evaluation and design of road transport systems. For example, many road safety studies focus on a single road user group (c.f. Elmitiny et al., 2010) or a single countermeasure (c.f. Chiou and Chang, 2010), leaving other crash causing factors and their interaction untouched.

Intersections comprise many interactions between different road users and non-human agents (e.g. road, road infrastructure) which makes them complex systems (Larsson et al., 2010). The systems approach argues that a failure to consider the interactions between components in complex systems leads to a lack of understanding of how systems behave and to the design of inefficient systems (Dekker, 2011; Rasmussen, 1997). Intersections will better support road user behaviour through an understanding of complexity of the intersection system and interaction of infrastructure, environment, vehicles and road users.

The Cognitive Work Analysis framework (CWA; Rasmussen et al., 1994; Vicente, 1999), underpinned by sociotechnical systems theory, provides appropriate means to examine interactions between road system components in a manner that is consistent with the systems approach. Moreover, the authors argue that methods such as CWA should be used in road transport system design to ensure that appropriate road environments are produced. Although previous applications have used CWA to describe and evaluate road user behaviour induced by existing road transport systems (Cornelissen et al., 2012, 2013; Stoner et al., 2003) and design of driver support systems (c.f. Birrell et al., 2011; Hilliard and Jamieson, 2008; Lee et al., 2006; Seppelt and Lee, 2007), applications of CWA in road design are not yet forthcoming.

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The aim of this article is to demonstrate the value of applying an Ergonomics systems analysis method, CWA, to evaluate intersection design. The study described evaluated whether traditional and future intersection designs adequately support road users and their interaction by examining the interaction of infrastructure, environment, vehicles and road users. Proposals to better support road transport systems through intersection design will also be provided. This study will demonstrate the capabilities and value of these Ergonomics systems analysis applications, and suggest a way forward to address what is currently an intractable road safety problem.

1.1. Systems approach to road safety

Road transport has previously been described as a complex sociotechnical system (Larsson et al., 2010; Salmon et al., 2012). Technical components such as road infrastructure design, environment and vehicles interact with social components such as road users. Complex sociotechnical systems can only be understood and countermeasures can only be effective when the entire sociotechnical system and the interactions between its components are taken into account through the use of systems-based analysis methodologies.

The systems approach to road safety has been much called for (Emmerik van, 2001; Larsson et al., 2010; Salmon and Lenné, 2009; Salmon et al., 2012). The need for a systems approach is further evidenced by the high injury rate amongst some road users, including pedestrians, cyclists and riders (Elvik, 2010). The terms 'vulnerable' or 'unprotected' road user, used to describe this group, highlights the growing design incompatibility between different types of vehicles and road users (Elvik, 2010; Walker et al., 2011; Wegman et al., 2012).

Globally, road safety campaigns such as the Swedish Vision Zero (Johansson, 2009) and the Dutch Sustainable Safety programme (Koornstra et al., 1992) are acknowledged as the benchmark approaches to road safety (Elvik, 1999; Fahlquist, 2006; Wegman et al., 2012). While these programmes use the language of systems safety, they are not underpinned by complexity theory based systemic models (e.g. Leveson, 2004), but rather remain based on traditionally reductionist approaches (Emmerik van, 2001; Salmon et al., 2012). The kinetic energy model, for example, underlying many of the international safe system road safety strategies, reduces the road transport system to an equation of mass of an object and its speed at any instant in time (Corben et al., 2010b).

The majority of road transport research remains trapped in a reductionist paradigm. Research projects, for example, explore a single road user group (c.f. Archer and Young, 2009; Elmitiny et al., 2010) or a single or limited set of countermeasures (c.f. Chiou and Chang, 2010; Leden et al., 2006; Schepers et al., 2011). Evaluations are often restricted to modelling and simulation of operational performance (c.f. Cunto and Saccomanno, 2008; Zhu and Zhang, 2008), or mathematical risk or safety analysis (c.f. Gross et al., 2012; Hubacher and Allenbach, 2004; Miranda-Moreno et al., 2011; Pulugurtha and Sambhara, 2011). If human behaviour is considered, it often involves simulator studies (Rudin-Brown et al., 2012; Werneke and Vollrath, 2013), on-road studies focussing on single road user groups (Gstalter and Fastenmeier, 2010; Young et al., 2012) or is conducted after the design has been finalised or built (c.f. Mackie et al., 2013; Waard et al., 1995). When interaction of different groups of road users is considered, the task is often reduced to controlled lab settings and evaluates the response of one road user group to the other rather than studying a true interaction (c.f. Borowsky et al., 2012; Walker, 2005) or evaluates crash risk of two road user groups, e.g. drivers and vulnerable road users (Chaurand and Delhomme, 2013; Habibovic and Davidsson, 2011). Countermeasures developed then tend to focus on separating road users rather than supporting their interaction (c.f. Johansson, 2009; Wegman et al., 2012), or adding technological systems, such as driver support systems, to provide additional information or automate specific safety critical tasks (Dotzauer et al., 2013; Habibovic et al., 2013). Despite reported efficiency and safety benefits (Dotzauer et al., 2013; Hilliard and Jamieson, 2008; Lee et al., 2006), the question is whether such countermeasures compensate for bad system design or augment system design? Furthermore, such systems have been largely driver focussed, e.g. vehicle to vehicle (V2V) or vehicle to infrastructure (V2I) technology, and currently do not support the road transport system in its entirety. Few studies explore the full complexity of the interaction of the countermeasure, infrastructure, environment, vehicles and road users considering operational and safety performance.

1.2. Cognitive work analysis and road safety

In the field of Ergonomics, the systems approach to road safety is beginning to be actualised through the application of systemic modelling methods such as CWA (c.f. Cornelissen et al., 2013). CWA is a popular framework used for systematically designing and evaluating complex sociotechnical systems by outlining a system's constraints and potential behaviour emerging within those constraints (Vicente, 1999). The framework comprises five phases (Vicente, 1999), with each modelling a different constraint set. Work domain analysis, the first phase, describes system constraints from physical objects up to the functional purpose of the system. Next, control task analysis models situational constraints and decision making requirements. Third, the strategies analysis models different ways in which activities can be carried out within a system's constraints. Fourth, social organisation and cooperation analysis describes communication and coordination demands based on organisational constraints. Fifth, worker competencies analysis describes skills, rules and knowledge required by actors within the system.

Unfortunately, even some of CWA's applications in road safety remain limited in scope, e.g. focussing on the design of one countermeasure (c.f. Birrell et al., 2011; Stoner et al., 2003) or the evaluation of one road user group (c.f. Regan et al., 2009). However, the potential of CWA to consider the system holistically has been recognised (Salmon et al., 2005) and more systemic applications have been conducted recently (Cornelissen et al., 2012, 2013). These have proven useful in identifying issues arising from interactions between components such as road infrastructure and different road users. However, they have been conducted retrospectively to understand existing systems, which makes the opportunity to rectify issues somewhat limited. Applying systems-based Ergonomics methods during the road design and development process will provide the opportunity to remove design flaws and produce road design concepts that align with the systems approach to support all road users.

To demonstrate such a systems approach, the CWA framework was used to evaluate traditional and proposed intersection designs in this article. Specifically, CWA was used to describe the interaction of infrastructure, environment, vehicles and road users and the resulting behaviour of four different road user groups (drivers, motorcycle riders, cyclists and pedestrians) at both intersections.

2. Method

2.1. Intersections

2.1.1. Traditional intersection

This research was undertaken in Melbourne, Australia. Arterial intersections in Melbourne, see Fig. 1, are typically signalised