Accident Analysis and Prevention 74 (2015) 324–338

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

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

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ARTICLE INFO

Article history:
Received 13 June 2013
Received in revised form
19 September 2013
Accepted 1 October 2013
Available online 10 October 2013

Keywords:
Cognitive work analysis
Strategies analysis diagram
Intersection design
Systems approach
Safe systems

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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http://dx.doi.org/10.1016/j.aap.2013.10.002

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

Fig. 1. Traditional Melbourne intersection.

Source: Google.

intersections. Arterial roads carry multiple lanes of traffic and speed limits on approach are between 60 and 80 km/h.

In Australia, road users travel on the left-hand side of the road. When turning left, road users must approach the intersection as close to the left as possible. If a slip lane is present at the intersection, such as in Fig. 1, road users must turn left using the slip lane (VicRoads, 2009).

For right hand turns, road users have to approach the intersection as close to the centre of the road as possible and turn just right of the centre of the intersection. On some multi lane roads, traffic lane arrows display from which lanes a right hand turn may be made. Lane markings indicate how a turn is to be made and if present these should be followed. Right hand turns may be assisted by a traffic light with arrows. If the arrow is red, a road user must stop. If the arrow is green, a road user may proceed into the intersection. If there is no arrow present, a road user may enter the intersection if it is safe to do so but should negotiate oncoming traffic on the right hand turn (VicRoads, 2009).

2.1.2. A proposed design based on road safety safe system design principles

As part of a major road safety project, a new intersection design concept was produced aiming to improve safety at intersections through infrastructure design (Corben et al., 2010a). The proposed design, known as the 'cut-through intersection', was developed based on the principles of the road safety Safe Systems approach (Corben et al., 2010b; Johansson, 2009), see Table 1. The cut-through intersection, see Fig. 2, has traffic islands in the middle of the intersection, aiming to separate oncoming traffic and right turning traffic. The number of potential conflict points and the angle at which traffic potentially meets in the intersection are reduced. Traffic lights are positioned at the traffic islands and upon exiting the intersection. Attempts are made to resemble the original traffic light signalling system as much as possible in the cut-through intersection.

The cut-through intersection has the same footprint as the traditional Melbourne intersection. Due to its circular shape, no slip lane is fitted in the intersection and left turning traffic merges with and diverges from straight through traffic in the intersection. To turn right, road users are expected to use the cut-through lane; the curved turning lane, which has been created by the traffic islands in the middle of the intersection, see Fig. 2 on the right. To enter this lane, road users have to be in the right hand lane on approach. Close to the intersection, right turning traffic is separated from the straight through traffic through an additional traffic island. Straight through traffic will follow the circular shape of the intersection using either the left or middle lane on approach in a similar manner to the use of roundabouts. This traffic merges and diverges with traffic in the intersection.

Table 1
Road transport safe system design principles.

Speed	Design principle
>30 km/h	Vulnerable road users should not be exposed to motorised vehicles. Therefore, separate road users or reduce speeds below 30 km/h.
>50 km/h	Cars should not be exposed to other motorised vehicles in 90° crossings. Therefore, separate vehicles, reduce angles or reduce speeds below 50 km/h
>70 km/h or >50 km/h (if considerable weight differences)	Cars should not be exposed to oncoming traffic. Therefore, homogenise weights, separate vehicles or reduce speeds below 50 km/h

2.2. Data collection

Data used in this study was derived from an on-road study of different road users' (drivers, motorcycle riders, cyclists and pedestrians) behaviour at intersections (see below). In addition, document analysis was used to inform the CWA analysis. This included publicly available documentation on Victoria's road system (VicRoads, 2009, 2010, 2011b). The CWA analysis of the cut-through intersection was, in addition to the data above, informed by discussions with the intersection designers, a review of documentation describing principles behind the design and presenting detailed designs of the cut- through intersection (Corben et al., 2010a).

The on-road study collected data on road users' thought processes, decision making strategies and situation awareness whilst

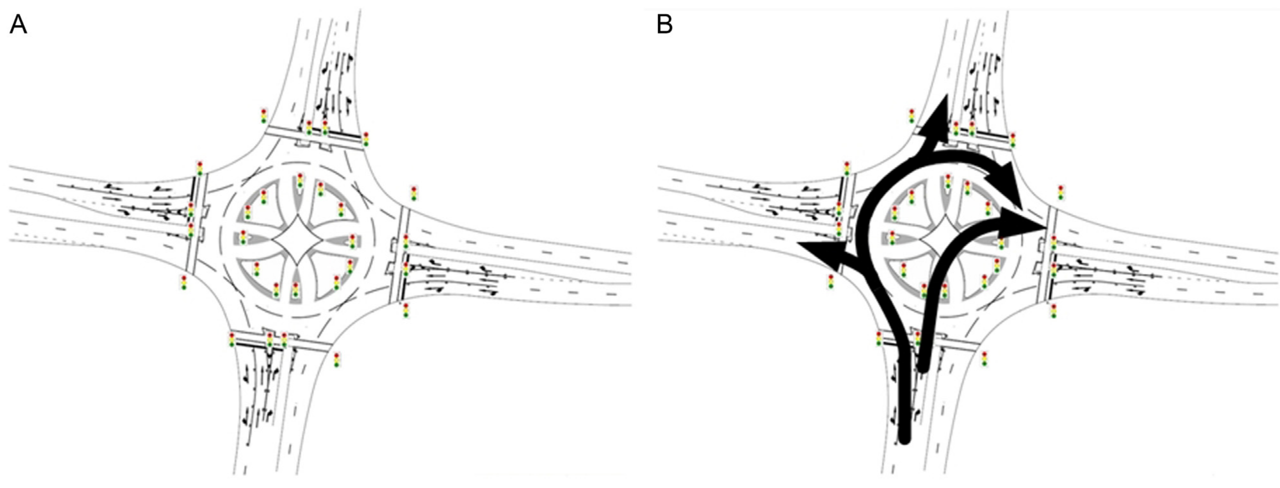

Fig. 2. Cut-through intersection

Source: With permission from Corben et al. (2010a).

negotiating intersections. Data collection methods included concurrent verbal protocols provided by drivers, motorcycle riders, cyclists and pedestrians as they negotiated a predefined route and post-trial critical decisions method-based interviews (CDMs; Klein et al., 1989). Verbal protocol analysis (VPA) was used to elicit thought processes and knowledge (Bainbridge, 1979). CDMs were used to identify cognitive processes underlying decision making in complex systems (Klein et al., 1989). VPAs and CDMs have been used extensively, including for the study of road user cognition and behaviour (c.f Walker et al., 2011). Concurrent verbal protocols were obtained by asking participants to think-aloud while they were executing an urban route comprising seven intersections. The present analysis used the data derived from two major four way signalised intersections within the study route. Participant training in providing concurrent verbal protocols consisted of a short training session at the research centre in which verbal protocols were explained and practised until participants felt comfortable with the procedure. Participants were then provided with the opportunity to practice providing verbal protocols during a test run on campus. Data collection started once on the main roads. The concurrent verbal protocols were recorded using a voice recorder placed in the vehicle (drivers), helmet (motorcycle riders) or through sunglasses fitted with voice recording capacity (cyclists and pedestrians).

CDM interviews were conducted once participants had completed the study route and returned to the research facility. The present analysis focuses on interviews relating to the two major four way signalised intersections within the study route. The CDMs were undertaken using a semi-structured interview procedure including a series of predefined 'cognitive' probes specifically designed to identify underlying thought processes and decision making strategies (O'Hare et al., 1998).

2.3. Analysis

The first three phases of CWA were applied to evaluate intersection system constraints influencing road user behaviour and subsequent behaviour possible. The CWA was conducted using the transcripts and document analysis.

From these sources, one analyst extracted key themes according to the principles of the different phases of CWA framework. For example, for the work domain analysis key themes extracted from the transcripts included physical objects (e.g. lane markings and road users), values and priority measures (e.g. safety and positive subjective experience) and functions that had to be executed (e.g. avoid conflicts with other road users and objects). For the control task analysis, key themes extracted included decision making requirements (e.g. assessing other road user's speed control to determine the current system state (e.g. state of traffic light)). Additional themes extracted for the strategies analysis included verbs (e.g. locating and avoiding) and criteria influencing the employment of strategies (e.g. weather conditions, presence of other road users). As common practice for applying the CWA framework, subsequent iterations of the different phases of CWA were conducted formatively, allowing for the identification of additional nodes and relationships not present in the transcripts or document analysis ensuring comprehensive coverage of possible system behaviour.

When items were referring to the same concept but were worded differently, terms used in official Victorian road transport system documents prevailed. The CWA was conducted by one analyst and reviewed by two other analysts, all with significant experience in applying the methodology.

The CWA framework, using the above described process, was first applied to the traditional Melbourne intersection. Subsequently, the CWA analysis was conducted for the cut-through intersection. This entailed modifying the traditional CWA analysis, describing changes in constraints and examining subsequent changes in emerging behaviour.

3. Results

3.1. Systems analysis of traditional and cut-through intersection

System constraints. The Abstraction Hierarchy (AH; Rasmussen et al., 1994) was used to assess differences in intersection constraints. The evaluation revealed that the constraints imposed at road users at both intersections were similar, see Fig. 3. The purpose of both intersections is to support road users' negotiation of the intersection. Values and priority measures, measuring the effectiveness of the system towards achieving the purpose, include safety, efficiency, a positive subjective experience for road users, compliance and keep upright for both intersections. Although it could be argued that values and priority measures of the cut-through intersection include 'reduce angles and speed at which traffic meet', these would be 'sub' values and priority measures of safety as defined here.

Purpose related functions that have to be executed to achieve the purpose of the system are the same for both intersections. The cut-through intersection removes the need for a gap acceptance

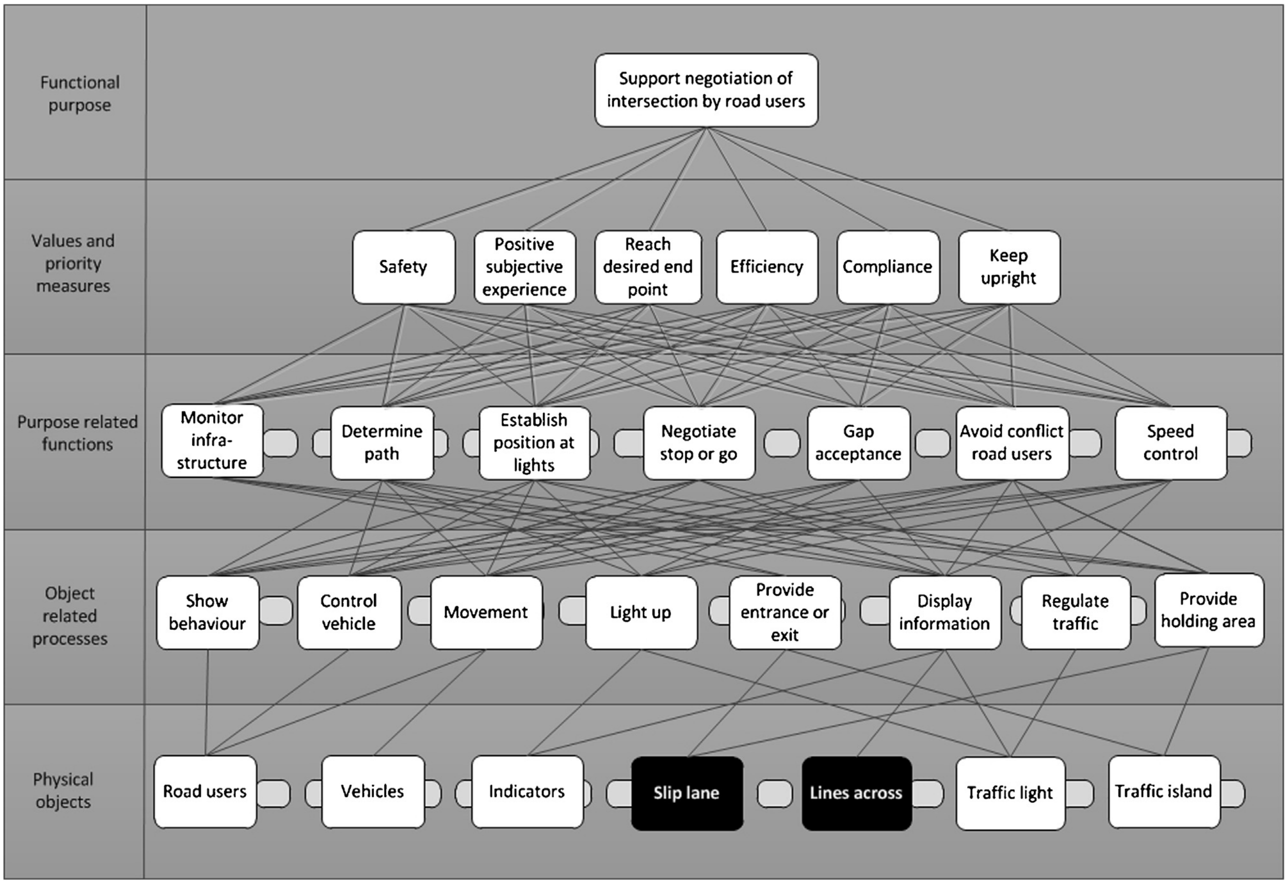

Fig. 3. Differences constraints work domain analysis from traditional to cut-through intersection.

task in the middle of the intersection, as road users are now divided by traffic islands. However, gap acceptance will occur upon entering or exiting the intersection and the cut-through lane, and therefore remains an essential purpose related function.

A difference in system constraints is seen in the physical objects comprising the intersection system. In the cut-through intersection, the slip lane has been removed. The slip lane afforded road users an option to turn left without using the main intersection. Lane markings have been replaced by traffic islands. Lane markings display information and allowed road users to follow them across the intersection. However, in the cut-through intersection this will be afforded by traffic islands. Traffic islands, however, were already present in the traditional system and therefore represent no change in constraints from a systems perspective.

Situational constraints. Differences between designs become more apparent when describing situational constraints shaping behaviour using Contextual Activity Templates (CAT; Naikar et al., 2006). The CAT defines when/where activities, purpose related functions from the AH, can be carried out and when/where they are most likely to be carried out. Situational constraints are defined as approach (from passing a directional sign until reaching the stop line), at the intersection (from crossing the stop line until entering the intersecting road) and exiting the intersection (entering the intersecting road). These represent three distinct stages of negotiating an intersection following Fastenmeier and Gstalter (2007). The main findings from the CAT analysis are overlayed onto the intersection diagrams in Fig. 4.

The analysis revealed that the functions 'determine a path' and 'determine and take a lane' occur earlier on approach in the cut-through than in the traditional intersections. The appropriate lane has to be taken before reaching the traffic island on approach. Traffic islands in the intersection prevent further changes to the path while in the intersection. The effect of these situational constraints on road user courses of action will be evaluated in the strategies analysis phase.

The positioning of these traffic islands also result in more instances and new locations of the gap acceptance task in the cut-through intersection, e.g. upon entering and exiting the cut-through lane, see Fig. 4. Therefore, while the traffic islands might not represent a change in overall system constraints in the AH, their redistribution through the intersection changes situational constraints on road user behaviour in the cut-through intersection.

Decision making processes. Decision ladders (Rasmussen, 1974) were constructed to examine differences in decision making processes across the intersections. A decision ladder exemplifying decision making in the cut-through intersection is depicted in Fig. 5. Decision ladders specify, at the top of the diagram, what options road users have available to execute the purpose related functions in the middle level of the AH. The left hand leg describes the information elements required to evaluate options for function execution. The right hand leg of the decision ladder subsequently describes how options can be executed (Rasmussen, 1974). Road user specific decision making processes are indicated by the use of initials (D(rivers), M(otorcycle riders), C(yclists) and P(edestrians)).

The analysis demonstrated that the options road users have to negotiate the intersection are different between the traditional and cut-through intersection. Road users wanting to turn left can no longer use a slip lane but rather merge and diverge with other traffic in the cut-through intersection. Turning right, in the cut-through intersection, can include using the cut-through lane and travelling the long way around (similar to negotiating a roundabout).

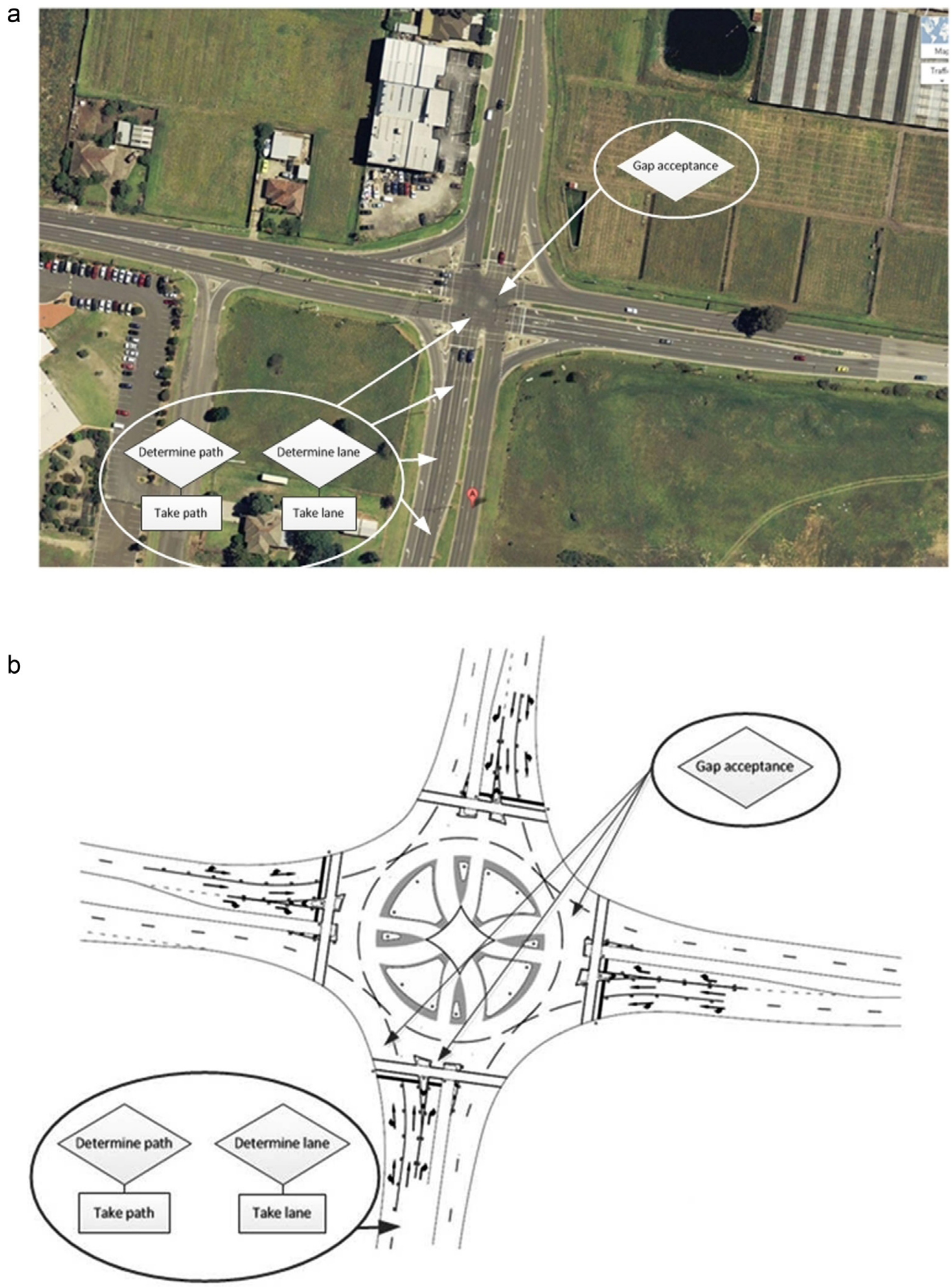

Fig. 4. Change in situational constraints for determine and take path and lane and gap acceptance.

Table 2
Changes to determine and take path.

	Traditional	Cut-through
Turn left	• Using footpath on left hand side (C, P) • Using main road (D, M, C) • Using slip lane (D, M, C)	• Using footpath on left hand side (C, P) • Using main intersection (D, M, C)
Turn right	• Hook turn[a] (M, C) • Go straight, perform a u-turn and turn left using slip lane (D, M, C) • Turn left using slip lane, perform u-turn and go straight (D, M, C) • Using footpath clockwise or anti clockwise (C, P) • Using right hand turning lane (D, M, C)	• Hook turn[a] (M, C) • Go straight, perform a u-turn and turn left (D, M, C) • Turn left, perform u-turn and go straight (D, M, C) • Using footpath clockwise or anti clockwise (C, P) • Using right hand and cut-through lane (D, M, C) • Turn right by travelling in the left hand lane all the way through the intersection, the long way around (D, M, C)

[a] A hook turn is executed by continuing on the left hand side of the road, joining traffic continuing straight across the intersection. Instead of going straight through, road users stop in front of traffic waiting on the left hand side of the intersection and go straight across the intersection with this stream of traffic (State of Victoria, 2009).

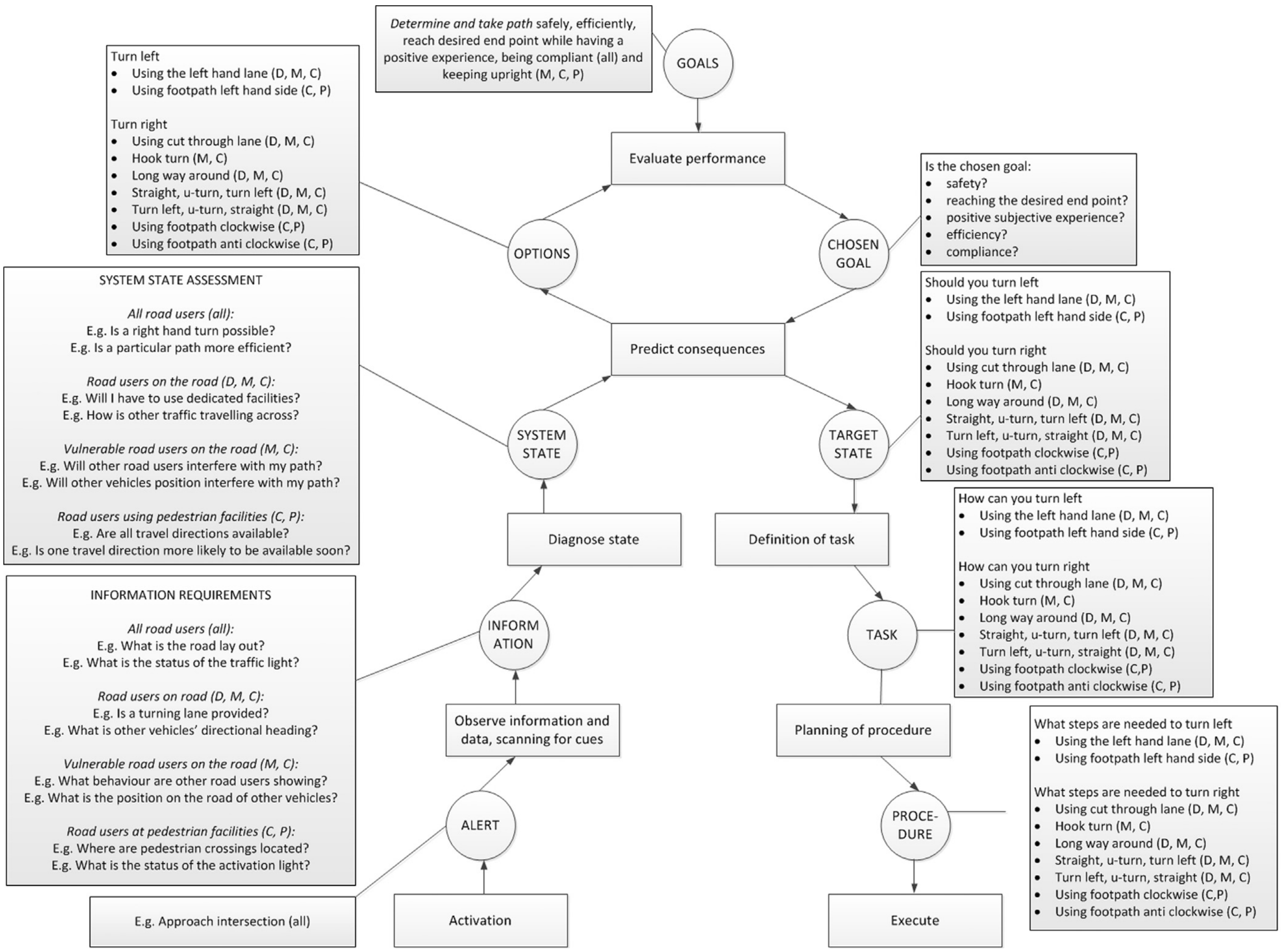

Fig. 5. Decision ladder extract determine and take path (e.g. turn left or right) for cut-through intersection.

Options to take the appropriate lane also differ between the two intersections. In the traditional intersection, each lane, except the left hand lane, carries a particular stream of traffic. In the cut-through intersection, the lanes on approach can be used for multiple paths through the intersection, see Tables 2 and 3. In particular turning right can be approached from all lanes. Specifically, turning right travelling the long way around the intersection (similar to negotiating a roundabout) can be executed from the left and middle lane and the right hand lane can be used to turn right using the cut-through lane. The changes in courses of action and complexity and conflicts this may create amongst traffic will be evaluated in the strategies analysis phase of CWA, discussed in the next paragraph.

Information elements, depicted in the left side of decision ladder, used by road users to decide on an appropriate path and lane include traffic lane arrows, vehicles' indicators, traffic lights and directional signs. As concluded from the CAT, in the cut-through intersection the decision to 'determine a path' and 'lane' are moved earlier along the approach. Unfortunately, the information elements, e.g. traffic lane arrows, remain at the same location as in the traditional intersection. Subsequently, in the cut-through intersection the information elements are provided after the decision point.

Road user strategies. The potential strategies adopted by different road users when negotiating intersections were identified using the Strategies Analysis Diagram (SAD; Cornelissen et al., 2013). The SAD, see Fig. 6, describes potential ways in which activities can be carried out based on the system constraints defined in the AH. This analysis provides detailed insight into how behaviour is shaped differently by the intersection designs.

Table 3
Changes to determine and take lane.

	Traditional	Cut-through
Left hand lane	• Turn left into slip lane (D, M, C) • Continue straight on (D, M, C) • Enter intersection to perform a hook turn (M, C)	• Turn left (D, M, C) • Continue straight on (D, M, C) • Enter intersection to perform a hook turn (M, C) • Turn right travelling the long way around (D, M, C)
Middle lane	• Continue straight on (D, M, C)	• Continue straight on (D, M, C) • Turn right travelling the long way around (D, M, C)
Right hand lane	• Turn right (D, M, C)	• Turn right using cut-through lane (D, M, C)

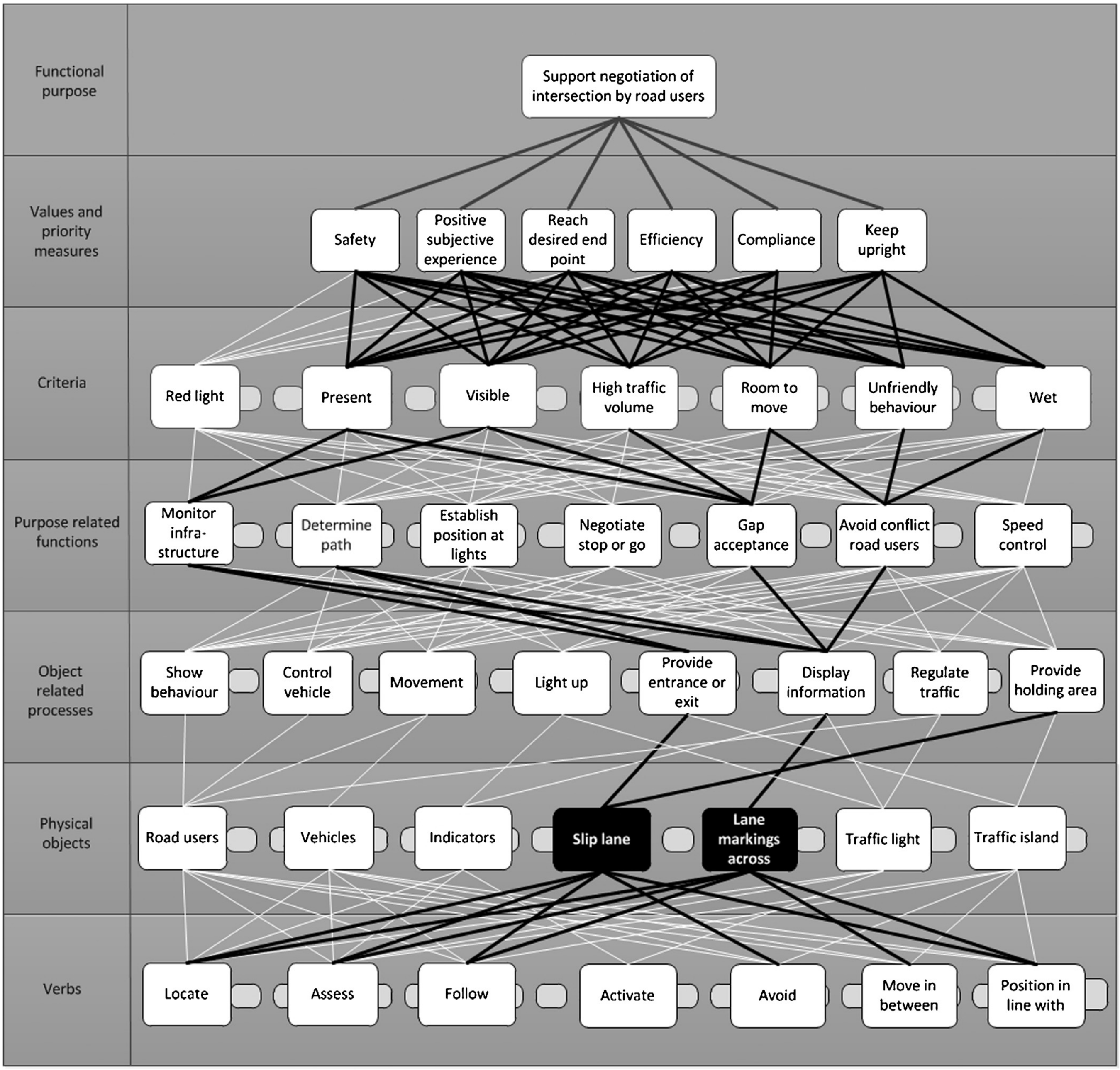

Fig. 6. Strategies Analysis Diagram extract, shaded nodes and links represent example strategies that are no longer possible in the cut-through intersection.

First, courses of action possible in the cut-through intersection change as a direct result of the removal of the slip lane and replacement of lane markings by traffic islands. For example, courses of action include 'locate traffic island' and 'avoid conflict with traffic island'. Courses of action to turn left will no longer include 'locate and enter slip lane'.

Second, the SAD analysis suggests that the cut-through intersection will produce temporary emergent behaviours that arise when road users first encounter the new design. Road users in the cut-through intersection will monitor the infrastructure, for example, to determine the layout and purpose of the new design (see Fig. 7). Courses of action include 'assess road' 'layout', 'assess if traffic islands divide road users' and 'provide protection' and 'assess traffic light position on the road'. In addition, other road user behaviour can also be assessed to gain an understanding of the cut-through intersection, see Fig. 8. For example, other road users' 'gestures', 'position on the road' can be assessed and their future 'directional heading' can be anticipated. These courses of action increase efficiency when infrastructure is self explanatory and road users display the correct behaviour. However, it can also decrease positive subjective experience, e.g. lead to confusion, when infrastructure misleads the user and other road users display great variability in their behaviour.

Third, the SAD analysis suggested a wide range of permanent emergent behaviours induced by the cut-through intersection. Traffic islands in the middle of the intersection, for example, afford protection and divide road users and therefore reduce the need for strategies to avoid conflict with other road users. It also makes positioning in the intersection easier as traffic islands are physical rather than symbolic constraints. Gap acceptance in the cut-through intersection will be easier. Upon exiting the cut-through lane, for example, there will be a better view of traffic in

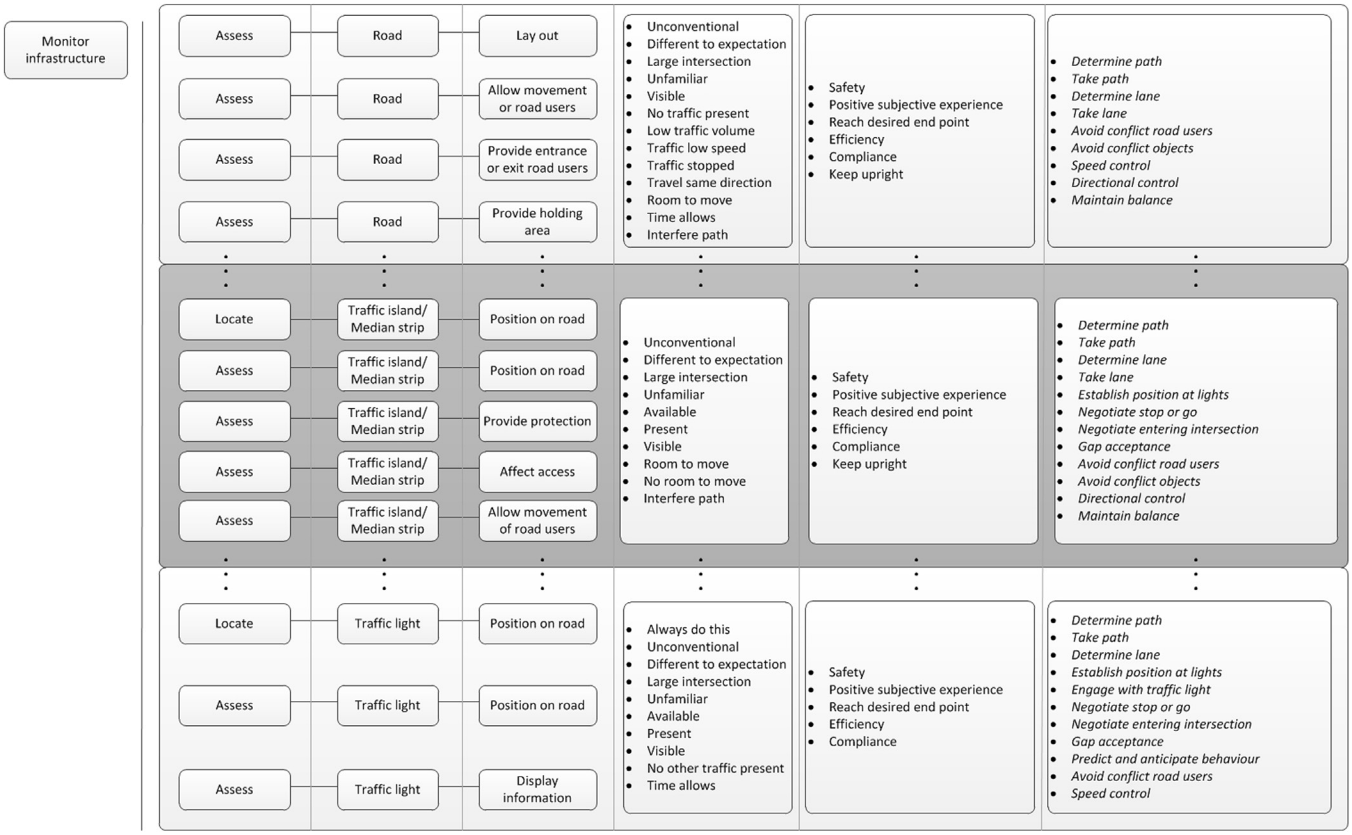

Fig. 7. Strategies flow chart 'monitor infrastructure' extract – temporary behaviour after introduction cut-through design.

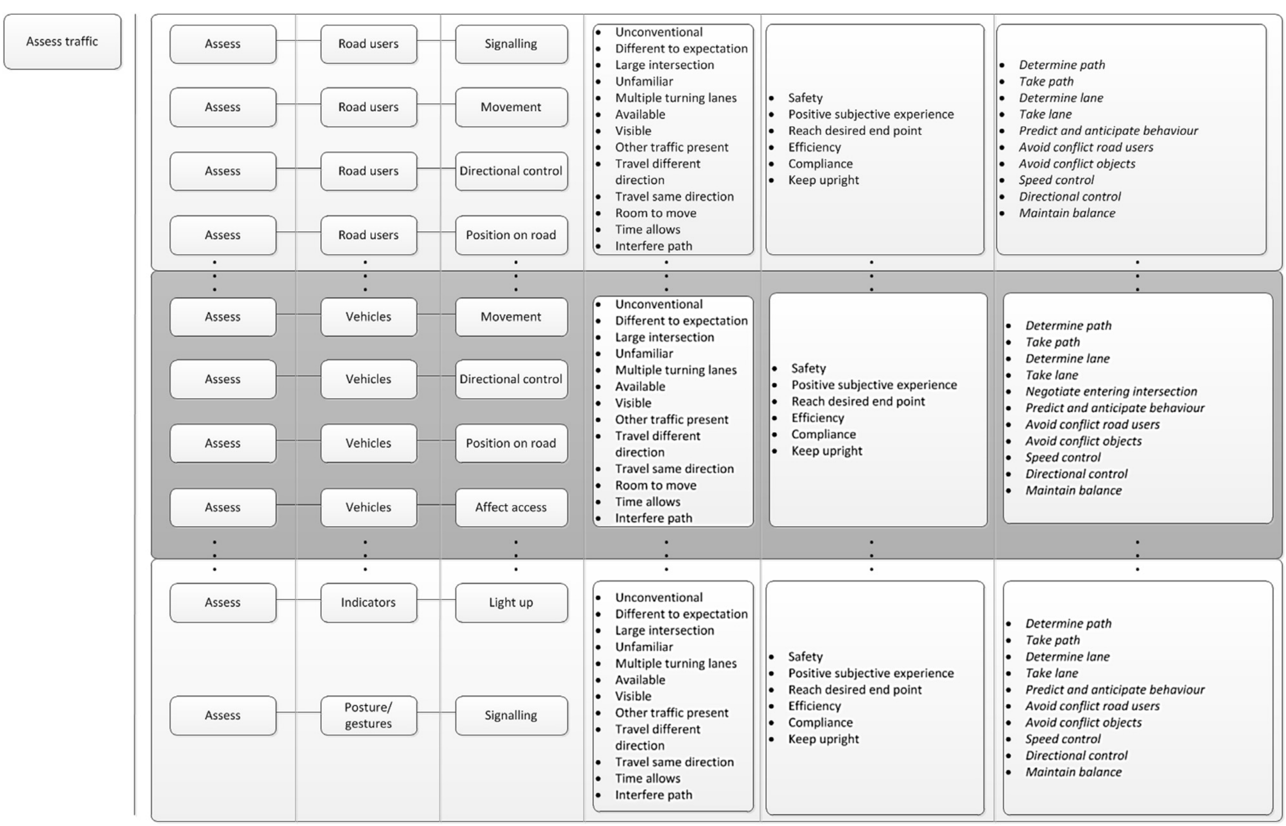

Fig. 8. Strategies flow chart 'assess traffic' extract – temporary behaviour after introduction cut-through design.

the intersection as no oncoming traffic is positioned in front. These changes satisfy positive subjective experience, efficiency and safety values and priority measures of the cut-through intersection.

Traffic islands afford movement of road users. Road user movement is intended for traffic islands connecting footpaths. However, traffic islands in the middle of the cut-through intersection also afford movement. Therefore, pedestrians and cyclists wanting to travel to the opposite corner of the intersection can 'enter those traffic islands' rather than travelling the long way around and crossing both intersecting roads. These courses of action are likely to be seen in 'low traffic volume' situations or when 'traffic is stopped' or 'travelling at low speeds' satisfying safety and efficiency values and priority measures. This option can subsequently be added to the decision ladder in the previous phase of the CWA framework.

Traffic islands on approach in the cut-through intersection push back decision to 'determine a path' and 'determine and take a lane'. Subsequently, on approach these decisions concur with execution of speed and directional control and infrastructure monitoring. Changes to path and lane selection occur earlier on approach where speeds are higher. This change therefore results in more complex combination of strategies at a particular point in time in the cut-through intersection.

Furthermore, the decision ladders demonstrate that information elements are not provided at this earlier decision point. Alternative courses of action include 'assess indicators', 'anticipate traffic light display information', and 'recall directional sign display information'. However, these courses of action entail collecting information from multiple sources across the intersection and involve anticipation, recollection and merging of information. Therefore strategies are scattered and complex and workload and uncertainty will likely be increased.

The CAT also described the option to travel the long way around in the cut-through intersection. For drivers, this option is not likely to satisfy 'efficiency' value and priority measures once 'familiar with the design'. However, cyclists may find that 'safety' and 'positive subjective experience' motivates them to travel the long way around, especially in situations of 'high traffic volume' and 'high speeds'. Taking the cut-through lane, for example, forces cyclists to cross multiple lanes of traffic from the left hand side of the road where cyclists often find themselves on approach. Travelling from the left hand side to the right hand turning lane occurs at higher speeds in the cut-through intersection since the decision point is moved earlier along the approach. When cyclists travel the long way around, however, other road users will at each exit point have to 'assess and anticipate cyclists directional heading and movement' and 'avoid conflict with cyclists'. This therefore negatively impacts the 'safety' and 'positive subjective experience' and makes it a double bind.

Furthermore traffic light positioning in the cut-through intersection shapes behaviour differently. Arrow traffic lights are located away from straight through traffic lights and road users may fail to locate them. In addition, traffic lights with arrows are placed upon exit of the cut-through lane. Unfortunately, road users may 'locate a red light' and stop and 'position themselves in the cut-through lane', thereby 'blocking access for traffic behind and adjacent'. Furthermore, if road users decide to turn right by taking the long way around, they will not face a traffic light when they meet the opposite traffic flow entering the intersection on a green light. Traffic meeting under such circumstances may prove challenging. Therefore the layout of the intersection, emergent behaviour and traffic light positioning and sequencing has to be considered to avoid conflict between road users. The findings are summarised in Table 4 below. Road user specific strategies are indicated by the use of initials (D(rivers), M(otorcycle riders), C(yclists) and P(edestrians)).

3.2. Evaluation of strategies in both intersections

Above, differences in behaviour between the two intersections are addressed. This section will address shortcomings of both intersections to support road users, see Table 5. Understanding the interaction of road users and design is important as without such understanding design induced problems will remain present in future road transport designs.

Pedestrians, for example, are not provided with tailored information when they determine their path across the intersection. Rather, they integrate different information elements across the intersection, e.g. 'road and lane layout', 'number of traffic islands' and 'traffic lights', 'angle of the intersection' and 'traffic movements' to anticipate which path across the intersection will be 'safest', a 'positive subjective experience' and 'efficient'. As a result of the lack of support, pedestrians may 'activate both traffic light buttons', and subsequently 'enter the road' when one light is 'green'. Their path is thus determined by the first pedestrian light to turn green. While this strategy minimises workload of pedestrians, it has disadvantages for the intersection system as a whole. The other light that was activated will turn green despite the pedestrian having used the alternative crossing. There is currently no means to deactivate the traffic light and the traffic light does not 'know' that the green time is no longer required. Therefore the green light will unnecessarily interfere with traffic travelling on the road. Such inefficiencies may encourage illegal strategies, e.g. traffic proceeding through red traffic lights, when the 'efficiency' value is high and the 'safety' value seems to be satisfied. Tailored information and smart traffic light solutions could support pedestrians, and the intersection system, better.

Cyclists can take many different paths across the intersection. Courses of actions to decide and switch between the options include 'assess the intersection lay out', 'traffic behaviour', 'speeds', 'volume', 'directional heading' and 'movements' as well as 'weather and road surface conditions'. These are conducted parallel to courses of action related to 'positioning themselves amongst other traffic', 'avoiding conflict with road users and objects', and engaging in 'speed' and 'directional control'. This provides extra workload for cyclist and indicates that intersections do not adequately support cyclists. The lack of support for cyclists impacts the intersection system. Because of the cyclists unpredictability, other road users have to 'assess cyclist' behaviour', 'movement' and 'directional heading' and 'anticipate their path'. Knowing the criteria and values and priority measures driving behaviour of cyclists should help design intersections better. Intersections should include a path option for cyclists that is as safe and has a positive subjective experience similar to using the pedestrian crossing or hook turn and as efficient as a right hand turn.

Motorcycle riders and cyclists that 'engage with the traffic lights' engage in courses of action to ensure the activation of the traffic light sensor underneath the road surface. These strategies, however, may compromise their own 'safety'. For example, motorcycle riders and cyclist may 'move up and down the traffic light sensor' or if 'other traffic is present', they may 'position themselves in front of the stop line' to 'allow other traffic to activate the traffic light sensor' for them. This places motorcycle riders and cyclists potentially in conflict with pedestrians and traffic on the road. While the incompatibility of the sensor and motorcycle riders and cyclists has to be addressed the intersection system already affords a potential solution, namely the activation light at pedestrian crossing facilities. This light provides feedback regarding activation of the traffic light and therefore reduces the need to anticipate the activation and engage in strategies to activate the traffic light sensor when it in fact has already been activated. Considering currently unsupported road user behaviour and unexplored possibilities of the system to support road users better will

Table 4
CWA evaluation of intersections.

System constraints		
Removal slip lane	D, M, C	E.g. Slip lane no longer affords movement of road users and provides no entry or exit point for road users.
Replacement lane markings by traffic island	D, M, C	E.g. Affordances of lane markings, e.g. display information to take path across intersection, now afforded by traffic islands.
Situational constraints		
Traffic islands in middle	D, M, C	Create more instances and relocate location of gap acceptance task
Traffic islands on approach	D, M, C	Push the decision to determine and take the appropriate lane and path forward on approach
Decision making		
Slip lane and traffic islands shape path options	D, M, C	E.g. The option to turn left using slip lane available in traditional intersection but not in cut-through intersection E.g. The option to turn right travelling the long way around the intersection
Slip lane and traffic islands shape lane options	D, M, C	E.g. in traditional intersection, dedicated lanes for each path, except perhaps for left hand lane E.g. in cut-through intersection, right hand turn can be made from any lane
Traffic islands on approach push decision forward on approach	D, M, C	E.g. traffic islands on approach in cut-through intersection relocate decision point for determine path and lane earlier on approach. Arrows have not been moved and therefore provided after decision has already been made.
Direct behaviour changes		
Removal slip lane	D, M, C	E.g. Strategies turn left using slip lane removed
Replacement lane markings by traffic island	D, M, C	E.g. Locate and Follow lane markings will become locate, follow and circumvent traffic islands
Temporary emergent behaviours		
Monitor infrastructure to understand new lay out and determine path	All	E.g. Assess road layout, position of entrance and exit points and holding areas E.g. Locate and assess traffic islands position on road, whether they provide protection, affect access and allow movement of road users E.g. Locate, assess traffic light position on road and information it displays to assess relevance and status.
Assess traffic to understand new lay out	All	E.g. Assess road users signalling, movement, directional control and position on road. E.g. Assess vehicles movement, directional control, position on the road and whether they affect access. E.g. Assess Indicators and cyclists gestures signalling.
Permanent emergent behaviours		
Traffic islands in middle divide and protect road users	D, M, C	E.g. Avoiding conflict with other road users in middle of intersection is easier. E.g. Aligning with traffic islands makes positioning in middle of intersection easier E.g. Different angle of approach of oncoming traffic makes gap acceptance easier
Traffic islands allow movement of road users	C, P	E.g. Cyclist and pedestrians can take the traffic islands connecting the footpaths E.g. Cyclists and pedestrians can take the traffic islands in the middle to turn right (e.g. in low volumes of traffic, traffic stopped or at low speed)
Traffic islands on approach divide road users	D, M, C	E.g. Courses of action related to determine and take path and lane occur earlier on approach when courses of action also include speed and directional control and monitor infrastructure, and speeds are higher.
	C	E.g. Cyclists will have to travel from left hand side of the road to right hand lane earlier on approach at higher speeds or use the traffic island and pedestrian crossing to reach the right hand lane
	D, M, C	E.g. Last minute changes in path and lane options will not occur and road users are protected once close to the intersection
Path option long way around	D, M	E.g. Drivers and motorcycle riders find not satisfy efficiency value and priority measure
	C	E.g. Cyclists find safety and positive subjective experience may influence decision to travel long way around.
Arrows not provided at decision point	D, M, C	E.g. Assess arrows to determine what lane is appropriate E.g. Assess, indicators and other road user behaviour, assess and anticipate traffic light information, recall directional sign to anticipate what lane is appropriate
Traffic light repositioning	All	E.g. Traffic lights at different positions, therefore road users fail to locate relevant light. E.g. Traffic light upon exiting cut-through lane, stop in cut-through lane, and block access intersection system. E.g. No traffic light to prevent traffic travelling long way around meeting entering traffic opposite direction.

ensure that such design induced problems are addressed in future designs.

4. Discussion

The aim of this study was to demonstrate the value of applying systems-based Ergonomics methodologies in the evaluation of road design concepts. It was argued that systems analyses describing the interaction of infrastructure, environment, vehicles and road users in intersections can provide an understanding of the level of support that design concepts provide road users. Moreover, it is argued that intersections designed based on systems analyses will better support the behaviour of all road users (e.g. drivers, motorcycle riders, cyclists and pedestrians).

The CWA outputs highlighted differences and commonalities between the traditional Melbourne intersection and the proposed safe system based cut-through intersection. While the proposed cut-through intersection appears physically unconventional in structure, the system constraints imposed on road user

Table 5
Unsupported design induced strategies.

Unsupported design induced strategies		
Pedestrians no tailored information to determine path Pedestrians activate both traffic lights and decrease efficiency system	P	Provide path information Smart traffic light solutions can be deactivated or know when to deactivate
Cyclists have many options to negotiate an intersection. Many strategies to choose between options. Variability makes them unpredictable road users.	C	Provide option for cyclists to negotiate intersection based on understanding of constraints. E.g. provide options as safe and positive experience as pedestrian crossing and as efficient as right hand turn.
Motorcycle riders and cyclists engage in strategies to ensure traffic light sensor activation. E.g. repeated positioning on traffic light sensor. E.g. position in front of sensor and/or stop line to allow other traffic to activate sensor. Decreases efficiency and safety of system.	M, C	Make traffic light sensor compatible with all road users Provide feedback of sensor activation, e.g. activation light, to road users.

behaviour did not differ significantly from the traditional intersection. This means, that purpose and objects and functions used to achieve the functions are not changed. The distribution of constraints throughout the cut-through intersection, however, shape behaviour differently as described by situational and decision making constraints. The Ergonomics systems analysis was also able to demonstrate the different emergent road user behaviours that are induced by the cut-through intersection. In addition, the analysis highlighted how design induced problems were not addressed by either design. Understanding road user behaviour as an interaction of the intersection infrastructure, environment, vehicles and different road users, the study provided insight into opportunities to further improve intersection designs.

CWA is therefore proposed as a viable and useful approach for evaluating and informing road design concepts. Moving forward it will be useful to investigate how CWA can be integrated with other road design methods; however, it is concluded from the present analysis that using Ergonomics system based methods is important for road safety to fully embrace the safe systems approach. First, using such methods, e.g. CWA, will allow road transport designers to determine whether design concepts effectively support the behaviour of all road users and interactions between road users. For example, the analysis demonstrated that the latitude for behaviour afforded to cyclists leads to complex and risky interactions with other road users. It also demonstrated that information elements, such as traffic light activation lights, are currently provided to part of the system, e.g. pedestrian facilities, but could provide value for the wider system. For example providing an activation light on the main road would reduce the need of motorcycle riders and cyclists to ensure activation of the traffic light sensor. CWA structurally shows how objects can be functionally integrated and complement each other in intersection design.

Second, using CWA can highlight requirements for additional support for different road user groups. For example, the analysis demonstrated the lack of tailored support for pedestrians to determine a path across the intersection. This leads to reduced efficiency, for example, through pedestrians activating multiple traffic lights.

Third, considering the interaction between road users and infrastructure using CWA will enable designers to ensure delivery of timely, redundant and complementary information elements. The analysis showed that arrows on the tarmac in the cut-through intersection were provided after the decision to choose an appropriate lane had already been made. In both designs, it is the main information element provided to determine a lane, yet often they are not available, e.g. when blocked by other traffic. Therefore, road users have to locate and combine information elements throughout the intersection system to anticipate the purpose of the lane in front in absence of other complementary, readily available information elements. Analysing strategies supports describing when, where, what and why information elements should be provided to support the intersection system.

Fourth, analysing the interaction between infrastructure, vehicles and road users specifically supports consideration of vehicles and road users as an integrated part of the design. From the analysis, it was clear that road users rely heavily on other road users and vehicles behaviour. However, this implies that the other road users provide correct, consistent and useful information. Despite this, road user education currently only addresses use of signals, but does not educate people on courses of actions they could employ to support interactions with other road users. Understanding of the road transport system, as presented by CWA, can define education requirements. Supporting road user interaction through understanding of this in the intersection system context will provide solutions that increase safety, efficiency and positive subjective experience of the road transport system.

Fifth, by describing and assessing the range of strategies afforded by the intersection system, designs can be evaluated for the extent to which they support positive strategies and discourage negative strategies. In the current evaluation for example, it was found that the cut-through lane supported positive strategies for drivers, e.g. traffic islands reduced the number of strategies required for avoiding conflict with other road users. However, the design also increased the workload and unpredictability of cyclists by providing them with additional options to negotiate the intersection. Moreover, some of the new strategies created potential conflicts such as cyclists travelling the long way around, similar to negotiating a roundabout, to turn right.

CWA allows the evaluation of temporary and permanent emergent behaviours of road transport system designs. Temporary behaviours provide insight for recommendations to better support road users who are novices with the intersection. However, these behaviours will level off as road users become more experienced with the intersection. Also, over time the proportion of experienced users of the intersection increases. These experienced users will provide more reliable behaviour that novice users can use to determine how to use the intersection. The absence of such temporary behaviours, or levelling off of behaviours, however does not necessarily mean a design is good. Rather, road users may have adapted their courses of action to accommodate bad design. Therefore, it is critical to systematically evaluate permanent behaviours induced by a design. It should be assessed if the design adequately supports all road users and their interaction, whether timely, redundant and complementary information is provided, and positive courses of actions are supported and negative courses of actions are discouraged.

Based on the analysis of the intersections presented in this paper, it is evident that both traditional and concept intersections currently do not support all road users equally. Further, emergent behaviours that could create conflicts between road users have not been considered. Worryingly, the analysis suggests that new intersection design concepts underpinned by the safe systems road strategy fall some way short of being 'systemic'; that is, the cut-through intersection does not fully support all road users and safe interactions between them. Paradoxically then, it appears that the much heralded road transport safe systems philosophy has not produced an intersection that is consistent with systems approach principles.

The analysis using CWA demonstrated that design principles for system based road transport systems should not focus on providing barriers separating components of the system, as proposed by the road transport safe system philosophy, but rather support the interaction of different components and allow it to be flexible and adaptive in response to the dynamic nature of the road transport system. For example, vehicle and infrastructure design should provide a limited but flexible range of options for road users, supporting them effectively and making them predictable but also adaptable. Design principles for infrastructure and vehicle design as well as road user education should consider the interaction of road users, vehicles, infrastructure and environment to support the positive use of road transport systems. Vehicle and infrastructure design should minimise the complexity of decision making and minimise the number of decisions for all road users, without making them more complex. Redundant, timely and complementary information elements should be provided based on understanding of road users' strategies, decision making processes and interaction between infrastructure, environment, vehicles and road users. For example, based on such understanding, information elements can be positioned to support decision making processes at the right time and right place in contrast to distributing information elements based on physical distances and distribution through intersection system. Road transport designs should be inclusive designs considering all road users, their specific characteristics and requirements at all times. This includes not using one road user as a blue print but rather considering the effect on all road users of the interaction of the environment, infrastructure, vehicles and different road users. Positive countermeasures for one road user should not compromise outcomes for other road users. All road users should be equally supported. The interaction between road users should be supported by accounting for different characteristics, requirements and strategies rather than exacerbating these differences. Such design principles embrace the complexity and support the interaction of different road transport system components rather than reduce the complexity by separating components of the system.

It is argued that systems analysis and design methods such as CWA are critical for actualising the systems approach in road designs. Without the use of such methods emergent behaviours will not be understood before designs are implemented in the real world. Importantly, methods such as CWA provide a low cost analysis approach that can be applied to early road design concepts such as paper-based designs. In the present analysis, CWA was able to provide insight into emergent behaviour as well as future opportunities for design supporting positive interactions between infrastructure, environment, vehicles and road users.

As a methodological case study, it is worth addressing how the CWA approach contributes to road transport evaluation methods. Researchers have called for improvements to the road design evaluation process (El Esawey and Sayed, 2012). Currently, operational and safety evaluation of road transport designs is conducted through conflict point analysis (Federal Highway Administration, 2000), risk rating based on e.g. kinetic energy of collisions (Corben et al., 2010a), crash prediction functions (Gross et al., 2012) or mathematical modelling of intersection variables (Miranda-Moreno et al., 2011). Such approaches reduce the problem of safety to either potential conflict points, or a selection of variables. These reductionist approaches fail to comprehensively and systematically describe interaction of infrastructure, environment, vehicles and road users. The CWA approach as presented in this article provides a method to understand, evaluate and manage road user behaviour as an interaction of intersection infrastructure, environment, vehicles and different road users, embracing rather than reducing complexity. It therefore supplements approaches such as conflict point analysis by not just providing insight into where but also what and why conflict points occur for whom and how they can be managed. The networked representations also provide insight into relationships between a large range of variables, irrespective of predictive value. Arguably, the current analysis is rather qualitative of nature. Quantitative analysis of constraints shaping road user behaviour could however be conducted using scoring systems depicting relative strengths of links in the networks, for example (Birrell et al., 2011).

Attempts to evaluate the interaction of human behaviour and infrastructure design to date has mainly reduced the problem to a single road user group or countermeasure to allow experimental design, e.g. simulator studies (Rudin-Brown et al., 2012; Werneke and Vollrath, 2013) or on road studies evaluating infrastructure changes already built in the environment (Mackie et al., 2013; Waard et al., 1995). The CWA approach presented here affords the evaluation and design of road transport systems through a low cost desktop effort throughout the entire road design process, from concept to implementation. Using Ergonomics system analysis methods such as CWA, evaluation of emergent behaviour can be conducted prior to infrastructure being built and using and evaluating the interaction of different road user groups rather than focussing on a particular road user group e.g. when using simulators.

Unfortunately, CWA is often regarded resource intensive, despite being argued that its application time is half that of other Ergonomics task analysis methods (Salmon et al., 2010). The use of software tools could be of assistance. As shown in this article, CWA modelling efforts have an extended shelf life as changes in the road transport system can be entered as modifications in the model and differences can be evaluated and managed. The current study was conducted by one analyst only and reviewed by two others. The resource requirement could be distributed and the formative approach could be strengthened by using multiple analysts. The use of multiple analysts is also likely to increase the validity and reliability of the analysis (Stanton et al., 2009), ensuring the validity of the assumptions made by analysts. Future directions will include evaluation of the validity and reliability of CWA. In addition, the integration of CWA with existing road transport methods will be explored in future research.

In summary, while system safety has been acknowledged and global road safety campaigns use system safety language, applications of system safety remain sparse. This study has demonstrated that future designs based on road safety safe systems principles fail to address all road users equally and fail to anticipate road user emergent behaviours. Using Ergonomics system analysis methods such as CWA is essential for future improvements in road safety. Only then can changes in behaviour due to changes in intersection design be fully anticipated. Based on such understanding road transport designs can be systematically designed, integrating all road users and countering instances of incompatibility of infrastructure, environment, vehicles and road users.

Acknowledgement

Miranda Cornelissen's contribution to this article was conducted as part of her PhD candidature which is funded by a Monash

Graduate Scholarship and a Monash International Postgraduate Research Scholarship. Dr Paul Salmon's contribution to this article was funded through his Australian National Health and Medical Research Council post doctoral fellowship.

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