Distributed Situation Awareness in Road Transport: Theory, Measurement, and Application to Intersection Design

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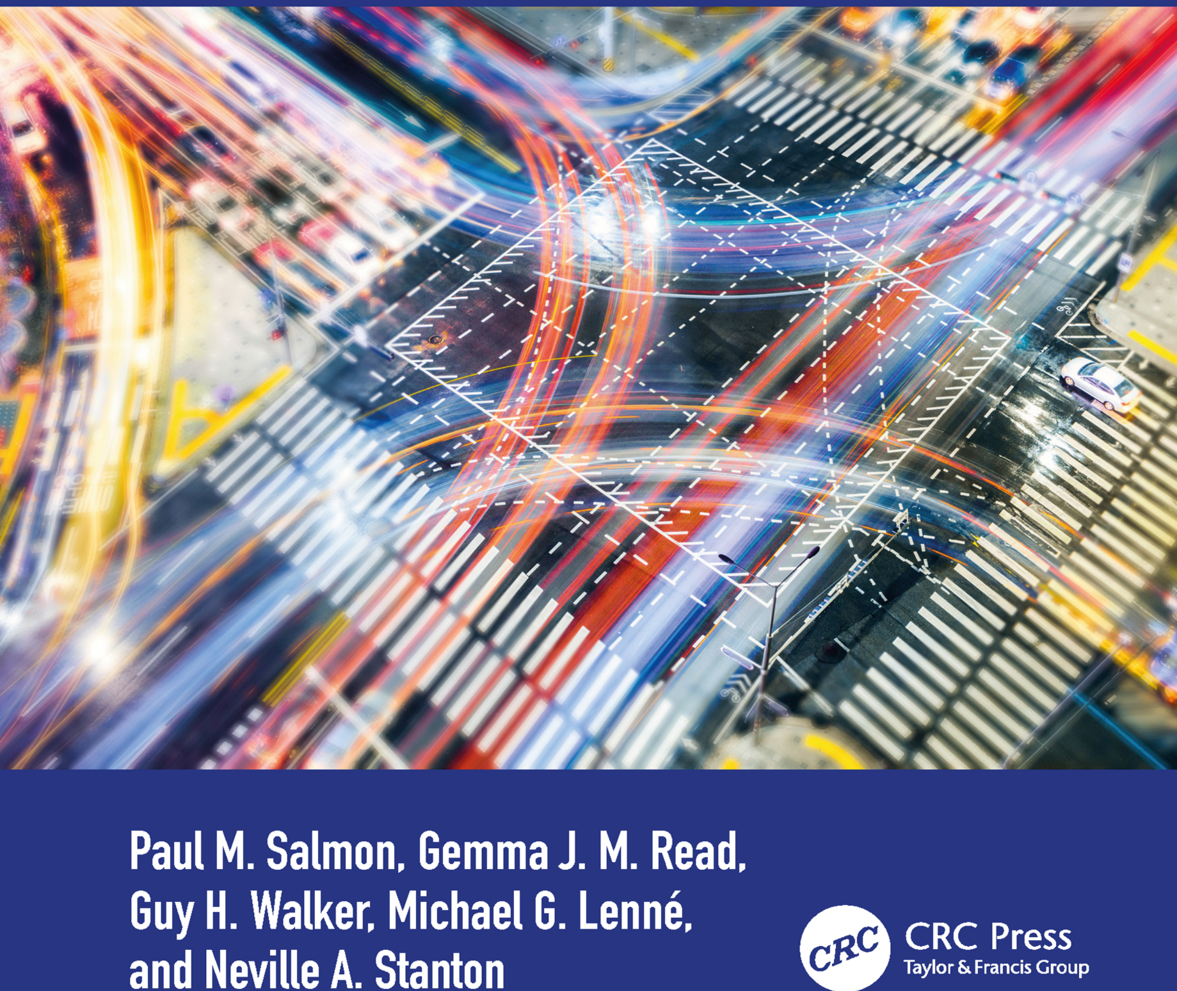
THE HUMAN FACTORS OF SIMULATION AND ASSESSMENT SERIES

Distributed Situation Awareness in Road Transport

Theory, Measurement, and Application to Intersection Design



Paul M. Salmon, Gemma J. M. Read, Guy H. Walker, Michael G. Lenné, and Neville A. Stanton

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This book is dedicated to all those who have been affected by road trauma.

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Preface

A driver approaches an intersection, unaware that a cyclist is about to move in front of him and into the right-hand turning lane.

Travelling down a country lane, a driver glances at the road ahead before overtaking the vehicle in front. Although she looked, she failed to see the motorcyclist approaching in the opposite direction.

A truck driver's attention is diverted from the road by a text message. Glancing at his phone for only seconds, he does not see the stationary traffic ahead.

A driverless vehicle transports a family home from their day out. Mum sleeps whilst dad and the children interact with their tablets. All four are unaware that the vehicle's automated systems have failed to detect the pedestrian crossing the road in front of them.

While these four scenarios are hypothetical, they represent very real risks in our road transport systems. Worldwide, well over a million lives are lost each year through road collisions, with millions more suffering from serious injury (WHO 2018). By 2030, it is estimated that roads will be the world's seventh deadliest killer (WHO 2018). The numbers are startling enough, yet they do not begin to describe the pain and suffering that is associated with road trauma.

Whilst all road collisions are caused by multiple interacting factors, one aspect is constant across them—almost always at least one of the road users involved is momentarily not aware of something important, be it other road users, the road conditions, hazards in the environment or the safest way to negotiate a particular road situation. Within the realms of Human Factors and Safety Science, the concept that we use to study people's awareness in complex and dynamic environments is known as 'Situation Awareness' (SA). SA provides theoretical models and analysis methods, which can be used to understand how humans, teams, organisations and even entire systems develop and maintain appropriate levels of awareness of 'what is going on' (Endsley 1995a). It has been used to optimise performance and safety in many areas such as aviation, process control, defence, maritime and rail. This is typically achieved by performing analyses to understand what SA comprises, to identify what factors influence the acquisition and maintenance of SA, and through designing interventions that will optimise SA (e.g. technologies, displays, warnings, training programs, procedures).

Surprisingly, at the start of the program of work described in this book, SA had received less attention in road safety. Though various simulator studies had investigated factors that influence driver SA (e.g. mobile phone use), there were few examples of where SA had been used to inform the development of interventions designed to prevent road trauma. Moreover, exactly how to study SA on the road and use this information to inform the design of appropriate road safety interventions was not clear.

In response, the authors sought funding through the Australian Research Council Discovery scheme to support a research program that would investigate the potential role of SA as a framework to design safer road environments. Whilst the work was to be undertaken in road transport, the intention was to develop and test a framework that could be used in other safety critical domains too. An additional aim of the work was to further advance SA theory and methods. This book describes the ensuing program of research.

The research involved using SA as a framework to tackle the long-standing problem of collisions at intersections (also known as junctions). Collisions at intersections represent a significant road safety issue worldwide. In Australia, for example, around 20% of all road deaths occur at intersections (Bureau of Infrastructure, Transport and Regional Economics 2016) and the majority of urban road crashes and a substantial proportion of rural crashes occur at intersections (McLean et al. 2010). Intersection crashes account for around half of all car, pedestrian and cyclist crashes and a third of all motorcycle crashes (Vicroads 2011). Similar issues are reported across the world. Whilst many attempts have been made to improve safety at intersections, at the onset of this research, the continuing high incidence of intersection-related trauma suggested that a new approach was required.

The authors felt strongly that SA, in particular a systems approach to SA considering intersection systems and the SA of all agents, human and non-human, was required. This belief was held on the basis of our previous successes applying a systems approach to understand and enhance SA in other domains (Salmon et al. 2009; Stanton et al. 2006, 2017). In addition, it was apparent to us that most intersections appeared to have been designed with the driver in mind, with little consideration of the SA needs of other road users (e.g. cyclists, motorcyclists, pedestrians) or of how different road users interact, and, critically, without ensuring that drivers would be aware of other more vulnerable road users. A final aspect that strengthened our resolve was the fact that, at the time, most intersection research was focussed on drivers and drivers alone. Although systems theory emphasises the importance of examining the interactions between all components, few researchers were examining the interaction between drivers and other road users such as cyclists, motorcyclists and pedestrians. Taking all of this together, it was unsurprising to us that collisions at intersections were continuing to occur and that they would often involve drivers and other kinds of road users.

The research program was completed in 2016, creating new insights into SA, SA in road transport, how to study road user SA naturalistically and how road environments as well as elements of the wider road transport system could be designed to optimise the SA of all road users. In addition, a series of novel intersection design concepts were produced in an attempt to provide exemplars on how to design to support SA and prevent collisions at the intersections of the future. These were subsequently evaluated to gather initial feedback from different road user groups.

The purpose of this book is to share the research approach, our analyses and findings, and to communicate the key findings with researchers and practitioners. In addition, the aim is to provide the reader with practical guidance on how to apply the core methods applied during the research program. This includes guidance on how to conduct on-road studies of SA and how to apply the Event Analysis of Systemic Teamwork (EAST; Stanton et al. 2013) and Cognitive Work Analysis (CWA; Vicente 1999). Accordingly, the book covers SA theory and methods; a series of naturalistic studies of driver, motorcyclist, cyclist and pedestrian SA; the design approach adopted; the intersection design concepts themselves; and our evaluations of them. In closing, we provide suggestions on how our approach can also be applied to other issues, both in transport and in other domains. Finally, the appendices section provides step-by-step guidance on how to conduct on-road studies of SA and on how to apply EAST and CWA.

Who Should Read This Book?

This book is intended to be of interest to researchers, students and human factors and safety practitioners who are faced with solving complex SA-related issues in the safety-critical industries or have a more general interest in SA. We believe that the different approaches employed are useful for understanding and optimising SA in any domain in which human and non-human agents operate together in a complex and dynamic environment. We hope that experienced human factors researchers and practitioners will find some new methods, insights and learnings from reading the material and that researchers new to human factors and/or SA will find useful guidance and advice.

Naturally, the book also outlines our findings in relation to road user behaviour at intersections. We hope that these will be of interest to road safety practitioners who can use the information to improve the design of intersections, other road environments, standards, policies and other initiatives.

Why Should You Read This Book?

There are a number of books available that describe SA theory and methods, present studies of SA in different contexts or provide guidance on how to study SA and how to design systems to optimise SA (Banbury and

Tremblay 2004; Endsley and Jones 2011; Salmon et al. 2009; Walker et al. 2018). Further, there are many books that outline different approaches that can be used to enhance road safety (e.g. Guttman 2017; Johnston et al. 2017; Tiwari and Mohan 2016). Despite this, there is little in the way of guidance on how to study SA in road transport and how to take everything that we know about SA and design road environments to support it. Further, there are few books that provide an overview of research programs that move from transport analysis through to design and evaluation. This book intends to address these gaps and to provide the reader with tools and advice for taking a similar approach to solve SA-related issues in transportation systems and beyond. Finally, this book also provides state-of-the-art reviews of SA models and measures, enabling the reader to understand which models and measures are available and what their main strengths and weaknesses are. This information can be used to support the study of SA in any domain.

How to Read This Book

We expect that some readers will be highly familiar with the methods and approaches discussed, whilst for others, there will be much new information. We have tried to achieve a balance in the level of detail provided and, where possible, refer the novice reader to other texts that they may find useful for further guidance.

We use the example of our work in intersection analysis, design and evaluation to illustrate our approach throughout the book. However, you will find other examples discussed throughout the book and general principles drawn out that can be applied to broader transport issues as well as domains outside of transportation.

This book is divided into six main sections:

1. Introduction to situation awareness models and methods
    - Chapters 1 through 3 provide a review of popular SA models and methods along with an overview of the SA-related research undertaken to date in road transport. The theoretical and methodological approach adopted to study road user SA throughout the research program is also outlined and demonstrated through a case study.
2. Naturalistic studies of road user SA at intersections
    - Chapters 4 through 6 present a series of naturalistic on-road studies that were undertaken to assess the SA of drivers, motorcyclists, cyclists and pedestrians in different road environments and to identify the factors underpinning collisions between

them. The findings provide key conclusions regarding SA in different road environments, the factors that cause collisions between different road users and how to design to support SA across different road users.

3. Designing for SA: a sociotechnical systems approach
   - Chapters 7 through 9 describe the use of a sociotechnical systems theory-based design process to identify road user SA requirements, generate novel intersection design concepts, conduct initial evaluations and, subsequently, refine the designs. The three novel intersection design concepts are presented in Chapter 9.
4. Evaluation of intersection design concepts
   - Chapter 10 presents a multi-road user evaluation of the three intersection design concepts presented in Chapter 9.
5. Conclusions and future applications
   - Chapter 11 provides an overview of the conclusions and recommendations arising from the research and identifies future research directions for DSA (Distributed Situation Awareness) in safety critical systems.
6. Appendices
   - The appendices section contains practical step-by-step guidance on how to conduct on-road studies of SA and on how to apply EAST and CWA.

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Whilst the book has five authors, many researchers, administration staff and students made significant contributions throughout the program of research. We would like to express our heartfelt thanks to all staff and students from the University of the Sunshine Coast and Monash University who have been involved in this research. We thank Ashleigh Filtness, Natassia Goode, Nicholas Stevens, Kristie Young, Miles Thomas, Bride Scott-Parker, Miranda Cornelissen, Vanessa Beanland, Michelle Van Mulken, Natalie Taylor, Eryn Grant, Pene Mitchell, Erin Stevens, Nebojsa Tomasevic, Ash Verdoorn, Casey Rampollard and Kerri Salmon. This book would not exist without your contributions.

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Neville A. Stanton, PhD, DSc, is a chartered psychologist, chartered ergonomist and chartered engineer. He holds the chair in Human Factors Engineering in the Faculty of Engineering and the Environment at the University of Southampton in the UK. He has degrees in occupational psychology, applied psychology and human factors engineering and has worked at the Universities of Aston, Brunel, Cornell and MIT. His research interests include modelling, predicting, analysing and evaluating human performance in systems as well as designing the interfaces and interaction between humans and technology. Professor Stanton has worked on design of automobiles, aircraft, ships and control rooms over the past 30 years, on a variety of automation projects. He has published 40 books and over 300 journal papers on ergonomics and human factors. In 1998, he was presented with the Institution of Electrical Engineers Divisional Premium Award for research into system safety. The Institute of Ergonomics and Human Factors in the UK awarded him The Otto Edholm Medal in 2001, The President's Medal in 2008 and The Sir Frederic Bartlett Medal in 2012 for his contributions to basic and applied ergonomics research. The Royal Aeronautical Society awarded him and his colleagues the Hodgson Prize in 2006 for research on design-induced, flight-deck, error published in *The Aeronautical Journal*. The University of Southampton has awarded him a doctor of science degree in 2014 for his sustained contribution to the development and validation of human factors methods.

Section I

Situation Awareness Models and Measures

1

Situation Awareness in Individuals, Teams and Systems: An Overview of Situation Awareness Models and Their Utility for Road Safety Research and Practice

Introduction

At its broadest level of description, Situation Awareness (SA) refers to how agents, human or non-human, develop and maintain an understanding of 'what is going on' around them (Endsley 1995a). Within human factors and safety science, SA has become an important lens through which to view and understand behaviour, providing a powerful framework to support the design of tools, technologies, procedures and environments that aim to optimise performance. In road transport, lack of SA regarding factors such as other road users and their behaviour, hazards, the road conditions and the road rules is often cited as a contributory factor in collisions. As a result, how to optimise road user SA has become an integral consideration in the design of vehicles, training and education programs and road environments.

As discussed in the preface, this book describes a program of research that utilised recently developed SA theory and methods to support the development of novel design concepts to optimise safety at intersections (also known as junctions in some jurisdictions). Whilst a specific theoretical framework was adopted, at the beginning of this research, there were (and still are) various models of SA available, each with their own strengths and weaknesses, and each potentially with a role to play in transport system analysis and design. The aim of this chapter is to provide an overview of different SA models and discuss some of their strengths and weaknesses when used in the road transport context. The intention is to explain why we chose the theoretical approach adopted throughout this program of work as well as to showcase how the concept has evolved since it first emerged within our discipline. The reader is also provided with the necessary reference material to select an appropriate theoretical framework for their own context.

Uses of SA

Depending on the theoretical and methodological approaches employed, SA models and methods are used by researchers and practitioners to

- Describe how individuals (Endsley 1995a), teams (Salas et al. 1995) or systems (Salmon et al. 2009) develop and maintain appropriate levels of SA during task performance
- Make inferences on what SA comprises during different scenarios (i.e. what information is gathered and assimilated by individuals, teams, organisations and systems in different scenarios)
- Inform the design of artefacts, technologies, procedures, training programs and systems that support the development and maintenance of SA
- Assess the quality of SA against a normative ideal (Endsley 1995b)
- Identify how and why SA was 'lost' or degraded during an adverse event of some sort (Salmon et al. 2015, 2016c)

SA has been explored in many operational contexts, including military settings (e.g. Endsley 1993; Stanton 2014; Stanton et al. 2006), surface transportation (e.g. Golightly et al. 2010, 2013; Ma and Kaber 2007; Salmon et al. 2014a; Walker et al. 2011), aviation (Jones and Endsley 1996; Salmon et al. 2016c), maritime (Sandhaland et al. 2015), sport (Bourbousson et al. 2011; James and Patrick 2004; Macquet and Stanton 2014; Neville and Salmon 2016), healthcare and medicine (Bleakley et al. 2013; Fioratou et al. 2010; Hazlehurst et al. 2007; Schulz et al. 2013), process control (Salmon et al. 2008a; Sneddon et al. 2015) and emergency response (Blandford and Wong 2004; Seppanen et al. 2013).

This popularity has led to high levels of debate and contention, in particular around the validity of different theoretical models and of different SA measures. Arguably, SA is the most hotly debated human factors and safety science concept of all time (Dekker 2015; Endsley 2015; Salmon et al. 2008b; 2015; Stanton et al. 2015, 2017b). As a result, there are many definitions and models presented in the literature.

Definitions and Models of SA

Various definitions and models of SA are available. These can be broadly categorised as those relating to the SA held by individuals, teams and socio-technical systems. For a detailed review and comparison of models, the reader is referred to Salmon et al. (2008b) and Stanton et al. (2017b); however, for the purposes of this book, we focus mainly on the most prominent individual, team, and systems models: Endsley's three-level model (Endsley 1995a), Salas et al.'s model of team SA (Salas et al. 1995) and Stanton et al.'s model of Distributed Situation Awareness (DSA; Stanton et al. 2006).

Individual SA

Consistent with the dominant research trends of the time, early definitions and models of SA focussed on individual operators (e.g. drivers, pilots, control room operators) and the cognitive processes involved in developing and maintaining awareness. Mica Endsley, a pioneer in this area, introduced the most widely known and used definition which stated that SA is:

> *'the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future'* (Endsley 1988).

Endsley also introduced an information processing–based 'three-level model' of SA (see Figure 1.1). This describes SA as an individual's mental model of the ongoing situation that incorporates the following three levels:

- Level 1, perception of the elements in the environment
- Level 2, comprehension of their meaning
- Level 3, projection of future system states

The three-level model describes how SA is a central component of information processing that underpins decision making and action. SA in this model is influenced by various individual (e.g. mental models, workload), task (e.g. difficulty and complexity) and systemic factors (e.g. system complexity, interface design).

Level 1 SA involves perceiving the status, attributes and dynamics of task-related elements in the surrounding environment (Endsley 1995a). At this stage, the elements are perceived and no further processing takes place.

Level 2 SA involves the interpretation of level 1 data to allow individuals to understand its relevance in relation to their task and goals. During level 2, 'the decision maker forms a holistic picture of the environment, comprehending the significance of objects and events' (Endsley 1995a, p. 37).

Finally, level 3 SA involves anticipating future task and system states by forecasting the likely behaviour of elements in the environment. Here, individuals use level 1 and 2 SA along with their mental models of similar situations to forecast likely events. Mental models play a key role in SA, directing attention to pertinent elements in the environment (level 1 SA), facilitating the integration of elements to aid comprehension (level 2 SA), and supporting the generation of future states and behaviours (level 3 SA).

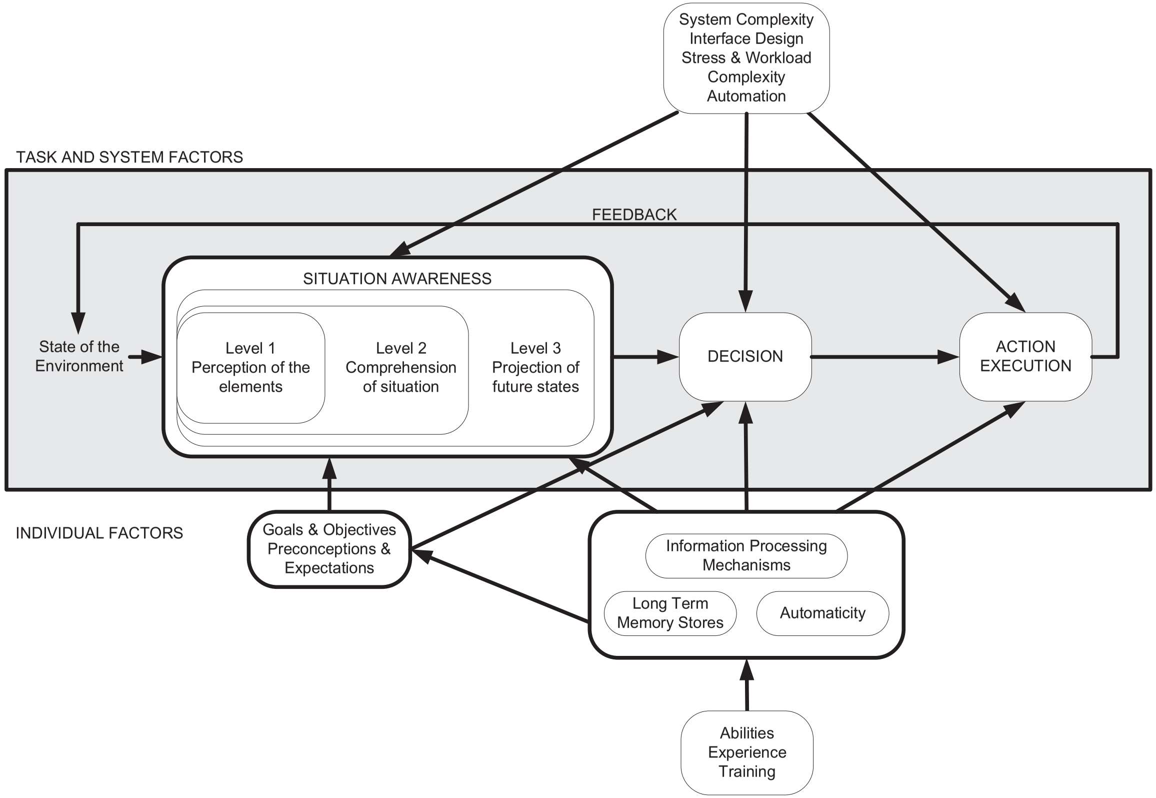

FIGURE 1.1
Endsley's three-level model of SA. [Adapted from Endsley, M. R. (1995a). Towards a theory of situation awareness in dynamic systems. *Human Factors*, 37, 32–64.]

Endsley's model has been used extensively to study driver SA in different contexts and the original paper outlining the model referenced driving as an example of a dynamic environment in which SA was relevant. When used to describe SA development and maintenance during driving, the model suggests that, directed by their mental models, drivers attend to and perceive relevant elements within the driving environment (e.g. other road users, their location, traffic signals, road signage, obstacles). They then integrate these elements to comprehend their meaning in light of their driving goals (e.g. the car in front is slowing down and the traffic light ahead is red so I need to slow down), and then use this in combination with their mental model to forecast future states (e.g. the pedestrian waiting on the side of the road is likely to cross in front of me).

Team Models

As interest grew, definitions and models expanded from the individual level to the team level. Salas et al. (1995) define a team as 'a distinguishable set of two or more people who interact dynamically, interdependently and adaptively toward a common and valued goal, who have each been assigned specific roles or functions to perform and who have a limited life span of membership'. The Big Five model of teamwork (Salas et al. 2005) identifies five key teamwork behaviours (leadership, mutual performance monitoring, backup behaviour, adaptability and team orientation) along with three key supporting mechanisms (shared mental models, mutual trust and communication). Notably, SA underpins, or is underpinned by, these behaviours and supporting mechanisms.

Eduardo Salas and colleagues (1995) defined team SA as:

> *'the shared understanding of a situation among team members at one point in time'* (Salas et al. 1995, p. 131).

Most attempts to describe team SA have focussed on the need for team members to develop a shared understanding of the situation (Nofi 2000; Perla et al. 2000). Salas et al.'s model of team SA remains one of the most popular. This suggested that team SA comprises two core processes: individual SA and team processes. According to Salas et al. (1995), the perception of SA elements is influenced by the communication of task objectives, individual tasks and roles, team capability and other team performance factors. Comprehension of this information is affected by the interpretations made by other team members, and so individual SA is developed and then shared with other team members, which in turn leads to updates and modifications to team members' SA. Thus, a cyclical process of developing individual SA, sharing SA with other team members and then modifying SA based on other team members' SA is apparent.

Salas et al. (1995) also highlight the importance of team processes such as communication, assertiveness and planning, all of which contribute to the development and maintenance of team SA. In addition to team processes, Salas et al. also point to the key role of individual factors such as pre-existing relevant knowledge and expectations and cognitive processing skills such as attention allocation, perception, data extraction, comprehension and projection (Salas et al. 1995).

Shu and Furuta (2005) expanded on earlier team SA models by proposing the concept of mutual awareness. This is the mutual understanding of each other's activities, beliefs and intentions (Shu and Furuta 2005). They describe how team SA is a partly shared and partly distributed understanding of a situation amongst team members. For example, in a vehicle, mutual awareness would be achieved when both the driver and the passenger are able to understand each other's behaviours and motives when driving to a particular location. Shu and Furuta (2005) defined team SA as, 'two or more individuals share the common environment, up-to-the-moment understanding of situation of the environment, and another person's interaction with the cooperative task' (Shu and Furuta 2005, p. 274). Although popular in settings such as defence, team SA models have received much less attention in road safety research than individual models.

Systems Models

More recently, an increased emphasis on systems thinking in human factors research and practice has led to an interest in applying SA to overall sociotechnical systems. In a seminal article that marked the beginning of this paradigm shift, Neville Stanton and colleagues defined DSA as:

> *'activated knowledge for a specific task within a system…. [and] the use of appropriate knowledge (held by individuals, captured by devices, etc.) which relates to the state of the environment and the changes as the situation develops'* (Stanton et al. 2006, p. 1291).

A systems approach to SA was first discussed by Artman and Garbis (1998) who argued that SA can be held by the overall joint cognitive system. They argued that SA is distributed not only across team members but also throughout the artefacts that teams use. Stanton and colleagues built on this work to develop the DSA model (Salmon et al. 2009). Inspired by Hutchins' seminal work on distributed cognition (Hutchins 1995a,b), the DSA model argues that SA is an emergent property that is held by overall systems and is built through interactions between 'agents', both human (e.g. human operators) and non-human (e.g. tools, documents, displays). Hutchins (1995b) described how information processing can be viewed at the sociotechnical system level and describes how both humans and artefacts engage in cognitive processes. He demonstrated this by explaining how joint cognitive cockpit systems remember their requisite landing speeds during landing descents. The plane needs to reduce speed at different points on approach and descent, and these speeds are dependent on the weight of the aircraft. In addition, airspeed must be reduced in concert with changes to the flaps and slat settings. As the requisite speeds change across flights based on differences such as aircraft design and weight, they are difficult to memorise. Pilots therefore use an external representation of descent speeds, known as 'speed bugs', to remember the appropriate values during each flight. The speed bugs are set on the airspeed indicator (Figure 1.2). Remembering the appropriate airspeed during phases of descent therefore involves interactions between the pilot/s, the speed card (which assists in identify the correct speed for the weight of the aircraft), the airspeed indicator dial and the speed bugs that pilots can place at the relevant speeds on the dial. The information is distributed across the cockpit system, and further, a non-human agent holds the SA of speeds, which pilots access at the appropriate time. A more straightforward everyday example of distributed cognition is that

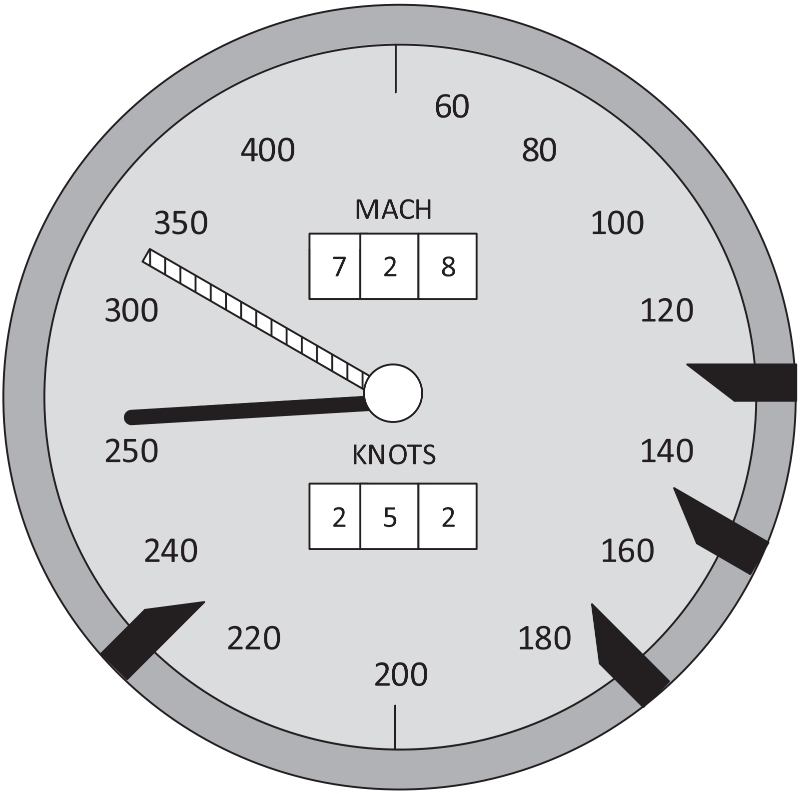

FIGURE 1.2
Example use of speed bugs on airspeed indicator as external representations of required landing speeds. [Adapted from Hutchins, E. (1995b). How a cockpit remembers its speeds. *Cognitive Science*, 19, 265–288.]

people generally no longer memorise telephone numbers, rather they rely on their mobile phone to remember numbers for them. Stanton et al.'s DSA model was built based on similar principles.

There are various descriptions of the DSA model available in the literature (see Salmon et al. 2008b; Stanton et al. 2009). Stanton et al. (2006) outlined a series of core tenets that were subsequently updated by Stanton et al. (2017b). They include the following:

1. SA is an emergent property of a sociotechnical system. Accordingly, the system represents the unit of analysis, rather than the individual agents working within it.
2. SA is distributed across the human and non-human agents operating within the system. Different agents have different views on the same situation. This draws on schema theory and the perceptual cycle model, highlighting the key role of experience, memory, training and perspective.
3. Systems have a dynamic network of information upon which different operators have each their own unique view, and contribution to. This is akin to a system's 'hive mind' (Seeley et al. 2012). The compatibility between these views is critical to support safe and efficient performance, with incompatibilities creating threats to performance, safety and resilience.
4. DSA is maintained via transactions in awareness between agents. These exchanges in awareness can be human to human, human to artefact and/or artefact to artefact. Such interchanges serve to maintain, expand or degrade the network underpinning DSA. Transactions between agents may be verbal and non-verbal behaviour, customs and practice. Technologies transact through sounds, signs, symbols and other aspects relating to their state.
5. Compatible SA is required for systems to function effectively: rather than have shared awareness, agents have their own unique view on the situation that connects to form the systems DSA.
6. Genotype and phenotype schema play a key role in both transactions and compatibility of SA.
7. DSA holds loosely coupled systems together. Without this coupling system, performance may collapse. Dynamic changes in coupling may lead to associated changes in DSA.
8. One agent may compensate for degradation in SA in another agent.

According to the DSA model, a system's awareness comprises a network of information upon which different agents have distinct views and ownership—as mentioned above, something that is akin to a hive mind of the system (Seeley et al. 2012). For example, a driver will have one view of the intersection situation, whilst a motorcyclist engaged in the same intersection situation will have a different view (due to the distinct tasks they each have to perform). Pedestrians and other road users in the environment will have also have their own unique view, as will police, the traffic lights, the relevant traffic management centre and advanced vehicle automation systems.

In addition, each agent will bring different information to the situation. For example, the driver will communicate his or her intentions via their actions and their vehicle (e.g. indicators), as will the motorcyclists. Traffic control systems such as traffic lights will provide information on the status of the intersection, right of way and the required behaviour of users (e.g. stop or go), and in-vehicle route navigation systems will provide location and navigational information. According to the DSA perspective, safe and efficient performance of the intersection relies on these different views connecting together as well as 'transactions' in SA where appropriate exchanges in awareness are made between the right agents at the right time. A transaction in this case represents an exchange of SA between agents (where agent refers to both humans and artefacts). It is important to note that transactions represent more than just the communication of information; rather, they represent the exchange of SA where one agent interacts with another and both modify their SA as a result of the interaction. Agents interact with one another and exchange elements of their SA, and they are integrated with other information and acted on and then passed onto other agents (Sorensen and Stanton 2015).

Different agents may use and interpret information differently depending on their goals and role within the system. For example, an amber traffic light coupled with the location and speed of other vehicles may lead to a driver deciding to stop at the traffic lights, whereas the same information may lead to a motorcyclist deciding to increase speed and pass through the intersection. Both actions may be safe; however, each agent is driven by a different understanding of the situation and of the appropriate course of action. All are using the information for their own ends and reaching a unique interpretation.

Rather than possess shared SA (which suggests that agents need to understand a situation or elements of a situation in the same manner), the DSA model instead suggests agents possess unique, but compatible, types of awareness. Agents experience a situation in different ways as defined by their own personal experience, goals, roles, tasks, training, skills, schema and so on. Compatible awareness is achieved when these different views connect together to create an appropriate systems level of SA (Stanton 2014; Stanton et al. 2006, 2009). For example, at intersections, the SA held by drivers, cyclists, motorcyclists and pedestrians is different in terms of the information that is perceived, how it is integrated and what understanding of the situation is achieved (Salmon et al. 2014a,b). These differences also occur within road user groups—individual drivers also have different SA to one another as do individual motorcyclists and so on (Salmon et al. 2014a,b). Compatible SA is achieved when these views enable road users to interact safely and the intersection to operate safely.

A final feature of the DSA model is that it can also be scaled down to consider how individual agents develop and transact SA. This part of the model is based on schema theory—the idea that individuals possess mental templates of past experiences that are mapped with information in the world to produce behaviour. Bartlett (1932) described schema as active organisations of past reactions and past experiences, which are combined with information in the world to produce behaviour. He used cricket to show how, when making a stroke, batsmen do not produce entirely new behaviour, nor do they merely repeat old behaviour. Rather, the stroke is 'literally manufactured out of the living visual and postural "schemata" of the moment and their interrelations' (Bartlett 1932, p. 201).

The seminal perceptual cycle model (Neisser 1976; see Figure 1.3) provides an overview of schema-driven human behaviour and how schemata

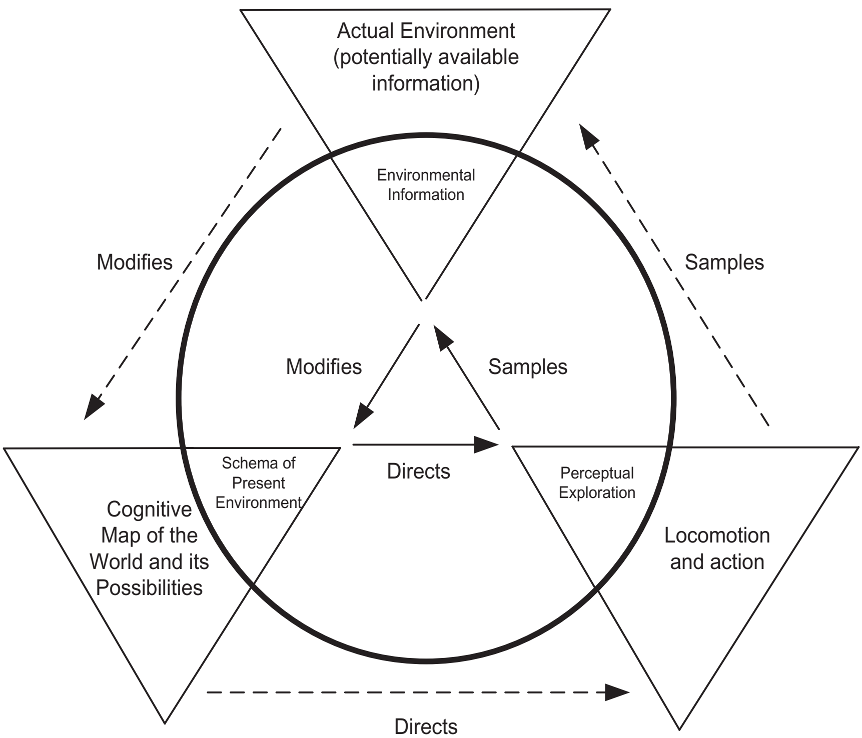

FIGURE 1.3
Neisser's perceptual cycle model.

anticipate perception, direct behaviour and are continually modified. This suggests that perception is an active, rather than a passive, process and that perception can be viewed as guided exploration in the sense that active schemata direct where we look, listen, touch and what we expect to see, hear and feel (Stanton et al. 2009). Exploration leads to adaptation to the environment by the perceiver, which guides future exploration and so on.

The form and nature of schemata determine what we are able to perceive. Neisser argues that schemata interact with the temporal nature of events, by linking the past to the future in two main ways. First, the anticipation of what will happen next determines what we do: what information we look for and attend to. Second, we understand the stream of activity though the anticipation (and continuous modification of that anticipation) to make sense of the events as they unravel through the interaction. We see, hear, feel, smell and taste the whole experience in terms of its meaning to us as individuals (Stanton et al. 2009).

Building on Smith and Hancock (1995), Stanton et al. (2009) used Neisser's perceptual cycle model to describe the schema-driven nature of SA. They argued that schemata direct how we interact with the world (i.e. seek information), how we perceive the world and how we use this to determine the actions required for a given task. Stanton et al. (2009) also used the genotype and phenotype schemata distinction (Neisser 1976) to show how individuals possess genotype schemata for different situations that are triggered during task performance to form an active phenotype schema. The genotype schema is subsequently updated based on the individual's interaction with the world. For example, in the road transport context, drivers possess genotype 'intersection' schemata that become triggered upon encountering intersections. The task-activated phenotype schema directs and guides their interaction with the intersection and perception of it (what their expectations are, where they look, how they interpret information) and how they behave (whether they brake, change lanes or accelerate through the intersection). The resulting interaction then strengthens or updates the genotype intersection schema, which, in turn, influences behaviour at the next intersection and so on.

Summary of SA Perspectives

A summary of the three perspectives, including example models and the unit of analysis associated with each viewpoint, is presented in Table 1.1.

TABLE 1.1

Summary of Different SA Model Perspectives

SA Model Type	Example Model	Unit of Analysis in Road Transport Studies	Key Concepts and Processes	Example Road Safety Studies
Individual	Three-level model (Endsley 1995a)	Individual road users, e.g. drivers, cyclists, motorcyclists	Perception of elements Integration and comprehension of elements Projection of future system states	Ma and Kaber (2005)
Team	Team SA model (Salas et al. 1995)	Driving 'team', e.g. drivers and passengers, drivers and vehicle systems, teams of road users	Perception of elements Integration and comprehension of elements Projection of future system states Teamwork processes (e.g. communication) Shared SA	N/A
System	DSA model (Stanton et al. 2006)	Road transport system including both human (e.g. road users) and non-human agents (e.g. traffic control systems, signage, vehicles)	Schemata Perceptual cycle Genotype and phenotype schemata Distributed cognition Compatible SA SA transactions	Salmon et al. (2014a,b)

Application of SA Models to Intersections

The different definitions and models have important implications for how researchers and practitioners conceive SA to operate and indeed how they might propose to study and optimise it. Since the focus of this research program was ultimately on developing new intersection designs, we now demonstrate each of the three perspectives by using them as a lens to describe how SA works at intersections.

The individual approach suggests that the driver develops a mental model of the current state of the intersection in relation to his or her driving goals. Elements in the intersection environment are perceived (level 1), integrated, and comprehended in light of driving goals (level 2), which, in combination with the driver's existing mental model of intersections, allows future states to be projected (level 3). For example, based on perceiving the status of the traffic lights, the surrounding traffic and the weather and road conditions, a driver may anticipate that the lights are about to turn to red and that the vehicle in front is likely to brake sharply in response. This in turn directs decision making and action, whereby the driver decides to slow down in anticipation of changing traffic lights and the vehicle in front braking. In the intersection context, various pieces of information are critical, such as the status of traffic lights, road signage, the driver's own vehicle speed and position, the positions and manoeuvres of other vehicles, the behaviour of other road users (e.g. pedestrians, cyclists), roadway markings and weather conditions.

From a team SA viewpoint, SA at intersections can be examined at either the driving team level (e.g. a driver and their passengers) or the road user team level. The focus of analysis would initially be on how each team member acquires the SA required to negotiate the intersection. Beyond this, the team SA view would involve looking at how and what SA is shared between team members. For example, sharing of SA might involve a passenger providing directions to a driver or telling the driver to slow down as they are exceeding the speed limit. Alternatively, if the analysis was considering teams of road users, this might involve examining how the intentions of one road user are shared with another (e.g. via indicators or brake lights). Finally, how this sharing of SA updates each team member's individual SA is also of importance. In the case of the passenger providing directions, here the driver's SA is updated by the communication with another team member.

The systems approach focuses on the SA held by the overall intersection system as well as the role that each agent plays in SA development and maintenance. Intersection operation is distributed between various agents, including different road users, their vehicles, the road infrastructure (e.g. traffic lights, signage) and other elements of the road system such as road markings. Each agent holds their own SA, which, when connected through transactions in SA, enables the intersection system to function effectively.

For example, a driver holds SA regarding the goals of the driving task, operational aspects of the driving task (e.g. position on road) and route information (e.g. directions required to achieve driving goals). Vehicle displays and exterior lights hold SA regarding speed and future manoeuvres to be made (i.e. lane changes through indicators). The intersection infrastructure (i.e. traffic lights, pedestrian crossing lights, traffic light cameras) holds SA regarding right of way through the intersection, traffic levels across the intersection and road user infringements.

Importantly, neither drivers, other road users, nor artefacts (e.g. vehicles, in-vehicle displays, road infrastructure) alone hold sufficient SA to allow safe operation of the intersection. Drivers, for example, are not required to be aware of the level, location, and behaviour of traffic coming through the intersection in the opposite direction. The intersection system as a whole, however, requires this information to be able to coordinate traffic signals and maintain an appropriate level of throughput and efficiency and to enforce compliance. Likewise, drivers are not required to have the same understanding of the situation as other road users passing through the intersection in the same direction; rather, they need to be able to exchange relevant portions of SA with the other road users. For example, the cyclist does not need to understand a driver's SA related to their goals, to vehicle control, and to the driver's SA of other vehicles in front of them; however, they do need to understand whether the driver has seen them and what the driver intends to do next. Most important under a systems view then is the compatibility and connectedness of each agent's SA. It is the transactions or exchanges of SA between system components that are critical. This compatibility between agents binds sociotechnical systems together (Salmon et al. 2009; Stanton et al. 2009). Inappropriate transactions, or transaction failures, such as a driver being distracted and failing to notice a cyclist, can lead to collisions at intersections.

From the systems viewpoint then, intersection systems should be analysed as a whole, not as component parts. On the contrary, the individual perspective described earlier offers a (typically) driver-centric view, attempting to determine the quality of SA held in the head of drivers in a situation. Key omissions are evident from this viewpoint. First, different road users would have different SA in this situation depending on their goals, experience and so on, yet driver SA would be compared to some normative ideal (i.e. what we think driver SA should be at intersections). Further, the SA of other components of the system is also typically overlooked within the individual approach. There is little benefit gained from examining the SA of just one road user, or one form of road user (e.g. drivers) when attempting to enhance safety at intersections—each unique set of SA needs should be considered. Finally, the importance of the SA held by the intersection and all of its component agents is overlooked through this perspective, yet each portion is critical to the system functioning effectively. Arguably it is difficult to improve intersection performance without understanding the SA-related interactions between components.

Conceptually then, the DSA model appears to translate well in the intersection context. Indeed, it overcomes some of the criticisms that have been directed at the current road safety approach (Hughes et al. 2016; Larsson et al. 2010, Salmon et al. 2012a). By taking the system as the unit of analysis, DSA shifts the focus from individual road users onto the interactions amongst multiple road users, their vehicles and the road infrastructure. Further, depending on scope, DSA can even extend to policy, training and education programs. Rather than try and understand the 'component' road users in the system by analysing their individual cognition, DSA bypasses this by focussing on the interactions and 'transactions' between them. By describing and interrogating the road transport system's DSA, it is possible to determine who in the system has access to what knowledge at different points in time (e.g. Stanton et al. 2006). This is powerful in design, as it allows all road users to be considered and designed for.

Which Approach Is the Most Useful to Support Intersection Analysis and Design?

It is our view then that DSA provides the most appropriate perspective with which to study SA at intersections, and indeed in road transport generally. It is acknowledged, however, that this represents a significant departure from most existing definitions. The notion that SA resides in both human and non-human (technology, artefacts) agents is particularly controversial (Endsley 2015), as is the idea that overall sociotechnical systems can have SA. These advances are, however, in line with recent movements within human factors and safety science. The so-called systems thinking approach, whereby concepts are examined at a systems level, is now extremely popular (Salmon et al. 2017) and is beginning to receive traction in road safety circles (e.g. Hughes et al. 2016; Salmon and Lenne 2015; Salmon et al. 2016b). Moreover, consideration of human and non-human agent awareness is becoming increasingly relevant given technological advances such as artificial intelligence and advanced automation.

Advanced vehicle automation provides a clear example of where a systems approach to SA is required. Take the recent Tesla Model S crash in which a driver was killed when his vehicle, operating in autopilot mode, failed to detect a truck crossing its path and collided with it whilst travelling at over 70 mph (Banks et al. 2018; NHTSA 2017). Here, the vehicle's autopilot system was not aware of the truck's white trailer as it had failed to detect it against the bright sky. In addition, the driver had failed to take control of the steering wheel at previous points during the drive despite receiving repeated alerts to do so from the vehicle. Both the vehicle and the driver were ostensibly not aware of the truck and the risk of colliding with it. There can be no question then that SA has much to offer in analysing incidents such as these and in supporting the design of automated vehicle systems and indeed the wider road transport system in which they operate. It is, however, important to note that the way in which SA is defined plays a significant role in how SA is examined and designed for. For example, taking a systems perspective would enable designers to fully consider the SA requirements of both the driver and the automated vehicle systems as well as how they interact together to update each other's SA. On the contrary, an individual psychological perspective might shift the focus onto the driver and overlook the automated vehicle systems (since they are not human). The importance then of appropriately mapping SA definitions and models to the issue in question cannot be understated.

Summary

The aim of this chapter was to outline prominent theoretical models within three distinct perspectives on SA: individual SA, team SA, and systems SA. We have identified DSA as the most suitable approach when attempting to understand and enhance safety at intersections, and in road transport generally. This is becoming increasingly apparent given the current shift towards the use of vehicles with advanced levels of automation. There are various useful applications of DSA in road transport, including analyses of road crashes, analyses of behaviour in different road environments/scenarios, analyses of road system DSA, identification of DSA requirements and the design of vehicles, new road environments, training and education programs and road safety strategy and policy.

For the research program described in this book, the intention was to develop a series of new intersection design concepts that would (a) support SA across all intersection users and (b) facilitate safer interactions between different forms of road user (e.g. drivers and cyclists, drivers and motorcyclists, drivers and pedestrians). Ultimately, the aim was to use SA as a framework to create safer intersections. For these reasons, a DSA perspective was adopted as it was felt that this would enable a deeper understanding of behaviour and provide important design insights based on several key tenets. These include the following:

- The intersection system is taken as the unit of analysis. This is important, not least because it suggests that collisions between road users are caused by the intersection losing SA, not individual road users. In most meaningful contexts, SA is not something that can be held by one individual alone and therefore cannot be lost by one individual alone.

- There are a diverse set of agents that contribute to intersection behaviour, including road users (e.g. drivers, cyclists, motorcyclists, pedestrians), road infrastructure (e.g. traffic lights, road markings, signage), vehicles, documentation (e.g. road rules), the natural environment and other infrastructure (e.g. buildings, advertising). SA is distributed across these agents. Attempts to improve SA at intersections therefore need to consider these agents together and how they interact with one another.
- Different road users, regardless of type, have differing views on the same intersection situations. We do not need or indeed want them to have the same view. This is highly novel in road design and is not something that is typically considered when designing road environments.
- Incompatibilities between intersection agents SA lie at the root of intersection collisions. For example, collisions between drivers and cyclists are often underpinned by one or both road users' understanding of the situation not fully incorporating the other's location and behaviour. Compatible SA is thus a key consideration when designing intersections.
- Continuous transactions in SA between agents serve to maintain the intersection's DSA. Incompatibilities arise when transactions are not optimal (e.g. incomplete, erroneous, misunderstood) or are not present. As with compatible SA, this suggests that transactions in SA between different agents should be a key design consideration.

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