The Adverse Effects of Paradigm and Pragmatism on Road Safety

With Case Studies in Traffic Conflicts Technique and Cyclist Safety at Roundabouts

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Dedicated to Dr Jacqueline Griggs and Rose Boyd. I am richer for having known you.

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Abstract

This thesis takes a multi-disciplinary approach to the hypothesis that "Engineering paradigm and pragmatism are having an adverse influence on road safety."

This proposition has been examined through a wide-ranging qualitative literature review, a systematic quantitative literature review and a survey of Australian road authorities. These provide evidence and reasons for adverse effects, drawing from both social science and engineering perspectives.

The hypothesis was then tested using two known problems in road safety and a proof by contradiction methodology. If rejecting accepted paradigm (case study 1) and pragmatic practice (case study 2) lead to significant new knowledge being found, then current paradigm and pragmatism are forming a barrier to optimal road safety research.

The paradigmatic case study considers Traffic Conflict Techniques (TCT), which theorises that crash risk assessment can be determined based on observations of normal traffic events. While TCT is used for problem diagnosis, numerous conceptual and practical difficulties prevent a Holy Grail for safety practitioners being realized: TCT cannot predict crash risk independently of a crash record. The case study considers this problem by rejecting the TCT paradigm and developing a new theoretical framework based on Extreme Value mathematical theory – the only proven basis for predicting rare events from observations of more common events. The method developed by this theoretical case study, labelled Traffic Events Theory (TET), overcomes all known problems associated with TCT. In particular, TET is mathematically complete and should therefore enable risk assessment to be undertaken without recourse to a crash record.

The pragmatic case study involves cyclist safety at roundabouts, and whether radial roundabouts are safer than tangential roundabouts. This has been theorised but cannot be shown using the pragmatic approach of associating crash data with geometric design features due to the inherent complexity of roundabouts. The pragmatic case study rejects the pragmatic approach in favour of an observational method applied to a tangential roundabout converted to a radial design. This has identified geometrically-related implications for motion detection in peripheral vision. In particular, the case study identified that tangential geometry created conditions under which an approaching driver could not physically detect a cyclist, exacerbated negative associations between cyclist tracking and safety, and made more likely situations where a circulating car will briefly hide a cyclist from an approaching driver.

These are all effects that have not been identified using the type of statistical safety studies that traffic engineers use for pragmatic reasons.

The case study results represent valuable contributions to road safety knowledge. They also confirm, under a proof by contradiction approach, that “Engineering paradigm and pragmatism are having an adverse influence on road safety.” That is, adverse effects on road safety are systemically-based with anecdotal case studies presented by other researchers not merely troubling incidents occurring in isolation.

But if this hypothesis seems critical of traffic engineering and the road safety field, it also offers practitioners the opportunity to reinvigorate their profession into the dynamic, politically-aware and socially-engaged practice that characterised the golden age of engineering.

1. Introduction

That road safety is an important issue in public policy does not need a literature review or survey of professionals to identify. Road safety campaigns are announced on the daily news, as are offences of high exceedances of blood alcohol or speed limits, and the annual road toll as at the latest fatality. "Road safety" represents government priority, a police warning, and a clear and present danger of the road system.

This has not always been the case. Road deaths in Australia rose along with motorisation from the first introduction of cars until 1970 when a concerted effort made to understand the causes of road deaths and reduce their incidence started to bear fruit. Australian authorities implemented a series of major road safety responses, starting with compulsory seatbelt legislation. The road toll has been reducing ever since, despite an increasing Australian population combined with increasing rates of motorisation. Figure 1 presents road toll data for NSW along with major events affecting the road toll. In 1910, there were about 4,000 motor vehicles in NSW, which then had a population of some 4.37 million people. In 2017, there were more than 6 million motor vehicles and a population of some 7.8 million, but the number of road deaths per 100,000 population in 2017 was less than half that of 1910[1]. Notably, at the peak of some 29 deaths/100,000 population, the number of motor vehicles registered in NSW was under 2 million[2], or less than a third of the way to 2017 levels, but more people were killed on NSW roads in 1970 than Australia-wide in 2017.

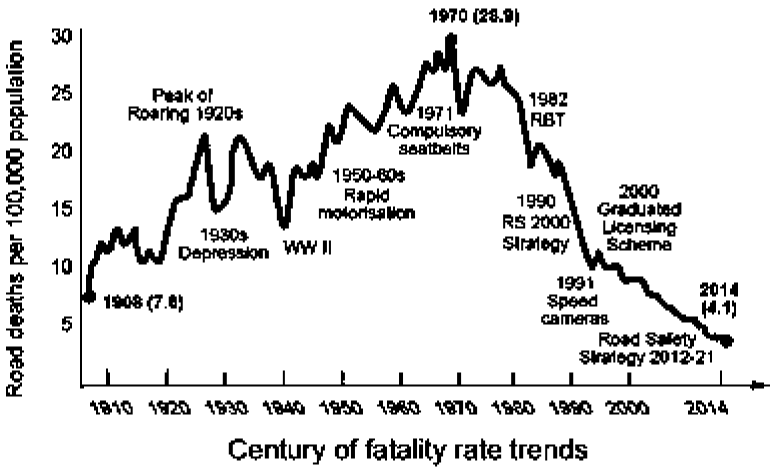

Figure 1: NSW road fatality rate trends 1908-2014

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[1] Transport for NSW Centre for Road Safety, https://roadsafety.transport.nsw.gov.au/statistics/fatalitytrends.html accessed 15 August 2020.

[2] Department of Motor Transport NSW 1969-1970 Annual Report.

The road crash trend is similar Australia-wide. The Australian peak for road deaths also occurred in 1970, at 30.4 per 100,000 population[3]. The road fatality rate in 2018 was 4.60 per 100,000 population, the lowest since records started in 1925[4], at which point the rate was 11.8 – noting that the 2018 figure also includes road fatalities for the Northern Territory (which are generally about three times higher than the rest of Australia[5]) while the 1925 figure does not.

Such an impressive road safety result is attributable to hard work from traffic engineers, police, public health advocates, doctors, researchers and many others. It is also mirrored to a greater or lesser extent worldwide as national governments face up to the road safety problem that accompanies significant motorisation, and the loss of people who are often in the most productive period of their lives. Most people would therefore be surprised to hear it claimed that those who design and operate the road system – and even the road safety experts who have developed and promulgated safety rules that attract police enforcement, fines and imprisonment – are ignoring evidence about road safety. Yet in Hauer (2019b), the author states that:

> "Decisions that highway and traffic engineers make significantly affect the safety of road users.... One would like this judgment to be informed by evidence-based anticipation of their likely safety consequences and by a professional ability to balance safety against mobility and other dimensions of 'utility'. I show that these desiderata are largely unfulfilled."

And, after presenting a number of rhetorical questions:

> "These questions are motivated by the ease with which road design and operational decisions that affect life and limb can be made on opinions and beliefs that are unsupported by evidence; they are prompted by the concern that one can adopt policies and procedures based on such beliefs and follow them for decades without the need for factual knowledge being recognized; they are aroused by the observation that when evidence runs counter to opinion the latter often wins the day."

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3 Office of Road Safety, OR 7, Road traffic accident data and rates: Australia, States and Territories 1925-1981.

4 Combining data from Australian Transport Safety Bureau (2005) "Road crash casualties and rates, Australia, 1925 to latest year", pub ATSB Canberra ACT; Bureau of Infrastructure, Transport and Regional Economics (2019), Road trauma Australia 2018 statistical summary, BITRE, Canberra ACT; and Bureau of Infrastructure, Transport and Regional Economics (2011), "Road trauma Australia 2010 statistical summary", pub. BITRE, Canberra ACT.

5 Australian Transport Safety Bureau (2003) "Road Fatalities Australia: 2002 Statistical Summary", p. 15. Pub Transport Safety Statistics Unit, ATSB Canberra ACT.

Hauer (2019b) blames engineering judgment for the problems he identifies: how it is developed (or not) and how it is applied. In a slightly earlier paper, the author examines the relationship between road safety researchers and traffic engineering practitioners and observes:

> "Road users have to trust that those who produce and operate roads act on evidence and safeguard their interest. This, as I have shown, does not always work as it should." (Hauer 2019a)

Here, he identifies multiple dysfunctions in the researcher-practitioner relationship detrimental to road safety, such as the difficulty of challenging unfounded beliefs once these are formed, and conflicts of interest.

Are Hauer's observations and conclusions accurate? While his papers present case studies in support of his arguments, these could be aberrations better regarded as exceptions to otherwise good practice, rather than evidence of a wider problem. This dissertation will argue that the issues Hauer (and others) identify are systemic problems that stem from a common cause, characterised by a combination of the approach engineers bring to traffic in general and to problems in road safety in particular (i.e. their paradigm); and their natural responses to practical factors encountered on a day-to-day basis (i.e. their pragmatism). In terms of a hypothesis adopted for the purposes of this dissertation, a shorthand version is:

> "Engineering paradigm and pragmatism are having an adverse effect on road safety."

To some extent, this thesis focuses on road safety research over road safety per se, where "research" includes assessment of road safety risks and determining cost-benefit rather than implementing physical treatments. However, these are so intrinsically interlinked that separating out road safety research over practice in the hypothesis would be misleading. In terms of Hauer's papers, this hypothesis treats entrenched "opinions" and "unfounded beliefs" that are broadly accepted within the road safety field as engineering paradigm, while adherence to adopted procedures and dysfunctional elements in the researcher-practitioner relationship that are not paradigmatic in nature are considered to stem from pragmatism.

As the commentary at the start of this dissertation should indicate, that an adverse influence exists does not deny that much good also exists and, indeed, dominates. Perhaps an alternative phrasing "…can have…" would capture this duality better, but this would not adequately express that adverse influences are currently occurring. An increase of only 0.1

per 100,000 in Australia's annual road toll applied to our population of some 25 million people is 25 lives lost per year. Serious injuries are typically an order of magnitude greater and other injuries greater still. Hence any adverse influence in road safety has the potential to reap a considerable human and social toll, and the phrasing of the hypothesis reflects this potential.

As Hauer might attest, that issues exist in the road safety field is apparent in many different ways. Given that traffic engineering for cyclists is a special concern of this dissertation's author, one such issue that displays systemic characteristics is the use of statistical safety studies to examine cyclist safety. This can be considered as a mini case study to help establish the intent of the dissertation's hypothesis.

As context, within the field of road safety, the practical research which assesses whether infrastructure interventions improve road safety outcomes takes the form of safety studies. "Statistical" safety studies take readily available, large volume, quantitative information from police reporting of crashes and counts of traffic undertaken by transport authorities and apply mathematical techniques to associate crash rates with factors that characterise a particular site: traffic volume, composition, speed, road geometry, etc. Correlations between risk and site/ infrastructure factors are used to determine what factors influence crash risk, and how, to ascertain the safety benefit of treatments.

While this might seem like a reasonable approach, statistical safety studies are subject to a number of well-documented limitations. Hydén (1987) mentions randomness and rarity of crash occurrences, lack of timeliness, data incompatibility (particularly when data is taken from different jurisdictions), lack of site information being collected as part of crash reporting, inconsistency in crash reporting, as well as regression to mean effects – the fact that infrastructure treatments are usually applied to sites with a higher than average crash record, but that this record may be a result of the randomness of crashes and a reduction in crashes may be a similarly random effect of crash statistics averaging out. Noland (2013) raises concerns about safety studies failing to account for randomness and contrary effects related to human behaviour. Hauer (2005) focuses on the use of regression analysis for cross-sectional studies (where sites with and without a particular treatment are compared to identify safety effects) and concludes that for similar reasons to those raised by Noland, cause-effect judgments made by such studies cannot be justified.

For safety studies focusing on cyclists, additional issues apply, notably in countries such as Australia that have a low cycling modal share: low cycling volumes result in low numbers of cyclist-involved crashes, making it difficult to correlate locations, types of treatments or specific infrastructure features to safety outcomes; small numbers in crash data mean that randomness and reversion to mean effects have a comparatively large influence; cyclist-involved crashes are significantly under-reported, exacerbating small numbers issues; cyclists are not counted on a routine or comprehensive basis and are difficult to count through methods commonly used for motor vehicles, but if the exposure of cyclists to risk cannot be determined, then nor can the degree of risk i.e. safety.

It should not be surprising that a Cochrane review undertaken by Mulvaney et al. (2015) concluded that:

> "Generally, there is a lack of high quality evidence to be able to draw firm conclusions as to the effect of cycling infrastructure on cycling collisions. There is a lack of rigorous evaluation of cycling infrastructure."

And more specifically regarding the evidence (which comprised police crash data in fourteen of the twenty-one studies):

> "We carried out a thorough search for relevant papers. The quality of the evidence was low with 20 of the included 21 studies using a controlled before-after study design. Few studies considered how factors such as weather and volume of traffic may affect collision rates. Few studies considered how changes in cycle rates seen as a result of installing infrastructure may affect changes in collision rates."

Similarly, Vanparijs et al.'s (2015) review of bicycle safety studies found that 98% did not collect exposure data, hindering meaningful analysis and interpretation of results. So if Hauer (2019a) sees research findings being ignored, then for cyclists, the research findings are not even being reliably established.

On an individual safety study scale, the effect of paradigm can be seen in that police crash data is considered of an acceptable standard for motor vehicle safety studies and is therefore used for cyclist safety studies even though it is clearly inadequate. A pragmatic element to this is that inexpensive, available data will be used in preference to significant, difficult and costly data collection. A similar paradigmatic/pragmatic couplet relates to vehicle volume data used (or not, in the case of bicycles) to establish exposure risks.

More broadly, that motor vehicle traffic is routinely and systematically counted whereas cyclist traffic is not reflects a different level of combined paradigm and pragmatism: if traffic engineers want to achieve the greatest reduction in crashes with given resources, it makes sense to target the worst crash types or locations for the majority mode (cars). Motor vehicle traffic data is vital to identifying these. The more difficult and costly counting of cyclists is only indicated when the data indicate major cyclist crash involvement in particular crash types or locations.

But how does this approach relate to moral dimensions such as the duty of care to vulnerable road users or children (who cycle but do not drive)? This question itself implicitly accepts this dissertation's hypothesis: that adverse effects on road safety are occurring (to cyclists); that these are systemic to the road safety practice of traffic engineers rather than being an aberration (a trade-off of resources is endemic to the practice); and insofar as the practice of traffic engineers embodies their approach, values and methods of doing things, this adverse safety effect stems from traffic engineering paradigm and pragmatic practice (through the norms and practices brought to a trade-off between cyclists and motor vehicles).

Additional questions could easily be raised, for example, regarding the contrary effect of inducing traffic (and hence increasing crashes) through "safety" works that make driving faster and cheaper; and so on. Such broader questions are vexed, multi-layered and worthy of in-depth consideration. Many similar questions have been raised by traffic engineers and road safety practitioners in documents such as Carter (ed.) (2017). However, while Carter (ed.) (2017) recognises the need for professional judgment to be applied, it does not guide how this professional judgment should be formed. Nor does it question what paradigm is brought to the trade-off between safety and mobility. (To contrast, Hauer's (2011) examination of Cost Benefit Analysis demonstrates that in some assessments, the estimations used mean that one hour of life is valued at less than one hour of delay).

This dissertation focuses on the individual safety study scale as more concretely demonstrating the effect. In doing so, it also proposes an underlying context that Carter (ed.) (2017) lacks and a framework for the work of Hauer, Noland and others. But if this dissertation emphasises the influence of engineering paradigm and pragmatism, these are not considerations well reflected in the academic literature produced by engineers, certainly in terms of why and how these form and perpetuate, often in the face of contrary evidence. To consider this, the dissertation must step outside the form of a typical engineering thesis and embrace sociological perspectives.

That is, if in this hypothesis, paradigm and pragmatism are considered to be naturally attractive in the road safety field – there is a tendency for these to emerge and be embraced in a largely engineering-based profession – then the professionals involved are far from orphans. A concept dating to the 12th century has been most familiarly expressed in English by Sir Isaac Newton (1675):

> "If I have seen further it is by standing on the shoulders of Giants."

There is no similar quote about making sure the giants are standing on firm footing, aren't leaning strangely, or suggesting that while one is up there, one ought look behind to see whether a nearby hill might give an even better view.

More concretely, the term 'paradigm' was popularised by Kuhn (1962) in his seminal *The Structure of Scientific Revolutions* – which Le Coze (2018) calls "…one of the most influential thesis [sic] in the field of philosophy and history of science of the 20th century" and Green (2016) notes is the single most widely cited book in the social sciences, at least according to Google Scholar. Kuhn argued that science does not progress via a linear accumulation of new knowledge, but undergoes periodic revolutions or 'paradigm shifts' in which the nature of scientific inquiry within a particular field is abruptly transformed. Le Coze (2018) summarises the import of Kuhn's work as:

> "The main idea to retain is that we, individually and collectively, make sense of reality through constructs which are fallible as time passes. Data are not picked up independently of established worldviews which organise meaning."

At a base level, this points to a tendency for humans to become invested in paradigms. In addition to a simple understanding of this as exemplified by a paradigm passed from teacher to student, the issues previously raised regarding statistical safety studies point to pragmatic choices forming a sort of practical or embodied paradigm, giving rise to a similar tendency to adhere to current practices. But if paradigm helps us make sense of reality, new information threatens that reality and humans will tend to ignore, minimise or reject findings that contradict established paradigm.

To progress knowledge in the most efficient and effective way, researchers and practitioners need to be aware of this effect and be open to methods of enabling an evolution of knowledge to occur through many smaller paradigm shifts rather than waiting for a paradigm leap to create a revolution. However, issues identified in traffic engineering practice indicate that these smaller paradigm shifts do not seem to be occurring, at least broadly enough and at a high enough rate to enable the most effective road safety response. Rather than this dissertation seeking to criticise road safety practitioners, it is hoped that it might help to highlight issues to these practitioners and promote evolutionary knowledge growth by underlining the need for this to occur – as well as opportunities that can flow from changes to the approach. If this seems a lofty aim, the alternative presented by Hauer (2019a) is bleak:

> "Just describing some dysfunctions of the current research-practice relationship, as I did here, is not likely to induce action. Too many have too much at stake in the status quo. Action is likely to come when road-users and their political representative will recognize that whenever opinion is used by those building and operating roads rather than evidence, road-user safety and taxpayer interest are likely to be compromised."

Structure of the dissertation

This dissertation is structured in a fairly conventional way. The literature review in Chapter 2 examines what is meant by engineering paradigm and explores the current understanding of 'engineering paradigm' as this applies to traffic engineers and road safety practice. Evidence for adverse effects from paradigm and pragmatic factors is found in science and engineering across multiple fields of enquiry, with various drivers for the effect and application to both traffic engineering and road safety research.

Chapter 3 then presents the methodology adopted in this dissertation. In response to the scientific tradition that underlies engineering epistemology, the methodology involves reforming the thesis' proposition to support a proof by contradiction approach, based on demonstrations of paradigm and pragmatism undermining efficient production of road safety knowledge. Two case studies are outlined, one focusing on paradigm and the other on pragmatic practice. For readability reasons, the case study results are presented in separate chapters.

Chapter 4 presents a reconsideration of the theoretical framework for Traffic Conflict Techniques (TCT). TCT has been proposed as a method for undertaking safety studies based on observing traffic interactions as a proxy for crashes, hence enabling the limitations of crash data and its collection to be overcome. However, TCT in practice falls short of its theoretical potential, in addition to which current practice is associated with a long list of unresolved conceptual issues. The case study adopts the proposition that the paradigm embedded in TCT's theoretical framework has exacerbated rather than aided resolution of these issues and impeded the realisation of TCT's potential. Using the logic of proof by contradiction, if the body of knowledge represented by the theoretical framework (i.e. paradigm) has optimally advanced TCT, then rejecting its paradigm and reconsidering TCT from first principles should not give rise to a new approach that can address outstanding issues. Chapter 4 presents the results of such a rejection and reconsideration.

The second case study is presented in Chapter 5. This examines the safety of roundabouts for cyclists – specifically, the difference in safety performance of roundabouts designed using a tangential design philosophy (common in Anglophone countries) versus a radial design philosophy (common in non-Anglophone countries). Previous research gives some indication that radial roundabouts are safer for cyclists than tangential roundabouts, however the significant variability between individual roundabouts coupled with low volumes and crash involvement of cyclists makes it difficult to confirm the safety association or establish causal reasons for it. Statistical safety studies point to vehicular speed as being the dominant driver of safety at roundabouts. The assumption that the lower speed environment produced by a radial roundabout over the equivalent tangential roundabout is likely to explain the safety benefits implies that a similar result can be achieved using speed-reducing treatments in general. The case study theorises that the pragmatic use of mass data in safety studies has led to other causal factors for better cyclist safety at radial roundabouts being overlooked (and the implication that design approaches at roundabouts relying on speed reduction alone will not achieve an optimum safety benefit for cyclists.) Using the logic of proof by contradiction, if it is true that statistical safety studies have optimally identified causal factors, then an observational safety study should not be able to identify any other causal factors. If such non-speed causal factors can be identified, then the pragmatic use of statistical safety studies in preference to other types of safety studies indicates pragmatism is undermining the advancement of road safety knowledge.

Chapter 6 summarises the dissertation, discusses the significance of the research in terms of both the hypothesis and the case studies, and considers future research directions. This is followed by a conclusion in Chapter 7. Chapter 8 completes the dissertation proper by presenting references.

Five appendices are also provided, labelled as A to E.

2. Literature review

Introduction

The hypothesis that engineering paradigm and pragmatism are having an adverse effect on road safety reflects the fact that roads are generally designed and managed by engineers. This does not mean all people responsible for the transport system are engineers, but the majority of both engineers and non-engineers responsible for the care, control and management of road infrastructure are effectively disciplined into acting and thinking as engineers. Australian evidence for this can be seen by the technical guidance used by road authorities in designing and managing roads. While now superseded, *Traffic Engineering Practice* was first published by the National Association of Australian State Road Authorities in 1965 as:

> "… a practical guide to traffic engineering for highway and transport engineers in Road Authorities, Local Government, and engineering consultants, and as a reference for engineering students." (Austroads, 2006).

Engineers are clearly the focus for the publication because they are the ones tasked with responsibility over roads. Reconfigured into a series of parts between 1988 and 1999, and updated over the years, the various *Guides to Traffic Engineering Practice* remained as the default guidance for Australia and New Zealand until replaced from 2007 onwards by an equivalent set of Guides to Road Safety, Road Design and Traffic Management. Although extensively based on the previous guidelines, the new series omits references to "engineer" or "engineering" in its title.

More specifically, then, the hypothesis of this dissertation is that those who work in improving road safety ("road safety practitioners") are influenced by the paradigm embodied in the (traffic) engineering mindset and by pragmatic responses to professional realities. This is evident in research activities in the topics examined, methods used and viewpoints brought to analysis and interpretation; and in the technical practice that then emerges in response to research findings. Current research informs not only future research, but contributes to the profession's "body of knowledge", as embodied by formal documents such as road design guidelines and the behavioural norms incorporated into management of the road system – such as speed limits or road rules. A research agenda that is not pursued in the most effective way can have a long-term impact on the safety of road users. That traffic engineers might be taking a less than optimal approach to road safety research or its results has already been noted in Chapter 1, regarding the weaknesses of using statistical road safety studies to understand the impact of infrastructure on cyclist safety.

The methodological approach used in undertaking this literature review, as well as reviews of other literature undertaken in other parts of the dissertation, are provided as Appendix A. As an overview, the traditional role of a qualitative (or narrative) literature review is to identify the extent of academic thought regarding a thesis topic and thus establish a framework for analysing research findings. However, very little literature was identified that directly addresses the hypothesis as framed. The most relevant was found in the field of road safety research, but even this literature tends to provide tantalizing glimpses rather than a sustained focus on the topic. On the other hand, literature in other fields both implicitly supports and/or illuminates the hypothesis, but usually as part of examining a different topic.

Therefore, this literature review addresses the hypothesis by first considering what the broader literature reveals about "engineers", the "engineering paradigm" and pragmatic influences on both. Sub-headings are provided within the literature review as an aid to following the themes explored. While this would seem to indicate a literature review based on sociology, Australian engineering perspectives are also drawn upon to further illuminate themes and topics[6]. The literature review thus provides a multi-disciplinary view rather than being grounded in any one theoretical framework of either sociology or engineering. It is also a view that uses the Australian experience as a continuous narrative thread, albeit that the themes and content are explored through the international literature and, where comparative information is available, are broadly reflective of OECD trends.

The themes and understandings developed from the broader review of literature are then used as a lens (or theoretical framework) for examining the scant but more relevant literature produced by the field of road safety, enabling a textured and nuanced consideration of this literature despite its paucity.

The Chapter 2 literature review concludes with a short summary integrating themes and historical perspectives into a narrative view of the hypothesis.

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[6] This focus on the Australian perspective reflects a systematic quantitative literature review undertaken at the outset of the thesis process that identified historic narratives regarding the evolution of traffic engineering as a practice in Australia (Appendix B). This was found in the 'grey' literature not available via academic databases and not similarly identified for overseas traffic engineering traditions.

Engineering and the scientific tradition

Literature dealing with the philosophy of technology displays a great deal of interest in the concept of engineering paradigm, in the form of epistemology – defined by the Oxford English Dictionary (2019) as:

> "The theory of knowledge, especially with regard to its methods, validity, and scope, and the distinction between justified belief and opinion."

Summarising the main authors, concepts and developments in the philosophical study of epistemology[7] would exceed the scope of this dissertation. A starting point for the epistemology of engineering is the concept of the scientific tradition. Russell (1945)[8] explains what being 'scientific' entails as:

> "In the welter of conflicting fanaticisms, one of the few unifying forces is scientific truthfulness, by which I mean the habit of basing our beliefs upon observations and inferences as impersonal, and as much divested of local and temperamental bias, as is possible for human beings."

Crotty (1998) describes the scientific tradition as having an objectivist epistemological view, i.e. that truth and meaning reside as knowable objects; and a stance of logical positivism, i.e. the belief that this objective knowledge can be identified through empirical observation or logical deduction. Engineers are well recognised as operating within this tradition. The greater question pondered by the philosophy of technology is how technology differs from science.

Here, Boon (2011) starts with Aristotle's consideration of scientific versus technological epistemologies over two millennia ago. He sees Aristotle's differentiation between *epistêmê* and *technê* as analogous to the idea held by many modern authors that "science aims at truth while technology aims at use." Boon argues that in the strictest sense, this differentiation does not exist and science and technology as epistemological practices cannot easily be distinguished. Boon goes on to argue that Bunge's (1966) advocacy of the (alternative) "technology as applied science" concept has been misrepresented and, though dated, this is more relevant than the position taken by subsequent authors, whose focus on technology and

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7 In the literature, "epistemic" is used synonymously with "epistemological". Although the former is shorter and easier to read, the latter occurs more frequently and is the version used in this dissertation.

8 Bertrand Russell's (1945) classic *A History of Western Philosophy* is a good primer for concepts and conceptual issues, stretching as it does from Greek civilisation to the early 20th century.

technological design has resulted in the epistemological relationship between science and technology being overlooked.

Boon defines engineering science as "scientific research in the context of technological applications" i.e. having the same epistemological aims and methodologies of science, but also having domain-specific objectives. This is differentiated from technology, technological design or engineering design, though Boon does not define this last field. He does, however, present two characterisations of engineering design to demonstrate that it is distinct from engineering science. The first of these is Dym and Little's (2004):

> "the systematic, intelligent generation and evaluation of specifications for artifacts whose form and function achieve stated objectives and satisfy specified constraints."

The second is from the US Accreditation Board for Engineering and Technology:

> "the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic science and mathematics and engineering sciences are applied to convert resources optimally to meet a stated objective."

Much more has been said regarding the complexity in the distinctions and relationships made between science and technology/ engineering. To give some feel for this:

- Figueiredo (2008) implies engineering is clearly distinct from science in his proposal for a model based on transdisciplinary relationships.
- Koskela et al. (2017) contrasts Rankine's 1872 characterisation of engineering design as an approach of logical deduction to Shewart's 1931 focus on engineering in industrial production, and the roles of induction and abduction in addition to deduction.
- Grimson and Murphy (2015) propose a three-layer model to describe the epistemological basis of engineering, comprising a foundational layer of subject material such as mathematics and science, a middle layer of domain knowledge related to engineering problem learning outcomes, and a capstone layer of engineering competences.
- De Vries (2003) uses an empirical case study to show that technology cannot be described adequately as applied science, that different types of technological knowledge can be distinguished, and that defining knowledge as 'justified true belief' is not very appropriate for defining technological knowledge because it does not do justice to all types of technological knowledge.

- Frezza, Nordquest and Moodey's (2013) approach to differentiating 'science' from 'engineering' and 'engineering science' suggests that the purpose and manner of knowledge application are useful distinguishing features.

What is clear is that engineering is grounded in the scientific tradition, with considerable debate as to how (and even whether) engineering is differentiated as a practice from science. Unfortunately, the sociological literature does not consider in any detail how engineering epistemology affects the production of engineering knowledge in specific rather than generalised terms i.e. while the broad question of how engineers constitute 'knowledge' is considered, the process by which 'practice' becomes constituted is not.

Lloyd, Ferguson, Palmer and Rice's (2001) book *Engineering the Future: Preparing Professional Engineers for the 21st Century* provides an overview to Australian engineers' perspectives in terms of engineering epistemology. The authors distinguish engineering from technology by characterising technology as a body of knowledge related to adapting the physical world to human needs. Engineering is then a practice developed from the need to create artifacts or systems of technology, and operating within the natural laws of science.

Lloyd et al. (2001) are dismissive of assumptions that only scientists conduct "pure science" (i.e. the extension and refinement of knowledge by research), given that at the time they were writing fewer than 30,000 Australians with science qualifications were engaged in scientific research and development while some 15,000 engineers were undertaking research and development. Despite engineers numbering only half as many as scientists, and mainly worked in the manufacturing and infrastructure industries, the reasonably comparable populations do not point to a major epistemological schism between technology and science. However, Lloyd et al. do acknowledge paradigmatic (in their words, "standpoint") differences between engineers and scientists. They considered these to be derived from differences in educational formation and practice approaches. Without examining their reasoning in detail, 'educational formation' arguably reflects some degree of paradigm while 'practice approaches' raises the potential for pragmatism to become incorporated into "standpoint" differences. This describes a way in which pragmatism becomes incorporated into a professional engineering paradigm, over and above an epistemological driver for practice.

A more detailed view of traffic engineering in Australia is given by McLean (1998), in an invited paper of the 14th Australian Road Research Board Conference. He reviewed the development of the traffic engineering profession and of road research in Australia from its inception in the 1950s and concluded that Australian traffic engineering research (‘engineering science’) was characterised by the tradition of a rigorous, analytical approach to the investigation of traffic problems (i.e. an approach compatible with the scientific tradition), input from a range of specialist (non-engineering) disciplines, and strong interaction between the research and practitioner communities. This last point echoes sociological differentiations between science/ engineering science, and engineering and/or engineering design. But how set are the paradigms within each of these? The literature tends to use static language in describing paradigm, whereas practices can and do change[9].

To appreciate McLean’s (1988) snapshot of the road safety field in terms of the evolution of engineering paradigm, it is useful to contrast his narrative with Moore and Hughes’ (1991) review of the roles of manager, practitioner and researcher in Australian road safety research. These papers present quite different perspectives of what is ostensibly the same profession, probably due to McLean’s retrospective view.

As a start, the brief mention of “the investigation of traffic problems” above perhaps skips over an important epistemological characteristic of engineers highlighted by Moore and Hughes. A theme to emerge from their work is the high value engineers base on problem-solving and the application of research findings compared to other researchers. This points to the difference between science and engineering science being in the outcome, and the difference in value given to problem-solving being epistemologically based.

McLean (1988) provides detail about the non-engineering input to Australian traffic engineering research by first identifying two different approaches to road safety studies: comprehensive analysis of accident data – the “mass data” approach – and the detailed examination of a limited number of accidents – the “in-depth study” approach. Mass data approaches were hampered by a lack of data. The lack of data also hampered the road safety agenda, apart from adoption of systematic data collection programs. However, an in-depth study found strong sociological factors associated with road safety, which gave rise to the conclusion that road safety could not be considered solely from an engineering perspective. The road safety agenda was therefore constructed around human effects.

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9 This may be implicit in the epistemological literature’s references to ‘knowledge’, as knowledge does evolve and develop. Lloyd et al.’s ‘body of knowledge’ perhaps implies this more strongly, as ‘knowledge’ can also possess overtones of immutable truth.

By Moore and Hughes' time, accident frequency studies – using McLean's mass data approach – dominate over other investigation techniques:

> "Accident frequency is a basic tool used by traffic management authorities to identify hazardous sites for possible remedial treatment. However road safety practitioners often have a limited view of sites and tend to rely on traditional investigation techniques and countermeasures. Consequently there is a need for research to develop improved techniques for investigation. The roles of manager, practitioner and researcher provide the interaction between need, research and practice. The interaction between these elements should be improved to develop more appropriate analytical techniques."

Moore and Hughes' differentiation between researcher and manager or practitioner implies that all road safety practitioners operate within the same paradigm, if not actual discipline, and that is of the traffic engineer. Moore and Hughes thus signpost a loss of interdisciplinary imperative and a convergence of practice around "traditional investigation techniques" compared to McLean. The professional paradigm has changed.

Further, while McLean's review treats mass-data and in-depth study approaches essentially equally, Moore and Hughes consider accident frequency as a "basic tool", with (all) other forms of analysis now secondary. But in assessing the risk related to any given accident frequency, knowledge of traffic volumes is necessary to provide an exposure basis for comparing different results. McLean points to a major achievement of Australia's traffic engineering profession being a count scheme that would enable traffic volume data from permanent stations and sample surveys to be expanded to network-wide estimates of traffic volumes and growth factors. In Moore and Hughes' world, the count scheme is now providing this information – and McLean's "consolidation phase" and "progressive implementation and refinement of proven techniques" is now considered to have "narrowed road safety practitioners' view of sites." More specifically, Moore and Hughes state:

> "In this environment it is easy for practitioners to [content] themselves with existing analysis tools and continue to apply old methods in selecting and verifying improvement projects… In addition, there is the risk that novel analysis methods, however well supported by rigorous research, may be judged less acceptable to top level program managers than the time honoured proven techniques."

Research produced using novel or innovative methods is more likely to be ignored and the pragmatic response is to avoid these methods. It would seem that McLean's brave new world of quantitative data has produced more than one unintended consequence.

The willingness of researchers to use "old methods" or "time honoured proven techniques" mirrors the results found by Foster, Rzhetsky and Evans (2013) and Rzhetsky et al. (2015) of pragmatic considerations having a major influence on scientists' choice of research subjects – a topic that will be explored in more depth later, in relation to disciplinary boundaries. Moore and Hughes point to other pragmatic reasons for inefficient research agendas that are equally difficult for researchers to ignore:

> "…[there is a] demand driven by public opinion that sites where there are high accident frequencies should be upgraded. This demand is reinforced by the manager's own social conscience and in the past year a very large window of opportunity has been opened by the Commonwealth Black Spot Program. The sudden need to increase the traffic output of improvement projects brings with it a compelling need to streamline analysis methods and to produce documentation of projects to a standard sufficient for the purpose of securing Commonwealth funding of the projects."

To some extent, this describes an example of the "fallacy of defence-in-depth" argument, which will be covered as part of exploring engineering judgment. It also describes a situation led by paradigm. Relying as they do on a calculation of crash numbers, Black Spot programs are an extension of McLean's mass-data approach involving comprehensive analysis of accident data – though with methodologically weaknesses that are ignored, for example, reversion to mean effects or confounding effects from behavioural adaptation. Those for whom the domain-specific logics for judging quality align with Black Spot analysis results – whether or not they are engineers – drive a research agenda that aligns with the engineering paradigm. For pragmatic reasons, engineers comply with rather than challenge the given agenda. Doubts regarding the efficacy of Black Spot programs are conspicuously absent[10]. Nor is commentary made about how public opinion has been formed about the importance of road safety. This is an agenda pushed by road safety practitioners, with McLean (1988) noting that the National Safety Council had been directed its efforts at creating public awareness of growing accident rates and exhorting motorists to "drive safely".

Taking a wide-view perspective, Moore and Hughes (1991) paint a picture of engineers as applied sociologists in the mould of Law and Callon (1988), namely as engineer-sociologists

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[10] Austroads undertook a review between 2013-17 of treated Black Spots that did not achieve expected safety benefits. While one of the intended outputs was to "identify why targeted treatments failed expectations", the other two were to "assess if correct treatments were used and/or correctly installed and maintained" and "recommend improvements to treatments, procedures and processes". These point to the expectation that a poor result reflects a failure of engineering practice rather than weaknesses in the Black Spot approach.

enforcing their paradigm on multiple aspects of a system through pragmatic responses to other engineer-sociologists. That is, engineer-sociologists influence public perception, which in turn creates political pressure for the Black Spot program; they establish assessment standards for Federal funding; and researchers choose methods that produce the greatest amount of output that satisfies these assessment standards[11].

Moore and Hughes do not acknowledge paradigmatic effects or lack of interdisciplinary thought as affecting research. The authors instead point to the distance between practitioner and researcher as a root cause for inefficient research, considering that the more removed researchers are from users, the more likely that results of research will not be put into practice. Nor do Moore and Hughes mention a feedback loop that could result from engineering managers making a pragmatic or conservative decision to favour "proven" (i.e. traditional or mass-data) techniques, namely that the people they manage will also avoid research based on non-traditional (or novel) methods – whether in commissioning/ undertaking such research, or supporting it, or applying its findings. Such a feedback loop will entrench a paradigm of conservatism into research agendas and discipline the next generation of engineering manager into valuing paradigmatic inflexibility.

There are indications in Moore and Hughes' work that such a feedback loop may already have developed, with the authors themselves appearing to assume that all actors they identify in the research "problem" – managers, researchers and practitioners – should or do approach the problem in an engineering manner. In particular, after acknowledging that a balance needs to be struck between curiosity-driven (basic) research and applied research, the authors note that:

> "Research as an end in itself is usually wasteful and therefore socially unjustified. It may be useful to the researcher and the research community to undertake research which does not yield any immediate return. However in times of economic downturn there is a strong incentive to avoid expenditure of resources without the expectation of an appropriate return."

This is a value assessment: given their previous statement that basic research presents new opportunities, compared to applied research being more likely to lead to community benefits

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[11] The setting of assessment standards may also have been in response to McLean's description of generational iterations of engineer-academics training engineers, many of whom will go on to be engineer-academics training the next generation. Rojter (2004) points to this situation occurring in his description of engineer-academics being preferentially recruited as university lecturers while Lloyd et al. (2001) present evidence of engineer-academics with no background in management delivering 60% of management courses for engineers.

in the short term, the absence of "wasteful" and "socially unjustified" research could arguably lead to a depreciation of research assets over time. This value assessment is not further questioned or debated. Again, there is an assumption of values being understood and agreed to by author and reader. But given the authors' previous positive statements about basic research, at least the final sentence in the above quote could be read as a statement of what is rather than what should be.

Engineering as a profession

Historically and epistemologically, engineering may have its roots in the scientific tradition, however the characteristics that now define "engineering" are more commonly recognised in terms of engineering as a profession.

In the post-war period, the professionalisation of occupations has grown apace. To give some indication of this, between 1940 and 2019, the proportion of people aged 24 to 29 graduating with a bachelor degree in the US rose from 38.1% to 93.5%[12]. The situation is similar amongst its OECD peers, such as Australia. Along with this, the sociology of the professions has developed as a field of study – and an extensive one at that. Barber (1963) observes that:

> "Although it is still only a partly developed field of specialized knowledge, the sociology of the professions is already too large a body of theoretical analysis and empirical research to be more than sketched in this paper."

Barber was writing some twenty-five years after the sociology of the professions became a recognised field and some fifty plus years ago. Nonetheless, Barber's paper discussing "Some problems in the sociology of the professions" is still relevant in two important methodological ways.

- Firstly, Barber (1963) views the professions in general. That is, the forces and processes that lead to professionalisation have an overarching commonality. This is relevant because authors tend to view their experiences and understandings from "within the whale". It should instead be remembered that literature regarding other professions could be applicable to engineering – albeit that some care needs to be taken in the interpretation.
- Secondly, the contrary effect of Barber's broad view is the lack of insight provided into engineering in particular: a tension exists between breadth and depth. In terms of

[12] National Center for Education Statistics, US Department of Education, *Digest of Education Statistics*, https://nces.ed.gov/programs/digest/d19/tables/dt19_104.20.asp accessed 15 September 2020.

following a topic or theme, this can be offset by recognising that the intersection of two broad views can be used to provide a narrower focus.

Regarding the concepts developed through the study of the professions, Buyruk (2013) provides a succinct summary of the fundamental characteristics defining a profession, as described by seminal authors in the field. These are:

- high-level systematic knowledge gained through education;
- a central professional organisation; and
- autonomy for its members in the execution of the occupation.

Lloyd et al. (2001) provides an alternative view to this sociological perspective. For these authors, the emergence of engineering as a profession in Australia involves establishing reputational strength, which reflects efforts to develop engineering both in Australia and worldwide. This is compatible with Barber (1963) and Willmott's (1986) descriptions of professionalisation. However, Lloyd et al. (2001) contend that professionalism amongst engineers working as employees in a position subordinate to a 'client' is distinct from professionalism conceived as for, say, medicine, which is practised in a state of individual autonomy – a distinction not explored by either Barber or Willmott, and at odds with Buyruk. Lloyd et al. further question whether sociological assumptions of 'professions' that stem from the Industrial Revolution remain current. These assumptions principally relate to the social organisation of the professions and cultural inculcation such as employee status, mentoring within workplaces and a voluntary professional body applying a code of conduct.

In other respects, Lloyd et al.'s (2001) work reflects concepts from the sociology of the professions. The authors include a detailed consideration of the evolution of engineering education, the Institution of Engineers as its professional body and the status of the engineering profession in Australia. The authors have little to add to the question of paradigmatic or pragmatic influence on the production of engineering knowledge, for engineers generally or road safety in particular.

Overall, Buyruk's summary is considered to provide a useful framework for breaking the field of the professions into thematic areas in which engineering paradigm and pragmatism can be more feasibly examined.

Education and paradigm

Considering systematic education as a characteristic of a profession, and its results as the professional paradigm, studies in education and the professions intersect in the development of a student into a professional.

Gray and Fernandez (2018) note that in educational research, studies tend to focus on how students develop "designerly" identities rather than exploring underlying epistemologies and the ways these impact on identity commitments. That is, most studies tend to describe and analyse rather than explore and critique. An example of this is Weedon's (2016) examination of the development of engineering judgment. Weedon describes and analyses a group of students engaged in a design project, but does not consider how effectively the approach develops engineering judgment, the quality of the judgment produced, or whether this judgment engages with other taught practices. This focus on description/analysis is unfortunate as this thesis' hypothesis concerns the explore/critique side of the equation.

But if the effects of paradigm and pragmatism are not explicitly explored in educational research, the need for an appreciation of a societal understanding and social skills by engineers is stressed by several authors. That this typically highlights concern about their absence rather than their presence raises questions about whether the skills of graduating engineers are sufficient for their practice needs. This is relevant to the hypothesis in terms of a professional engineering paradigm leading to sub-optimal results.

Glover and Kelly's (1987) discussion of the standing of the engineering profession points to the potential value of humanities training to engineers, and in support of this position cites the 1980 Finniston report on the engineering profession and its problems[13]. The need for a sociological imagination has been stressed by several authors in more recent years:

- Mulder (2000) notes that the rationalist approach of engineering instruction focusing on scientific and mathematical principles is not a solid base to solving society's modern problems, especially as these are only in part of a technological nature; and that cultural, ethical and organisational issues are often not only preconditions for a solution, they are part of the realm in which an engineer has to develop solutions.

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[13] The Finniston report documented the outcomes of the Committee of Inquiry into the Engineering Profession led by Sir Monty Finniston. The inquiry was established by the UK Labour Government of the time in recognition of dissatisfaction in the engineering industry with the Council of Engineering Institutions (Hamilton, 2000).

- Lloyd et al. (2001) contend that every engineering process, construction or product is an outcome of the complex interactions of human values, knowledge, skills and limitations.
- Menzel, Aaltio and Ulijn (2007) identify entrepreneurialship and organisational intrapreneurialship as the basis of technological innovation and firm renewal. As engineers have the role within companies of producing and developing innovations, engineers must be able to cooperate well with other fields of expertise, with both technical knowledge and social knowledge required to make these innovations meaningful.
- Frezza, Nordquest and Moodey (2013) argue that the best engineering answers are judged pragmatically and routinely involve social context, with these aspects being intrinsically necessary to the foundations of engineering.
- Trevelyan (2013) notes that many more perspectives can be brought to the practice of engineering than are usually evident in discourses on engineering education. He follows this up in Trevelyan (2014) by demonstrating the extent to which Australian engineering practice now involves the use of skills such as negotiation and communication, with the application of scientific knowledge becoming a minor element of the engineering task.
- Cunningham and Kelly (2016) draw from empirical studies of engineering in practice to identify the social contexts of engineering as a major part of engineering practices.

Other literature exposes an engineering paradigm amongst at least students and early-career engineers that is at odds with sociological elements of practice needs. King and Magun-Jackson (2009) cite Paulsen and Wells (1998) as finding that engineering students are more likely than students in humanities/ arts, social sciences and education to believe that knowledge is certain, simple and acquired quickly; and Trautwein and Ludtke (2007) as finding that engineering students are more likely to have naïve certainty beliefs than students in other academic majors (humanities/ arts, mathematics/ natural sciences, business, social sciences, medicine and law), as well as being the only group to show an increase – albeit slight – in their certainty scores during the period of the study. Beddoes, Montfort and Brown (2017) also cite research suggesting that engineering students do not change as epistemologically during undergraduate education as other students. However, their own work found contextual variations in how students express epistemological belief and brings into question whether single-dimensional studies adequately capture complicated epistemological stances. This work was based on examining personal epistemologies rather than developing a normative philosophy of engineering or an understanding of an overarching "engineering epistemology."

Gray and Fernandez (2018) more positively explore how engineering practice is influenced by epistemology. Their approach analyses in depth the way assumptions are made by students by using critical qualitative meaning reconstruction. Their case studies describe how three engineering students in a transdisciplinary undergraduate program struggle to engage with ontological and epistemological perspectives in relation to human-centred engineering approaches and socio-technical complexity[14]. This reveals characteristic barriers in how students engage with other people's viewpoints, plus related epistemological and ontological claims implicit in these viewpoints. Again, this provides indications of a strong and inflexible epistemology amongst at least student engineers.

However, as with other research focusing on undergraduate rather than practising engineers, these results do not provide evidence about the epistemological growth students may need in order to become effective engineers. Gray and Fernandez' case studies illustrate situations in which paradigm formed along disciplinary lines does not support effective transdisciplinary practice, but this may be adequate for disciplinary practice. And a further four students whose experiences were not used as the basis for case studies could perhaps have had no similar struggles within the transdisciplinary program.

Overall, though, these educational studies paint a picture of students going into engineering education with an already-established paradigm biased in favour of technical knowledge over social knowledge. This is actually not an unreasonable position, given the typical pre-requisite competencies required for the engineering degree. But engineering education does not seem to be effective at developing students' social skills, leading to the likelihood that the engineering paradigm of at least graduating and early career engineers is inadequate for their actual practice needs. It should not be surprising if what is classed as professional engineering paradigm at graduate level leads to future sub-optimal results.

Considering the Australian perspective, Rojter (2004) reflects on the developments of the preceding decades, focusing on engineering education. Rojter cites Hudson (1975) as finding that (possibly British) humanities students were more effective in conceptualizing an issue

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[14] Ontology refers to what sort of things exist in the social world and assumptions about the form and nature of that social reality. It is concerned with whether or not social reality exists independently of human understanding and interpretation; for instance, is there a shared social reality or 'multiple context-specific realities'. (Michael Bergin, Waterford Institute of Technology, 2017.)

into a problem which could be further conceptualized, while engineering graduates were less conceptual but more effective in setting the parameters of the problem and, in a mechanistic way, solving it. Rojter considers that a combination of both skills best describes the needs of engineering practice, and the basis of a reflective practitioner. Rojter also describes a survey of Australian employers undertaken in the late 1980s showing concern with the lack of social literacies and knowledge of human affairs amongst engineering graduates. Employers placed a high priority on addressing these subjects through engineering curricula, even at the expense of core engineering and fundamental science subjects. A 1991 survey of government, private and multinational companies conducted by Monash University found that a knowledge of languages was highly valued, probably with an eye to globalization. Both of these surveys reflected skills and knowledge required in the workplace but not acquired in engineering education.

In contrast, Koehn and Koehn (2006) seem to contradict Rojter's 1980s employer survey result by finding that employers of civil engineering alumni rated "The broad education necessary to understand the impact of engineering solutions in a global/ societal context" at a lower level than ten mainly technical subject areas. However, this could: reflect the phrasing, which emphasises the global; point to changes in engineering education over the interceding twenty years; or reflect differences in engineering education and practice between Australia and America.

Lloyd et al. (2001) broadly agree with Rojter but perceive problems in the curriculum in terms of engineering management. Lloyd et al. criticise the failure of universities to meet the minimum set by the Institution of Engineers that 10% of course content be management studies, and the subsequent watering down of this goal. Lloyd et al. (2001) cite several sources in regard to this. A submission by the Association of Consulting Engineers, Australia (ACEA), to a 1987 task force on management education noted that:

> "…most engineers were not people orientated, and that many lack communication skills."

ACEA proposed to moderate the emphasis given to technological subjects in favour of an early grounding in management studies, suggesting about 15% of course time as an appropriate level for the latter.

A 1988 Review of the Discipline of Engineering, chaired by Williams, found that employers:

> "…judged as unsatisfactory the [lack of] emphasis given to oral and written communications skills, industrial relations and the management of people, the management of costs and resources, engineering as part of a broader business context, and the involvement with non-engineering disciplines in project work."

The 1992 report *Skills for the Future – Engineers and Scientists Achieving Enterprise Performance* reached the same conclusions, but also found confirmation of employers' criticisms in feedback from young engineers.

In 1998, a survey undertaken of all 93 separate academic faculties, departments and schools in Australia offering engineering undergraduate courses asked respondents to rate factors from 1= not important, 2= important, 3= very important. The results are shown as Figure 2.

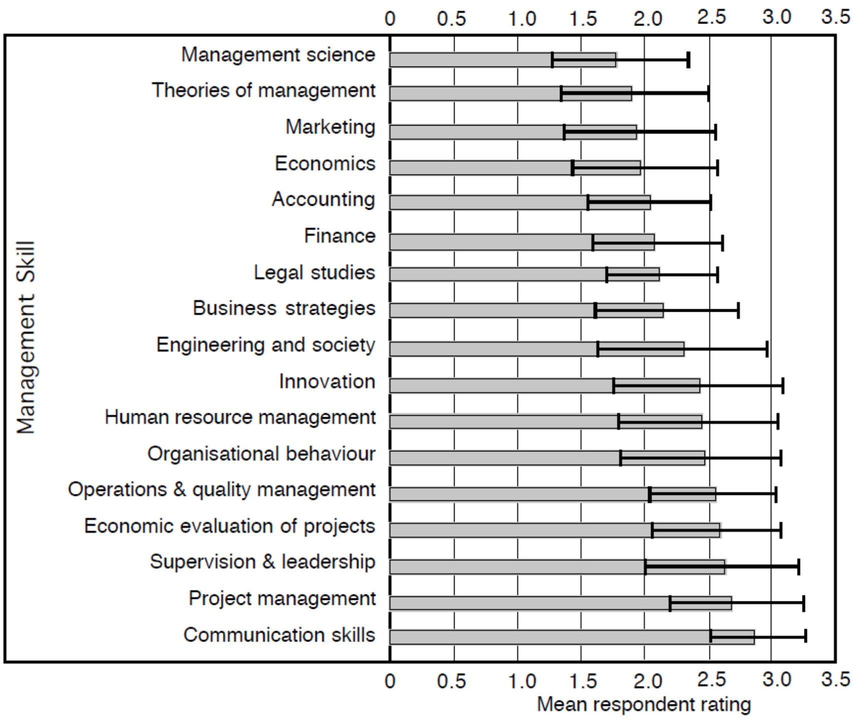

Figure 2: Mean importance of management skills. Source: Lloyd et al. (2001).

The three elements rated as having the highest importance are arguably non-technical, albeit that most might be considered 'non-technical' by engineers. "Engineering and society" rated mid-field and noticeably higher than the next element of "Business strategies", though this is slightly obscured by the error bar[15].

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[15] These results are not directly comparable to Koehn and Koehn (2006), but there is some similarity in the ranking in the latter's survey of "The broad education necessary to understand the impact of engineering solutions in a global and societal context" at tenth in a list of fifteen, given that some of the fifteen combine multiple factors that are stand-alone in the 1998 survey – notably "An understanding of the elements of project management, construction, and asset management" and "An understanding of business and public policy and administration fundamentals."

More philosophically for the profession, Sharma et al. (2018) point to the problems of an ongoing under-representation of women in engineering for Australia, where only 6,000 of the 18,000 required positions of engineers every year are filled by graduates from Australian universities (the rest coming from outside Australia). While the capacity implications for the country are arguable, Engineering Australia President, Trish White sums up resulting concerns:

> “We're very concerned about the lack of graduates coming through. To have a strategy where we rely so heavily on migration for our workforce is very risky”.

In Australia, only 13% of the engineering workforce are women, and women in their 20s to 30s leave the profession at ten times the rate of men, contributing to capacity limitations. Australia is no orphan. Saavedra, Araújo, de Oliveira and Stephens (2014) would be far from the first or last to observe that the number of women in engineering education and careers is still very low in Western countries, despite efforts to improve the proportion of women engineers. Fouad et al. (2016) note that in the U.S. 20% of engineering graduates are women but only 11% of engineers are women. These statistics pointing to a departure of half of all female graduates from the profession were unchanged over two decades. Even in Sweden, the percentage of women accepted into engineering programs is only 25-30% (IVA, 2019). The President of IVA, Tuula Teeri, has echoed Australia’s concerns regarding the impact on engineering capacity:

> “Women are needed if Sweden is to meet the significant workforce needs in engineering. We want to present the facts and contribute knowledge to create better conditions so that women can further their careers.”

Sharma et al. (2018) identify barriers to women reaching higher levels of science and technology professions as being not only pay, progression and work security issues but also unconscious biases, stereotypes and some myths, and that these have societal, cultural and institutional roots – the last of which would include both engineering schools and workplaces. Interestingly, Stoet and Geary’s (2018) examination of trends worldwide point to the propensity to graduate in STEM (Science, Technology, Engineering and Mathematics) degrees reducing with increasing gender equality. The authors posit that women have less incentive to choose high security, well paid careers (such as offered via STEM education) as gender equality and social security increase, and therefore choose not to. Coexisting with this might be that people prefer to excel than to compete and as girls (and then women) tend to have superior language abilities from an early age, they are attracted to fields in which this is seen as an advantage – which is not the case in STEM education.

Whatever the causal factors, Saavedra et al. (2014) note that gender issues or gender discrimination are not perceived as significant by those working in technological fields. Given the impact on talent and capacity resulting from female under-representation in engineering, quite apart from the value brought by diversity, the attitude towards institutional factors perpetuating ongoing female under-representation in the profession is arguably a particular case where a lack of broader sociological understanding amongst engineers works against practice needs and achieving optimal results.

Australia is not alone in finding a disconnect between engineering education and practice needs. King (2011) notes that national reports have pushed for the broadening of engineering education in the United States five times since 1918, but that for the most part, there has been no movement in engineering education. In India, Madheswari and Mageswari (2019) point to conventional teaching-learning practices as failing to produce employable engineers with the skills to meet future demands, noting that around 25% of the world's engineers are in India but it lags in research and innovation. King (2011) also links increased breadth and flexibility in engineering education as facilitating greater entry of ethnic minorities and women into the profession.

If Lloyd et al. (2001), Rojters (2004), King (2011), employers, graduates, educational reviewers and even engineering educators all agree that it is desirable for studies in humanities-based subjects to be incorporated into engineering curricula, why do these authors also find a lack of action on such recommendations? This is relevant to the hypothesis in terms of a professional engineering paradigm inadequate to practice needs leading to sub-optimal results. The complexities of engineering instruction via academic schools, and their relationship to professional associations, are considered in the following section.

Academic schools and professional associations

Regarding university professional schools and the process of professionalisation, Barber (1963) provides the general context that in emerging professions, the members leading the bid for professional status will try to establish and strengthen the role of university professional schools. As weak or only marginally professional schools are a threat to the standards of the university, the university will in turn try to strengthen the professional school. A university professional school can borrow resources from other university departments, giving scope for transmission of a breadth of relevant knowledge. Over time, the university school becomes the leading innovator and systemiser of ideas for its profession, but is insulated from cultural and social interests that exist outside the academic environment, leading to a tension with practising professionals.

This broad description could explain a mismatch between practice and education in the early years of the professionalisation process in particular. During such times, students are instructed in more and more specialised technical knowledge while practitioners (who in emerging professions are not homogenous in terms of knowledge and community orientation) retain broader skill sets.

Rojter (2004) is quite direct in blaming academic institutions for overly technically-based engineering curricula and a lack of progress over twenty years in extending engineering curricula to incorporate social sciences and humanities, faulting:

> "… academic culture, operating within engineering schools and faculties in Australia, that is based on scientific norms derived from science…"

Rojter argues that engineering education is reluctant to incorporate subjects in the humanities and social sciences because these knowledge bases engage a conversation within a value-laden framework that is absent from scientific concepts of knowledge embedded within the tradition of engineering education. He references adoption of a scientific paradigm within engineering as part of attempts to address university unease with engineering as a university professional school, given its roots in practical matters – a slightly more negative take on the strengthening of the 'weak' university professional school described by Barber (1963) – and contends that (lack of) culture change in engineering education reflects a culture that has strong historical connections to the standing of the engineering profession in Australia.

In regard to "roots in practical matters", a theme emerges in Moore and Hughes (1991) of the difference between engineers and other researchers within the scientific tradition in the value engineers base on problem-solving and the application of research findings. This indicates a paradigmatic if not epistemological bias within engineers towards pragmatism. Yet this fundamental element of engineering seems to be resisted by the engineers' own academic school for paradigmatic reasons originating outside of engineering.

Lloyd et al. (2001) agree with Rojter's (2004) criticism of academic paradigm in opposing curricula change, citing a 1996 major review of engineering education as recommending:

> "…no less than a cultural change in engineering education which must be more outward looking with the capability to produce graduates to lead the engineering profession in its involvement with the great social, economic, environmental and cultural challenges of our time."

As the two sets of authors would have drawn from similar sources, agreement in this viewpoint is perhaps not surprising. However, Lloyd et al. also point to more prosaic problems, noting (p.54) that while management would ideally be integrated into other studies:

> "…practicalities dictate for most that it be taught in separate subjects… because of the difficulties in finding engineering lecturers able to, or interested in, teaching management."

Similarly, Leonardi (2003) cites Hilburn and Humphrey's (2002) claim that one of the major problems engineering professors face when trying to teach students how to work in teams is that the teachers themselves have not been trained to work in teams.

These observations point to pragmatic forces in action within university professional schools, outside of the scope of Barber's (1963) brief overview. One such force is related to the inevitable relationship of professions with professional associations (as noted by Buyruk, 2013). For graduates of a given university to be accepted as members of the association, the curriculum must meet accreditation standards imposed by the professional association. This places at least some part of curriculum development outside of the academic sphere and complicates any proposal to change the curriculum. In the engineering field, accreditation extends to mutual recognition agreements between professional associations of different countries, further complicating curriculum development. Rojter (2004) also notes that where the accrediting associations recommended the incorporation of the humanities and sociology into curricula, they were quietly ignored. In his time, the accrediting professional association had become more of an advisory body that was unlikely to generate change.

However, Rojter (2004) provides no concrete rationale for why universities ignored the accrediting body, given a presumable incentive to conform with their recommendations in order to maximise the employability of graduates. This points to a second pragmatic effect reflected by Lloyd et al.'s comment, being university expertise. While it is true that academic schools can borrow resources from other university departments, as mentioned by Barber (1963), lecturers from these other university departments might not know how to modify their usual course content to be relevant to engineers. Meanwhile, some academic schools could have financial reasons to prefer using existing lecturers from within the school to teach new subjects, whether or not these lecturers have sufficient experience. Insofar as either approach leads to an inadequate teaching result, students will provide negative feedback on the new subject, particularly in a course such as engineering where elective choices are few and the subject would be viewed as occupying valuable curriculum space. Indeed, the lack of curriculum space is one reason that King (2011) advocates for engineering to follow other major professions in the U.S. academic system in changing from a bachelor's level degree to a graduate-level professional degree built upon the base of a liberal undergraduate education.

Lloyd et al. (2001) provide a view of other pragmatic pressures in Australia. In 1981, the Federal government withdrew funding for engineering courses. A 1994 report into the implementation of curricula recommendations found progress had been made but also identified "lack of time and resources" as a barrier and that "the development of communication skills requires intensive teaching methods and the reduced funding levels have presented extreme difficulties." A 1998 survey of engineering management academics adds a quantitative dimension: 60% of those delivering engineering management studies had no management qualifications. Hence pragmatic issues regarding funding and availability of resources form barriers against engineering faculties implementing any intent. The pragmatic response from the Institution of Engineers of watering down the goal for the amount of management subjects taught could not have improved the situation.

Rojter's (2004) description of recruitment into engineering faculties as being through research doctoral degrees rather than of practitioners also implies that engineering lecturers would have limited practical experience in using sociological skills, which would undermine the effectiveness of teaching these. Lecturers from university humanities departments would be similarly constrained, with Mulder (2000) referring to the inability of social scientists to lecture in a comprehensible way to engineering students. This probably reflects in part engineers' lack of exposure to sociological concepts up to that point, as Mulder also notes the inability of engineers and engineering students to grasp conceptual reasoning on social-cultural processes.

It seems, then, that in engineering education, pragmatic as well as paradigmatic effects lead to a paradigmatic feedback loop. Here, the paradigm taught to engineering students is narrowly placed in the sciences, ultimately producing lecturers with the same narrow mindset. These are recruited into engineering faculties in preference to (or in the absence of) practitioners or interdisciplinary lecturers, where they construct curricula and pass on the received mindset to their own students. These students, having mainly been exposed to such teaching, prefer the established approach and can be resistant to subjects they see as originating from outside the scientific tradition. Such a feedback loop could only be broken with a concerted effort to recruit engineers or others with practical experience who can communicate to students the value of subjects based in the humanities and social sciences, and who are capable of developing courses relevant to students, for whom such subjects will by necessity occupy only a small part of the overall curriculum.

Mulder (2000) presents a study of experiments in teaching interdisciplinary courses, project based learning and interdisciplinary projects at Delft University of Technology in the context of exactly these problems. She discusses resistance from engineers to new ways of thought and teaching basic sociological knowledge in terms of engineering culture, rather than the academic culture mentioned by Lloyd et al. (2001) and Rojter (2004). Mulder identifies four features that are more present in engineers than other academic groups:

1. Quantifying as much as possible
2. Neglecting those cause-effect relations that cannot be quantified
3. A tendency to make human demands subordinate to the optimised performance of technological artefacts
4. A strong tendency to perceive the engineer's task as the optimised fulfilling of tasks that are externally determined, without any responsibility for the consequences that the fulfilment of tasks might have.

The first point quite clearly relates to the positivist epistemology of engineering: the beliefs that truth and meaning reside as knowable objects, and that this objective knowledge can be identified through empirical observation or logical deduction. The second is a 'next logical' (but arguably erroneous) step from the first, of ignoring the non-quantifiable. The third is an extension of the second to the even more ill-defined, non-quantifiable needs and wants of humans. The last is interesting, in that it perhaps represents the logical end state: having rejected the non-quantifiable and human, an engineer's task becomes neutrally defined as a technical exercise outside the socio-political domain.

Mulder (2000) found success in prosecuting a multi-disciplinary agenda by providing (copious) examples to engineers of practice failures relating to specific and often non-quantifiable factors – as well as some successes, to offset impressions of these examples forming a simple criticism of technology. Arguably, these examples show that a strong commitment to positivist epistemological stance of engineering, coupled with the paradigmatic/ pragmatic approach of ignoring non-quantifiable factors, can lead to adverse practice effects i.e. a generalised demonstration of the hypothesis.

Mulder's features of engineers do not perfectly align with characteristics identified by other authors who have examined engineering culture. Leonardi (2003) presents McIlwee and Robinson's (1992) well-cited contention that three main components of engineering culture recognized by most engineers are:

1. an ideology that stresses the centrality of technology, and of engineers as producers of technology;
2. the acquisition of organizational power as the base of engineering success; and
3. a self-centred "macho" belief in the value of engineers[16].

Apart from the fact that Mulder's (2000) features are taken from her (or her institution's) experience of engineers and could represent a slightly different incarnation of engineering culture, as she was writing almost a decade later than McIlwee and Robinson (1992), there is actually reasonable agreement between Mulder's versus McIlwee and Robinson's characterisations. Mulder's features of quantifying as much as possible and excluding the non-quantifiable are compatible with the centrality of technology in engineering ideology; McIlwee and Robinson's "macho" includes aspects such as assertiveness, which arguably reflects the positivist belief that truth and meaning can be known and the assumption that being an engineer implies possession of true knowledge; and if Mulder doesn't discuss the power dynamics within engineering as a profession, nor does she contradict McIlwee and Robinson's identification of this as a component of engineering culture.

In fact, Mulder's features arguably represent a way of thinking or doing where as McIlwee and Robinson's components describe the culture formed as a result of Mulder's features. Accepting that both versions may describe aspects in the subject of engineering culture, Mulder's features are more relevant to this thesis in terms of linking engineering epistemology to engineering culture. The linking of epistemology to culture also provides a lens for understanding how negatively indicated cultural and practice results can emerge, why

[16] Leonardi (2003) puts to one side the question of whether these components accurately depict engineering culture, although he notes that many studies would agree that engineers understand these components to be key features of engineering culture.

established professional paradigm would be difficult to change, and some guidance regarding how these issues might be addressed.

Neither Mulder's nor McIlwee and Robinson's work involved traffic engineers, but as traffic engineering is placed within other engineering disciplines, the culture of traffic engineers is expected to be similar to that of other engineers. This brief contrast of Mulder (2000) to McIlwee and Robinson (1992) also indicates why this dissertation does not further cover the literature related to engineering culture, which has been extensively examined by sociologists: the literature considers engineering culture in ways other than those central to the hypothesis.

Autonomy, judgment and human psychology

Leonardi (2001) identifies the importance of the individual and of autonomy in engineering culture. Autonomy as a characteristic of a professional occupation is not straight-forward to measure, particularly given that occupations will have levels of codified practice. However, a key conceptual difference between non-professional and professional occupations is that for the former, the tasks of employees are heavily proscribed as part of achieving a desired goal, while for the latter, employees are expected to determine how they will achieve the goal. Using this conceptualisation, professional judgment is a key element in the autonomous characteristic of a profession.

Hauer (2019b) notes the importance placed by engineers on (their) professional judgment by quoting Davis (2012):

> "Judgment is central to engineering … one who otherwise knows what engineers know but lacks engineering judgment may be an expert of sorts, a handy resource much like a reference book or database, but cannot be a competent engineer."

Hawse and Wood's (2017) survey of engineering graduates and professionals confirms that sound professional judgment is highly rated as a capability necessary for success in the engineering workplace.

Professional judgment clearly has application in pragmatic decision-making, potentially reflects engineering paradigm, and is used in ensuring that engineering practice is being applied in an optimal way. But how well is professional judgment understood and developed by engineers?

Cropp, Banks and Elghali's (2011) study of experienced engineers undertaking contaminated land risk assessment suggests that 'standard procedure' does not accurately represent how highly proficient domain practitioners make complex decisions. Such practitioners instead use a 'novel' combined process using social judgment theory (whereby new ideas are subconsciously compared with an individual's point of view to determine how these ideas are judged) and integrating this into a coherent explanation[17] of the data. So, they use an engineering, scientific method to analyse data but combine this with a human, social judgment approach to make decisions.

Similarly, responses to Q10 in the Road authority survey (Appendix C)[18] point to risk aversion (a social response) rather than risk management (a scientific response) being used in decision-making. Here, variable degrees of knowledge and experience exist and what is considered a "coherent explanation" varies between individuals. There is also no opportunity to independently review and obtain feedback on the quality of the decision made.

Yet in commenting on four descriptions of professional judgment, Koen's (1992) engineering concept of engineering judgment is characterised by Davis (1992) as:

> "Good judgment for a particular engineer is judgment meeting the standard of his or her profession. It is inherently a professional judgment, good because it satisfies standards set by the profession, standards that (presumably) must be learned. Engineers do not think like other people."

No element of human, social judgment is implied in deferring to standards that "must be learned." Nor does this describe how engineering judgment applies in situations where no agreed professional standard exists. This is a situation the Road authority survey attempted to explore regarding research, its approaches and methods, and barriers to innovation. Responses to the survey demonstrate a greater struggle with lack of information, political will and challenging a car-dominated paradigm than Koen would suggest. Indeed, some responses point to a Koen-like approach as undermining the ability to exercise sound judgment, in that reliance on "standards set by the profession" gives no fall-back if the standards (codified into documents such as Australian Standards and Austroads guidelines) do not apply.

Nor is the contention that engineers "do not think like other people" supported by Cropp et al. (2011). Koen's co-contributors, Delattro (1992) and van Zandt (1992), both emphasise that

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17 "Coherent explanation" refers to the theory of explanatory coherence, whereby a hypothesis coheres or is coherent with propositions that it explains, that explain it, that participate with it in explaining other propositions, or that offer analogous explanations; and propositions are incoherent with each other if they are contradictory.

18 "If there is a treatment/s you currently do not use but would like to use, please list the treatment/s and barriers to their use."

the fundamentals of good judgment do not vary significantly between professions, unlike the domains of required factual and technical competence. As with Barber (1963), commonalities in the human condition provide for recognisable, repeated patterns. In this case, this is commonality in the fundamentals of good judgment.

This point is made more explicitly by Baybutt (2017), who presents a pragmatic view of cognitive biases along with guidance on how to address these psychological factors[19]. Similarly, in addition to their survey, Hawse and Wood (2017) review literature about how to develop wise judgments. However, there is little indication that such advice has penetrated into, much less improved, engineering practice.

Hauer (2019b) considers engineering judgment in some depth and notes that definitions of engineering judgment are few, much less agreed upon. He quotes Peck (1977):

> "Almost all people in the practice of engineering would agree that successful practice requires a high degree of engineering judgment, but few would agree on the meaning of the word judgment itself."

Hauer (2019b) characterises Peck (1977) as thinking that to the 'engineering scientist' the exercise of judgment may seem to be a poor substitute for sophisticated analysis, while to the practitioner it is often an impressive name for guessing. Nobel prize winner Richard Feynman, in discussing NASA management culture, famously said:

> "As far as I can tell, 'engineering judgment' means they're just going to make up numbers!" (Feynman, 2001, p183).

Feynman drew a distinction between engineering analysis, which he considered to be trustworthy, and engineering judgment, which he considered to be arbitrary and subjective. Hauer (2019b) disagrees with this sentiment but has significant concerns with how well traffic engineering judgment serves road safety:

> "Decisions that highway and traffic engineers make significantly affect the safety of road users. The documents that guide highway and traffic engineering practice suggest that many of these decisions be made by 'engineering judgment'. One would like this judgment to be informed by evidence-based anticipation of their likely safety consequences and by a professional ability to balance safety against mobility and other dimensions of 'utility'. I show that these desiderata are largely unfulfilled."

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[19] In the field of hazard and risk analysis.

And, after presenting a number of rhetorical questions relating to how engineering judgment in road safety manifests in practice:

> "These questions are motivated by the ease with which road design and operational decisions that affect life and limb can be made on opinions and beliefs that are unsupported by evidence; they are prompted by the concern that one can adopt policies and procedures based on such beliefs and follow them for decades without the need for factual knowledge being recognized; they are aroused by the observation that when evidence runs counter to opinion the latter often wins the day."

The SQ literature review provides support for Hauer's statements by finding that in Australia, research into cyclist safety at infrastructure appears to have mainly occurred after publication of national practitioner guidance. That is, rather than research creating evidence upon which practical guidance is based, publication of new guidance tends to spawn research into the safety effects of published guidance. That some of this subsequent research is related to concerns with the new guidance is demonstrated by Patterson (2010), who used an international literature review to point out that updated practitioner guidance regarding bicycle lanes in roundabouts was contrary to the available evidence. Comments in the Road authority survey also point to concerns with Australian practice being at odds with international evidence, proven treatments not being applied in Australia, and treatments in use not being supported by evidence.

Patterson (2010) spurred further research and a change to the guidance within five years of her paper rather than decades, but as the offending guidance was itself based on state-based guidelines that had been in use for years, Hauer's (2019b) criticisms retain their potency[20].

Why is there such a difference between the importance given to engineering judgment and the effect of its practice? Rae and Alexander (2017) suggest that in estimating safety risk, domain experts may have superior understanding of causal mechanisms, but that beyond this further domain expertise does not translate into increased forecasting accuracy. So when estimating risk, experts do not have access to privileged information but are as handicapped by a lack of information as others. Prior knowledge without an understanding of bias or feedback on inaccuracies merely gives rise to a false sense of competence. This, then, is the true state of engineering judgment, and when authors such as Koen (1992) place engineering

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[20] Meanwhile, Patterson (2013) produced a degree of practical change in Adelaide some twenty years after Adelaide City Council first set a strategic objective of implementing contra-flow cycle facilities.

judgment apart from other disciplines, and particularly when they characterise it as a form of heuristic that matches the paradigm of an idealised scientific method, they isolate engineering judgment from the learnings that could be derived from other disciplines. This is an isolation endemic to the discipline.

By contrast, Delattro (1992) and Elstein (1992) both refer to ongoing professional practices intended to improve the exercise of professional judgment – as do Rae and Alexander and, as previously noted, Baybutt (2017) and Hawse and Wood (2017). Davis' (1992) observation that:

> "…empirical research into clinical judgment is more advanced than such research into engineering judgment."

can perhaps best be considered as an understatement.

Reflecting back to Rojter (2004), an understanding of professional judgment forms just one element based in the humanities excluded from the education and formation of a professional engineer in Australia. Belief that the scientific method applies in all aspects of engineering and produces unambiguous, 'true' results prevents engineering students or professionals being taught practical methods to overcome biases in judgment. Without self-reflection and understanding, the exercise of engineering judgment becomes the guessing game criticised by the frustrated Feynman, and prone to the dominance of opinion, belief and counter-evidential decision-making observed by Hauer (2019b). A paradigmatic aversion to the humanities thus undermines road safety decision-making through the path of engineering judgment.

Engineering judgment can also be viewed from the slightly different perspective of human error, which Timpe, Giesa and Seifert (2004) note has emerged as an important discipline of engineering psychology. Cascio (2015) defines engineering psychology (also known as human factors psychology or human engineering) as the study of the capacities and limitations of people with respect to their work environments[21]. Engineering psychology principally revolves around systems design that helps humans avoid error.

Work in this field is most well-known to traffic engineers through Reason's (1990) 'dynamics of accident causation' model (aka 'Swiss Cheese' model) shown in Figure 3.

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[21] 'Engineering' in this sense refers to the interaction of humans and engineered environments.

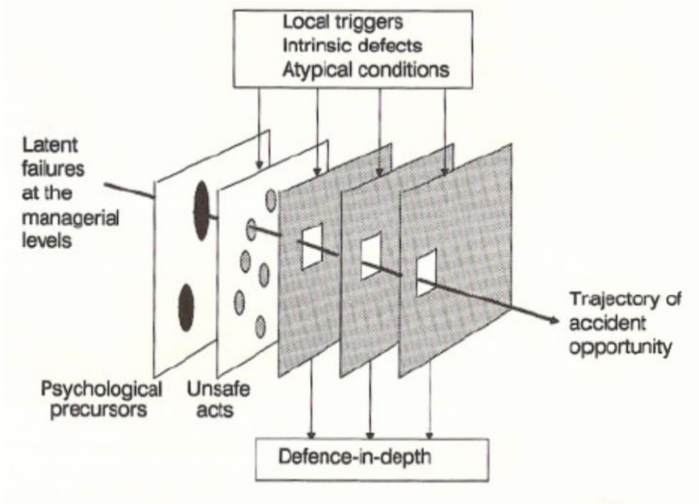

Figure 3: 'Swiss cheese' dynamics of accident causation model. Source: Reason (1991).

This underlies the Safe Systems approach adopted by road safety agencies in Australia and internationally, and hence represents established road safety paradigm. The Australian College of Road Safety (2010) summarises attention to the design and management of road infrastructure, vehicles and travel speeds under this approach as "safer roads, safer speeds, safer vehicles and safer road users", where defence-in-depth is provided by recognising that road trauma levels are largely determined by the interaction of these key elements.

Less well known by traffic engineers is the "fallacy of defence-in-depth" argument, ascribed by Le Croze (2018) to Rasmussen's (1997) combination of self-organisation with defence-in-depth theories. One aspect of this is that adaptation by local agents can be transferred upwards, to managerial levels. This describes pragmatic conditions by which road safety knowledge can be subverted. One way this can occur is when the actions of individual road users breach 'defence-in-depth' safeguards but fail to result in a crash because of the larger accident sequence needed, and this ultimately affects road managers' perceptions and hence decisions.

Other routes are less direct. We have already met one example briefly in relation to Black Spot funding, where public opinion that sites with high accident frequencies should be upgraded spurred Federal funding for exactly this via the Commonwealth Black Spot Program. Local actors thus convinced managers to provide funding (and hence counter-measures) not at sites exhibiting the highest risks but where high traffic volumes and effects such as the randomness of crashes produce an easily viewed crash record.

Another example is in the long-accepted principle of non-feasance. This was a defence applied to road authorities to defects in the road system that contributed to crashes, on the basis that if the authority is not aware of a defect, it could not be expected to remedy it. As Austroads (2012) notes regarding civil liability issues for road authorities:

> "Fear of civil litigation should never be the primary concern when forming a local strategy, policy, standard or procedure; making a local decision or determining an action; nor should it stop reasonable innovation and pilot studies from taking place that have the objective of securing a better outcome for all road users." (p.13).

Yet it is exactly this attitude, embodied in road authorities discouraging discovery of defects to minimise exposure to claims and road maintenance costs, that led in 2001 to the High Court overturning the concept in favour of road authorities demonstrating reasonable care (Austroads 2012). In this case, local (traffic engineering) agents prioritising cost minimisation arguably affected managerial perceptions regarding reasonable maintenance budgets, leading to non-feasance becoming a method of cost control rather than a reasonable legal protection. Evidence that this attitude still exists can be seen in the results of the Road authority survey (Appendix C), particularly in regard to Q10, as previously noted.

More direct indications of the fallibility of engineering judgment is provided by Collins and Leathley (1995), who consider how psychological explanations of human behaviour can illustrate why dispositions towards errors in the engineering process might occur. Collins and Leathley list a variety of errors to which all humans are prone, based on social and cognitive psychology. Collins and Leathley cite Tuler's (1988) suggestion that people build "mental models" of how a given system works to help address informational and time constraints. These give rise to meta-cognitive skills or ways of thinking that are generally useful, but "mental set" or fixedness of the mental model creates a barrier to alternative ways of thinking. Resulting cognitive biases are:

- Overconfidence in estimations and plans – Rules of thumb based on paradigm can improve speed and efficiency of thought. But if these work *most* of the time, they can be expected to work *all* of the time – leading to errors.
- Future choices based on previous experiences – An emerging picture can influence choices of subsequent actions (such as what further data collection or analysis to undertake) that affect the final picture revealed.
- Accepting confirmatory evidence in favour of contradictory evidence – There is a tendency to focus on evidence that supports established thought and overlook or forget contrary evidence.

- Options that are not readily observable may not be considered – This can include things that would be quite easy to see, if their existence were considered possible.
- A tendency towards conservatism – Due to social pressures, problems are more like to be dismissed than accepted and investigated.
- Thinking in causal series rather than causal nets – Immediate results of actions may be understood but not consequences on other parts of the system.

These biases present fairly obvious ways in which "mental models" can influence choices of methodology, analysis and interpretation in road safety analysis and research. In this sense, the description of "mental models" represents not an over-arching epistemological commitment but a framework for understanding more in line with Kuhn (1962) – i.e. a description of paradigm.

Other social and cognitive psychology drivers of human error mentioned by Collins and Leathley (1995) are:

1. Conformance – social pressure can affect judgment, to the extent of changing an individual's perceptions.
2. Cognitive dissonance – holding conflicting ideas or opinions produces an uncomfortable psychological tension and (unconscious) methods of reducing this are often irrational.
3. Group behaviour – a number of biases have been observed in groups of people working together, such as 'group think'.

In many ways, Collins and Leathley (1995) mirrors this thesis' hypothesis regarding the adverse effects of paradigm. Unfortunately, as the authors focus on safety analysis, their suggested techniques for overcoming psychological predispositions to err have very limited applicability to road safety, though arguably some application to elements of traffic engineering practice. Collins and Leathley conclude:

> "In the fields of safety and reliability analysis it is often incumbent upon us to address the 'weak link in the chain'. In the future our weak link may not be the power of our analytical techniques, but our ability to apply them correctly… Our principle and overriding suggestion is that there be greater input from the field of psychology into the domain of safety and reliability analysis and into engineering in general… As professional safety and reliability analysts we must make all efforts to ensure that we can never be the 'weak link' in the chain."

Some quarter of a century after these words were written, Hauer (2019a) and (2019b) present very similar sentiments, for an engineering discipline that retains its ‘weak links’.

Disciplinary boundaries

In terms of the autonomy of professionals, the space within which they practice is also relevant. The preceding examination of literature has demonstrated that the boundaries of professional engineering practice are flexible and have changed over time. But how are the limits of the engineering profession addressed?

The available literature is still scant and not focused on engineers[22], but findings relating to their paradigmatic cousins in science can cast light on the situation for engineers. So far, paradigm appears to be a secondary factor compared to the pragmatic effects of operating within a system defined by disciplines.

Leahey, Beckman and Stanko (2016) examine the effect of interdisciplinary cooperation on scientists’ research. The authors cite Zuckerman et al. (2003) in pointing out that (disciplinary) fields are not arbitrarily constructed but reflect the distinct environments that disciplines face and the formal and tacit skill sets that members acquire. Leahey et al. find penalties in interdisciplinary work (fewer papers published), which the authors attribute to cognitive and collaborative challenges associated with interdisciplinary research. That is, difficulties in researchers’ ability to understand and accommodate others’ epistemologies as part of research activities slows the production of literature. This also extends into the peer review process.

Millar and Dillman’s (2012) analysis of interdisciplinarity in earned doctorates basically places engineering between the physical sciences and social sciences, which is at the lower end of their scale compared to the average. Unfortunately, their study tends to describe/ analyse differences between the fields and knowledge domains of disciplines rather than explore/ critique disciplinary mindsets and their knowledge production. Still, observing that in 2001-03, interdisciplinary work in engineering was at about the same rates as the physical sciences (physics and chemistry) or mathematics; and noting that the previous conclusion that engineering practice extends beyond the technical realm implies that engineers should instead exhibit higher rates of interdisciplinarity than either mathematics or the sciences; then Millar

[22] Research into disciplinary boundaries has been facilitated by technological advances enabling reasonably large datasets to be accumulated and examined, including via SQ literature reviews. As such, research is relatively contemporary and not yet abundant.

and Dillman's results point to epistemological inflexibility and a failure of paradigm compared to practice needs.

Jacobs and Frickel (2009) agree with Leahey et al. in noting barriers to interdisciplinary research, in terms of:

- epistemological barriers involving incompatible styles of thought;
- research traditions, techniques and language that are difficult to translate across disciplinary domains;
- disciplinary structures that reinforce these inefficiencies through specialised journals, conferences, and departments that route communication inward; and
- administrative barriers, not described but arguably supportive of disciplinary structures but also possibly extending to the peer-review process.

Hence pragmatic forces reinforce paradigm, in terms of self-prescribed limits of practice, and in terms of at least research activities.

These examinations of interdisciplinarity only consider barriers between cooperating researchers. Foster, Rzhetsky and Evans (2013) and Rzhetsky, Foster, Foster and Evans (2015) examine the barriers that affect the content of the research produced. These authors examine strategies used by scientists in choosing research subjects, and find that conservative research focused on supporting scientific careers is the most prevalent choice. That is, pragmatic self-interest dominates over paradigmatic effects. Chapman et al. (2019) paint an even more worrying picture of how authorship, *h*-index of individuals and journal impact factors are being used and abused to further academic careers, and even raise ethical questions as to the appropriate goals of an individual's research.

Wang, Veugelers and Stephan (2017) also provide indications that the success of self-interest over knowledge has an impact on the larger body of knowledge that results. The authors agree that research that is novel (or innovative as Foster, Rzhetsky and Evans put it, and following a risky strategy) is more likely to be ignored through bibliometric indicators. But they also find that this research is more likely to achieve high impact and recognition overall.

Here, the desire to contribute to the field may provide a counteracting force for the pragmatic and paradigmatic pressures arrayed against interdisciplinarity. Jacobs and Frickel (2009) show that, in general, interdisciplinary research has grown rapidly since the 1990s. Their description of how fields change over time and at different rates supports Whitley's (2000) contention that not all fields are equally entrenched in disciplinary thought and that fields may change at different rates. Millar and Dillman (2012) report rates of interdisciplinary research increasing quite significantly for engineering between 2001-03 and 2004-08, pointing to engineering developing epistemological flexibility at a higher rate in fairly recent times, at least for US doctoral research.

A notable contrast to Leahey et al.'s (2016) conclusion that interdisciplinary research leads to less research being produced is McLean's (1988) description of very fruitful and influential interdisciplinary arrangements in the early Australian traffic engineering field. McLean's observation that road safety could not be considered solely from an engineering perspective points to some ceding of domain to other disciplines, perhaps enhanced by the small size of the early traffic engineering profession that "…limited the intellectual resource available to address research issues."

This acceptance of multiple human effects in the domain of road safety supports Lo and Kennedy's (2015) proposal that reactions to category blending (i.e. the combination of fields to produce new fields of study) are affected by cognitive limits and by domain-specific logics for judging quality. In McLean's case, human factors (such as driving under the influence of alcohol) were understandable to engineers and the strength of the effect, as judged by road safety metrics, was sufficient to convince engineers of its relevance.

McLean narrates that the interdisciplinary approach was formalised when the Australian Road Research Board established a Human Factors Committee in 1962, bringing together specialists from psychology, medicine, optometry, mechanical engineering, highway engineering and traffic engineering. The establishment of this Committee is compatible with Whitley's (2000) description of (in this case internal) factors influencing the degree to which disciplinary thought is entrenched; and Lo and Kennedy's (2015) argument that the difficulties associated with category spanning (i.e. working across fields) may be reduced, and the benefits accentuated, when category spanning is popular.

McLean notes that the Committee served an important educational function. The education of engineers would help maintain epistemological flexibility by reinforcing reasons for a multi-disciplinary approach, and by supporting the logic by which sociologically-based research represented quality in a traffic engineering domain. That the interdisciplinary approach itself promoted research productivity is indicated by McLean's comment that the Human Factors Committee helped establish a ground-breaking research program, and is compatible with

Leahey et al.'s (2016) conclusion that if interdisciplinarity represents a high-risk approach to research, it also tends to give high rewards.

McLean also describes a major contribution to the traffic engineering field as being the development of traffic theory, notably: applying probability theory to the description of traffic phenomena; the refinement and application of gap-acceptance theory; and the theory of vehicle-actuated and coordinated signal control – all extensively mathematically-based. McLean says of this:

> "One of the important long term contributions of this work is that it developed a tradition of a rigorous analytical approach to traffic engineering research in Australia. Young traffic/transport academic staff [were] appointed in other Civil Engineering Departments during the 1960's and subsequently were brought up on this approach and have incorporated it into their own teaching and research programs. Through their teaching, we now have a generation of practising traffic engineers with an understanding of traffic theory, and the ability to apply it to practical traffic engineering problems."

While positively framed around research quality, this description also signposts a situation in which the scientific epistemology of the mathematics field became ascendant in traffic engineering. Young academic staff incorporating the approach into their own teaching and research programs sounds like another route by which, if Rojter (2004) were to describe it, "The science hegemony became further entrenched in engineering education." This would have longer-term impacts on the propensity to undertake interdisciplinary research.

McLean ended his history by noting that traffic engineering research appeared to be in a consolidation phase. With effort being expended on the implementation and refinement of proven techniques, it seemed to him that a focal point for traffic engineering research in Australia had been lost. In fact, that an increase in single-disciplinary research reduces research value is the natural corollary of interdisciplinarity increasing research value.

As McLean was writing at a point in time, the signposts in his work cannot be followed further. McLean does not record when the Human Effects Committee was disbanded. (Its research agenda seems mainly to have been prosecuted in the 1960s and 1970s.) However, in terms of interdisciplinarity, the SQ literature review (Appendix B) found that Australian research is more likely to be attributed to a single author than overseas research. This larger proportion of single author papers indicates less collaboration by Australians than their international counterparts, and by a considerable amount: almost one in three Australian papers are written by an individual while only one in five overseas papers have a single author. As per Chapman et al. (2019), this could reflect national culture. However, considering only New Zealand and Canada, which have arguably similar cultures to Australia, overseas research still involves broader inter- and intra- field collaboration than Australian research. The interdisciplinarity of traffic engineering practice has changed significantly since McLean's time and paradigmatic boundaries have solidified.

The road safety literature

The preceding literature review has examined the hypothesis from several different angles due to the scarcity of literature directly relating engineering paradigm or pragmatic practice with the production of road safety knowledge. To the extent that such literature exists, it is produced in the field of road safety research. This section considers this literature in light of the themes and understandings developed by the literature review.

Elvik (2004) defines road safety (evaluation) research as any research designed to estimate the effects on accidents or injuries of one or more road safety measures. In considering theoretical frameworks, Elvik (2004), Schepers et al. (2014) and Noland (2013) all raise the issue of human behaviour as an element affecting road safety[23].

- In attempting to explain how road safety measures influence road safety, Elvik (2004) follows Evans' (1985, 1991) proposition that an "engineering effect" and "human effect" combine to give a road safety effect. Elvik uses this to develop a framework for assessing whether road safety interventions "make sense". This framework is based on eight generic risk factors associated with engineering effects and five factors eliciting behavioural adaptation.
- Schepers et al. (2014) contend that road safety models are focused mainly on risk, and that while traffic and transport literature offers models for travel behaviour that help to explain exposure to risk, no framework exists linking exposure-to-risk (resulting from travel behaviour) with risk itself (resulting from interaction between road user(s), vehicle(s), and infrastructure). The authors review travel behaviour theory; theories explaining the link between exposure and risk; crash risk theories, based on physics and social science

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[23] Elvik (2004) notes that most road safety research does not have a strong theoretical basis guiding the design of studies and interpretation of study findings, with theoretical elements most frequently revolving around the statistical modelling used. The theoretical frameworks outlined in this section represent attempts to provide this theoretical basis.

theories; and injury risk theories, mainly based on physics. The authors then propose a road safety framework incorporating all of these elements.

- Noland (2013) provides a comprehensive overview of theoretical frameworks in the context of road safety policy. These are based on risk compensation – notably the idea of 'risk homeostasis', being that road users are willing to accept a certain level of risk and that reducing risk in one way will lead to greater risk taking in another – and human behavioural adaptation. Noland follows Michon (1989) in differentiating between "aggregate models" of road user behaviour based on economic models that assume rational behaviour and maximising utility, and "process models" based on psychological or cognitive models of individual driver behaviour involving mental processes and empirically-observed behaviour. Noland proposes a theoretical framework that extends the utility maximization framework to a generalized cost approach, based on risk-mobility trade-offs.

Hence there is some recognition of a human element to road safety, as raised by McLean (1988). But in each of these pieces of work, there is a divide between accepting a human aspect to road safety and successfully incorporating such aspects into practice. None of the proposed theoretical frameworks have found widespread use.

Regarding engineering epistemology and road safety, Noland makes the point that:

> "The study of crashes should be inferential and seek to test hypotheses based on a theoretical model. Engineering tends to focus on deterministic goals and deterministic modeling, primarily for forecasting the effects of various changes. Inferential hypothesis testing conflicts with the inherent epistemology of engineering sciences that seeks to build models to forecast changes from a given effect. The latter is certainly appropriate in many fields of engineering, however, when dealing with human behavior more stochastic approaches need to be taken. The engineering approach has resulted in the development of CMFs[24] that are deterministic and then used to forecast outcomes."

That is, road safety research should be based on reasoning rather than simple cause and effect goals and models; and while the latter approach is acceptable in some fields of engineering,

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[24] Noland (2013) cites Shen and Gan (2003) in defining Crash Modification Factors (CMFs) as the parameter estimates from models used to forecast the reduction in crashes from a specific change, typically in the road infrastructure. For example, the crash rate impact of installing a median in an undivided road. Noland also notes that CMF calculation techniques suffer from various problems, with one of the main being the lack of control for other factors that may affect crash rates. CMFs are a type of mass-data study with particular importance in prioritise budgets for engineering treatments and as part of cost/benefit analyses.

randomness and contrary effects need to be recognised and considered in traffic engineering because of the effects of human behaviour.

Noland's comments indicate a fundamental conflict between an engineering paradigm located solely in the scientific tradition and practice needs that also relate to human behaviour. This reflects themes to previously emerge regarding engineering education and its inclusion (or otherwise) of humanities subjects into the curriculum. Hence "the epistemology of traffic engineering" could be very validly contrasted with "the epistemology that should apply to traffic engineering".

Reflecting on Lloyd et al. (2001) or Boon's (2011) conception of engineering/ engineering science, summarised as "Engineering is science applied to technology and systems of technology", one of the most important differences between the engineering and scientific approaches arguably lacks detailed treatment in the literature examined so far: that in applying science to technology/ technological systems, engineers firmly locate their practice within a social context. Much has been made in the sociological literature about engineering design as a specific area or mode of practice, for example grappling with how engineers incorporate efficiency into design. But the need for engineering design to be efficient, or cost-effective, or so on, is established by society. This is arguably implicit in Dym and Little's (2004) characterisation of engineering design being to "achieve stated objectives", but more explicit in Moore and Hughes' (1991) comments about (ethical) values:

> "The environment in which traffic engineering is currently practised recognises an expressed community goal to improve transport safety… Perhaps a future generation may consider our efforts should have been directed towards energy conservation in transport. However we are obliged to accept the values of the day."

Here, the epistemological inflexibility noted of engineering students compared to other students could instead be interpreted as reflecting a paradigm in which if engineers are problem-solvers, they are not in charge of establishing the value system for the problem.

But as McLean (1988) demonstrates, and as argued by proponents such as Trevelyan (2014), an abrogation of engineer responsibility in setting agendas is not necessarily true in actual engineering practice. Were Koehn and Koehn's (2006) engineering alumni and their employers rating "The broad education necessary to understand the impact of engineering solutions in a global/ societal context" in terms of the adequacy of training in the sociology of decision-making for engineers, or their view of how well the role of engineering in society was defined? While the former may arguably be lacking, the identity commitment to ‘engineer’ of students just as arguably reflects a strong sense of the engineer’s place in society, and the decision-making structures of society that determine that place.

In his comments regarding “the inherent epistemology of engineering sciences”, Noland (2013) also contends that the human-oriented approach required in road safety differentiates (traffic engineering) practice needs from those of other engineering disciplines. This is reflected in the concept of “Engineering as science applied to technology”, which implies that the practice needs of engineers relates to the particular technology that defines each engineering field. Hence engineering paradigm needs to vary between technological fields for its practical results to be satisfactory.

Here, traffic engineering is arguably the field of engineering most influenced by the sociology of its technology. Currently, at least, a car considered as part of traffic is not an artefact operating in isolation but a technology operated by humans; the laws under which drivers and other road users function are societally based; permissions and constraints provided by the road environment are often socially rather than physically constructed. So, while Boon cites Rase (1961) as pointing to the strong technical training of chemical engineers in the basic laws of their engineering discipline, and techniques relevant to the discipline: “The basic laws commonly used in chemical engineering are laws of chemistry and physics…”, McLean (1988) notes that: “Unlike branches of engineering which are based on making use of materials with definite physical properties, there are few absolute physical laws in traffic engineering.” (Mathematics is properly regarded as an engineering tool, common to all disciplines.)

Paradigm in an established profession starts in formal education. Rojter (2004) explains that in Australia, engineering at university level was not viewed by other academic disciplines as a proper area for academic study. To overcome this and gain acceptance by the university community, engineering at universities adopted scientific norms of highly codified knowledge. When the (then) Institution of Engineers Australia decided to associate the professional engineering qualification with a four-year degree, technical institutes or colleges (which had hitherto had a greater focus on the hands-on element of engineering) saw the degree as their end-point. They began to match their curricula to that of the universities, until the end of the technical institutions and colleges at the close of the 1980s. After that:

> "The science hegemony became further entrenched in engineering education when as a result of poor intakes into science in many universities the faculties of science and engineering merged. The scientific view of engineering was further enhanced by government research bodies through research funding and unlike for other professions, such as law, medicine and architecture, where academic recruitment placed value on practitioners, the recruitment of academics into engineering schools was, by and large, through research doctoral degrees which often could have been carried in science faculties."

Hence instruction in practical elements wane as scientific elements wax. This is exacerbated in traffic engineering by the lack of a specific paradigm space for the discipline, thanks to the low demand for University-trained traffic engineers. In Australia, traffic engineering is not offered at undergraduate level and so few traffic engineers complete the two Masters courses that have long been on offer in Australia (to both domestic and international students) that one is now not being offered.

Instead, traffic engineering instruction is via the civil engineering curriculum. Here, the few specific traffic engineering subjects included in the civil engineering degree follow a standard engineering education approach of training in the basic laws, such as traffic capacity and flow characteristics. This is despite such 'basic laws' being arguably less relevant to traffic engineering than human-oriented topics of sociology, cognitive psychology and behavioural economics. Hence the formation through tertiary education of civil engineers who go on to practise in the traffic field is arguably very different to the actual practice needs of traffic engineers.

Indeed, McLean's (1988) "Unlike branches of engineering which are based on making use of materials with definite physical properties…" neatly characterises civil engineering as being the disciplinary opposite of traffic engineering. Noland (2013) quotes Hauer (1999) as stating in an unpublished manuscript, in regard to the civil engineering tradition as applied to traffic engineering:

> "...they have erected a conceptual framework which cannot recognize the basic fact that people adapt to circumstances whereas inanimate matter does not. The consequence of this fundamental misconception is that speed, reaction time and similar parameters are treated as constants in all the formulae and computation that are at the root of geometric design standards [for roads]."

Ewing and Dumbaugh (2009) similarly note that:

> "…the fundamental shortcoming of conventional traffic safety theory is that it fails to account for the moderating role of human behavior on crash incidence."

These are statements of the incompatibility of the scientific civil engineering paradigm with the humanist field of traffic engineering. It is an irony that education in the former might lead to practice in the latter, and that moves to ensure professional competence through increasing formal education and educational standards – as recommended in the UK by the Finniston report and as described as occurring in Australia by Rojter (2004) and Lloyd et al. (2001) – have for traffic engineers enshrined a focus on technical competencies in often erroneous concepts over actual practice needs.

Given that practitioners in the most human-influenced engineering sub-discipline are provided with no exposure to subjects addressing human factors, it should not be surprising that Noland (2013) finds weaknesses in how traffic engineers understand and apply methodologies related to CMF indicators. Problems with CMFs do not represent the only analytic and methodological flaws noted by Noland (2013) in the road safety field. Noland also cites Hauer's (2011) finding that in some cost-benefit analyses, an hour of life can be valued at less than an hour of delay, and Holz-Raul and Scheiner (2011) suggesting that projects that reduce time can lead to more fatalities – these results relating to the difficulties of (in the first example) estimating the statistical values of life and time, and hidden in the complexity of cost-benefit analysis.

Noland (2013) also identifies a tendency to use dated studies to develop new guidance. Here, Noland builds on Washington, Lord and Persaud's (2009) critique of expert panels. Washington et al. found that while expert panel processes are intended to produce consensus on CMFs, the social interactions of expert panel members and the collaborative goal of reaching consensus may create a bias, masking the uncertainties in CMF estimates and the shortcomings of reviewed research. These findings should not be unexpected. Authors such as Chhibber, Apostolakis and Okrent (1992) have extensively examined the use of expert panels and identified (in their case) a taxonomy of issues regarding the use of expert judgment, where particular issues relate to a failure to adequately understand and treat biases and dependence. While Chhibber et al.'s effects were related to probabilistic safety studies, which involves quite different processes compared to those studied by Washington et al., the biases and dependence issues were broad and not counteracted in the CMFs expert panel process by (say) adopting the Delphi method, or using an independent analyst to educate the experts about their own biases and aggregate responses, albeit that both of these methods have their own drawbacks.

Foster, Rzhetsky and Evans' (2013) conclusions about scientist research choices and Moore and Hughes' (1991) description of traffic engineers' research production provide a supplementary explanation for the effects observed by Noland, by finding practical forces that lead to production and acceptance of paradigm-satisfying over knowledge-advancing research. (This is essentially the same effect as described by Kuhn (1962) in his seminal work on scientific advancement via paradigm shifts.) In the case of Foster et al.'s scientists, career advancement requires reliable productivity. Scientists achieve a high probability of publication by adopting a conservative strategy adhering to the research tradition in their domain. For Moore and Hughes' (1991) traffic engineers, projects that will be funded under Federal programs can be easily identified using existing analytic techniques and established methods. For both, using novel techniques is more difficult, time-consuming and risky. Who could blame either set of professionals for reacting to strong incentives in a rational way?

The corollary point for Noland's expert panels is that their task is to deliver guidance, with the process being to examine research. This task exists in the context that older studies satisfied the standards of their time while new studies (where these exist) challenge accepted norms and practices; or, per Chhibber et al., certain studies will be highly influential and lead to dependence issues in experts' judgment. In both cases, rejection of previously influential research implies rejection of the existing research tradition and accepted paradigms, opening the expert panel up to having to advocate for the newer research. It forces panel members into an uncomfortable position that both scientists and traffic engineers have both found in their own interests to avoid.

Conclusion

This qualitative literature review has explored the extent of academic discourse on the topic of this dissertation and found virtually no literature that directly addresses the hypothesis. Despite this, significant support and illumination has been found across multiple fields, and in social science, science and engineering disciplines.

Overall, the literature review confirms that paradigm and pragmatism are influencing engineering formation, practice and the research agenda, to the detriment of the knowledge produced. Here, the question of what constitutes 'paradigm' is complex and somewhat vexed. For sociologists, engineering epistemology has been extensively considered in terms of differentiating technology from science, with the scientific tradition as a base. This approach tends to use static language framed around simplified notions of engineering practice. In contrast, engineering commentators tend to discuss paradigm in terms of the dynamic needs of engineering as a profession. Lloyd et al. (2001) note that it was the exigencies of the Industrial Revolution that brought technical competence to the practice of problem-solving for the good of society (i.e. engineering), due to the increasing precision required to construct machines. The result is reflected in Lloyd et al. (2001) enthusing (p.88) that:

> "The famous engineers of the Industrial Revolution were great innovators and entrepreneurs with an excellent understanding of societal needs. These should be the most significant competencies inculcated in students."

McLean (1988) also describes a time of highly productive research in the then-new discipline of Australian traffic engineering. Key to a fruitful and influential interdisciplinarity in the field was a Human Factors Committee that expanded the scope of road safety engineering to human behavioural considerations and helped establish a ground-breaking research program.

It appears that subsequent specialisation, codification of knowledge and gate-keeping activities – many of which represent the pragmatic effects of the process of professionalisation – have given rise to current characteristics of engineering paradigm. These include a focus on technical competencies to the exclusion of sociological understandings, and represents a mismatch of paradigm to practice needs particularly evident in traffic engineering and hence road safety.

Amongst the engineering disciplines, traffic engineering is rare if not unique in that its basic laws revolve around human behaviour. Rather than the focusing on the creation of economically or technically efficient artifacts, traffic engineering aims to manage human behaviour by mediating it through the design of the environment and social constructs (road rules, parking restrictions, etc.). And unlike liquids, solids, gases and so forth, the fundamental unit of traffic engineering – the road user – displays reflexivity: road users react in human ways to changed conditions, leading to randomness and confounding effects in traffic and in road safety studies.

Over time, multiple and complex pragmatic and paradigmatic influences have transitioned traffic engineering in Australia from a small, heterogenous professional base that strongly considered human factors to a specialist field in civil engineering where socially-based skills are poorly valued. This is despite employers, educators and engineers agreeing that the subjects taught do not adequately align with the practice needs of graduates due to a lack of exposure to training in the humanities. For the current profession, pragmatic pressures on traffic engineering practice (including road safety research) create a feedback loop aligning the research agenda to what is now an epistemologically-inflexible engineering paradigm. The result, then, is for paradigm and pragmatism to undermine both road safety research and the application of its results.

While the literature reviewed to develop this picture is often historic rather than contemporary, more modern authors such as Trevelyan (2014) in many ways deliver the same message, while reinforcing Lloyd et al.'s (2001) observation of modern practitioners having little appreciation for the history of the profession and the factors that have led to the current situation. Or, as writer and philosopher George Santayana famously put it:

> "Those who cannot remember the past are condemned to repeat it."

The problems created by a lack of human understandings are apparent in how engineers regard professional judgment. Elstein (1992) discusses professional judgment in the health field and Koen (1992) in the engineering field. The former talks about teaching expected utility theory to health practitioners to help them be more sceptical about their own intuitions and to show how quantification and formal problem structuring can help their thinking. The latter regards engineering judgment as being exceptional, with heuristics being used to (and implicitly capable of) balancing competing priorities. Koen's engineer apparently has no need to address internal biases or develop sound judgment because the scientific tradition provides absolute truth in an environment divorced from social context.

The field of engineering psychology contradicts any claims for such exceptionality by pointing to cognitive biases present in all humans. Many of these are based around "mental models" proposed by Tuler (1988), which coincide with Kuhn's (1962) description of paradigm and paradigm shift. These models of how a given system works are used to address informational and time constraints and represent a different view of paradigm as an error-prone set of internalised heuristics used to address very human limitations. Compared to the static umbrella of epistemology, this understanding of 'engineering mindset' as a set of functional heuristics tuned to certain systems and fitting within a paradigm shaped by education is more like a set of babushka dolls – except that many such dolls may exist at any one level, leading to the tortured (though fun) analogy of babushka Tardises.

It is also questionable whether a firm boundary really exists between science and engineering. If engineers are problem-solvers whose epistemology has evolved, so are scientists, and these epistemic cousins might be better thought of as occupying different ends of a spectrum of practice, separated more by aims, knowledge and problems than their approach to knowing. This, indeed, is reflected in many of the sociological considerations of engineering epistemology.

Hence while ‘engineering paradigm’ might be thought of as a technical, scientifically-based mindset, statically located in practice needs, it is more correct to say that paradigm represents a currently accepted tradition that reflects pragmatic influences at least as strongly as it reflects an overarching engineering mindset; and that a professional engineer’s paradigm should be aligned to engineering practice needs. Paradigm will also reflect the domains of knowledge related to the technological basis of each engineering discipline. For traffic engineering, the current paradigm reflects the civil engineering discipline and basic laws reflect those of materials science and physics. This is at odds with a discipline whose basic unit of ‘traffic’ is a group noun for individual road users, and whose basic laws are human behavioural. Despite this, pragmatic pressures reinforce the status quo, both through engineering education (recruitment of educators, placing of traffic engineering in the civil engineering discipline) and practice (setting of standards, funding requirements and so forth). The negative impacts of adherence to the current paradigm, including belief in intuition as the basis of engineering judgment, are highlighted by authors such as Noland (2013) and Hauer (2019b) in their anecdotes of counter-evidential decision-making.

Finally, the identity of engineers as problem-solvers can be considered as being ascendant over a more fluid professional paradigm, to the extent of being a more elemental part of engineering epistemology than even mathematical proficiency. This raises the potential for an appeal to the needs of traffic engineering practice to be able to shape the conceptual paradigm of traffic engineers. Historical perspectives taken from decades ago raise the question of why such appeals have not borne fruit previously. However, still extant concerns as raised by Hauer (2019a) and (2019b) indicate that additional efforts in the area are warranted, for the sake of road users and broader communities worldwide.

3. Methodology

This chapter provides:

- a general introduction to the use of the case studies in examining the thesis topic
- overviews of the two case studies selected
- the approach to the literature reviews undertaken for each case study
- the method adopted for each case study.

Introduction

Adopting a typical social sciences approach to a dissertation, primary research would aim to investigate further one of the themes raised in the literature review contained in Chapter 2. For example: the 'mindset' of engineers; road safety related topics in engineering education; the range of methods typically used by engineering researchers when researching road safety; the decision-making processes practitioners use when designing and building infrastructure; or forums for policy makers, practitioners and researchers to discuss road safety (e.g. the Australian College of Road Safety and its annual conference).

However, in providing support for this thesis' proposition that engineering paradigm and pragmatism are having an adverse influence on road safety, the literature review reveals that many of these topics have already been explored and/or their issues well recognised. So, in relation to the five examples above:

- engineering epistemology is already a principle focus of the (major) field of the sociology of technology
- traffic engineering receives scant treatment in (civil) engineering education. The curriculum issues are broader than road safety related topics, with an over-riding issue being the lack of curricula changes;
- the methods used by researchers are not necessarily flawed, but are mainly chosen with reference to pragmatic factors rather than in respect of the problem under consideration;
- decision-making is influenced by all manner of flaws from the poor development of engineering judgment to lack of placing decision-making in a social context;
- the research discussed in road safety forums would appear to be affected by paradigmatic and pragmatic issues and lack of multi- and inter-disciplinary limitations.

Hence the detailed study of any one of these themes would not significantly illuminate the overarching issue of the adverse effects of paradigm and pragmatism. At best, such detailed study would slightly expand an existing body of knowledge.

The case is arguably worse for an engineering approach to a dissertation considering road safety, where primary research would typically take the form of a road safety study of a treatment[25] using a describe/analyse method.

Instead, considering the purpose of primary research from first principles and in the context of a thesis, it is intended to contribute to knowledge about the thesis' hypothesis. In the social sciences approach, focusing on a particular aspect is usually required because of the scope of the field and hence its knowledge base. In the engineering approach, the treatment examined is aimed at addressing the issue being explored.

In this light, the more fundamental question raised by the literature review revolves around why known issues have not found greater traction, given the potential consequences. Here, the concluding remarks of the literature review suggest a different way to conceptualise the problem raised by the hypothesis and how primary research could contribute to knowledge. If the identity commitment of engineers as problem-solvers is an ascendant and elemental aspect of engineering epistemology, then the lack of progress in addressing the adverse effects of paradigm and pragmatism on road safety must arguably reflect ignorance of such adverse effects and/or a belief that any such adverse effects lie within the bounds of acceptable engineering practice.

As the literature review indicates, apart from the route of engineering education, paradigm tends to reinforce itself through the biases and precedence errors common in human judgment. For example, the logic that if the quantum of adverse effect from paradigm and pragmatic practice were sufficient to warrant these to be changed, then they would have been changed; the fact that they haven't indicates that the quantum of adverse effect must be acceptable. And traffic engineers can point to the truly remarkable achievements of road safety practitioners noted in the Introduction in Chapter 1 as further evidence that any adverse safety effects must be minor. If primary research can instead demonstrate that paradigm and pragmatism are creating adverse effects beyond the minor, then this research would directly confirm the thesis' hypothesis and demonstrate that this hypothesis provides a significant contribution to the road safety field.

The primary research undertaken in this dissertation is therefore intended to satisfy first-principle aims rather than conform to disciplinary norms. As the literature review has

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25 And/or a modelled treatment.

revealed, such an approach is risky for this dissertation's author in that it subverts established, easily recognised and well understood paradigms, but is also likely to generate a greater contribution to knowledge than paradigm-satisfying research. And given the topic of this thesis' hypothesis, the novel approach must surely be indicated over the mundane – as long as the novel approach is well specified and matched to the research topic, rather than chosen for novelty alone.

Developing the approach

In terms of a methodological approach to primary research, the literature that most closely approaches the thesis' proposition arguably comes from the road safety area and presents anecdotal evidence. Anecdotes are compelling as they demonstrate an actual case of an issue or problem rather than theorising whether the issue or problem might possibly exist. However, they also have limitations. Hauer (2019a) identifies the main problem of using anecdotal evidence in isolation from other types of evidence:

> "Anecdotes are good for illustration and can stimulate debate. But to argue [addressing the problem] is necessary one has to show that [the problem] is widely prevalent. How to convince that what the anecdotes illustrate is actually quite common? I could add story to story, pile example atop example but this would only make an overlong paper longer and would still fall short. In the final account only informed readers can say whether, in the light of what they know, the issues I raise are common."

That is, as every anecdote can be considered to be a particular case in isolation, any number of anecdotes can only illustrate rather than demonstrate a systemic effect. In particular, anecdotes challenging paradigm are likely to be rejected by those with a loyalty to that paradigm. Propositions based around anecdotal evidence therefore face barriers to changing engineering beliefs. Similarly, while the literature review uses sociological literature to explore the proposition, Kant and Kerr (2018) note that engineers are not often interested in philosophical discussions and many would equate philosophy with personalised viewpoints and value systems. Hence a philosophical treatment of the proposition would be equally unconvincing to engineers.

The starting point for a suitable methodology must therefore be to acknowledge current engineering epistemology and present evidence in these terms. At the most basic level, this means assuming the scientific tradition. Translating this into a 'scientific method' to some extent opens a can of worms around what this actually means. An appropriate philosophical examination of the 'scientific method' would start at Plato and Aristotle, progress through John Stuart Mill and Thomas Kuhn, and continue to the present day. Andersen and Hepburn (2016)[26] provide a good account regarding the inability to define a single 'scientific method' accepted and applicable to every situation, despite how commonly the phrase is used. Numbers and Kampourakis (2015) present a more populist consideration of the problem.

Happily for this dissertation, while both Andersen and Hepburn (2016) and Numbers and Kampourakis (2015) outline the problems of defining a single 'scientific method', the former also describe variations on a universal scientific method as being present at all levels of science education materials; and that this has been identified through numerous studies as forming part of both students' and teachers' conception of science. Meanwhile, the latter comment on "Easy to grasp, pocket-guide versions of the scientific method…" and the popularity of the term in common discourse. Rightly or wrongly, many aspects of popularised methods or generalised approaches can be assumed to be recognised and accepted by engineers as being 'scientific'. The method characterised by Andersen and Hepburn (2016) involves observing and describing a phenomenon, formulating a hypothesis which explains the phenomenon, designing and conducting experiments to test the hypothesis, analysing the results and drawing a conclusion – in other words, reflecting a fairly traditional form of PhD dissertation. As it appears in scientific journals, this form can be described as either:

> "…not an arbitrary publication format but rather a direct reflection of the process of scientific discovery"

or, more realistically:

> "…retrospective reconstructions of [research] activities that often do not preserve the temporal order or the logic of these activities, but are instead often constructed in order to screen off potential criticism."

(with both quotes being from Andersen and Hepburn, 2016).

In any case, this method is reflected in the current dissertation through the literature review (observing and describing), adoption of a hypothesis, this methodology (designing and conducting experiments to test the hypothesis), analysing results in the next two chapters, and then presenting the conclusions.

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26 Andersen and Hepburn (2016) represents the Stanford Encyclopedia of Philosophy's entry regarding the scientific method and is an authoritative source summarising literature in the field.

However, the thesis' proposition that engineering paradigm and pragmatism are having an adverse influence on road safety is not easy to experimentally demonstrate. The issue here, which also applies to Hauer's difficulty regarding anecdotes, is that examined by Karl Popper. Rather than going into detail on Popper's (seminal) *The Logic of Scientific Discovery*[27], Andersen and Hepburn (2016) can be cited in regard to a few pertinent points. Namely, Popper's observation that regardless of the amount of confirming evidence, we can never be certain that a hypothesis is true; and in describing the Popperian scientific tradition of falsification. The understanding brought by the Popperian tradition is that science is risky: if observations show the predictions from a theory to be absent, the theory (or belief) is refuted. This is the opposite of pseudo-science or (say) religious belief. Scientific hypotheses must be able to be proven false if they are to be considered true – falsification must be a possibility for a hypothesis to have validity. Hence demonstrating an effect exists in line with the thesis proposition is not sufficient to establish that the proposition has any claim to validity.

Luckily, there is a well-established mathematical and logical method for establishing the validity of a proposition by showing that if the proposition were assumed to be false, a result against accepted knowledge occurs. The contradiction of accepted knowledge can only be resolved if the original proposition is in fact true. This is the proof by contradiction approach, perhaps most well-known in terms of mathematical proofs such as demonstrating that the square root of 2 is an irrational number[28]. The approach lends itself to situations where it is difficult to prove a hypothesis for reasons as described by Popper and is therefore a method indicated for examining the current hypothesis.

The logical opposite of the thesis' hypothesis is that paradigm and pragmatism are **not** having an adverse effect on road safety. If no adverse effect is occurring, then the body of road safety knowledge must be being produced in an optimal way – a proposition that can more easily be tested. As disaggregating paradigm and pragmatic effects is likely to be difficult and the results potentially confusing, it is desirable to instead conduct two separate case study experiments, with one focused on paradigm and the other on pragmatic practice.

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[27] Published in English in 1959, based on a 1934 original written in German.

[28] The mathematical proof that √2 is irrational involves assuming it is rational i.e. can be expressed as a fraction comprising irreducible numbers. Following the logic through the maths gives the result that the fraction would have even numbers at both top and bottom. A fraction cannot be both irreducible and divisible by 2, so the original proposition that √2 is rational must be untrue.

The methodology adopted is therefore to take two case studies of known problems in road safety, establish the understandings developed for these through road safety research (i.e. the extant body of knowledge) as a base, revisit the problems using alternative paradigm and practice, and test for whether a contribution to knowledge emerges. If the current paradigm and pragmatic practices are leading to research knowledge being optimally produced, then challenging paradigm and pragmatic practice respectively should not lead to a contribution to knowledge, except by using hitherto unidentified approaches, theories, technology or similar, which are therefore indicated against in the case studies. Finding significant results for outstanding research problems (i.e. ones that have been extensively considered by the road safety field) by ignoring current paradigm and pragmatic practice, and using only established understandings and technologies, thus indicates that paradigm and pragmatic practice are not producing knowledge in an optimal way. And the original hypothesis is demonstrated.

The detailed method for each case study is particular to that case study, since these are quite distinct. The methods for paradigmatic and pragmatic case studies will therefore be presented separately in this chapter. Literature reviews establishing the extant body of knowledge for each case study topic are necessary to understanding the case studies and in terms of informing the adopted method. However, they are not relevant to methodology per se and would represent significant detours within this chapter. Therefore, the literature reviews are presented in the following chapters as part of each case study. A summary only of each is provided in this chapter as context to the detailed method applied in each case study.

Although the case studies are distinct, they are linked in that each takes as its starting point the use of mass data for statistical safety studies. In these studies, mass data such as traffic volumes, crash statistics and hospital admissions are collected and mathematical techniques such as regression analysis applied to associate crash risk with observable factors (traffic volume, composition, speed, road geometry, etc.). The limitations of these types of safety studies are well documented and mentioned in Chapter 1. For safety studies focusing on vulnerable road users, waiting for sufficient data to be collected to facilitate mass data analysis presents an additional moral hazard. Low cyclist modal share means many years might be required before enough cyclist injury crashes occur for an infrastructure treatment to be assessed under a mass data approach. During this period, cyclists are exposed to an unknown degree of risk, with any further infrastructure intervention confusing the question of which infrastructure caused what impact.

The use of mass data by traffic engineers for safety studies is both paradigmatic – as noted in Chapter 2, mathematics accords with the current engineering paradigm and the theory applied to the majority of safety studies revolves around statistical formula; and pragmatic – since such data is collected by jurisdictions, for the researcher it is relatively cheap, easily available and of a consistent quality. It should therefore not be surprising that the two case studies chosen both start with the mass data approach, though they then head in very different directions.

In terms of those directions, Andersen and Hepburn (2016) note that theoretical reasoning and experimental practice are two ways in which a scientific methodology is undertaken. That is, apart from a traditional view that the primary role of experiments is to test theoretical hypotheses, experiments can also be driven by the desire to obtain empirical regularities and to develop concepts and classifications in which these regularities can be described[29]. Nersessian (2008) has argued that new scientific concepts are constructed as solutions to specific problems by systematic reasoning and that analogy, visual representation and thought-experimentation are among the important reasoning practices employed. Writing in the field of aviation, Ferroff et al. (2012) conclude that in areas involving safety systems and human performance research, qualitative methodologies as well as quantitative methodologies are justified and methodologies should be selected to produce good quality research rather than conform to paradigm. The description of a field involving safety systems and human performance could also be seen to apply to the traffic environment, in which case qualitative methodologies are as equally valid to road safety research as quantitative ones. Qualitative methodologies are also compatible with broader theoretical frameworks for road safety, which acknowledge the role of human factors as well as physical factors.

As mentioned, the remainder of this chapter will introduce the two case studies, present summary literature reviews as context for each case study, and outline the method applied in each case study investigation.

[29] However, the difference between theory driven experimentation and exploratory experimentation should not be seen as a sharp distinction in that theory-driven experiments may also be directed at various kinds of fact-gathering, while exploratory experiments are usually informed by theory and are therefore not entirely theory-free.

Paradigmatic case study: Traffic Conflict Technique (TCT)

Overview of the case study

The case study chosen is the theoretical framework of Traffic Conflict Technique (TCT). TCT is described in detail in the literature review in the following chapter. The pertinent points in terms of case study selection are paradigm (the focus of this case study), potential (significance for the field) and practice (the outstanding problems unresolved by paradigm). The case study takes a theoretical form and has not yet been tested with empirical data.

PARADIGM

With Elvik (2004) noting the general lack of a strong theoretical base in road safety research, TCT is an ideal paradigmatic case study as it is an example of a road safety theory that is self-contained and reflects an engineering paradigm that, as applied to this particular road safety technique, is strongly defined[30].

Work in the field has been accompanied by the development of theories and formal definitions. As a tradition that has developed over a long period, the resulting theoretical framework establishes a mindset or paradigm for road safety researchers in the TCT field. As observed regarding 'engineering paradigm', the TCT paradigm has also evolved over time and has been shaped by pragmatic influences. Unlike engineering, however, the identified issues regarding TCT are generally considered by researchers to be technical problems rather than reflecting a lack of additional perspectives being brought to the established paradigm: there is no equivalent to Rojter (2004) or Lloyd et al. (2001) for TCT.

POTENTIAL

The problems of mass data techniques have already been mentioned. Traffic Conflict Technique (TCT) is a method proposed for undertaking safety studies based on observing traffic interactions (or 'encounters' or 'events') as a surrogate for crash-related (mass) data. The ability of TCT to overcome mass data limitations in safety studies would be highly beneficial. A significant amount of work has been invested into the field over forty to fifty years, including international workshops and calibration exercises. Papers on TCT studies

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[30] TCT is, however, not the only example. Crash prediction modelling and the use of Crash Modification Factors, the development of traffic models, and other specialised fields of enquiry might fit this description. TCT was initially examined as a possible methodology for the pragmatic case study, which created some familiarity with the field and outstanding issues in the field – an example that "…experimental practices are messy and often do not follow any recognisable pattern", as per Andersen and Hepburn (2016).

and reviews appear with regularity in all of the major traffic engineering and road safety journals. From the perspective of the case study, TCT not only has significance but considerable effort has been expended on realising its potential. If an adverse effect of adherence to paradigm is demonstrated, this should have strong implications for road safety and road safety research. If the demonstration provides a more effective manner of approaching TCT, this would comprise a significant contribution to knowledge in its own right.

PRACTICE

While conflict studies are used in some areas of road safety practice, Johnsson, Laureshyn and de Ceunynck (2018) note that no single indicator proposed for TCT has been found to capture all aspects of a traffic encounter. There is no single agreed method for undertaking TCT studies, although different countries have adopted different standardised approaches: the Swedish Traffic Conflicts Technique first developed in the 1970s has most recently been updated by Laureshyn and Várhelyi (2018), while the micro-simulation Surrogate Safety Assessment Model (SSAM) developed by Gettman et al. (2008) for the US Federal Highway Administration has been made freely available so that developing countries can use it in their traffic engineering practice.

Additionally, TCT does not apply to single-vehicle crashes and produces poor results for mixed traffic. Even within the practice of the standardised approaches, TCT has not been operationalised such that conflicts can be used as a surrogate for crashes without recourse to an historic crash record, which reintroduces many of the mass data issues. As such, the potential of TCT has not been realised.

Summary of the case study literature

The consideration of the academic literature for TCT in the next chapter is qualitative and follows an historical narrative approach that explains the development of its theoretical framework and identifies the major outstanding issues in the field. This type of approach was chosen because Traffic Conflicts Technique (TCT) has developed in a messy, iterative manner, strongly shaped by available technology. Laureshyn et al. (2016) observe that researchers new to the field:

> "…struggle to gain a clear overview of the current state of the field. The literature in this domain is vast and diverse; while many of the old (but still highly relevant) research effort reports exist only in paper format and are hard to reach, the publications related to the technical improvements in this area seem to grow in number very rapidly. Even for more experienced researchers there is a risk of losing track of the critical points of attention. The lack of holistic overview seems to lead to "reinventing the wheel" and errors from the past being repeated."

The literature review (or overview) in the next chapter essentially aims to develop the clear, holistic overview of the state of the field that is currently lacking. Major paradigmatic points identified from the literature overview are:

- The basic tenant of TCT is that conflicts can be used as surrogates for crashes in safety studies. Such surrogates are alternatives or complements of safety analyses based on accident records and occur more frequently, making safety easier to analyse.
- The definition of 'conflict' in current use is, per Amundson and Hydén (1977):

> "…an observable situation in which two or more road users approach each other in space and time for such an extent that there is a risk of collision if their movements remain unchanged."

- Conflicts differ in their degree or 'severity', with increasing levels of severity indicating poorer safety. (However, there is no accepted definition for 'severity'.)
- The most popular indicator of conflict/conflict severity is (or has been) Time-To-Collision, defined by Hayward (1971) as:

> "...the time that remains until a collision between two vehicles would have occurred if the collision course and speed difference are maintained."[31]

- The next most popular indicator is Post-Encroachment Time, which Chin and Quek cite as being defined by Allen et al. (1978) as:

> "…the time between the first road user leaving a common spatial zone and the second arriving at it."

Issues in TCT paradigm remain, notably about the fundamental concept of a 'conflict' and its 'severity' and what these actually refer to; the validity of a process model for crashes i.e. whether and how conflict is related to collision; the role of evasive manoeuvres in indicating

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[31] Time-to-Collision is generally abbreviated to TTC in TCT literature and studies, but this is a little confusing in a broader work such as this dissertation. Therefore Time-To-Collision will be used to in full rather than abbreviated, except when quoting others. This is similarly the case for other indicators.

either safe or unsafe conditions; and how measurement methods or indicators used in TCT relate to fundamental definitions.

The greater issue for TCT is that while some studies have shown correlation between measures for conflicts and crash risk as established by historic crash records, there is a high degree of inconsistency regarding whether any correlation exists and what measure or indicator is associated with correlation in any particular situation. Indeed, researchers who calculate crash prediction models or crash modification factors using mass-data approaches have pointed to the far better reliability of correlation with actual crash risk achieved through their work than has yet to be demonstrated by TCT. A similar situation of inconsistent correlation applies to the more recent innovation of applying Extreme Value (EV) theory to TCT, where EV theory is a proven mathematical theory that could link conflict (or, more specifically, observed traffic events) to crashes.

Hence TCT currently cannot be used to calculate absolute crash risk independently of an historic crash record and, as such, a major aim of TCT has not been realised. Even within a more limited use of TCT, Johnsson, Laureshyn and de Ceunynck (2018) conclude in the abstract to their review of surrogate safety indicators:

> "The results show that various indicators and their combinations can reflect different aspects of any traffic event. However, no existing indicator seems to capture all aspects. Various studies have also focused on the validity of different indicators. However, due to the use of diverse approaches to validation, the large difference in how many locations were investigated and variations in the duration of observation at each location, it is difficult to compare and discuss the validity of the different surrogate safety indicators. Since no current indicator can properly reflect all the important aspects underlined in this article, the authors suggest that the choice of a suitable indicator in future surrogate safety studies should be made with considerations of the context-dependent suitability of the respective indicator."

That is, even as an accepted component of current practice, the weaknesses inherent in all surrogate indicators currently in use means that road safety practitioners should approach TCT with care.

Method applied to the case study

From the literature review, a number of outstanding issues exist regarding TCT. As a broad summary, in no particular order and acknowledging degrees of overlap, these issues are:

a) definition of a conflict

b) identifying the boundary between non-conflicts, conflicts and crashes
c) lack of a collision course (and hence observable ‘conflict’) in some traffic encounters
d) the inability to define or measure single-vehicle events leading to crashes
e) the concepts of proximity and severity in TCT
f) lack of models linking measured traffic conflict to crashes
g) the validity of evasive action as a measure of conflict
h) exposure versus risk: increases in ‘conflicts’ do not necessarily lead to reductions in safety, or vice versa
i) temporally-based measures of conflict (conflict indicators) do not uniquely characterise conflicts
j) lack of consensus on measures/ indicators to use in TCT, with different measures/ indicators giving different results
k) the validity (or otherwise) of assumptions about road user movements, and hence the future kinematic state of vehicles, made to enable conflict to be assessed
l) statistical association between aggregated conflicts and crashes still relies on crash data and ignores heterogeneity in the estimation procedure
m) difficulties in how to account for differences in conflict characteristics known to be related to crash consequences: road user vulnerability, speed, mass, collision type, collision angle, etc.
n) the tension between combining dimensions of conflict to create a single indicator versus using a range of indicators to represent various encounters, at the expense of comparability
o) what calculated indicators actually characterise
p) questionable compatibility of Extreme Value theory with TCT indicators.

One approach to try to address these issues is to consider them separately and attempt to resolve them through addition, exploration and amendment of the existing body of work that comprises the TCT field. This is the approach being pursued by most researchers in the field and is based on building upon the existing engineering paradigm, as expressed as a tradition of work.

As per the introduction to this chapter, a proof by contradiction approach to the pragmatic case study is to reject paradigmatic elements of TCT, reconceptualise TCT around first principles and examine the results in terms of the outstanding issues.

From the literature review and as summarised above, the paradigmatic elements of TCT are:

- The definition of a conflict
- Models of association between conflicts and crashes theorised by road safety researchers (notably severity hierarchies for traffic events)
- The established measures/ indicators in current use.

Rejecting these elements essentially leaves as last-man-standing the concept that non-crash traffic events can be used as a surrogate indicator for crash events to reveal information about the safety conditions at a site. To progress this concept, Extreme Value (EV) theory provides the obvious basis for an alternative approach as it is the only theory proven to be able to link observations of more common events to the likelihood of rarely observed extreme events occurring.

Having adopted EV theory as a basis, a process of logical deduction can be applied and the results tested, in terms of: their ability to offer a realistic alternative to TCT; whether such an alternative can address the existing issues applying to TCT; and, if so, to what degree. These issues, summarised above, are identified in the detailed literature review presented in the next chapter and have been well explained by different authors – these are not novel, unknown or rejected by researchers practicing within the TCT field. And in broad terms, this case study approach is still based on the understandings and learnings developed from the TCT field of study as applied separately from the established tradition i.e. freed from their paradigmatic superstructure. Under the methodological concept, if the engineering paradigm that has led to the current version of TCT provide for the optimal development of road safety knowledge, then rejecting paradigmatic elements should not facilitate a reformulation of TCT that can address outstanding issues within the field.

Of course, a failure to develop a reformulated TCT does not prove that such a reformulation is impossible, though the difficulty of the task could perhaps be correlated to the degree by which paradigm is well-matched to TCT research. As the next chapter will demonstrate, this eventuality does not need to be considered.

Pragmatic case study: cyclist safety at radial versus tangential roundabouts

Overview of the case study

The case study chosen is the effect on cyclist safety of radially-based roundabouts (used in non-Anglophone countries) versus tangentially-based roundabouts (used in Anglophone countries). The difference between radial and tangential roundabouts, safety of cyclists at roundabouts and theories of safety mechanisms are described in detail in the literature review in the following chapter. The pertinent points in terms of its selection are pragmatism (the focus of this case study), potential (significance for the field) and practice (outstanding problems in using a paradigmatic approach). The case study takes the practical form of a before-after study of a roundabout reconstructed from a tangential design base to a radial design base.

Pragmatism

Mass data safety studies typically analyse many occurrences of the same type of infrastructure – T-junction, four-way intersection, etc. – to form the correlations that underpin safety conclusions. For example, comparing the safety record of a group of four-way intersections with no priority controls against a group of similar four-way intersections with give way controls provides a way to correlate the give way control to crash risk. Mass data safety studies are favoured for the paradigmatic reasons that the mathematical techniques used are based in established theory, and for the pragmatic reason that such data is relatively easily available and of a consistent, relatively high quality. In terms of “relatively”, however, Chapter 1 notes that cyclists are a road user type for whom the mass data approach has known limitations due to a lack of exposure data, the under-reporting of crashes and a low modal share translating to a greater effect from crash randomness than for motor vehicles. Despite this, mass data safety studies remain the main way in which cyclist safety in general and at roundabouts in particular are investigated.

As the literature review for this case study will demonstrate (Chapter 5), mass data safety studies have identified an over-representation of cyclists in crashes at roundabouts, along with indications that the crash risk at roundabouts designed according to the design base used in Anglophone countries (tangential) is higher than at roundabouts following the design base used in non-Anglophone countries (radial). A roundabout in Adelaide, South Australia, that lies on a cyclist route and has a record of cyclist crashes was therefore reconstructed on a trial basis from a tangential to radial design base, with the aim of reducing cyclist crashes. This created the conditions for a before/after case study.

POTENTIAL

Cyclists are vulnerable road users for whom traffic crashes are likely to result in injury. As a mode, its users include children, for whom society generally accepts a higher duty of care than for adults. Despite the over-representation of cyclists in crashes at roundabouts, roundabouts produce major safety benefits for motorised road users and continue to be constructed on roads for safety and traffic management reasons. Clarification as to the mechanisms behind the cyclist crashes at roundabouts would enable roundabouts to be designed and installed that are safer for cyclists. The benefits of this would not just be direct, but also be relevant for encouraging cycling as a mode of traffic, which is a stated policy of Federal, State and local governments due to the cross-sector benefits of cycling compared to driving.

As will be identified in the literature review for this case study (Chapter 5), mass data safety studies point to traffic speed as a safety factor for roundabouts in general. This has translated to the theory (or assumption) that the different speed environments created by radial compared to tangential roundabouts underpins their relative safety performances for cyclists. In the absence of any other known safety mechanisms, this would indicate that applying speed-reducing treatments or methods at roundabouts – other than adopting a radial design base – could achieve the same safety benefit for cyclists.

If, however, the greater safety of radial roundabouts over tangential roundabouts is also related to other mechanisms, then speed-reduction as a stand-alone safety treatment will not achieve the same degree of safety improvement for cyclists as using radial roundabout design. The identification of such safety mechanisms would therefore represent a contribution to knowledge for this particular problem. Since any such safety mechanisms are currently unknown, identifying new safety mechanisms would also contribute to the body of knowledge of the road safety field more generally.

PRACTICE

As the variability within infrastructure characteristics increases, the ability to associate a safety effect with any one characteristic decreases. Roundabouts are a prime example of this. While the size and number of lanes are relatively simple to define, priority rules operate in such a way that traffic volumes, speed, composition and turning movements at each leg create numerous combinations and permutations, and these exist in addition to other geometric features such as camber, superelevation, turn radii, lane widths and sightlines. The overall result is that the safety impact of particular elements of infrastructure design at roundabouts is difficult to determine.

Vehicle speed is the only safety mechanism for which design elements have been linked to cyclist safety at roundabouts. While other research indicates the possibility that other safety mechanisms exist, none has been correlated to geometric design and hence design countermeasures. Mass data safety studies have not shed light on such safety mechanisms and a continued favouring of mass data studies, even when they are not indicated for the problem at hand, cannot change this situation.

Summary of the case study literature

The academic literature presented in the next chapter considers factors relevant to the pragmatic case study regarding specific topics, as literature overviews. These literature overviews are undertaken following a qualitative literature review approach but similarly to the historical literature review of the paradigmatic case study, the aim of these is essentially to develop a clear understanding of relevant factors rather than to be comprehensive or exhaustive.

The first three literature overviews consider:

- radial versus tangential design of roundabouts, as technical background to the case study
- the cyclist crash risk at roundabouts, as an unresolved safety issue
- traffic speed as the main safety mechanism associated with safety at roundabouts.

These literature overviews demonstrate that the crash risk at roundabouts has been extensively studied. Cyclists are recognised at facing a higher risk than their proportion of the traffic volume would indicate. The main crash type is ‘entering car-circulating cyclist’, where the entering vehicle fails to yield to a cyclist already on the roundabout. Vehicle speeds have been identified as a key factor for roundabout safety in general. While there is some indication of a lower crash risk for cyclists at radial compared to tangential roundabouts, the variety of conditions studied and the use of different roundabout bases in different countries makes this safety effect difficult to confirm. As radial roundabout design is associated with lower approach speed, it could be expected that this would provide greater safety than tangential design. This also implies that apart from converting tangential roundabouts to a radial design base, other techniques to lower approach speed could be applied at tangential roundabouts to achieve similar safety outcomes.

The next three literature overviews consider identified safety effects that may apply at roundabouts in addition to traffic speed effects. These literature overviews inform the method adopted for the case study and the interpretation of results, noting that traffic speed is the only safety effect identified using mass data safety studies. The literature overviews relate to:

- Safety in Numbers
- Looked But Failed to See
- Conflict Point Theory.

SAFETY IN NUMBERS refers to the non-linearity of risk whereby increasing numbers of vehicles leading to a proportionately lower number of crashes. While empirically observed, the lack of a proven causal chain and no consistently calculable effect has led to some caution being applied to the strategy of encouraging cycling in the expectation of fewer crashes. In terms of infrastructure design and the safety of cycling through a roundabout, a pure 'Safety in Numbers' effect would be independent of the design basis of the roundabout, except as this attracts/ discourages cyclists. It is therefore incompatible with the theorised safety impact of radial versus tangential design, independently of cyclist numbers. A causal chain for the 'Safety in Numbers' effect has recently been proposed that is analogous to the impact of herd, flock, swarm and schooling behaviour of prey animals on reducing the risk of predation by reducing exposure to predators. This mechanism is important in suggesting that cyclist density within the traffic stream rather than pure cyclist numbers drives the 'Safety in Numbers' effect, accounting for the lack of consistency in its impact. However, it has not been confirmed in practice.

LOOKED BUT FAILED TO SEE refers to crash situations where an apparent failure to detect a hazard does not correlate well to objective assessments of visibility or conspicuity. For example, Langham et al. (2002) studied collisions with police cars parked on the hard shoulder of a motorway, where drivers were apparently unable to detect in daylight a reasonably large vehicle having high-contrast paintwork and operating flashing roof lights, sitting well out of the traffic lanes on a wide shoulder.

Causal chains are cognitive, centring on 'inattention blindness' and 'change blindness' and cannot be investigated using safety studies based on mass data approaches. One study has found that cyclists who position towards the centre of the roundabout traffic lane are perceived more frequently than those positioned towards the edge of the lane, however no follow-up research has been undertaken to confirm this. Insofar as geometry influences cyclist positioning, this would caution against the implication that safety benefits from radial roundabout design can be achieved by reducing traffic approach speeds, if cyclist positioning is not also addressed.

CONFLICT POINT THEORY explains the lower rate of crashes for cars at roundabouts compared to the intersections they replace in terms of the number of locations where vehicle paths overlap or conflict. The theory is paradigmatically attractive and is presented as a causal mechanism in Australian road safety guidance. However, the evidence does not support but rather challenges Conflict Point Theory. In particular, for cyclists, the number of conflict points is not markedly different for a radially compared to a tangentially designed roundabout and the theory cannot explain a safety difference between the two designs.

Method applied to the case study

From the results of the literature review, a proof by contradiction approach to the pragmatic case study involves rejecting a mass data approach. The rejection of easily (and cheaply) obtained crash and traffic volume data, except insofar as available data can be used to validate the case study results, has implications on the method adopted for a practical case study.

Firstly, the systematic quantitative (SQ) literature review (Appendix B) informs study design, and particularly data sources for safety studies. In the road safety field, alternatives to mass data sources underpinning broad-scale statistical analysis are relatively few. These can be summarised as prospective surveys, road user surveys, video observation, naturalistic studies, video simulation and computer modelling. These types of study designs are likely to produce qualitative rather than quantitative data. As previously noted, Ferroff et al. (2012) argue that in safety studies, there is a case for using qualitative as well as quantitative methodologies.

Hydén (1987) notes that looking at the process leading to crashes is a demanding task as it is almost impossible to obtain observational data. Therefore, examining the process leading to crashes is instead based on historical data, where the information is extracted from crash investigation studies – that is, the statistical (mass) safety study approach is adopted. An observational study provides this direct observation data, enabling examination of the ‘pre-crash’ phase and, indeed, the ‘non-crash’ event.

Nonetheless, comparability of results is fundamental to a safety study if its results are to have application in other settings. Here, the SQ literature review (Appendix B) identifies that cyclist exposure is an issue of concern in studies regarding cyclists at infrastructure. Study design based on road user surveys, naturalistic studies or video simulation have very limited opportunity to account for exposure at infrastructure and are therefore indicated against. Of the remaining study design options, a prospective study involves examination of effects over a long timeframe, which is not compatible with the practicalities of the chosen case study (discussed in more detail below). Hence video observation is considered the preferred data collection method.

Secondly, the dissertation is framed around the impact of infrastructure on cyclist safety. Austroads (2013) *Guide to Road Safety – Part 2: Road Safety Strategy and Evaluation* identifies three basic types of methods for evaluating road safety treatments:

- Cross-sectional studies – these compare sites with and without the treatment, usually over the same time period; the treatment sites and the comparison sites are different sites.
- Before/ after studies – these compare sites before a treatment is installed with the same sites after the treatment has been installed. Investigators select the sites for study but do not influence treatments in any way and simply observe any differences associated with the treatment.
- Experimental before/ after studies – these are a type of before/ after study where the investigators have an active role in influencing the selection of sites for treatment, usually by randomly allocating sites to a treatment group or control group, or some other procedure to eliminate bias in the results.

These are all site-based studies. Cross-sectional and experimental before/after studies are based on aggregating results across a number of sites, which is difficult in the case of roundabouts – as has been previously noted. As noted in the Introduction (Chapter 1), Hauer (2005) discusses limitations of cross-sectional studies in considerable detail, concluding that the (common) use of regression analysis in such studies does not produce justifiable causal relationships being identified.

(Non-experimental) before/after studies have the advantage that many of the environmental factors normally controlled for through the collection and analysis of large amounts of data do not change between the after and before situations and are thus accounted for by default. Such factors include traffic composition, turning versus through volumes, local speed limit, number of lanes, road width, camber, and so forth. Hence (non-experimental) before/after studies represent the preferred approach.

The availability of possible case studies was determined by surveying local and state government road and traffic authorities across Australia. This identified an opportunity to study the before/after conversion of a tangential roundabout to a radial design base, which was being undertaken for reasons of cyclist safety. (This road authority survey also asked respondents various questions about their experiences with cyclist safety and infrastructure. The background, methodology and results are presented for information in Appendix C[32].)

The case study site is the intersection of Beulah Road and Sydenham Road in Norwood, an inner-eastern suburb of Adelaide. Both Beulah Road and Sydenham Road are local roads and Beulah Road is a designated cycle route providing access to the east of Adelaide's CBD. A large number of cyclist crashes had been identified as occurring at the tangentially-designed roundabout, prompting the state road authority to trial modification of its geometric design to essentially convert the roundabout to a radial design base. This presented an ideal pragmatic case study, given the safety issues and question marks related to cyclist safety at radial versus tangential roundabouts previously outlined, and that no conversions of tangential to radial design – or radial to tangential design – are known in the literature. In seeking to identify a hitherto unknown safety mechanism affecting the safety of cyclists at roundabouts, the case study could also make a meaningful contribution to the body of knowledge regarding the safety of roundabouts for cyclist safety and, if the mechanism also operates in other settings, more broadly.

The conceptual method for the case study was to record video observations of traffic before and after the intervention was made. Close examination of the video was then undertaken to identify differences arising in behaviour and interactions in the after situation compared to the before situation, with the aim of identifying any that could be related to the geometric changes in isolation from the vehicle approach speed reductions expected of a radial roundabout compared to a tangential roundabout. The approach was thus exploratory, resulting in several approaches being taken to identify different effects as they were noticed. A major element was to examine traffic interactions for what these revealed about yielding behaviour, since the

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[32] This work was undertaken as part of the exploratory phase of the PhD – another example of "…experimental practices [that] are messy and often do not follow any recognizable pattern", as per Andersen and Hepburn (2016).

main crash type affecting cyclists related to yield failures. This examination was facilitated by coding traffic interactions in an iterative manner that progressively added code fields to capture the noted changes in performance of the roundabout. The coding enabled a structured analysis to be undertaken to determine significance.

As an overall piece of work, the case study was extensive – the coding-related element alone examined 2,956 motor vehicle and 887 cyclist movements through the roundabout. It should be noted that the full details of the case study are not provided in this or subsequent chapters. This is because the production and analysis of data through the case study represents an exploratory exercise. As such, the case study produced significant amounts of data that are not relevant to the proof by contradiction aim of demonstrating that a safety mechanism exists that has not been identified through the pragmatic use of a mass data approach to safety studies. However, for information and reference, the full detail of the case study is provided in Appendix D. This includes:

- background regarding the site (including traffic data and crash statistics);
- methodology, including data collection issues and the coding system developed;
- results, broken into the three zones of the approach to the roundabout, departure from the roundabout and interactions on the roundabout; and
- analysis of the results, including the coded data.

4. Results of the paradigmatic case study (Traffic Conflict Technique)

As noted, the basis of the proof by contradiction approach for the paradigmatic case study is an attempt to develop a competing proposal to the existing theoretical framework for Traffic Conflicts Technique (TCT) that, insofar as a theoretical case study can confirm, overcomes issues identified for TCT. If so, this indicates that an adherence to TCT's paradigmatic elements has hindered this field of study.

This chapter presents the literature review undertaken regarding TCT and the results of applying the proof by contradiction approach to the case study of TCT.

Literature overview

As previously noted, the limitations of safety studies based on crash events have been understood for a long time. The difficulty has been in finding alternative methods for undertaking safety studies. For example, Robertson, Mclean and Ryan (1966) followed ambulances in Adelaide in 1963-1964 in order:

> "To gather data in Australian conditions basic to the design of roads, traffic organization and vehicles, by the objective study of the medical and engineering aspects of injury-producing accidents."

This extended research beyond summary crash data to a detailed examination of injuries, vehicle damage and crash reconstruction, but was still dependent on crashes occurring.

Laureshyn and Várhelyi (2018) note that the general concept of using surrogates of crash events as a way of measuring safety was in existence as early as 1957[33]. In fact, Williams (1981) mentions McFarland and Moseley (1954) as being the first to formalise a method already being used by highway engineers of diagnosing operational or safety deficiencies by observing erratic driving, unsafe manoeuvres and "near misses" at problem locations. In any case, Perkins and Harris (1967[34]) were the first to attempt to overcome many of the limitations of statistical analysis by defining twenty objective traffic characteristics related to accident patterns. These were considered to lead to traffic conflicts (or "impending accident situations.") Others followed suit, often using their own ideas about traffic characteristics and

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[33] The term 'surrogate' is widely used in TCT. Johnsson, Laureshyn and de Ceunynck (2018) clarify that surrogate indicators are meant to be alternatives or complements of safety analyses based on accident records.

[34] Sometimes quoted as 1966, which was when the work was undertaken, compared to 1967, which was when the authors published a number of papers on Traffic conflict characteristics.

responding to the many limitations to Perkins' and Harris' techniques that were soon identified. Though studies often found contrary results, the Traffic Conflicts Technique (as the new field became known) drew considerable interest[35].

A conference on the growing field of Traffic Conflicts Technique (TCT) was held in Norway, with Amundson and Hydén (1977) providing a definition for conflict as:

> "…an observable situation in which two or more road users approach each other in space and time for such an extent that there is a risk of collision if their movements remain unchanged."

This was an early contribution to the theoretical framework for TCT. However, in practice, conflicts were mainly recorded by observing evasive actions such as swerving and hard braking. Zheng et al. (2014a) quote Parker and Zegeer (1989) as defining traffic conflict in line with the actual practice of observing evasive actions:

> "… an event involving two or more road users, in which the action of one user causes the other user to make an evasive maneuver to avoid a collision."

This became the definition in use. This implicitly assumed that crashes are rare and unusual (i.e. stochastic) events, and that there is some correspondence between the observation of evasive action and the presence of safety or operational deficiencies (Glauz and Migletz, 1980). Despite the phrase "two or more", conflicts involving more than two road users were generally rare and complex enough to be ignored. Neither definition allows for single-vehicle conflicts despite the existence of single-vehicle crashes.

Figure 4 conceptualises TCT in terms of traffic events ranked by 'nearness to collision', though most commentary at the time related the ranking of traffic events to the outcome severity of crashes. No consistent definition for 'traffic event' has been found in the literature, but a 'traffic event' can be considered as the simultaneous passage of two or more vehicles through an area under observation.

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35 Williams (1981) provides a good overview of studies and difficulties encountered up to the time of his writing. "Traffic Conflict Technique" or "Traffic Conflicts Technique" are used interchangeably. Williams used the latter.

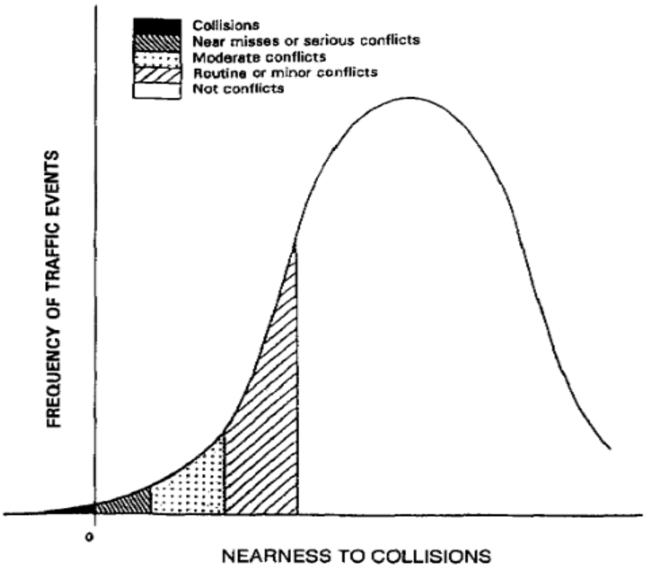

Figure 4: Distribution function for traffic conflicts, Glauz and Migletz (1980).

The relationship between conflicts and crashes was strongly debated. Glauz and Migletz (1980) argued that evasive manoeuvres could not be considered as surrogates for crashes. Williams (1981) criticised the popularity of TCT despite a lack of evidence linking conflicts to crashes, also noting that crashes involving property-damage-only had not been found to be a good indicator of injury crashes, which were in turn not a good indicator of major injury crashes; and that these different severity categories often involve different collision types. A more fundamental conceptual problem in defining and measuring conflict on the basis of evasive action, as Zheng et al. (2014a) observe, is that this implies that conflicts and crashes are of the same nature except for the presence and the success of an evasive action. However, many crashes occur that are not preceded by evasive action, while evasive action taken on a precautionary basis to avoid crashes could be indicative of safer rather than less safe conditions – the road user has the time and ability to see an impending collision and avoid it. This brings into doubt the practice of using of evasive actions as surrogates for crashes in TCT.

Subjective ratings of the severity of evasive manoeuvres introduced additional complexity and, over time, the dominance of evasive action as a basis for TCT waned. El-Basyouny and Sayed (2013) and Zheng et al. (2014a) point to Amundson and Hydén’s (1977) definition independent of evasive action as now being accepted internationally – at least on a conceptual basis.

Williams (1981) was one to advocate for using more objective measures in TCT. Within a few years, Hydén (1987) codified training, recording, testing and evaluation for manual data gathering to help address subjectivity issues in a seminal work on the Swedish Traffic-Conflicts Technique, which Hydén notes was first developed in Lund University in 1974. Sweden's adoption of a codified TCT method reflects its status as an innovator and forerunner in the TCT field, though others soon followed suit. Similarly to Kruysse and Wijlhuizen (1992), Hydén's early use of filming allowed data gathering to occur separately from coding of conflicts, which enabled the reliability of human observers to be benchmarked.

Although it is likely that the reducing costs and increasing access to video-taping assisted emerging TCT practice to move away from evasive actions as a basis, filming came at a cost penalty and enabled only modest gains in efficiency as examining hours of filmed traffic movements was still required. Direct human observation remained the norm as TCT practice developed. Time-based (or temporal) indicators were found to be more reliably assessed by observers and became accepted over evasive behaviours as TCT indicators of conflict. However, subjectivity of observers remained a concern since conflicts still had to be observed, characterised and differentiated between, even if their assessed values were now to be objectively based. As a result of these issues, the popularity of TCT waned in the 1990s. Subsequent technological advances have provided new interest in the field.

Most recently, there has been some revisiting of the role of evasive behaviour in TCT, principally related to issues with temporal indicators. Temporal indicators will be described and discussed in some detail further on, but Tiwari, Mohan and Fazio's (1998) conflict study of pedestrians crossing at mid-block locations confirms the problem of applying temporal indicators to mixed traffic situations, finding only a weak relationship between conflicts and the crash record. Tageldin and Sayed (2015) demonstrate that in a less-organized traffic environment with highly mixed road users, TCT indicators designed to detect evasive actions (such as deceleration, jerk, and yaw rate) are better able to detect conflict than temporal indicators. And evasive behaviour remains the basis of codified methodologies for TCT in Sweden and Holland (known as Swedish TCT and DOCTOR, respectively). Here, Laureshyn et al. (2017a), Laureshyn et al. (2017b) and Laureshyn and Várhelyi (2018) add a pragmatic limitation to conceptual limitations by noting that application of Swedish TCT to vulnerable road users presents difficulties – including regarding assumptions of braking as the main evasive manoeuvre.

Hydén (1987) also proposed the first conceptual safety hierarchy for traffic events, as per Figure 5.

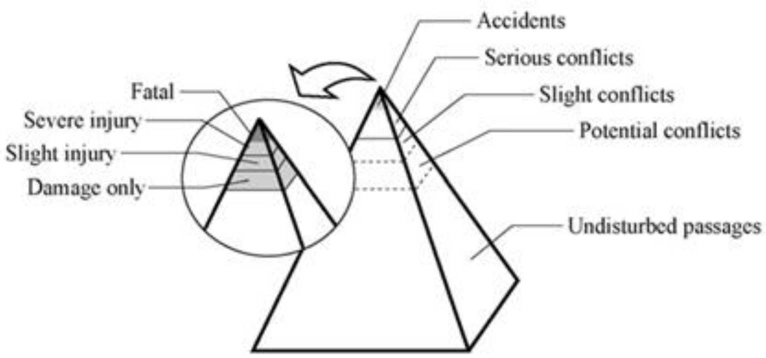

Figure 5: Pyramidal safety hierarchy. Source: Hydén (1987).

Zheng, Ismail and Meng (2014a) note that TCT theories based on severity hierarchies for traffic events are used to justify examining conflicts rather than crashes as the basis for safety. As hierarchies hypothesise traffic event distributions in terms of nearness to conflict and thence collisions, these arguably follow in the tradition of Glauz and Migletz's (1980) distribution function for traffic conflicts.

Although illustrated as a three-dimensional shape, Hydén (1987) describes only two dimensions: probability (the area of the pyramid) and degree of seriousness (or 'severity', being the height of the pyramid.) Svensson (1998) has suggested that the safety hierarchy is diamond-shaped, as per Figure 6. In contrast to Hydén's pyramid, in Svensson's diamond the probability of undisturbed passages decreases past a certain point. To some extent, this implies that 'severity' is linked to nearness, with 'undisturbed passage' becoming less probable because no limit is applied to the distance between road users. That is, two cars passing each other at a distance of 1m represents high severity; two cars passing each other at a distance of 1km represents very low severity; and there is a very low probability of no severity (undisturbed passage) if distant passing is included in the safety hierarchy.

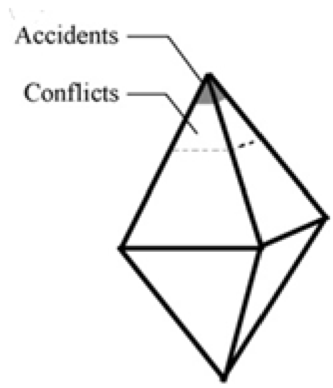

Figure 6: Diamond safety hierarchy. Source: Svensson (1998).

Both hierarchies rank all traffic events according to their severity and frequency, and provide a visual representation of a safety continuum where boundaries exist between traffic events. These boundaries separate traffic events into different types, being non-conflicts, conflicts and crashes, with ‘conflicts’ thus being a sub-set of traffic events. In terms of defining these boundaries, indicators had to be developed with which to rank traffic events. One of the most popular of these was Time-To-Collision.

Hayward (1971) defined Time-To-Collision as:

> “...the time that remains until a collision between two vehicles would have occurred if the collision course and speed difference are maintained”.

No evasive action needs to be observed to determine Time-To-Collision. Hydén favoured the time-based measure of Time-to-Accident to capture the severity of a conflict, with Time-to-Accident being:

> “…the time that remains to an accident in the moment when evasive action has just been started, presupposed that the road-users continued with unchanged speeds and directions.”

Conceptually, Time-to-Accident is a momentarily value on the otherwise continuous Time-To-Collision curve. It has the same limitation as Time-To-Collision (as discussed overleaf) but does not require an evasive action as part of its conceptual definition. For accidents that occur without any evasive action, Time-to-Accident has a (well-defined) value of zero.

Speed was difficult for observers to reliably estimate. Despite this, Hydén emphasised the importance of recording speed in addition to Time-to-Accident to allow serious conflicts to be differentiated from non-serious conflicts. According to Hydén, then, a temporal proximity measure is insufficient to adequately characterise conflict severity. A relationship between severity and speed, on the other hand, probably had conceptual validity in addition to any empirical correlation through velocity as a proxy for the energy of a collision – the proxy value of this being (and remaining) well-accepted and understood thanks to simple equations of motion.

In contrast to the difficulties with speed estimation, trained observers were in general agreement that a conflict was severe if Time-to-Accident was less than 1.5 seconds. Time-To-Collision was similarly easy to reliably estimate. Hydén (1987) reported on the experience of a calibration study for TCT, which identified good commonality in severity rating between eight teams of observers based on:

- Minimum Time-To-Collision, or Time-To-Collision$_{min}$ – the minimum value of Time-to-Collision assuming unchanged speed and trajectory
- Minimum distance between road users
- Conflict type.

Hence pragmatism based on human factors drove the use of temporal indicators in TCT studies.

As alluded to earlier, both Time-to-Accident and Time-To-Collision have conceptual issues associated with them. Laureshyn et al. (2017a) note field observation studies showing that many (even close) encounters in traffic do not have an actual collision course. Zheng, Ismail and Meng (2014a) note that assumptions about road user behaviour – speed, trajectory, braking and their extrapolation – are limited in matching actual road user behaviour. Laureshyn et al.'s (2016) SQ literature review of the field of surrogate safety measures used in TCT provides a discussion of these and other limitations. But an outstanding question is what ratings of severity actually measure.

From Debnath et al. (2014), TCT measures (or indicators) that have emerged and are not based on evasive manoeuvres can be broadly grouped as temporal (expressing severity or nearness to crash in terms of time) or non-temporal (expressing the risk of crash in terms of distance or the rate of change in vehicle positions.) Debnath et al. (2014) refer to both groupings as quantitative measures, compared to evasive manoeuvre-based measures that express severity or nearness to crash spatially and are qualitatively assessed. Again, Laureshyn et al. (2016) provide a little more detail. Amongst other things, they examined literature from 1967 to 2015, identifying the most common surrogate safety indicators in use in conflict studies and grouping these into four 'families.' Noting that a publication could refer to indicators in more than one family and hence be counted more than once, the families and their frequencies of use are:

- Time-To-Collision related measures (90 publications)
- Post-Encroachment Time related measures (40 publications)
- Deceleration related measures (25 publications) – this includes jerk, being rate of change of deceleration
- Other (10 publications).

After Time-To-Collision, Post-Encroachment Time was the most popular surrogate indicator in use. Chin and Quek (1997) cite Allen et al. (1978) as providing the first definition for Post-Encroachment Time as:

> "…the time between the first road user leaving a common spatial zone and the second arriving at it."

As with Time-To-Collision, it is a temporal measure. Unlike Time-To-Collision, Post-Encroachment Time is not based on a collision course. However, it is based on transverse trajectories, which introduces the issue that vehicles with similar or nearly opposite trajectories do not have paths that intersect: in the parlance of the definition, they do not have a common spatial zone. Hence Post-Encroachment Time is not without its problems, which are similar to though distinct from Time-To-Collision's.

Despite their shortcomings, Time-To-Collision, Post-Encroachment Time and related temporal measures have emerged as principal measures for ranking the seriousness of traffic events and for differentiating between conflicts, severe conflicts and non-conflict events – as indicated by the frequencies of use noted by Laureshyn et al. (2016). This has become more the case as advances in technology increasingly enable such measures to be more objectively and accurately measured, overcoming the limitations of variability in the manual categorisation of traffic events. In particular, the potential for automated video analysis to completely replace manual data collection and analysis has become realistic. Sayed, Zaki and Autey (2013), in a proactive safety diagnosis approach to cyclist crash risk, were amongst the first to demonstrate that automated video analysis was a feasible technology. This does not mean that it is readily available or easily applied, although its use in conflict studies is becoming increasingly common. Nor does automated video analysis overcome issues of how conflicts are identified and how these might relate to crash rates. Laureshyn and Várhelyi (2018) observe that in application, users of the Swedish TCT "…have been 'stretching' it a bit…" (p18) and that an (unidentified) subjective component plays an important role in the conflict observation process. Laureshyn et al. (2017b) note that Dutch method, DOCTOR, is more explicitly subjectively-based. These observations point to some as yet unidentified assessment factor or factors existing outside the theoretical framework of TCT as embodied in adopted methodologies. An unidentified subjective component is incompatible with truly objective assessment through automated video analysis.

For methods based on both evasive action and temporal measures, there are difficulties relating measured conflict to the crash process, and severity of conflicts with predictions of crash rates or crash severity.

Svensson (1998) identified that some traffic engineering treatments do not achieve safety improvements by reducing the number of conflicts. Similarly, Daniels and Wets (2005) quote van Minnen (1994) as finding that the number of conflicts at a roundabout increase compared to the intersection they replace, but that the severity reduces; and Hydén and Várhelyi (2000) as finding no change in the number of car-car conflicts in the same situation[36].

In the field of active transport and vulnerable road users, treatments such as shared road space or contra-flow cycling in one-way streets more obviously increase the number of conflicts, but seek to create safer traffic encounters. Indeed, attempts to increase levels of walking and cycling would – if successful – increase the number of conflicts by increasing exposure rates for vulnerable road users. Yet it has been found that the safety result of increased levels of walking and cycling is a reduction in the rate of collisions with these road users – the ‘safety in numbers’ effect. (The literature review for the pragmatic case study, presented in the next chapter, considers issues in assumptions of a simple linking of conflicts with crash rates via examinations of Conflict Point Theory and the Safety in Numbers effect, touching on the non-linearity of risk for both topics.)

Hence as Zheng, Ismail and Meng (2014a) note in their discussion of open questions, insights and proposals for future research on TCT, several issues remain with the technique:

- *The lack of consensus on which indicators or measures to use*
  Different measures have varied characteristics, preferable application conditions and provide different results. For example, Guido et al. (2011) used two temporal measures based on Time-To-Collision; two measures based on deceleration rate; and one based on distance/speed, and concluded that the assessment of roundabout safety is sensitive to the selected measures. Johnsson, Laureshyn and de Ceunynck (2018) reach a similar conclusion, with particular regard to vulnerable road users.
  But if these measures do not produce consistent results regarding a fundamental degree of

[36] In these studies, ‘conflict’ appears to be as defined as for Conflict Point Theory (discussed in Chapter 5, as part of the literature review to the pragmatic case study), where a conflict point is: “…a location where the paths of two motor vehicles, or a vehicle and a bicycle or pedestrian queue, diverge, merge, or cross each other.” Robinson et al. (2000).

safety, what are they measuring? Nor can these measures be easily or reliably combined to provide comparable overall ratings of safety.

- *The lack of a link between measures of severity and crash risk/outcomes*
  Severity of traffic conflicts is identified by either the intensity of evasive actions or the proximity in time and/or space. In both cases, thresholds differentiating conflict from non-conflict for objective measurement are not agreed upon. Nor is severity as defined by proximity measurable in a meaningful way in the case of crashes, when severity could be any outcome from property-damage-only up to fatality. Relating this to severity hierarchy models, boundaries between different types of interaction are not well defined, the shape unknown, and TCT only measures conflicts – still a small portion of total traffic events.
- *Assumptions about road user movements made to enable conflict to be assessed*
  The complex behaviour of road users makes simple assumptions of unchanged speed and direction and constant acceleration or decelerations, plus their extrapolation, of limited value. While some researchers construct a probability spread of likely options for road user movements, this method increases complexity and brings into play data requirements for algorithms to 'learn' probability patterns. In particular for vulnerable road users, walkers and cyclists display travel patterns with a much greater spread of characteristics than motorists.

Given that TCT is in current and active use, these issues are not of purely theoretical interest. For example, Gettman et al. (2008) developed the Surrogate Safety Assessment Model (SSAM) as a micro-simulation model for the US Federal Highway Administration, which has made this model freely available for others to use. The Swedish Traffic Conflicts Technique was most recently updated by Laureshyn and Várhelyi (2018) in support of its ongoing use.

Two particular outstanding issues for TCT are definitions and practical understandings of 'conflict' and 'severity'. These are so foundational to the concept of TCT that they are discussed separately as follows.

Conflicts

Zheng, Ismail and Meng (2014a) point to the validity of a process model for crashes as being an issue not addressed in the conceptual basis of TCT[37]. Traffic conflict and collision could

[37] This observation reflects Noland's (2013) criticism that engineering tends focuses on deterministic goals and deterministic modelling rather than inferential hypothesis testing.

be mutually exclusive outcomes, where the occurrence of a traffic conflict as an event complements the collision and is made distinct from it by the presence and degree of success of an evasive action. Or traffic conflicts could precede the evasive action, which can either be successful (no collision ensues) or unsuccessful (a collision occurs). Zhang et al. (2014a) point to this latter argument being in the ascendency at their time of writing, but there being no strong consensus.

Laureshyn et al. (2017a) add further doubts by noting that encounters without a collision course might have crash potential as well, since even minor changes in the spatial or temporal relationships between road users can lead to a collision course. This is supported by Laureshyn et al.'s (2010) observation that an interaction between two road users could smoothly switch from being a collision course event to being a non-collision course event and vice versa. Also, Laureshyn and Várhelyi (2018) note that the majority of the situations a human observer would select as conflicts having a collision course would not be classified as such if more accurate tools for speed and position measurements were used. It is counter-intuitive for the danger of the situation (as defined by whether or not it is a TCT-defined conflict) to change dramatically due to very minor (and reversible) speed changes or minor inaccuracies in measurement.

Several models have been developed to link traffic conflicts to crashes. Zheng et al. (2014a) summarises these as:

(1) Traditional regression model
This is based on applying (well known) regression techniques to establish relationships between traffic conflict counts and crash counts. However, a stable crash-to-conflict ratio is difficult to ensure, especially when mixing varied conflict severity levels because the boundaries to distinguish severities are not well determined. This model also suffers in its reliance on crash counts as a basis.

(2) Two-phase model
This extension of regression techniques proposed by El-Basyouny and Sayed (2012) uses a lognormal model to predict conflicts by taking traffic volume, area type (urban/suburban) and some geometric-related variables as covariates. It then uses a negative binomial model to predict crashes based on the estimated conflicts. While a relationship between conflicts and collisions was found in El-Basyouny and Sayed's case study, lack of information about traffic and geometric conditions at sites is a constraining

factor. The model also suffers in that the influence of various road, traffic and environment-related factors on traffic conflicts is complex, and driver behaviour-related factors that might assist in reducing conflicts are not well-understood.

(3) Extreme Value theory model

This was first used as part of a TCT analysis by Campbell, Joksch and Green (1996) but is usually attributed to Songchitruksa and Tarko (2004, 2006). Under this model, conflict is regarded as an example of applied Extreme Value (EV) theory, with crashes the extreme event whose probability this field of statistics seeks to forecast. In TCT, conflicts between road users are considered as risky events and EV theory estimates the risk of a crash event based on observed values of conflict measures. It has the advantage that it does not rely on a crash record to determine the level of safety and that EV theory has been mathematically proven i.e. if a non-random relationship between conflicts and crashes exists, then EV theory can be used to estimate crashes from conflict data without first specifying the nature of this relationship. Using EV theory, Jonasson and Rootzén (2014) conclude that due to selection bias, near-crashes could be a better indicator than crashes for assessing road safety.

(4) Causal model

This model has been proposed as an alternative to the traditional traffic hierarchy, based on a counterfactual test of the conflict definition[38]. That is, the definition of conflict says that if the movements of involved road users had remained unchanged a collision would have resulted. So whether an encounter ends up as a crash is determined by its initial conditions and whether or not events occur that prevent the crash – one or more road user takes evasive action. The model proposes that a probability distribution for the initial variables and evasive action can give the probability of a crash-related outcome. The model currently remains a mathematical statement based on the definition of conflict, hampered by the lack of detailed knowledge of the evasive action mechanism. As the model is based on the definition of a conflict, issues with this definition affect the model, and notably the question as to whether evasive action is indeed a fundamental element in every crash process. (It is proposed in the model in relation to a definition statement rather than external evidence.)

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[38] Laureshyn et al. (2016) attribute this approach to Davis et al.

(5) Probabilistic framework based on all possible collision points

Under this model, the probability of collision between two interacting road users at a given instant is calculated by summing the probabilities of all possible motions that might lead to a collision. This overcomes the assumption of unchanging movement after a conflict is measured. In the pilot safety study, movement extrapolation was based on learning road users' trajectories, which restricts transferability to other circumstances. The relationship between the computed probability of collision and safety still needs to be validated.

The overall conclusion is summed up by Zheng et al. (2013): that difficulties and debates in traffic conflict studies remain, based around how to accurately define a conflict. What is actually being measured by conflict indicators is more accurately a question regarding severity.

Severity

If different measures used in TCT give different results, they cannot be quantifying the same characteristic, so what are they actually measuring? It is clear from the literature that they are attempting to measure 'severity' in some way, but also that what 'severity' represents is not well defined and is further confused by an attached historic meaning of 'severity' in road safety relating to the event outcome (property damage only, injury, major injury, fatality).

Tageldin, Sayed and Wang (2015) found that common temporal measures assume proximity as a surrogate for conflict severity. However, this was not valid in their case study of motorbikes in a highly congested shared intersection in Shanghai, China, where indicators of evasive action (deceleration, jerk, yaw-rate) had a higher potential to identify motorcycle conflicts. Meanwhile, Laurenshyn, Svensson and Hydén (2010) note Svensson's (1998) studies showing many (fairly) high-severity conflicts but few collisions at non-signalised intersections and few high-severity conflicts but more collisions at comparison signalised intersections, and her conclusion that the frequency of high-severity conflicts may have increased awareness and reduced crash risk – a reasonable enough conclusion but contrary to the severity-as-crash-risk assumption in TCT[39].

[39] Svensson (1998) identifies conflict in regard to the Swedish TCT, based on measurement of the speed and Time-to-Accident from the moment that one of the road users starts an evasive action compared to if they had continued with unchanged speeds and directions. An alternative explanation might be that where road users do not perceive danger or have time to react, few evasive manoeuvres and more collisions occur. In

Zheng, Ismail and Meng (2014a) agree that the severity of traffic conflicts is generally rated by either the intensity of evasive actions or the proximity of participants in time and/or space, but go on to observe that thresholds differentiating conflict from non-conflict are not agreed upon and to some extent depend on a judgment call. They also point out that severity as defined by temporal indicators is not measurable in the case of crashes. For example, at Time-To-Collision equal to zero, a crash has occurred, whether the severity is property damage only or a fatality.

Shelby (2011) illustrates the lack of a firm concept of severity in TCT by identifying (and then describing) four concepts of severity drawn from TCT literature:

- “the probability of crashing
- the magnitude of the damages from a potential collision
- both of the above
- a quantitative value, with no explicitly defined interpretation.”

The last is the least intuitively obvious. Shelby (2011) explains this by presenting cases where an indicator such as deceleration is used and has a quantitative value but its association with ‘severity’ or what is meant by ‘severity’ is never explicitly stated.

Interestingly, these four concepts do not cover severity as proximity to collision – as arguably indicated in Glauz and Migletz’s (1980) distribution function. Under Glauz and Migletz, ‘proximity’ is perhaps assumed to be the same as ‘probability’, or the concept is included in the other concepts. In the current discussion, proximity to collision can be taken as being a fifth concept for severity. As per Laureshyn et al.’s (2016) citation of Zheng, Ismail and Meng (2014a), it is also arguably the most common concept for severity.

Zheng et al. (2013) cite Bachmann et al. (2011) as indicating that the choice of measures and thresholds for identifying conflicts could give rise to non-conflicts being reported as conflicts. But while this may contribute to the problem, Laureshyn, Svensson and Hydén (2010) use a thought experiment to demonstrate that Time-To-Collision is not in itself a sufficient indicator of severity and that using proximity to wholly define and rate severity remains problematic:

> “Imagine two pairs of vehicles on a collision course, but in the first case the vehicle speed is 10 m/s and in the second case 20 m/s. When [Time-To-Collision] reaches 1.8 s in both cases, the drivers detect the risk and start braking with maximal deceleration of 6m/s^2. In the first case they will manage to stop after 1.6 s

this case, the mismatch between ‘severity’ and actual crash risk reflects error in the use of evasive action as the basis for determining conflict.

> and avoid collision, in the second case they will crash with a collision speed of 9m/s."

The two events of the thought experiment do not meet Bachmann et al.'s (2011) criteria for misclassifying conflicts, in that the chosen measure (Time-To-Collision) and threshold (1.8s) is the same in both cases. The ambiguity illustrated by the thought experiment can also be explained mathematically. Liu (2010) expresses Time-To-Collision as:

$$TTC = \frac{L}{V2 - V1}$$

Where: L is the distance between two conflicting vehicles

V1 is the velocity of one vehicle in the conflict

V2 is the velocity of the other vehicle in the conflict.

A small value of Time-To-Collision (i.e. high severity) could result from a small distance between vehicles *or* a large difference in vehicle velocities. But once the two dimensions of distance and velocity are reduced into the single dimension of time, the distance/ velocity contributions cannot be independently identified. Hence a single Time-To-Collision measurement can represent two different conditions having arguably different underlying severity values, with no means of differentiating between the two conditions. This ambiguity could be addressed if the relationship between distance and severity or velocity and severity are known and recorded along with Time-To-Collision – which reflects Hydén's (1987) proposed practice – but these relationships are likely to vary with traffic event types. Certainly, different crash types have different relationships to velocity. Nor is the combined severity function readily translatable to the real-world situation, and using separate values of distance and velocities to differentiate severity ratings seems rather to undermine the concept of aggregated indicators.

Similar arguments apply to other temporal measures.

Laureshyn et al. (2016) are also clear that proximity to collision is only one dimension of 'severity' and that another – the potential consequences in the event that a collision had taken place – should be considered. They go on to point out that the potential consequences of an event are dependent on the type of road users involved and their vulnerability, speed, mass, type of collision, collision angle, etc. The question that remains is how to incorporate such consequences along with proximity into a usable indicator.

From the pragmatic perspective of the Swedish Traffic Conflicts Technique, Laureshyn and Varhelyi (2018) provide an ideal theoretical definition of severity as "a nearness to a serious personal injury" but observe that it is not obvious how to estimate the injury risk in situations where the collision was actually avoided. They note that the most common practices are either to ignore the potential consequences or to use some subjective rules on how they can be integrated into the final severity score. The approach in the Swedish TCT is to record speed as a proxy for consequence.

Zheng, Ismail and Meng (2014a) observe that temporal measures have become popular partly because they integrate proximity and speed, with the latter providing some relationship to crash consequence through a speed/ kinetic energy relationship derived from Newtonian physics:

$$\text{Kinetic energy} = \tfrac{1}{2} \text{ x mass x velocity}^2$$

However, the relationship between velocity and the energy actually realised in a crash is neither direct nor consistent across crash types. Shelby (2011) outlines some factors affecting the relationship between vehicle velocities and crash energies, with main factors being relative mass, angle of collision and elasticity of collision[40]. Compared to Laureshyn et al.'s (2016) list, this omits only the vulnerability of the road user.

Shelby (2011) proposes using velocity information via Delta-V. Delta-V emerged in crash investigation reconstructions and is a good predictor of severity in the event of a crash. Delta-V refers to the change in velocity between pre-collision and post-collision trajectories of a vehicle, using equations of motion to account for mass and angle of collision. (The use of 'velocity' instead of 'speed' is deliberate, in that velocity is a vector quantity exhibiting direction whereas speed is a scalar quantity containing no directional information.) Shelby uses Delta-V by determining the probability of a collision for a range of conditions, calculating Delta-V (Shelby also adjusts for the elasticity of collision) and calculating the nominal cost of likely outcomes. Averaging these cost values then enables an overall rating to be given to a traffic event.

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[40] In terms of actual crash outcomes, factors such as population demographics (probability of robustness of the affected individual), vehicle fleet composition and age (and hence safety design and installed countermeasures) and so on also become relevant in a real-world situation, but these are arguably beyond a reasonable attempt at crash prediction to factor into safety assessment, at least with current technologies. Automated vehicle analysis might perhaps in the future identify and also account for vehicle characteristics.

Bagdadi (2013) also uses Delta-V but further observes that the likelihood of a collision is reduced by a road user's ability to execute an evasive manoeuvre. (Bagdadi moved away from a qualitative assessment of the start of an evasive manoeuvre to Time-to-Accident, being the more quantitative estimated time remaining before a crash will occur if the direction and speed of the involved road users remain the same as at the moment before the onset of braking.) Based on Hydén's (1987) finding that in urban environments braking occurred in 92% of vehicle-to-vehicle conflicts where an evasive manoeuvre is performed and about 88% of situations leading to crashes, Bagdadi introduced a term based on Time-to-Accident, the relative weights of road users, and estimated vehicle deceleration as determined through a naturalistic driving study. This term is subtracted from Delta-V and hence modifies it to a maximum severity equivalent to Delta-V. The severity assessed using this technique is shown to be very different to the severity based only on a standard TCT measure (not unambiguously stated, but apparently based on Time-to-Accident and conflict speed, or speed of the vehicle that performs the evasive action at the moment just before the evasive action takes place). The severity assessment using this term showed clear improvements to the standard TCT severity assessment where vehicles of different masses were involved.

A key feature in the technique is the attempt at combining the two ideas of severity represented by Delta-V and a temporal measure into a single indicator. Assumptions include the likelihood of evasive manoeuvres – in particular, the method was only used on safety critical braking events identified in a naturalistic driving database[41], being traffic events in the database where a sudden evasive braking manoeuvre by a car or heavy vehicle took place. This excludes events where the instrumented vehicle did not brake or where braking did not exceed the limit that would identify it as safety critical – for example, where the non-instrumented vehicle is a bicycle whose rider swerves to avoid the crash. Other limitations are associated with the use of Time-to-Accident and the applicability of the method in terms of being able to easily use it to examine general, non-instrumented traffic. As with Shelby (2011), the method is not known to have been used elsewhere.

Shelby's (2011) probabilistic method has some similarities to other TCT techniques that try to predict possible future vehicle paths based on previous vehicle paths. However, the incorporation of mass, angle of collision and elasticity of collision is directly aimed at relating

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[41] I.e. a database generated using the methodology of an experimental vehicle fitted with instruments being driven in normal traffic.

the event to a rating of probable outcomes. In fact, Delta-V is now used in TCT through the automated conflict analysis algorithms of the US Federal Highway Administration's Surrogate Safety Assessment Model (SSAM). But Laureshyn et al. (2017a) note that the Delta-V indicator used in SSAM is not sufficient in itself to distinguish severe from non-severe events:

- Time-To-Collision$_{min}$ is used as the time at which Delta-V is estimated, hence issues related to Time-To-Collision also apply to the Delta-V indicator.
- The indicator represents the potential outcome severity if a collision had taken place but does not include the nearness to collision: an event with a large Time-To-Collision$_{min}$ can have the same calculated value as one with a small Time-To-Collision$_{min}$.

The latter point is another expression of the issue illustrated through the mathematics of Time-To-Collision: distance and speed difference are not uniquely tied to values of Time-To-Collision, even if that speed difference value now accounts for mass ratios and angles of collision of involved participants.

Laureshyn et al. (2017a) have also attempted to combine the two dimensions of severity identified by Laureshyn et al. (2016) into a single indicator. Laureshyn et al. (2017a) propose using a measure called Extended Delta-V, based on Delta-V but incorporating a factor for the assumed rate of braking. Extended Delta-V makes use of a new time-proximity indicator of T_2, with T_2 basically being Time-To-Collision if a collision course exists and Post-Encroachment Time if one does not. This overcomes issues related to the presence or otherwise of a collision course, but under this proposal, the braking rate factor introduces into the assessment the complexity of another assumption about road user behaviour. Nor is it clear that Extended Delta-V overcomes the loss due to aggregation of unique properties of the values being aggregated, which is the issue enabling ambiguous values of Extended Delta-V to exist.

There is another question about indicators for severity, in terms of what is understood from their calculation in a conceptual sense. Laureshyn, Svensson and Hydén (2010) built on the concept of crash hierarchies by adding micro-level behavioural data – primarily indicators describing the motion of road users: Time-To-Collision, an indicator they called Time Advantage, a supplementary measure T_2 to Time Advantage, Time Gap and Speed. They then proposed that another way to classify severity is to analyse the shape of continuous indicator profiles – curves of Time-To-Collision, Time Advantage, etc. – in the hope that a detailed analysis will reveal “typical” shapes characterising critical situations and other shapes reflecting “normal” (non-critical) processes. Their hypothesis was that the severity of encounters could be better described by elaborating on the shape of the severity hierarchy and the assumption of a ‘true’ hierarchy for a specific set of indicators, and that different sites will have crash hierarchies with different degrees of accumulation of traffic events allocated to different parts of the hierarchy – i.e. of different shapes that vary with differing site conditions. A boundary between non-conflict and conflict events would still apply.

Laureshyn, Svensson and Hydén (2010) also emphasise that the behaviour described by the severity hierarchies underpinning their theoretical framework could reflect other qualities in traffic besides safety – factors such as mobility, convenience, etc., and the desire to balance these qualities – which are poorly considered in other theoretical discussions regarding TCT. The authors also bring into question what the whole shape and the accumulation of events at different levels represent, given that more severe conflicts can be associated with better safety. Applied to a theoretical situation, Laureshyn et al.’s (2010) framework is not known to have been used in practice. Their work also considered ‘encounters’ between two road users rather than ‘conflicts’ – the latter being a concept whose definition has been much debated and discussed, as already noted.

Extreme Value theory in TCT

As has been mentioned in passing, Extreme Value (EV) theory suggests a robust statistical framework for TCT, and is arguably the only theory to do so, given outstanding questions about the relationship between conflicts and crashes and the statistical pattern by which crashes might occur. EV theory is explained below, but the basic premise is that the relationship between rarely-measured or unmeasured values and more common measured values follows known (or knowable) mathematical patterns. This is the case even if the underlying relationship between recorded values is unknown, as long as the underlying events are non-random. For example, a 1 in 100-year rainfall event can be predicted from a much shorter rainfall record by charting the frequency of different magnitudes of rainfalls and applying EV mathematical formulae, because rainfall follows some form of non-random pattern.

Applying EV theory to TCT, unmeasured events (crashes) can be predicted on the basis of measured traffic events, as long as measured traffic events are accurately characterised. The advantage of using EV theory is that it is mathematically proven and automated video analysis is able to deliver increasingly accurate characterisations. A disadvantage is that EV theory has not been shown to produce accurate and reliable results in TCT, albeit that good correlation has been found in a few isolated studies – as has arguably been the case with other TCT approaches.

There are (of course!) complications and technicalities regarding the use of EV theory. Appreciating these calls for which a more detailed overview of the theory. The following summary is adapted from Campbell, Joksch and Green (1996) and Kotz and Nadarajah (2000). A generalised description of how EV theory is applied follows this theoretical summary.

The mathematical foundations of EV theory were mainly laid in the early to mid-20th century when it was shown that for large samples, the extreme values – those lying at the tail ends of a graph of values – follow certain distributions. Depending on the parent distribution governing the values being examined, the distribution of these extreme values follows one and only one of three families of asymptotic distributions. In simple terms:

- The extreme values from most common statistical distributions follow the first (Gumbel) solution.
- Two other statistical distributions give rise to extreme values following a second (Frechet) solution.
- The Weibull solution is essentially the Frechet applying to minimum instead of maximum values.

Further, when expressed in log-normal form, distributions of the second and third families are converted into distributions of the first family – giving rise to Generalised Extreme Value theory. EV theory assumes that the variable being examined is not entirely random but follows some underlying distribution. The actual pattern of this distribution does not have to be known. As long as it exists, the extreme value distribution will follow one of the three asymptotic forms noted above. EV theory also assumes that there are no discontinuities in the distribution as the variable being examined approaches zero. In the event of such discontinuities, the extreme value distribution would estimate the proportion of events that exceed some threshold (greater than zero) in the measure.

As Ferreira and de Haan (2015) note, there are two fundamental approaches to applying EV, both of which are widely used: the Block Maxima (BM) method and the Peaks-Over-Threshold (POT) method.

- The Block Maxima approach consists of dividing the observation period into non-overlapping periods of equal size and restricting attention to the maximum observation in each period. The new observations thus created follow – under extreme value conditions – approximately an extreme value distribution. Parametric statistical methods for the extreme value distributions are then applied to those observations.
- The Peaks-Over-Threshold approach consists of selecting those of the initial observations that exceed a certain high threshold. The probability distribution of the selected observations then approximates a known distribution.

The Block Maxima approach is somewhat wasteful of data as only one data point in each block is taken (Bommier, 2014.) For example, the second highest value in one block may be larger than the highest of another block but is not used. The Peaks-Over-Threshold method uses the data more efficiently as it considers several large values instead of only the largest one. However, this method needs a threshold to be used which is neither too high (to get enough observations) nor too low (to exclude non-extreme values.)

Additional complexities include the assumption of stationarity in data, i.e. that patterns within the data are constant. This is compared to non-stationarity in data, such as seasonal fluctuations in temperature/ rainfall (Bommier, 2014.) Such factors can be considered further but are not the focus of the current research.

The practical application is to survey something of interest – in the case of TCT, using an indicator of conflict. The largest values of these are then sampled using either the Block Maxima or Points-Over-Threshold approach to form a new data set. EV theory mathematic formulae are applied to this subset to test for goodness-to-fit and hence determine the characteristics of the underlying distribution. The most direct approach is to assume the first (Gumbel) solution, in which case the distribution of observed extreme values should appear to follow a straight line. If the data does not follow a straight line, a log transformation is undertaken to convert the distribution via Generalised Extreme Value Theory, and again tested for fit. Once a distribution is established, the probability of an event having a value in excess of a specified threshold is calculated, or the frequency between certain sized events. For TCT, the threshold and probability would be related to crashes, with thresholds potentially enabling minor versus major versus fatality crashes to be considered separately. And the probabilities for these events can be calculated even though the corresponding crash events have not been observed and do not form part of the data set.

EV theory has importance in addressing the fundamental question in the theoretical framework for TCT: can non-crash events be used to provide insight into crash events? Under EV theory, the answer is yes, if the traffic events up to and including crashes follow some non-random distribution – which is the only reasonable assumption that has so far been put forward for collision probability – and if the traffic events can be measured in a way that reflects crash potential.

Data needs for TCT

To determine the amount of data required to generate usable results in TCT, Hauer (1978) examined motor vehicle conflict data and found that traffic conflicts do not follow a simple Poisson distribution – a finding supported by Glauz and Migletz (1980), amongst others. Using a negative binomial model, Hauer (1978) concluded that while accuracy increases with survey duration, the increase in accuracy per additional day diminishes rapidly and there is not much to be gained by counting for longer than three days. The relative insensitivity of variance to mean estimates for different types of conflict meant that this estimate was also relatively insensitive.

In a discussion following Hauer's (1978) paper, William Gauz notes that variance-to-mean can be minimised by using a single observer to collect conflict data and hence three days may be a 'pessimistic' estimate of the amount of data needed for results to characterise conditions. Retting, Ferguson and McCartt (2003) cite Gårder (1985) as showing that a one-day conflict count provides a more accurate estimate of the expected number of crashes than a one-year crash history if the expected number of crashes is fewer than five per year.

Gauz also cautions that Hauer's statistical analysis is dependent on the definition of traffic conflicts, expected mean daily count and expected conflict rate; and that as the last of these varies with time of day and season, a partial count may be more practical than a daily count. In contrast to Hauer, Hydén (1987) found a variance-to-mean of 0.6 i.e. greater regularity than indicated by a Poisson distribution. The difference may be related to the use of a number of trained observers in the former compared to a single observer in the latter, hence according with Gauz. Interestingly, Hauer's 1978 work references an earlier conflict study by Hydén and noted that Hydén's results showed a smaller variability than the rest of the data. It appears, then, that Hydén and Hauer could be in general agreement.

Applying Extreme Value theory to TCT, there is little agreement on the data needs that might be required – but some indication that these might be greater than assumed for a non-EV approach. Tarko and Songchitruksa (2005) applied EV theory to Post-Encroachment Time using 8 hours of case study data examining right-angle crashes. They recorded 573 data points and identified through simulation modelling that using EV theory's Block Maxima approach, 15-minute blocks provided a compromise between the uncertainty of model estimates and the validity of the EV assumption. On the basis of the same case study, Songchitruksa and Tarko (2006) estimated that 30 to 50 days of data would be required in order to identify a right-angle crash frequency with a similar level of confidence to that obtainable from four years of crash data. While a month or two of data is a significant reduction on waiting for four years to determine relative safety, this is still a quite considerable data requirement to collect and analyse, even with advances in computer vision.

In comparison, Zheng, Ismail and Meng's (2014b) examination of freeway safety estimation found that the Peak Over Threshold approach gave better estimates of accuracy and reliability than Block Maxima. This work was based on three-hour observations at 21 directional freeway segments – a total of 63 hours of data, but indicating as little as three hours as being sufficient to determine crash frequency. While Zheng et al.'s study points to a lower requirement for data than estimated by Songchitruksa and Tarko (2006), Zheng et al. did not estimate an overall data requirement and the difference in time estimates could reflect that their freeway study recorded more events per hour than Songchitruksa and Tarko's intersection study. There are issues in identifying thresholds for Peak-Over-Threshold, and Songchitruksa and Tarko's (2006) data requirement for estimating crash frequency is not necessarily what is required when comparing sites or as part of a before/after assessment of a treatment, where being able to compare performance may be sufficient.

The case study: approaching TCT using Extreme Value theory

Rejecting the theoretical framework for TCT leaves as a starting point the proposition that non-crash traffic events can be used as a surrogate indicator for crash events to reveal information about the safety conditions at a site. As the literature review for TCT notes, Extreme Value (EV) theory presents a robust statistical framework whereby observations of more common events (in this case, non-crashes) can be used to predict rarely observed extreme events (crashes), and is the only known theory to do so.

EV theory predates TCT. Its application to TCT was first proposed by Campbell, Joksch and Green (1996), though usually attributed to Songchitruksa and Tarko (2004, 2006). In terms of the methodological approach for the proof by contradiction, EV theory does not represent a hitherto unidentified approach, theory, technology or similar. If the theoretical framework for TCT has been optimally produced, the current case study should be able to add little or nothing new to the TCT field.

Now, having a fundamental concept for a new theory, which will be labelled as Traffic Events Theory (TET) as an aid to clarity, does not mean that TET is demonstrated as being capable of overcoming issues in TCT or that TET exhibits any practical feasibility. Indeed, at this point, EV theory has been used in TCT and TET is not an obviously different approach. TET must be developed and expanded into a full theory whose differences to TCT can be understood and the implications of these appreciated, before it can be assessed as an advance in the field or otherwise. The remainder of this chapter is concerned with this exercise, as a logical extension of non-paradigmatic understandings of TCT and EV theory.

EV theory and composite indicators

Given outstanding issues in the reliability of indicators in TCT, there remains the possibility that no underlying statistical relationship actually exists between crash and non-crash events. In this case, EV theory does not apply and TCT is also invalidated as a concept. To some extent, this proposition can be rejected on the basis that statistical patterns have been identified for crash frequencies, albeit that the statistical pattern may not be consistent between sites or even at the same site under different conditions of weather, traffic flow, etc. (For example, Hauer (1978) notes the common assumption that rare events with a constant mean follow the Poisson distribution, but his examination of results led him to reject this and apply a negative binomial model to determine variance.)

More concretely, various TCT indicators derived from non-crash events have been found to correlate with crash risk derived from historical crash records. Regarding the use of EV theory in TCT to date, studies such as Songchitruksa and Tarko (2006), Zheng, Ismail and Meng (2014b) and Azevedo and Farrah (2015) have found a promising level of correlation between safety estimates and historical crash records[42]. The issue for operationalising TCT is that studies such as Guido et al. (2011), Laureshyn et al. (2017b), Tageldin, Sayed and

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[42] In fact, most EV theory-based TCT studies (such as Orsini et al. 2018) take the approach of attempting to modify or combine TCT indicators to provide the best EV theory result compared to a crash record i.e. to calibrate EV theory approaches to the historic data. In such studies, whether EV theory is applicable to TCT is not considered to be in doubt. This level of confidence in the applicability of EV theory reflects the status of EV theory as a proven mathematical theory whose characteristics are compatible with crashes as an extreme value of conflict.

Shaaban (2017), and Johnsson, Laureshyn and de Ceunynck (2018) find that the safety assessment is sensitive to the selected indicator. This introduces levels of uncertainty ranging to what indicator should be used for any situation to what a given indicator value is actually indicating, while the need to correlate indicators to an historic record to overcome uncertainties undermines much of the point of TCT compared to mass data safety studies.

Accepting EV theory as a base and considering the compatibility of existing TCT indicators with EV theory, a clue to incompatibility is provided by Mullakkal-Babu et al.'s (2017) consideration of what TCT indicators show in terms of causality when examining vehicle trajectories for a highway (emphasis added):

> "For example, consider a scenario where a vehicle follows a leader at a spacing of 1 m. This scenario would be deemed safe by a [Time-To-Collision] indicator that is based on **constant velocity assumption**. However, this scenario cannot be regarded as safe if we consider the probability that the leader may brake."

To expand upon this clue, recall the thought experiment offered by Laureshyn, Svensson and Hydén (2010) that demonstrated how two very different conditions could give rise to the same value for Time-To-Collision; and the observation from Liu's (2010) mathematical expression of Time-To-Collision that a small value of the indicator could equally result from a small distance between vehicles **or** a large difference in vehicle velocities. In other words, for Time-To-Collision and other temporally-based indicators, one value can represent two quite different states. This implies that indicators such as Time-To-Collision are currently measuring what Shelby (2011) describes as "a quantitative value, with no explicitly defined interpretation." Considering this ambiguity of values in terms of EV theory, combining two (or more) characteristics into a single indicator means that while EV theory may well apply perfectly to an indicator, it does not apply to any underlying characteristics and there is no method of understanding what the result returned actually means.

A thought experiment can be used to illustrate this effect. Imagine a situation where we wish to know something about the weather. We take temperature and rainfall measurements and add these together to form a composite indicator. Assuming a Celsius scale and Adelaide's climate (where most rain falls in winter and summers are very dry), a value of 40 could mean 40C + 0mm of rainfall in summer, 5C + 35mm of rainfall in winter, and anything in between. Applying EV theory to indicator results may well produce an accurate result in terms of determining the probability that days exceeding a composite value of 40 will be encountered (say). However, this will tell us nothing meaningful about the weather, since the indicator value characterises any one of multiple combinations of temperature and rainfall. EV theory is not compatible with our composite indicator in terms of that indicator being able to disaggregate into meaningful information the statistical result that EV theory can provide.

If this is the case, though, why do some safety studies demonstrate reasonably good correlation between EV theory-based predictions and historic crash data? Mullakkal-Babu et al.'s (2017) clue of constant velocity becomes more pertinent, as extending our thought experiment illustrates.

If we now assume our weather data is only collected in summer, one of the two values collected (rainfall) has a negligible influence on the composite value determined for the observed days. The frequency distribution of days rated 40 starts to approximate that of days with a temperature of 40C and no rain, and the composite indicator shows good correlation with actual conditions. Applying EV theory to the data gives results that accord reasonably with observations, but this correlation doesn't change the fact that the indicator remains unreliable in other circumstances.

Relating this to TCT, composite indicators could be expected to give fairly good results in certain conditions, such as a highway where speeds are relatively uniform and one characteristic of the indicator approaches a constant value; but poor results in other conditions, notably mixed traffic. A situation of reduced ambiguity might also apply where evasive action is used to define conflict, if this functions as a filter that excludes the most variable elements to leave a more uniform subset of data.

With this understanding in place, the problem of using composite indicators in conjunction with EV theory is highlighted and composite indicators are counter-indicated for TET. However, EV theory itself thus remains positively indicated as an underlying concept for pursuing a non-paradigmatic approach to TCT.

Eliminating 'conflict'

From above, indicators used in TET must be able to accurately characterise traffic events relative to crash risk for EV theory to be applicable. In terms of the use of EV theory in TCT to date, Zheng et al. (2014a) explain that in TCT, conflicts between road users are considered as risky events and EV theory estimates the risk of a crash event based on observed values of conflict. Different values or levels of conflict are generally differentiated through concepts of 'severity'. But given 'severity', there is no real reason for 'conflict' in TET. Under EV theory, rare and therefore unseen events (crashes) can be predicted on the basis of more commonly observed traffic events, as long as those traffic events are accurately characterised. Instead of a firm boundary existing between conflict, severe conflict and non-conflict events, all traffic events can be considered to lie on a safety continuum where one end is 'crash' and the other end 'safe passage'. As a result, safety hierarchies are no longer indicated per se, replaced by a statistical distribution of traffic events linked mathematically to crashes.

From a causal perspective, the logic of TET in the absence of conflict is simply that traffic events can be rated by 'severity', which is a statistical relationship between a measured traffic event and a crash event. The application of EV theory means using the extreme values within a data set, and these could perhaps be labelled 'conflicts.' But in this case, 'conflict' becomes an intermediate term used in the mathematical process rather than an underlying concept of the theoretical framework.

While this might seem like a technical point, de-emphasising the role of 'conflict' to the point of eliminating it from the paradigm overcomes several issues of TCT.

Firstly, the TCT definition of 'conflict' involves two or more road users, hence single-vehicle crashes are automatically excluded. This is not the case under TET: single-vehicle events are equally valid, as long as this is allowed for in how the event is characterised.

Secondly, the definition of conflict revolves around "if their movements remain unchanged". This immediately introduces assumptions about future vehicle trajectories and kinematic states. Indeed, the probabilistic method (which is starting to become feasible using automated video analysis) projects future paths and evasive actions to identify the multiple trajectories and states that road users could take. By identifying the many possibilities, it confirms the inaccuracies the assumptions about vehicle path and kinematic state introduced into TCT practice by the concept of 'conflict.'

Thirdly, the definition of conflict versus non-conflict introduces questions as to how boundary conditions between these (and minor or severe conflicts) should be set. A Time-To-Collision threshold of 1.5 seconds has traditionally been used in TCT practice, initially based on agreement amongst human observers that this seemed 'serious.' But as noted in the literature review, the indicators used and thresholds applied create variability in safety assessment and are particularly ill-suited where vulnerable road users are involved.

Lastly, under TCT, events need to be "observable", which introduces conceptual complexities and is incompatible with automated video analysis. This issue can be linked to the third point in that observable evasive actions can be used to differentiate between ‘undisturbed passages’ and ‘conflicts’ in the safety hierarchy but not necessarily in a satisfactory way, given questions about the role of evasive actions in the process model.

In contrast, TET makes no claim or implies any stance on evasive action or the process model for crashes as part of its theoretical framework.

However, basing TET on a firm statistical model does emphasise the need to accurately characterises traffic events as these relate to crash risk. This brings us to the issue of ‘severity’ in TCT.

‘Severity’ and ‘intensity’

As noted in the literature review, the use of ‘severity’ as a measure of conflict in TCT is an outstanding issue in terms of what conflict indicators are attempting to measure and what they are actually measuring.

Tageldin and Sayed (2015) found that common temporal measures assume proximity (defined as nearness to collision) as a surrogate for conflict severity. However, Laureshyn et al. (2016) are clear that proximity to collision is only one dimension of ‘severity’ and that the potential consequences in the event of a crash should also be considered. Such consequences depend on the type of road users involved and their vulnerability, speed, mass, type of collision, collision angle, etc. As Laureshyn et al. (2017a) note, extending the basic Newtonian physics concept relating energy to mass and velocity to include such other factors is already well recognised. However, there appears to be no generally accepted term for the dimension of severity related to crash outcomes in TCT beyond ‘potential consequences’, which has some connotations that do not fit well with characterising events in which no crash occurs or where ‘consequence’ is related to assumptions that are not necessarily realised. Therefore, this concept will be termed ‘intensity’. This term is broadly representative of the energy brought to the interaction by the parties involved and is a characteristic reflecting the road users involved, whether or not a collision course exists.

In terms of TET, it is reasonable to believe that if the severity of traffic events follows a non-random distribution compatible with EV theory, then proximity and intensity characteristics of severity also follow non-random distributions. Hence these indicators can be considered separately, as follows. To draw out the issues with current TCT research and how this is influenced by paradigm, Laureshyn et al. (2017a) will be used. This should not be interpreted as a criticism of this particular research. The opposite is true: it represents an exemplar approach to the theoretical understandings of TCT and how these inform a practical method. As such, it is considered a useful foil for the purposes of considering TET, rather than a straw man.

Proximity and temporal indicators

Following earlier work (Laureshyn et al., 2010 and Laureshyn et al., 2016), Laureshyn et al. (2017a) attempt to better define severity by using more than one indicator for the purpose, and considering both proximity and intensity dimensions of severity. They are far from the first to do so, with Hydén (1987) recommending that speed be recorded in addition to the temporal measure of Time-to-Accident to enable serious conflicts to be differentiated from non-serious conflicts. This approach is codified in the Swedish TCT method.

In attempting to capture both proximity and intensity characteristics of 'severity', Laureshyn et al. use the temporal indicator T_2 for proximity and extended delta-V to represent the energy if a crash were to occur (i.e. intensity). Extended delta-V is delta-V 'extended' to allow for the effect of braking. Both T_2 and extended delta-V are based on a number of assumptions regarding road user behaviour in assessing whether or not a collision path exists and the potential for evasive manoeuvres. T_2 is defined as the expected time for the second (i.e. later) road user to arrive at a conflict point, given unchanged speeds and 'planned' (i.e. assumed) trajectories. It is an extension to Time-To-Collision that is the same as Time-To-Collision if a collision course exists but unlike Time-To-Collision can also be calculated if no collision course exists, by assessing the time margin between two vehicles arriving at a common conflict zone. Laureshyn et al. use the minimum value of T_2 to determine the closest point of two vehicles in time during the interaction, which is then the point at which they calculate the intensity of the encounter. Interestingly, the authors address the ambiguity introduced by assuming future trajectories by focusing on through vehicles conflicting with turning vehicles (in their case, left-turns, equivalent to the Australian right-turn). In these events, the range of potential future trajectories is quite constrained and the inaccuracy introduced by presuming certain 'planned' trajectories is minimised. However, this approach does introduce questions about application of the method to other conflict situations.

As with Time-To-Collision, T_2 is a composite temporal indicator, with time derived from speed and distance. The issues of applying EV theory to a composite indicator have already been mentioned. The authors provide their reason for using a composite temporal indicator by citing Laureshyn et al. (2010) (emphasis added):

> “As indicated, the nearness to a collision has been studied extensively, since most traffic conflict indicators are exclusively based on some measure of proximity in time or space. **From a methodological perspective, the time-based measures are preferred, since they are the result of a combination of road users’ speeds and distances**.”

Combining speed and distance in an indicator makes methodological sense if the resulting indicator is the only measure of ‘severity’ used, in that it incorporates both a proxy for intensity (speed) and a measure of proximity (distance). But in the case of Laureshyn et al. (2017a), the authors are capturing the proximity and intensity dimensions of ‘severity’ separately. The statement of methodological advantage for a temporal measure is, therefore, difficult to understand. Indeed, from a methodological perspective, combining speed and distance in a time-based indicator could more persuasively be argued as comprising an unnecessary complication than as offering any positive value. Why, then, do Laureshyn et al. cite and use the proposition that a temporal measure is preferred/preferable?

In the historic development of TCT, temporal indicators were preferred because humans could more accurately assess a time difference than distance or speed in a dynamic situation. A preference for temporal measures in TCT noted by Zheng, Ismail and Meng (2014a) is also partly for reasons of paradigmatic concern as noted above: such indicators integrate proximity with speed, with the latter related to kinetic energy and hence providing a link to ‘severity’ in its character of intensity. But as noted, Laureshyn et al. capture intensity separately, based on the specific proposition that a temporal indicator is inadequate for the purpose. And as they are using video software to compute T_2 and extended delta-V, there is clearly no pragmatic reason to favour a temporal proximity indicator.

So while Laureshyn et al. mention methodology as a rationale, it appears that their use of a temporal indicator for proximity does not logically follow from a propositional starting point or confer any methodological or even pragmatic advantage in their case. In fact, the opposite is true: Laureshyn et al.’s use of extended delta-V is intended to integrate proximity with intensity. This accentuates the question as to why the proximity measure should, in itself, also measure intensity, while adding the question of why the intensity measure should seek to capture proximity[43]. The answer to this somewhat incestuous approach appears to lie in TCT paradigm.

From a TCT perspective, a collision course underlies the definition of conflict – the foundational basis of TCT – and the risk of collision is a fundamental and necessary component of TCT practice. Conflict involves two or more road users approaching a joint conflict point (or zone). Therefore, measuring proximity must reference the conflict zone and Laureshyn et al. (2017a) demonstrate paradigmatic compliance by adhering to this practice. Similarly, the paradigm of TCT has focused on capturing the 'severity' of conflicts and enabling different severities to be compared through some indicator, for the already noted reasons of historic practicality and paradigm. The approach of trying to combine different characteristics of severity into a single indicator is a paradigm also adhered to by Laureshyn et al. even when the propositional basis of the authors' approach is that previous indicators do not adequately capture intensity i.e. their logical proposition is that two separate indicators are required to adequately capture the separate characteristics of severity.

The greater paradigm issue for Laureshyn et al., then, is actually the TCT definition of conflict. This is interesting given the authors' overall approach intends to address a weakness of the TCT definition of conflict in terms of traffic encounters changing from collision to non-collision events. That is, they are willing to address conceptual problems regarding collision paths in the definition of conflict, having identified limitations through previous research, yet appear to adhere to the definition in terms of a proximity indicator, as previous research has not identified a contradiction. Paradigm can be contradicted where empirical evidence undermines it, but otherwise dominates, because it represents the starting point of knowledge; and empirical contradiction of a theoretical framework is an inadequate basis for questioning the theoretical framework per se. It can be added that Laureshyn et al.'s concession to an empirical contradiction is to use a slightly different indicator that enables 'near collision' paths to be considered in a similar way to collision paths i.e. it is paradigmatically satisfying.

A pertinent question that arises from this examination of Laureshyn et al.'s approach is, what other indicators could be used for proximity if not a temporal (i.e. composite) indicator? Researchers such as Laureshyn et al. constantly mention severity indicators as indicating

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[43] Despite extended delta-V being proposed as an integrated indicator, there is logic to a stand-alone measure for proximity in addition to this, to identify the point at which extended delta-V should be measured. But integrating intensity and proximity characteristics into separate measures of intensity and proximity is, overall, conceptually confusing rather than logical.

proximity "…in terms of time or space." Yet most indicators of proximity used have been temporal rather than spatial. Laureshyn et al. note in regard to their indicator (emphasis added):

> "The latest possible value of T_2 during an interaction, i.e. the moment when the first road user leaves the 'conflict zone' and after which a collision is no longer possible without a change of trajectories, has practically the same meaning as [Post-Encroachment Time] **and reflects the moment when the two road users are closest in space to each other**."

That is, in these conditions T_2 is considered to reflect proximity in space, even though it is measured and expressed in terms of a time value derived from speed and distance. Again, this reflects the adopted paradigm, where the 'conflict zone' has greater import than actual proximity, and closeness in time is more important than closeness in space.

In fact, indicators have been used in TCT that measure spatial proximity directly, even if these have fallen into desuetude. Grayson et al. (1984) calibrated eight different traffic conflict techniques in Malmö, Sweden. The study found Time-To-Collision$_{min}$ to be the most important factor correlated to severity ratings under the different TCT techniques (based on trained observers' subjective assessment of severity). But the second most important factor was the minimum distance between road users. This was measured between the two nearest points of both road users before, during or after the encounter[44]. Laureshyn et a. (2016) cite Ward et al. (2015) as describing calculations of Time-To-Collision based on the closest distance between two vehicles and the "closer rate" (speed at which this distance decreases; perhaps a homonym for closure?) A problem of this technique was that it could be measured even if vehicles were not on a collision course.

Under TET, the measurement of proximity via the single-dimensional form of distance means that EV theory applied to a frequency distribution for proximity would be free of any contrary effects arising from the ambiguity imposed by a temporal (and hence composite) indicator. A distance measure of proximity would also be free from the need to identify a collision zone for the road users, which introduces assumptions about future trajectories and kinematic state. Distance also satisfies other comments made by Laureshyn et al. (2017a) about T_2: it is continuous, can be measured with or without a collision path, and is indicative of nearness to

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44 The use of three distance situations reflects Swedish and Finnish TCT methods considering distance at the start of evasive actions, British TCT using the distance at the end of an evasive action, and a decision to also consider the distance during the encounter.

a collision. And in terms of feasibility, assessing distance from video footage is arguably easier than the calculation of T_2.

Intensity and future state assumptions

Laureshyn et al. (2017a) have a similar difficulty with intensity defined through delta-V as they have for proximity in terms of measuring it relative to a conflict zone. To this is added the complication that delta-V stems from road crash analysis practice. So if TCT paradigm assumes a collision course and two or more road users approaching a joint conflict point (or zone), road crash paradigm considers delta-V as calculated from known crash conditions. Hence for Laureshyn et al., ‘planned’ trajectories and a collision course are requirements when calculating delta-V. Indeed, this underpins Laureshyn et al.’s use of extended delta-V, which incorporates braking behaviour into calculations of delta-V – where this is possible.

Again, this approach reflects the TCT definition of ‘conflict’, which is not a requirement of TET. TET instead considers ‘severity’ as a statistical relationship between a measured traffic event and a crash event, with intensity one of two characteristics of severity used to characterise traffic events. But as TET allows intensity to exist separately from conflict, intensity no longer needs to be defined relative to a collision course and hence conflict zone. The only other realistic possibility is that it is measured at the point of closest proximity between the actors in a traffic event – which is in fact the approach proposed by Laureshyn et al. This traffic event could involve two or more road users as per the TCT definition of ‘conflict’, but as TET allows the case of a single-vehicle traffic event, the traffic event could equally involve a road user and part of the road environment. Hence the single-vehicle crashes allowed under TET’s paradigm can also be measured by its method.

Laureshyn et al.’s method for calculating intensity reflects assumptions regarding trajectory (mentioned previously) and kinematic state, in terms of an assumed deceleration rate to account for braking behaviour. From a paradigmatic viewpoint, this accords with TCT’s definition of conflict being ‘observable’ and hence implying evasive behaviour, as well as more pragmatic reasons regarding the causal chain linking conflict to crash. However, in introducing assumptions, it also introduces validity questions and starts to introduce paradigmatic issues related to the causal chain.

Characterising intensity separately to proximity, with both together describing ‘severity’, is a fundamental part of TET. Freed from TCT paradigm, intensity does not have to accord to issues raised by the definition of conflict. Mathematically, delta-V is calculated from velocity, mass and angle. While these underlying values must be measured relative to a datum, each of these is continuous and none requires a collision course between two road users in order to exist. Hence an intensity indicator similar to delta-V can be calculated under a TET methodology, albeit that this might not strictly be the delta-V defined by road crash analysis practitioners. A clear advantage of the TET approach to intensity is that no assumptions of trajectory or kinematic state need to be made. The measurement/calculation of an intensity indicator reflects the state of the traffic event at a point in time and location in space, following the premise that the relationship between intensity and crash potential is statistically based and established through EV theory. It is not complicated by issues regarding conflict zones, two but not one road users, assumed trajectories and so forth.

Linking proximity with intensity

The conceptual examination of the proximity and intensity characteristics of severity undertaken above has broader importance in terms of TET.

Ignoring for the moment the issues associated with the use of a temporal indicator for proximity and the future state assumptions inherent in the calculation of extended delta-V for intensity, Laureshyn et al. (2017a) present their results as a histogram and accompanying scatterplot diagram, as per Figure 7. (This is for delta-V; results for extended delta-V are presented in a different diagram.)

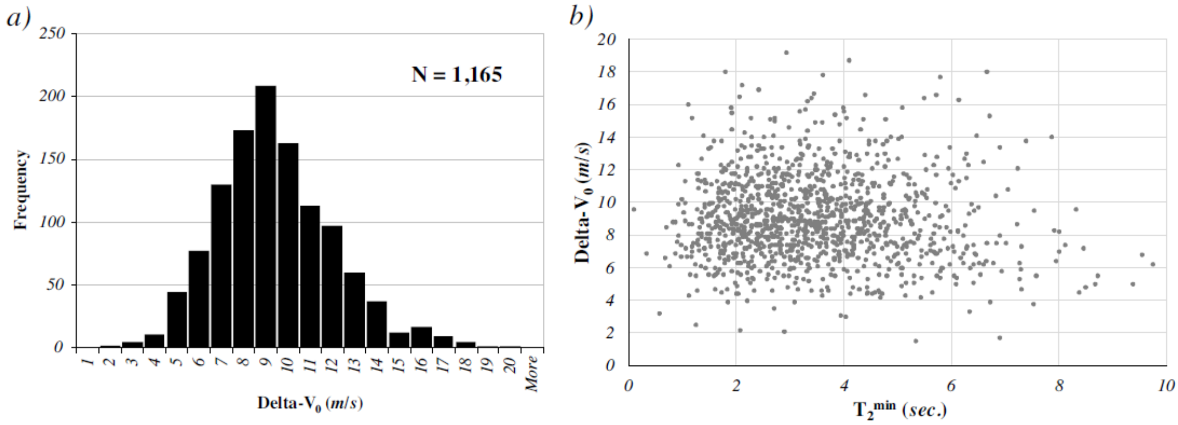

Figure 7: Delta-V results (a) as a frequency histogram and (b) scatterplot with T_2^{min} . Source: Laureshyn et al. (2017a).

The histogram shown as a) is a graph of the number of events observed at each value of an intensity indicator (delta-V). As the dataset presents a frequency distribution of the indicator, an EV theory analysis could be conducted on the data to determine the probability of extreme values of intensity.

The scatterplot of delta-V versus T_2^{min} shown as b) presents a graph of an intensity indicator against a proximity indicator. Laureshyn et al. note that this does not show clear patterns – unlike the bell curve of the histogram. Neither does it, nor the primary data, include frequency distribution information for proximity. Hence EV theory could not be applied to intensity. Further, unique records of intensity are not explicitly linked to proximity and no (direct) link between the likelihood and the intensity of a traffic event can be made.

The manner in which proximity and intensity are (or are not) linked to each other by Laureshyn et al. (2017a) is considered to be another element of their study that implicates the TCT paradigm. Under TCT, the 'severity' of a conflict is a property of two or more road users and it is this property which TCT indicators attempt to measure. But given two road users in a traffic event, two values of intensity must result for each proximity, for any event that is not of exact equals in a completely symmetrical traffic event – namely, the vast majority of all real-world situations. Road crash practitioners know that the crash outcome for car A hitting head on into the side of car B is very different for the occupants of car A compared to car B: an apparently single traffic event has two intensities that are not equivalent[45]. Using a grammatical analogy, an encounter between two road users is different for the object and the subject of the encounter.

While it does not have to be the case that only one value of intensity is assigned to each interaction between road users, TCT paradigm tends to push in this direction. Under TCT, the definition for conflict lacks dimensionality: it implies equality between involved road users. Laureshyn et al. (2017a) recognise that this is not true by using delta-V, but do not acknowledge that this presents a conceptual issue in contradicting the TCT definition of 'conflict.' If TCT paradigm defines conflict as a property between two road users and posits that conflicts can be differentiated by severity, what does it mean if two values of severity exist for every conflict? The logical conclusion is that two distinct risk profiles exist, reflecting the subject/object roles of the involved vehicles.

It may seem churlish to note that Laureshyn et al. (2017a) overlook this by simply stating that "…to describe the interaction severity the highest value [of delta-V] can be used." However, Laureshyn et al. are an exemplar partly due to their consideration of TCT paradigm, its limitations and implications. A discussion on what the two delta-V values imply on either a

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[45] Their jargon would differentiate between a bullet and target vehicle, for example, Hitzemann (2003).

conceptual or practical basis could be expected and the lack of such a discussion is sufficient to implicate TCT paradigm in the acceptance displayed.

For TET, two distinct intensities at a given proximity strongly implies two distinct statistical relationships and, as mentioned, risk profiles. Choosing the highest values from part of one statistical relationship and incorporating these with another would be a fraught activity for risk assessment based on EV theory, at least without serious consideration about the results. As such, the TET paradigm highlights an issue that TCT overlooks.

For TET, given that multiple crash risk profiles exist depending on whether the road users are the subject or object of the traffic event, and given that TET is free of the limitations imposed by the TCT definition of conflict (requiring two or more road users), the logical approach for TET is for every traffic event to be considered relative to a subject road user. Proximity is then measured between the subject road user and a hazard, whether that is some element of the road environment (street furniture, edge of road, etc.) or another road user. At the point of closest proximity, intensity is measured or calculated, relative to the subject rather than to a conceptual point such as a conflict zone.

Identifying crash risk

As the literature review indicates, an outstanding issue for TCT is that different indicators give rise to different results. In crash studies, correlation with historic crash data is used to identify which indicator best estimates crash risk, and this has so far varied from situation to situation. As such, the aim of identifying crash risk independently of crash data, or comparing relative crash risks of different infrastructure, has not been met.

For TET, statistical relationships can link proximity to frequency distribution and intensity to frequency distribution, allowing the extreme values of these to be calculated. However, this does not in itself produce an assessment of crash risk. On the other hand, if it is accepted that proximity and intensity can be reliably calculated, then ‘risk’ can be considered as lying at the intersection of these values. The question that arises is how to correlate proximity and intensity, especially given that each of these exist in EV theory conceptually as frequency distributions.

Laureshyn et al. (2017a) measure proximity and intensity separately and tie these characteristics to each other via a scatterplot, with a frequency histogram for intensity provided separately. Ignoring other issues with the indicators used and the difficulty of interpreting the scatterplot produced, this representational approach would not suit TET in that to apply EV theory to proximity and intensity, both of these must exist as frequency distributions and must also be explicitly and uniquely linked with each other. A scatterplot explicitly links proximity to intensity, but not frequency. Adding frequency would require another axis – giving rise to the use of 3D graphical representations for crash risk in TET, perhaps of a similar form to Figure 8.

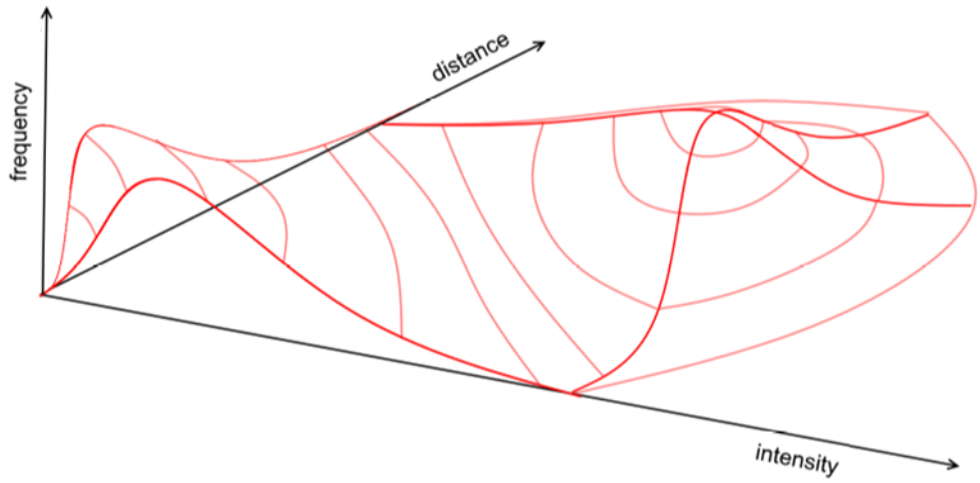


Figure 8: Conceptual 3D plot of proximity versus intensity.

Figure 8 shows both intensity and proximity (distance) following frequency distributions, hence the probability of extreme values of each of these can be calculated. As these distributions are uniquely linked to each other, the probability of a distance approaching zero (i.e. a crash) can be calculated for varying intensities, enabling different crash severity outcomes to be predicted. From a usability perspective, risk is simply interpreted via areas of high intensity and low distance. If calibrated against exposure, 3D plots from different sites or situations – such as a before/ after intervention – could easily be compared.

3D graphical representation therefore seems a practical way of representing crash risk. In terms of the data collection needed to support the representation, basing the theoretical framework for TET on a subject road user as suggested above would tend to lead researchers and/or practitioners to record both proximity and intensity for each traffic event, allowing frequency distributions to be recorded for both, with proximity and intensity uniquely linked i.e. recorded as well-characterised traffic events satisfying the requirements for EV theory to be applied.

Conclusion

In this case study, Extreme Value (EV) theory was examined as the fundamental concept on which to base an alternative theoretical framework to that currently underlying TCT. Using a process of logical deduction and the exemplar of Laureshyn et al. (2017a) as an aid to drawing out the issues, an approach labelled Traffic Events Theory (TET) has emerged.

The starting point for TET is the traffic event, for which no consistent definition has been found in the literature. A representative definition for a traffic event in TET could be:

> "A traffic event is a road user's encounter with the road system."

This definition describes a road user experiencing a continuous process of encounters changing moment by moment, with each moment containing the possibility of a crash event. This definition implies a firm subjectivity to TET: the traffic event is relative to a particular (subject) road user. This definition is also slightly different to the sense of a traffic event in TCT, which assumes that traffic events occur between road users. The TET definition includes non-road users, with 'road system' covering other road users without requiring their involvement.

The basic premise of TET is that traffic events can be rated by 'severity', which expresses a statistical relationship between a measured traffic event and its extreme case of a crash. Extreme Value (EV) theory provides a proven mathematical method to determine the likelihood of crashes based on observations of traffic events, as long as such observations accurately characterise traffic event 'severity.' The statistical relationship between severity and crashes does not have to be known for EV theory to apply.

'Severity' has two characteristics: proximity and intensity. Indicators for these characteristics need to be continuous, unambiguous and measurable/calculable. The obvious indicator to use for proximity is the minimum distance between the subject road user and a hazard during a traffic event. Intensity provides an indication of the energy embodied in the traffic event, relative to the subject road user, and is measured/calculated at the point of minimum distance. The road crash analysis indicator delta-V forms a good basis for an initial intensity indicator as it can be calculated from the velocity and collision angle measured for the traffic event and a mass estimated from road user characteristics. Other factors such as elasticity of collision could also be incorporated into an intensity indicator as suggested by road safety researchers.

Proximity and intensity must be collected as frequency distributions to enable EV theory to be applied to each, and uniquely linked to each other so that the results of applying EV theory can be interpreted. 3D plots are proposed as a way of visually representing the relationships between proximity, intensity and frequency, and easily comparing results.

TET needs to be further developed, refined and validated, but logical deduction indicates that TET forms a plausible alternative to TCT. The major benefit of TET's compatibility with EV theory, and the reason that this was pursued as a basis, is that TET can provide a quantitative assessment of crash potential from observations of non-crash events – which is not achievable using TCT.

TET also addresses virtually all outstanding issues of TCT as itemised in Chapter 3 in the methodology for this case study, and summarised as follows:

a) *Definition of a conflict* – 'Conflict' is not part of TET and definitional issues no longer apply.
b) *The boundary between non-conflicts, conflicts and crashes* – Under TET, all traffic events lie on a safety continuum, 'conflict' does not exist and no boundaries need to be identified.
c) *Traffic encounters without a collision course (and hence 'conflict')* – TET indicators do not rely on the existence of a collision course or 'conflict'.
d) *Single-vehicle events* – Single vehicle events can be measured using TET.
e) *The concepts of proximity and severity* – Whereas TCT confuses proximity with severity, TET clearly resolves severity into a combination of proximity and intensity, each of which are themselves clearly defined.
f) *The link between traffic conflict and crashes* – EV theory provides a statistical model associating traffic events with crashes.
g) *Evasive action as a measure of conflict* – TET is not based on evasive actions.
h) *Situations where 'conflicts' do not correlate with risk* – TET does not assume that 'conflict' is part of a process model for crashes or use 'conflict' to assess risk.
i) *Temporal measures do not uniquely characterise conflicts* – Temporal measures are counter-indicated for EV theory and are not used in TET.
j) *Different measures in TCT giving different results* – TET well-characterises 'severity' via proximity and intensity and the means of measuring these are applicable to all situations.

Multiple measures are not indicated, hence different results for the same situation should not occur.

k) *Assumptions about road user movements and the future kinematic state of vehicles* – TET does not require these assumptions to be made.

l) *Associating conflicts to crashes relies on crash data* – TET does not rely on crash data to establish statistical associations.

m) *Relating conflict to crash consequences* – TET characterises crash consequence through the intensity indicator. The subjectivity of TET points to different crash risk profiles existing for different road user and crash types, and supports their disaggregation.

n) *Use of a single indicator versus a range of indicators* – TET's means of measuring proximity and intensity applies in all cases, however the ability to disaggregate results could give rise to a range of risk assessments being undertaken, for example for different types of road users.

o) *What indicators actually characterise* – This is clearly specified in TET.

p) *Compatibility with Extreme Value theory* – TET is based on EV theory.

In terms of whether this theoretical framework has previously been proposed, Wang et al.'s (2016) concept of a Driving Safety Field also provides a framework for risk defined relative to a subject road user. This is based on field theory, where moving road objects such as vehicles and non-moving road objects such as lane markings are represented as component fields, with their union giving the total driving risk. This has similarities to the concept of a traffic event occurring in a road system under TET and is one of few risk indicators to represent risk in a vector form. Otherwise, it is quite distinct from other TCT indicators as well as TET. In particular, as Mullakkal-Babu (2017) note, the Driving Safety Field concept does not claim to represent the collision causal mechanism and interpreting the safety field risk measure presents some paradigmatic ambiguity. No other more theoretical framework more similar to TET has been identified. Overall, TET is considered to represent a theoretical framework that has not previously been explored by TCT researchers.

The proof by contradiction approach for the paradigmatic case study considers that developing a plausible competing theoretical framework to the existing paradigm of TCT, and one that overcomes issues identified for TCT, indicates that a paradigmatic adherence to TCT's theoretical framework has hindered rather than optimally advanced this field of study. The proposal of Traffic Events Theory is considered to satisfy these conditions.

The negative effect of an adherence to paradigm on road safety research is therefore considered to have been demonstrated.

5. Results of the pragmatic case study (cyclist safety at radial versus tangential roundabouts)

Literature overviews

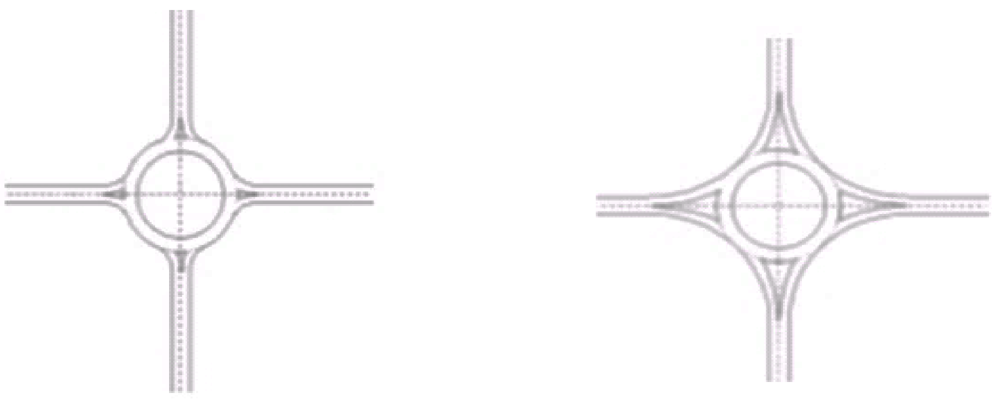
Radial versus tangential design

Roundabouts are a diverse class of traffic engineering treatment whose types are not equal, nor their safety effects. Roundabouts vary by size (generally classified from mini to small to compact to large); complexity (single or multi-lane, with/without slip-lanes on approaches); whether or not they are signalised; and, most fundamentally, on the design philosophy on which their design is based.

The roundabout design used in much of continental Europe features approach and departure legs that are aligned radially to the centre of the roundabout and are hence termed radial or continental roundabouts. Under radial design, the geometry is relatively ‘tight’, with narrow (single-lane) entry and exit lane widths contributing to speed reduction.

The roundabout design used by most Anglophone countries (UK, Australia, New Zealand, Canada), and also in some European situations (such as Sweden), follows the British model of roundabouts where the approach and departure legs are tangential to the centre of the roundabout. These are termed tangential roundabouts. Here, traffic speed reduction is achieved by deflecting vehicles from a straight-through path of travel. Under the tangential design, traffic speeds and capacity are generally higher and the space taken greater than for a radial design with an equivalently sized central island.

The difference in design philosophies is shown indicatively in Figure 9.



Radial design *Tangential design*

Figure 9: Radial versus tangential design. Source: Herland and Helmers (2002).

Herland and Helmers' (2002) illustration has popularised the use of 'tangential' and 'radial' as terms used to differentiate between these basic design philosophies in Australia. But radial and tangential are broad descriptors. Aumann, Pratt and Papamiltiades (2017) provide good coverage of the various design guidance elements of Australia and New Zealand, the United Kingdom, the Netherlands, Germany and the United States, though even this is a slight simplification due to underlying differences in how design guidance is applied in different countries. Due to the approach used in their reporting, Aumann et al. perhaps underplay differences between rural (high-speed) and urban (lower speed) environments and how/ whether roundabouts are used by pedestrians and cyclists. For example, Herland and Helmers note that the Swedish and Norwegian guidelines they reviewed recommended tangential exits for roundabouts outside urban areas, with Swedish practice recommending sharper exit curvature when unprotected road users were allowed to cross; and Swedish practice also recommending tangential entries, though with left-hand deflection to reduce speeds[46].

Meanwhile, Brilon (2005) notes that German design rules specify avoiding increases in capacity for roundabouts where possible. The design rules favour single-lane compact roundabouts; then if necessary for capacity, bypass lanes; followed by single-lane entry to two-lane compact roundabouts; and, finally, two-lane entry, two-lane roundabouts. Two-lane exits are not used on two-lane roundabouts and cyclists are banned from circulating lanes of these roundabouts. And while US practice is based on tangential design, this generally involves much larger streets and inscribed circles, with fewer of the compact single-lane roundabouts that mark both European and Australian/ New Zealand practice. Another complicating factor in understanding research findings is that design guidance may well change over time, presenting a legacy embodied in infrastructure form.

Nonetheless, the shorthand terms of radial versus tangential are considered reasonable for most purposes, with research results divided between radial for roundabouts located on Continental Europe and tangential for roundabouts located in Anglophone countries.

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[46] Hence Herland and Helmers (2002) categorise entry and exit design guidance as being distinct, identifying in addition to radial entry/radial exit and tangential entry/tangential exit the design bases of radial entry/tangential exit and left-deflected entry/tangential exit. However, these appear to be uncommon outside Swedish and Norwegian practice.

Cyclist safety at roundabouts

Roundabouts as a class of on-road treatment are well-known as being associated with improved safety for motorised vehicles – although Hauer (1997) notes that part of the reduction may be due to site selection bias – but presenting particular safety issues for cyclists. Literature reviews and summaries of research are given in, for example, Räsänen and Summala (2000), Daniels and Werts (2005), Patterson (2010), Campbell, Jurisich and Dunn (2011), Schramm et al. (2014), and Wilke, Lieswyn and Munro (2014). The SQ literature review for this dissertation found cyclist safety at roundabouts to be a common infrastructure theme, with 17% of papers focusing on this.

As an example of the types of results found, Kennedy et al. (2005) cite Layfield and Maycock (1986) as finding that the risk for pedal cyclists and motorcyclists relative to cars is higher at (UK, tangential) roundabouts than at other junction types. Jensen (2012) presents a meta-analysis of 19 before-after crash studies of conversions of unsignalised intersections to (presumably Danish) roundabouts as showing decreases in fatalities, severe and slight injuries of 87%, 75% and 66% respectively, but an increase in bicycle crashes of 21%.

Australasian research (where roundabouts follow a tangential design base) is undermined by a lack of reporting of exposure data. Nonetheless, Wood (1999) found that at New Zealand roundabouts:

- cyclists account for 6% of all crashes compared with 1% at traffic signals and 4% at priority junctions
- cycle crashes at roundabouts account for 24% of all injury crashes
- cyclists are 20 times more likely to be injured than other road users at roundabouts.

These results indicate over-representation of cyclist involvement in crashes at roundabouts compared to modal share and exposure, as roundabouts are generally rarer treatments than other intersection types, albeit that they are more common in urban than rural areas. The results are broadly in line with studies such as Robinson (1998), who found that cyclists comprise 18% of injuries at roundabouts in NSW compared with 6% at cross intersections, and that in non-metropolitan areas where cycling was more popular, 32% of those injured in two-party crashes at roundabouts were cyclists. In Cumming's (2012) examination of roundabouts in Victoria, close to 50% of roundabout crashes at inner Melbourne municipalities involved cyclists, contrasting with less than 10% of all reported crashes; and for Victoria as a whole, 24% of crashes at roundabouts involved cyclists compared to 4% of all reported crashes. (Regarding the difference between inner Melbourne and Victoria as a whole, inner Melbourne roundabouts are more likely to be smaller, have only a single-lane, be in a 50km/h zoned area and subject to higher cyclist use.)

Overall, the differences in cyclist crash rates at roundabouts compared to other intersections is sufficient to indicate an over-representation of cycle crashes even in the absence of exposure data.

The most common crash type for cyclists is ‘entering car/ circulating cyclist’ and this is much more dominant as a crash type in car-bicycle crashes than the car-car analogue of ‘entering car/circulating car’. Campbell, Jurisich and Dunn (2011) found entering vehicles colliding with circulating cyclists to be responsible for 69% of cyclist injuries at New Zealand roundabouts. Cumming (2012) found that the most common crash type of “entering-circulating” accounted for 48% of all crashes but 81% of crashes involving bicycles, typically with an entering car striking a circulating cyclist. And Aumann, Pratt and Papamiltiades’ (2017) crash analysis of Australian and New Zealand roundabouts identified that 93% of cyclist crashes occurred in speed zones of 60 km/h or less, with the most common crash type (entering motor vehicle-circulating cyclist) accounting for some two-thirds of cyclist crashes.

Comparing the safety performance of tangential roundabouts with radial roundabouts is complicated by the prevalence of different design features and legislation in different countries – such as zebra crossings on approach and departure legs for radial roundabouts and associated yield rules to cyclists. Such design features are often distinct between the two design types and create an underlying environmental difference in addition to general complications presented by roundabouts due to the many variables affecting risk. Elvik (2003) states that comparative studies should ideally control for factors such as vehicle flow, number of approaches, previous control type (stop, yield, signalised), speed limit, incoming traffic volume on minor roads as well as the presence of treatments for vulnerable road users (mixed traffic, cycle lane, cycle path), but gradient, traffic composition, sightlines and proportions of traffic turning in different directions are also relevant at roundabouts. Wilke, Lieswyn and Munro (2014) aimed to compare the effects of installing bicycle lanes in tangential roundabouts through matched pair selection but were unable to find appropriate pairs because of the wide range of variables at play and the resulting differences between individual roundabouts.

Acknowledging these issues, and the other provisos already recognised regarding the use of mass data and particular issues for cyclists, some observations can be made.

Firstly, it appears that for cyclists at radial roundabouts, general crash locations are similar at radial roundabouts to tangential roundabouts – subject to provisos about the types of cyclist provision (e.g. mixed traffic, bike lane or separated paths). For example, Spacek’s (2004) analysis of 130 Swiss roundabouts (90% of their 2,000 roundabouts being compact single lane designs with inscribed circle diameters between 25 and 40 m, zebra crossings and mixed traffic conditions) showed the majority of crashes occurring on entry, where almost half of all injury crashes involved cyclists.

Secondly, in terms of crash rates, the pattern of higher crash rates for cyclists at Australasian roundabouts than at other types of intersections does not appear to be true – or at least as true – of radial roundabouts. For example, Wilke, Lieswyn and Munro (2014) quote Brilon’s before-after analysis of 32 single-lane roundabouts as finding a 40% reduction in crash frequency involving all road users and more or less no change in bicycle crashes at locations with mixed traffic (a condition comparable to the Australian/ New Zealand situation) or with separate bicycle/ pedestrian paths. That is, the cyclist crash rate at the radial roundabouts examined was about the same as the intersections they replaced, unlike the higher cyclist crash rate at tangential roundabouts compared to other intersections. While this conclusion is not supported by Jensen (2012) or Daniels, Nuyts and Werts (2009), who in Denmark and Belgium respectively found that conversion of intersections to (radial) roundabouts led to increases in cyclist crashes, both studies included conversion from signalised and unsignalised intersections, different types of cyclist facilities, and under different speed limits. As a result, their findings cannot be taken as invalidating Brilon’s.

Thirdly, multi-lane roundabouts pose a significant risk to cyclists and are best addressed by separating cyclists from motorised vehicles, usually by providing a circulating path around the roundabout. There is a plethora of research supporting this conclusion. Brüde and Larsson’s (2000) review of 650 Swedish roundabouts, including 72 used by more than 100 cyclists a day, found that the number of bicycle accidents at multi-lane lane roundabouts was twice that predicted from traffic and cyclist volumes. Van Minnen’s (1998) examination of Dutch roundabouts found that two-lane roundabouts were less safe than one-lane roundabouts for all road users. Bergh (1997) cites a study of Swedish, Danish and Dutch roundabouts of varying radii, lane numbers, traffic flows and cyclist provisions as finding that small-scale, single-lane designs had the greatest safety. Hydén and Várhelyi (2000) recommend that to achieve the best cyclist safety result, roundabouts should be as small as possible, with single-lane entries, exits and circulating lanes. French research is not readily available in English, but Scrase (2005) quotes Guichet as saying that very large roundabouts with multiple lanes "…cause problems and are not good for safety." Turner, Roozenburg and Smith's (2009) overview of crash prediction models for Australia and New Zealand related cyclist risk at roundabouts to multi-lane roundabout installations. Hence multi-lane roundabouts can be considered as distinct from single-lane roundabouts, which are those most common in the urban area and most frequently encountered by cyclists.

The practice of providing a separated cycle path is also suggested as suitable for consideration in Australia (Austroads 2015), due to 'some evidence' that this is the safest design. The Australian guidance refers to the practice being appropriate to high traffic volume as well as multi-lane conditions. Daniels et al. (2009) cite Schoon and Van Minnen as finding in the early 1990s no major differences in crash rates for cyclists between mixed traffic, cycle lanes and separate cycle paths, but that injury rates indicated a separate cycle path was safer than both other design types at roundabouts with a considerable traffic volume. Since OECD (1998) notes that the roundabouts studied in a follow-up paper by Van Minnen and Schoon were small, with single circulating lanes and single lanes on both entry and exit roads, Schoon and Van Minnen's earlier research probably applies to single lane rather than multi-lane roundabouts. Bergh (1997) found that separate entry/exit crossing cycle paths were the best solution in high traffic flow conditions. Of course, this raises the question of what "high traffic flow" means in practice. Silvano and Linder's (2017) literature review of how geometry, traffic, and priority rules affect traffic safety at roundabouts concludes that for a daily vehicle volume of fewer than 8,000 vehicles/day, mixed traffic can be allowed, with a cycle path being the preferred option above this traffic limit.

Lastly, a specific finding of note from European research is that bicycle lanes in roundabouts increase rather than reduce cyclist-involved crashes – as reported in literature reviews in Daniel and Wets (2008), Patterson (2010) and Wilke, Lieswyn and Munro (2014). Although bicycle lanes were introduced as an option into Australasian guidance in 2009 (Austroads 2009), bicycle lanes are not an inherent feature of tangential roundabout design and have been installed in only a handful of Australian roundabouts. Patterson (2010) cites Clause 3.18.07 of New Zealand's *Manual of traffic signs and markings* as providing guidance that bicycle lanes in roundabouts are not supported, with the advice instead being that these should not be provided. Research regarding Australasian roundabouts is considered to exclude bicycle lanes in roundabouts unless specifically indicated otherwise.

Traffic speed as a safety mechanism

In terms of the actual mechanisms contributing to different crash risks at roundabouts, Chen et al. (2013) note that operating speed is widely accepted as a key safety-related variable for roundabouts, albeit that the exact relationship between speed and safety is not well specified. Several factors are more or less implicitly accepted as underpinning the speed mechanism. One factor related to speed is driver reaction time. Wilke, Lieswyn and Munro (2014) mention in passing that lower speed would provide greater time for motorists to scan for conflicting movements, including those of cyclists.

Turner, Roozenburg and Smith (2009) observe the relationship between speed and safety in their overview of crash prediction models for Australasia, the UK and Sweden; Wilke, Lieswyn and Munro (2014) note from their literature review a correlation between motorist entry speeds and crash rates for all users including cyclists; while Turner, Wood and Roozenburg's (undated) development of accident prediction models found speed/ crash risk associations for cyclists as well as motor vehicles for the entering/ circulating crash type at Australian and New Zealand roundabouts. Aumann, Pratt and Papamiltiades (2017) investigated a representative set of Australian roundabouts to identify contributing factors to the crashes occurring at the roundabouts. They adopt a speed of 30km/h for analysis purposes and suggest that this may also be a useful metric for design purposes, but acknowledge that further research would be required in confirming the appropriate design speed.

With researchers such as Campbell, Jurisich and Dunn (2006) observing that the radial design of roundabouts used in many European countries gives rise to generally lower traffic speeds, it would be expected that a roundabout that is radially designed should produce a better safety outcome than one that is tangentially designed, for the same site. Wilke, Lieswyn and Munro (2014) link average traffic speed variation to the likelihood of encountering a conflicting motorist movement, and this as having more relevance than roundabout geometry and sightlines. This implies that reduced speed variation could improve cyclist safety by reducing exposure risk. However, their study of bicycle lanes in Australian roundabouts did not investigate the relationship of speed variation with radial versus tangential design. Schramm et al. (2014) agree that the generally lower speeds engendered by radial roundabouts would be expected to result in greater safety for cyclists than tangential design, but go on to point out that there have been no studies to confirm this view.

Against this, Aumann, Pratt and Papamiltiades (2017) observe that motorist approach speeds measured across a range of single lane and multi-lane tangential roundabouts are surprisingly similar. Further, these findings correspond well with the work undertaken by Turner, Roozenburg and Smith (2009), where negotiation speeds are not determined by roundabout geometry but by restricted visibility to the roundabout entry on the right (i.e. in the yield direction). The proposition put forward is that when drivers don't know whether or not they will encounter traffic entering from the right, they have to slow down on the approach to the roundabout so that they can potentially give way. This gives rise to lower speeds and hence lower crash rates.

While both Aumann et al.'s (2017) and Turner, Roozenburg and Smith's (2009) observations are based on tangential roundabouts, under this theory, visibility limitations embodied within radial design guidelines could produce a safety effect additional to the geometric difference between radially and tangentially designed roundabouts. This safety effect does not undermine the proposition that radial geometry improves safety at roundabouts by reducing approach and/or negotiation speeds but rather provides a complementary mechanism related to speed reduction. However, some caution should be applied to Turner, Roozenburg and Smith's (2009) results, as their development of Safety Performance Functions (SPFs) involved combined data from single-lane and multi-lane roundabouts, hence it is unclear whether the very different conditions presented to cyclists by single-lane and multi-lane roundabouts might lead to the derived SPFs representing an averaged traffic environment rather than real-world situations. Further, speeds measured in the study are the free speeds of vehicles travelling through the roundabouts and not of vehicles turning left, right or yielding. While these speeds may be representative of the entering vehicle involved in a hypothesised failure mechanism for an entering-versus-circulating-vehicle crash type, the measurement of free speed may not be representative of typical conditions at a roundabout and hence conditions under which recorded crashes occur. In particular, in urban locations in Australasia, commuting is a major generator of cyclist flows and this typically occurs in peak periods, when free flow speeds are arguably less representative of actual traffic flow.

Overall, though, the opening sentence of this section stands: an association between speed and crash risk at roundabouts is widely acknowledged, even if the particularities driving it are not fully understood.

Safety in Numbers (SiN)

Smeed (1949) was the first to identify an empirical relationship between traffic fatalities and motor vehicle use (vehicle registrations and population). Looking at data from multiple countries, he found that increasing vehicle ownership led to a decrease in fatalities per vehicle. This relationship became known as Smeed's Law, but in more recent times has been referred to as Safety in Numbers (partly because the effect remains, but the actual relationship has been observed to vary when modern data is used); or the non-linearity of risk. Robinson (2005) describes Adams as being impressed by how well predictions from 1938 data (when the highest rate of vehicles per person was 0.23) fitted data for 1980 (with vehicle rates of up to 0.7 vehicles per person); and that in New South Wales, an almost identical relationship was observed when Smeed's Law was used to examine 110 years of road fatality data.

The non-linearity of risk has been well studied from the perspective of roads carrying different volumes of traffic, as noted by Satterthwaite (1981). Zhou and Sisiopiku (1997) cite Gwynn's 1967 work as being the first to suggest a U-shaped curve for the relationship between traffic volume and crash risk, with conditions of both high and low traffic volumes being associated with higher levels of crashes. Zhou and Sisiopiku's study found similarly shaped functions relating hourly traffic volume/capacity ratios and accident rates for weekdays, weekend days, multivehicle, rear-end, and property-damage-only crashes, but a generally decreasing trend with increasing volume/capacity ratio for single-vehicle, fixed-object and turnover crashes, and also for crashes involving injury and fatality.

Jacobsen (2003) presents data demonstrating that the effect also applies for both cyclists and pedestrians, and is stated by Robinson (2005) as being the first author to do so. For the complicated situation of a roundabout, the non-linearity of risk is evident from crash prediction models (essentially the basis of developing Crash Modification Functions). For Australasian roundabouts, Turner, Roozenburg and Smith (2009) calculate a crash prediction model for the circulating-cyclist-entering-vehicle crash type as:

$$A_{UCAR1} = 3.88 \text{ x } 10^{-5} \text{ x } Q_e^{0.43} \text{ x } C_c^{0.38} \text{ x } S_e^{0.49}$$

where:

A_{UCAR1} = annual number of entering versus circulating cyclist crashes

Q_e = entering motor vehicle flow on the approach

C_c = circulating cyclist flow perpendicular to the entering motor vehicle flow

S_e = free mean speed of vehicles as they enter the roundabout.

This demonstrates a non-linear relationship between crash risk (based on recorded crashes) and motor vehicle numbers, cyclist numbers and motor vehicle speed (determined as the free mean speed measured for unimpeded vehicles). Since the exponential values are all less than one, increasing cyclist flow leads to a decreasing crash rate i.e. the model displays a Safety in Numbers effect[47].

But correlation is not causation. Bhatier and Wier (2011) note this in calling for caution in the use of Safety in Numbers in transportation policy and planning dialogue and decision-making, stating that:

> "Analyses based on aggregated data can be hypothesis generating, but have limited utility for causal inferences about driver or pedestrian behavior at the scale of a specific street, intersection, corridor, or small-area level—at which pedestrian injury collisions actually occur and at which a "Safety in Numbers" effect would operate."

The authors go on to note that Jacobsen (2003) assumes both a causal relationship, with numbers causing decreases in risk, and a specific behavioural mechanism to explain this causal relationship – but that this causal inference does not consider challenges to internal validity, including confounding, the temporal direction of effect, and potential other alternative causal mechanisms.

The OECD/International Transport Forum (2013) puts concerns about the use of Safety in Numbers more baldly, stating that while cyclist safety is linked to the number of cyclists in traffic, insufficient evidence supports causality for the Safety in Numbers phenomenon. This is of critical importance as policy that adds more cyclists to the system without other risk-reducing measures may result in these cyclists being exposed to significant crash risks.

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[47] Turner et al.'s data set of 104 roundabouts in a speed zone of <70km/h comprised 69 single lane roundabouts (four of which were three-arm, the remainder four-arm) and 35 two-lane roundabouts (four of which were three-arm, three five-arm and the remainder four-arm). Hence it combines the very different conditions presented for cyclists at single and multi-lane roundabouts and does not accurately describe the crash risk at any one roundabout type. The authors also note that downhill gradient and circulating speed present a significant correlation with crashes. Also, the model did not fit well to three approaches with high entering motor vehicle volumes and high cyclist circulating volumes, where the reported mean crash rate of two crashes per five years was much higher than the model's predicted mean of about 0.75.

Against this, Elvik (2009) considers the non-linearity of risk for pedestrians and cyclists and finds that if very large transfers of trips from motor vehicles to walking or cycling take place, the total number of accidents may be reduced, with the Safety in Numbers effect for pedestrians and cyclists combining favourably with the effect of a lower number of motor vehicles to produce a lower total number of accidents. Turner et al.'s (2009) crash prediction model would support this for Australasian roundabouts in that the crash risk related to cyclist numbers is raised by an exponential of 0.38 while that related to motor vehicles is raised by 0.43 i.e. the risk contribution per cyclist is lower than the risk per vehicle – assuming changes in vehicular flow do not produce a contrary effect on mean free speed. Elvik's conclusion challenges the "common sense" notion that high injury rates for pedestrians and cyclists in existing transport systems implies that encouraging walking or cycling rather than driving will lead to more accidents. It is also interesting that no notes of caution are sounded regarding the use of crash prediction models such as that produced by Turner et al.'s (2009) as a means of assessing countermeasure effectiveness for cyclists, despite the well-known limitations regarding crash data used in their development, and modelling methodologies that combine data from many different sites and therefore indicate outcomes that may not result at any one treatment site. The observation that can be made is that both SiN and crash prediction models are based on empirical data, but one is problematic for traffic engineering paradigm while the other is compatible with it.

In any case, the concerns highlighted arguably relate to the extremes of understanding and applying the Safety in Numbers effect: relying on Safety in Numbers in the absence of any other safety measures has the potential to increase crashes with vulnerable road users, while discounting it entirely leads to a policy of discouraging active transport modes as part of a risk minimisation strategy.

In light of the questions about causation, Thompson, Savino and Stevenson's (2014) work is particularly interesting. While concepts of behavioural adaptation have generally been theorised to underly a causal mechanism, Thompson et al. (2014) explored the Safety in Numbers effect by constructing a simple, simulated environment and then varying the number of cyclists within the environment. This model did not allow for behavioural adaptation of drivers, who followed unchanged behaviours of collision avoidance, nor cyclists, whose rules related to travel route preference. Nonetheless, the authors were able to reproduce a Safety in Numbers effect closely approximating the exponential relationships between cycling numbers and the relative risk of collision as shown in observational studies. The association, however, was highly contingent upon bicycle density (being the number of cyclists located within a given radius of other cyclists) more so than bicycle numbers, with low, stable or decreasing density leading to a linear increase in crash risk with increasing bicycle numbers. The authors suggest two possible causal effects:

- Increasing bicycle density coinciding with increasing numbers may have the simple consequence of reducing the proportion of surface area per cyclist exposed to danger from cars.
- 'Selfish herd' theory – a closely related explanation from the biological sciences. This proposes that bird flocking, fish schooling, etc. is an adaptive mechanism that increases density and reduces risk of predation by minimising high-risk exposure at the periphery of groups. In terms of Safety in Numbers, each cyclist is subject to risk from cars at a rate proportional to their 'domain of danger', being half the distance between each cyclist and their nearest neighbour. Increasing density reduces the domain of danger and hence relative risk.

The two effects aren't necessarily intuitive. The first effect could be explained through the example that a cyclist following another cyclist no longer has their front, nor their leader's back, exposed to danger from cars. The second effect can be explained through a thought experiment of the cyclist crash risk at a roundabout. Imagine that at a given roundabout there is a 10% chance that the driver of an entering vehicle will fail to yield to a circulating cyclist. Then any one cyclist entering the roundabout with a vehicle on the approach leg is exposed to a 10% risk of a failure to yield. However, a cyclist who follows another cyclist into the roundabout is subject to a lower risk, because if a driver yields for a cyclist, s/he is very unlikely to fail to yield to a closely following cyclist. (In fact, even if the driver fails to yield to the lead cyclist, it is unlikely that the car would hit both cyclists.) Hence if increasing cyclist numbers leads to more cyclists following other cyclists in close proximity (i.e. greater density), then the crash risk per cyclist reduces.

While Thompson et al.'s (2014) study design has many limitations – which the authors freely acknowledge – the absence of behavioural adaptation as a causal mechanism and introduction of a probability-based mechanism may explain the consistent patterns of results found for car traffic and evidence of the same mechanism in vulnerable road users. It also explains contrary results where increased numbers of cyclists do not lead to increased density (for example, because motor vehicle volumes also increase) and hence risk does not reduce.

(Another possibility that accounts for no overall SiN effect being observed is that new infrastructure does result in a SiN effect, but this is overwhelmed by negative safety impacts resulting from particular design features.)

It is also possible that both behavioural and probabilistic SiN mechanisms exist and operate simultaneously. Stated preference surveys indicating that cyclists will change their routes depending on perceived safety do point to at least this form of behavioural adaptation. Against this, it is reasonable to assume that behaviour adaption should have at least some degree of cultural basis, in which case the similarity of effect across nationalities and time periods found by Smeed is arguably less consistent with behavioural adaptation. This might depend on exactly what “motorist adaptation” and “behavioural adaptation” entail, given that physiological parameters such as driver reaction are subject to thresholds limiting degrees of improvement, and this is an aspect that has not been well defined in the SiN literature. The close correlation of modelled safety results found by Thompson et al. (2014) with the SiN effects calculated from observational studies points to a likelihood that probabilistic SiN might dominate in the actual safety effect.

Looked But Failed to See (LBFS)

If a road user is to avoid a hazard, the ability to see it beforehand is helpful. Visibility and sight distance have been enshrined as key road safety concepts for road design practitioners and traffic engineers. For example, Chapter 3 of Austroads (2015) Guide to Road Design – Part 4B: Roundabouts is dedicated to sight distance and other visibility considerations.

However, for some time, road safety researchers and practitioners have found indications that lack of visibility (or conspicuity) does not adequately explain many occurrences or types of crashes. “Looked But Failed to See” (LBFS; also LBFTS) was coined by Staughton and Storie (1977) to describe such crashes. Rumar (1990) identifies two important causes of LBFS errors as being a perceptual limitation (illustrated by the failure to discern the relevant stimuli in lower levels of ambient illumination or where vehicles approach in the peripheral visual field of road users) and a lapse of cognitive expectation (illustrated by the failure to scan for a particular class of road user, or to look in the appropriate direction). White (2006) similarly identifies two broad categories of contributory causes for failures to detect hazards as ‘external’ environmental causes (such as poor road lighting) and visual/ psychological causes.

Langham et al. (2002) note that the majority of research regarding motorcyclists and cyclists had (at their time of writing) focused on sensory limitations, based on motorcyclist and cyclists being smaller and therefore harder to see. However, their study of drivers colliding with stationary police vehicles parked on the hard shoulder of a motorway presents a situation of drivers failing to detect what is objectively a highly conspicuous vehicle – and one that is difficult to make more conspicuous, considering that the police vehicles had high-contrast paintwork and were employing flashing roof lights. This draws into question the degree to which LBFS crashes are related to sensory conspicuity at all. Tin Tin et al.'s (2014) prospective study of New Zealand cyclists similarly questions the role of conspicuity aids (fluorescent clothing, retro-reflective clothing and lights) in reducing the incidence of motor vehicle crashes with cyclists. The authors point out that in studies involving simulated settings, test observers that are primed to expect an interaction could lead to positive correlations between conspicuity and detection, but that in real life conditions, drivers develop a visual search strategy that focuses on frequent, major dangers and filters out infrequent objects such as cyclists. This accords with a cognitive model of conspicuity focused on how humans process visual inputs to identify relevant information.

Ranney (1994) provides an overview of theoretical models emerging from cognitive psychology, in the context of the cognitive components of driving behaviour and the relationship (if any) to crash involvement. This provides an interesting and detailed consideration of theoretical models, particularly from an historic perspective. In more contemporary terms, Zhao et al. (2014) provide a short overview of the physical and psychological origins of the LBFS problem framed around higher-level cognitive functions, limitations of human visual processing, attention capture, and the focus of their research: change blindness (the failure to detect large changes to objects or scenes from one view to the next.) White (2006) discusses inattention blindness (the failure to detect a visible object when attention is focused elsewhere) and change blindness as the major mechanisms leading to the LBFS problem. Simons and Chabris (1999) note that both inattention and change blindness can occur even when the object or change is at the centre of the field of view.

There is evidence of a LBFS effect playing a role in cyclist crashes. Räsänen and Summala's (1998) analysis of 188 bicycle-car crashes found that in 37% of collisions, neither driver nor cyclist realized the danger or had time to yield. But while only 11% of drivers noticed the cyclist before impact, 68% of cyclists noticed the car before the accident and 92% of these believed the driver would give way as required by law. Herslund and Jørgensen (2002) hypothesised that in some situations, a nearby motor vehicle could draw the driver's attention to the bicycle or cause the driver to act cautiously to the benefit of the cyclist. However, such an effect has not been confirmed and for motorcycles, Pammer, Sabadas and Lentern (2018) find the opposite: that if a car poses a potential 'threat', then attention directed towards it leads to an inattention blindness to other vehicles (taxi and motorcycle, in their experiment).

In terms of roundabouts, Cumming (2012) notes that for cyclists, riding in the outer edge of roundabouts appears to increase crash risk, and cites Lund's use of a driver simulator allowing eye movements to be tracked. Lund (2008) found that drivers detect cyclists more rapidly when cyclists are located in the middle of the circulatory area rather than when cyclists are located towards the edge of a roundabout. Wilke, Lieswyn and Munro (2014) claim Lund's is the only study to demonstrate rather than conjecture or derive this behaviour.

Conflict Point Theory

Conflict Point Theory is a conceptual theory used in a narrative way to explain observed differences in crash rates at single-lane roundabouts and the four-way intersections they replace[48]. Conflict Point Theory has gained widespread acceptance despite the lack of a practical methodological application and the very specific situation to which it applies.

Conflict Point Theory explains the difference in crash risk between roundabouts and the four-way intersections they replace by theorising that the number of collisions is related to the number of conflicts between vehicles, which is related to the number of places where vehicle paths overlap – the conflict points. According to Daniels and Wets (2005), a conflict point is defined in the theory as:

> "…a location where the paths of two motor vehicles, or a vehicle and a bicycle or pedestrian queue, diverge, merge, or cross each other."

On the other hand, 'conflict' is not necessarily well defined in Conflict Point Theory. It is implicitly the same 'conflict' as per Traffic Conflicts Technique, discussed in Chapter 4. Daniels and Wets (2005) use a diagram from the U.S. Federal Highways Administration's *Roundabouts: An Informational Guide* (Robinson et al. 2000) to differentiate between merging, diverging and crossing conflicts, with an added effect under Conflict Point Theory

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[48] The theory could be generalised to three and five-way intersections, but these are typically not considered. These situations are perhaps "taken as read" as involving more or less complicated applications of Conflict Point Theory. Similarly, multi-lane roundabouts are discussed but rarely shown due to the complexity of representing the theory diagrammatically.)

being that the more severe conflicts (in terms of likely crash outcomes) are replaced by less severe conflicts – namely, right angle conflicts with low angle conflicts. (Note the diagram, reproduced as Figure 10 below, assumes right-hand drive.)

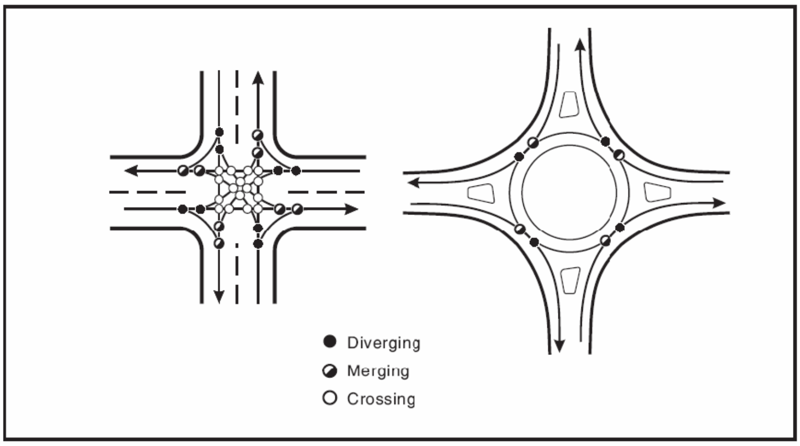

Figure 10: Conflict point diagram. Daniels and Wets (2005), sourced from Robinson et al. (2000).

The intuitive base for Conflict Point Theory is that a clear difference in the number of conflict points exists between roundabouts and comparable uncontrolled/ priority intersections. Cumming (2012) presents conflict point maps showing thirty-two conflict points for a four-way intersection compared to four ‘major’ conflict points for a single-lane, four-leg roundabout. These conflict points are described as “danger points - the physical locations where vehicles might collide”. The fact that these maps are taken from Austroads (2007) *Guide to Traffic Management Part 6: Intersections, Interchanges and Crossings* is an indication of the prevalence and acceptance of the theory in Australian traffic engineering practice, albeit that Wilke, Leiswyn and Munro (2014) refine the number of conflicts in the four-way intersection to sixteen on the basis that eight are considered to have a low probability of occurrence. In Robinson et al.’s (2000) maps, eight diverging, eight merging and sixteen crossing conflict points are replaced by four diverging and four merging conflict points, with a combination of high and low angle collision paths thus replaced by only low angle collision paths.

A limitation of Conflict Point Theory – and a reason for its exclusive application to roundabouts – is its failure to account for the other safety effects which must be in play at other locations, but where the number of conflict points is not related to crash risk. This applies at, say, merge situations. A philosophical question arises from this: if the number of conflict points is not related to crash risk in these other locations, why are they related in roundabouts? That is, why should "other safety effects" exist at non-roundabout treatments but not at roundabouts?

Daniels and Wets (2005) explicitly challenge Conflict Point Theory, arguing that under the theory, reducing conflict points by three-quarters from thirty-two to eight implies that the number of conflicts should also reduce by three-quarters – give or take a little bit for flow-on and contrary effects[49]. However, when conflicts are assessed, researchers have found that the number of conflicts might stay at more or less the same levels or even increase despite the reduction in conflict points. This invalidates the proposition that the number of conflicts is related to the number of conflict points.

In terms of the crash risk, if the number of crashes is related to the number of conflict points, then researchers should expect to see (say) a quarter of the amount of crashes previously observed. But while crash reductions are observed when roundabouts are installed, the degree of crash reduction is not uniform across geographic locations or crash severity types (property damage only, injury, casualty). That is, there is no correlation between the number of crashes and the number of conflict points for roundabouts as a class of treatment.

In terms of the proposition that roundabouts reduce risk by replacing high-angle conflict points with low-angle conflict points, Spacek's (2004) analysis of 130 Swiss roundabouts is notable for rejecting the British proposition that the flatter approach angles embodied in the tangential design basis reduce accident frequency and severity compared with the steeper angles embodied in the radial design basis. This proposition follows the idea that deflection gives better guidance to incoming vehicles and that the angles of intersection of the conflicting traffic streams are smaller (or lower). While this was confirmed with regard to single-vehicle crashes, for the more common multiple-vehicle crashes, Spacek finds that steep entry angles (in line with radial design) perform significantly better than lower angles (in line with tangential design) in respect to both frequency and severity of crashes. Spacek instead identifies that an insufficient deflection of the vehicle stream from the straight direction of travel results in failures to give way, increased pass-through speeds, and underestimates of these speeds by the other parties in conflict situations.

Turning to the application of Conflict Point Theory to cycling, Cumming (2010) uses a conflict point analysis of cyclists riding on the outer edge of roundabouts, as if in an

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49 Or, taking Wilke, Leiswyn and Munro's (2014) approach of omitting those with a low probability of occurrence, going from sixteen conflict points to eight should instead reduce the number of conflicts by half.

additional lane of traffic. This leads to 16 vehicle/cyclist conflict points compared to 4 for a single lane roundabout, explaining the higher crash risk experienced by cyclists compared to motorists and implying that if cyclists position in the same way as a motor vehicle, the cyclist crash risk should reduce. Wilke et al. (2014) then link this to the influence of cyclist tracking on crash risk and revising Cumming's conflict point analysis as per Figure 11, below.

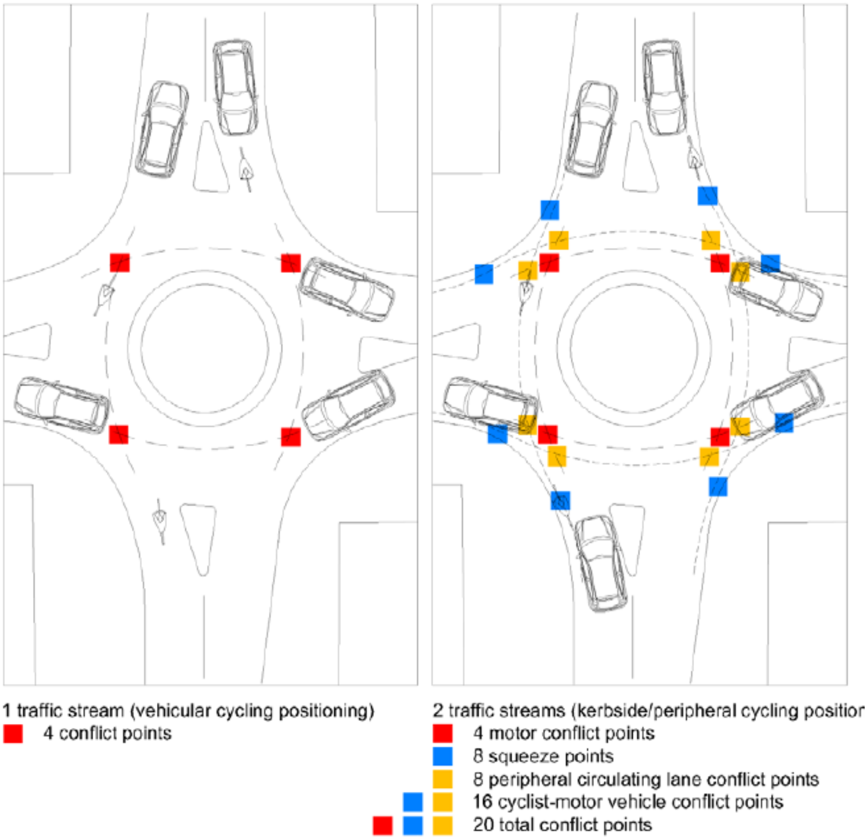

Figure 11: Roundabout conflict point analysis. Source: Wilke et al. (2014).

This does not explain why an increase in conflict points throughout the roundabout results in a crash risk heavily weighted towards a single crash type, or why replacing 32 conflict points at a cross-intersection with 16 conflict points at the equivalent roundabout should increase cyclist crash risk. Further, given that cyclists are legally required to ride to the left, a cyclist traversing the circulating lane from a central position must have moved away from the kerb somewhere on the approach and back on the departure. This implies that the 'squeeze point' conflicts on the approach and departure are not eradicated, merely relocated, and more crashes could be expected on the approach and departure. Finally, Cumming's (2010) analysis was made in the context of critiquing the Australian guidance of marking bicycle lanes within roundabouts, which is a specific circumstance. Wilke et al. (2014) found that even when bicycle lanes exist, most cyclists do not use them, though bicycle lanes could encourage a more kerb-wards tracking behaviour. In most roundabouts, cyclist do not traverse a roundabout while a car is also traversing it, so the car-car conflict points are not so much added to by cyclist-car conflict points as shifted.

Cumming (2012) acknowledges this by pointing out that number of conflict points is not the only factor leading to cyclist crashes at roundabouts, with his conflict point analysis indicating complexity and contribution to LBFS errors via inattention blindness. This point is lost in Wilke et al.'s (2014) commentary on conflict point theory and might have been better addressed by not raising conflict point theory at all.

Overall, then, there is no good evidence supporting Conflict Point Theory, either for vehicles in general or for cyclists in particular.

Indeed, returning to the philosophical question of why Conflict Point Theory should apply at roundabouts but not elsewhere, the same theory arose in Australia in the 1970s and was used to argue on theoretical grounds that T-junctions were safer than cross-intersections. Brindle (1984) challenged this on the available evidence. Andreassend (1985) summarises the intuitive error underlying this version of conflict point theory as:

> "The connection between conflict points and accidents is best seen as part of the exposure v. accidents chain at intersections. The interacting traffic flows at the various conflict points can be summed throughout a day to represent exposure for the various accident types that the conflict points depict. There may be relationships between the exposures and the frequencies of particular accident types but that does not give any connection between a simple count of conflict points and the number of accidents likely to occur."

Given the complexity of traffic flows at roundabouts, and the acknowledged effect roundabouts have on reducing traffic speeds, this proviso applies in spades to roundabouts.

A final point is that in theorising a relationship between conflict and crash, Conflict Point Theory is subject to all of the same issues regarding the definition of conflict and severity of conflict and crashes as are still outstanding in the much larger field of Traffic Conflicts Technique (TCT). In many ways, Conflict Point Theory is a (very) simplified version of TCT, and if TCT still has unresolved issues affecting its usability, Conflict Point Theory is based on a much less firm theoretical footing.

The case study site: Beulah Road/Sydenham Road roundabout

Beulah Road/Sydenham Road roundabout is located about 2km east of the Adelaide CBD and is the western-most and largest of four roundabouts lying along a 1.6km section of Beulah

Road. Beulah Road is a local collector in the City of Norwood Payneham and St Peters, running parallel to and between Magill Road, an arterial road to the north; and The Parade, an arterial road to the south. This section of Beulah Road is bounded by arterial roads, being Fullarton Road at its west and Portrush Road at its east. Beulah Road is also part of a strategic cycle route to the east of the City (the Norwood-Magill Bikeway).

When the (then) State Department of Transport, Planning and Infrastructure (DPTI) sought to improve Beulah Road for cyclists, it identified a poor safety record for cyclists at this roundabout in particular. For the ten-year period 2004-13, the site had 24 recorded crashes. 21 of these (or 87.5%) involved a cyclist, of which 13 were casualty crashes. This was one of the highest crash figures for any roundabout in South Australia over the time period. Given that cyclists only accounted for some 2-4% of total traffic[50], cyclists were significantly over-represented compared to their modal share. Furthermore, over the same time period, three roundabouts located on the same cyclist route to the east of the case study site recorded eight, fourteen and six cyclist-involved crashes respectively, of which four were casualty crashes in each location. 80% of the cyclist crashes were the ‘entering car/ circulating cyclist’ crash type. In comparison, nearby intersections on the same and nearby streets, representing T-junctions and four-way intersections with local streets and arterial roads, had no similar record of cyclist involvement in crashes. On the basis of exposure, then, these roundabouts had a much poorer safety record than other intersection types.

As the poor safety record posed by the roundabout for cyclists was a key problem and not one that could be adequately addressed using conventional methods, DPTI considered non-conventional approaches, with its design considerations documented by Zhang and Ma (2015a), (2015b). The design philosophy was based on Wilke, Lieswyn and Munro’s (2014) recommendation to reduce vehicle entry speeds to below 30km/h. On this basis, options examined included:

- Vertical geometric treatments – raised platforms, speed humps on approaches

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50 An 11-hour turning traffic count undertaken in May 2015 found that cyclists comprised 2.5% of traffic at the roundabout. Other count data from Adelaide indicates that cyclist numbers are less consistent than motor vehicles numbers. The Eco-Counter public site (http://eco-public.com/ParcPublic/?id=4586#), which provides data for Adelaide’s Frome Bikeway, indicates that cyclist volumes in May are around 15% lower than the annual average and 40% lower than the seasonal peak in March. While the latter coincides with event-based road closures in the City, these are mainly in the east and would also affect Norwood’s cycling numbers. Meanwhile, a resident objecting to DPTI’s proposals for Beulah Road as a cyclist route undertook a manual count as the basis of noting that cyclists “…only accounted for a third of traffic on Beulah Road on Saturday morning”. (Personal anecdote.)

- Reverse curves on the north-south approaches
- Perceptual countermeasures to reduce approach speeds – line-marking, central parking and landscaping.

However, Wilke, Lieswyn and Munro (2014) also recommend design that reduces cyclist tracking to the left, in order to increase cyclist visibility. For this reason, and reasons of constructability and cost, conversion of the existing tangential design base to one that accords with radial design was selected as a trial treatment for the roundabout. A comparison of before/after conditions at the roundabout is the basis of the case study.

The case study results are presented in detail in Appendix D. This contains additional background to the case study (including the description of the site, context for the conversion, before/after roundabout design details, traffic volumes, crash statistics and case study), methodology (including sampling strategy, method of data collection, issues encountered and how these were addressed) and information about the results (including data sets achieved, coding for quantitative examination and analysis of observed behaviour). The all-day data extends from 7am-5:45pm; the PM peak from 4pm-5:45pm.

Theorised safety mechanisms

The basis of the proof by contradiction approach is that if safety effects exist that have not been identified through statistical safety studies, then the pragmatic use of statistical safety studies has not optimally advanced road safety knowledge regarding radial versus tangential design.

As noted, statistical safety studies have identified speed as influencing safety at roundabouts, with lower speeds associated with greater safety. As the radial design base is known to give rise to lower traffic speeds, statistical safety studies would predict that the radial design of a roundabout would reduce crash risk compared to tangential design. Therefore, simply observing safety effects or behaviour changes from before to after conditions is not sufficient to satisfy the proof by contradiction approach. A credible causal mechanism must be identified for such effects apart from vehicular speed for the proof by contradiction case to be made. As a starting point for identifying possible mechanisms, the qualitative literature review identifies three safety effects theorised to apply at roundabouts in addition to traffic speed effects, but whose impact has neither been confirmed or contradicted by statistical studies. These are:

- Safety in Numbers (SiN)
- Looked But Failed to See (LBFS)
- Conflict Point Theory.

These effects are considered in this section, using relevant data from the case study. This data is subject to a number of provisos, which are discussed in the full presentation of the case study, supplied as Appendix D. Some other observed effects are also noted in this section.

Safety in Numbers (SiN) and probabilistic risk

A traditional Safety in Numbers (SiN) effect cannot be confirmed with an observational before/after study of this type. Specifically, such an effect would be confirmed through a mass data approach by considering a measured safety indicator (usually crash statistics) and cyclist numbers, and seeing how these vary in the after case compared to the before. For the case study site, there is no reliable proxy for crash statistics to quantify a safety measure and given a ten-year average of about two cyclist crashes a year in the before situation, an observation period of less than several years would be insufficient to accumulate enough data for comparisons to be made. This reflects the problem of mass data approaches for cycling.

The causal chain creating the SiN effect is generally considered to be based in cognitive psychology – that is, drivers becoming more aware of cyclists and the drivers' behaviour changing to reduce risk. This is to some extent supported by research in the field of LBFS errors. For example, Tin Tin et al. (2014) cite an eye tracking experiment conducted in the UK where drivers failed to see 22% of cyclists on the road, compared to 15% of motorcyclists and 4% of pedestrians. The cognitive contribution to SiN cannot be tested using the current case study due to the absence of eye tracking equipment, and because yielding effects that might result cannot be differentiated from the impact of a reduced speed environment in the after versus before situation.

However, Thompson et al. (2014) propose a probabilistic causal chain for SiN based on a greater density of cyclists reducing the exposure of any one cyclist to a vehicle, hence reducing the average crash risk. A thought experiment presented earlier in this chapter, in the literature review for Safety in Numbers, explains this probabilistic theory using the situation of a cyclist who closely follows another cyclist through a roundabout facing less risk from an entering car failing to yield. This reflects the known dominance of the circulating-cyclist-entering-car crash type at roundabouts lending itself to theorising how the probabilistic causal chain functions at a roundabout. This also describes the pragmatic case study conditions.

This probabilistic form of SiN is examined in this section, by consideration of:

- exposure
- close entering of the roundabout by cyclists
- behaviour on the approach/entry and its influence on close entering behaviour
- comparative speeds and their influence on close entering behaviour
- cyclists' close following of cars as an alternative causal chain.

While the case study did not confirm a probabilistic SiN effect functioning at the roundabout, it did find indications that this might exist, and that as the mechanisms underlying such a SiN effect do exist. Given the existence of these mechanisms, a probabilistic SiN effect would possibly come into play with greater cyclist numbers or density.

It is notable that under the probabilistic theory and for the example situation of a roundabout, the first cyclist's risk is unchanged – any safety benefit accrues only to the second cyclist. This is quite different to the expectation under a cognitive theory of SiN and presents a point to be mulled over if it were ever proposed to rely upon SiN effects to reduce overall crash risk. Caution is advised regarding such an approach.

Exposure

Thompson et al. (2014) propose a probabilistic causal chain for SiN based on a greater density of cyclists reducing the exposure of any one cyclist to a vehicle, hence reducing the average crash risk. A first test of this proposition is to compare the number of cyclists versus vehicles, as an indicator of density; and the number of bicycle encounters with vehicles, as an indicator of exposure. For roundabouts, the greatest risk to cyclists is from vehicles on the adjoining (yielding) leg, which accounts for the majority of encounters. Therefore, this analysis considers west-entering bicycles and north-entering cars.

As a methodological point, encounters were captured in the case study by recording the entering vehicle position when a bicycle crossed its yield line. For this analysis, an encounter was counted if an entering car was anywhere between its yield line and about 10m back from the yield line. The choice of 10m corresponds to Silvano, Ma and Koutsopoulos' (2014) finding that the positions of the interacting subjects are important predictors in a driver's decision to yield, with the decision point being located 10 metres in advance of the conflict zone (defined as per Traffic Conflicts Technique as a common crossing area where coincident trajectories would result in a collision). It also accords with Turner et al.'s (2009) linking of sight distance to increased speed and hence increased crash risk, with the greatest correlation being 10m back from the yield line.

Results for the before situation are presented in Table 1, presented left to right by the density. (The date form 15&18 May indicates issues with data collection that were addressed by combining observations from two days to form a usable data set. This also occurred for 6&7 May, however this analysis is only examining west-entering bicycles, for which data is from 7 May only.) As the PM peak (4pm-5:45pm) numbers will tend to influence daily (7am-5:45pm) results, the daily results presented in this Table exclude PM peak numbers.

This table includes "encounter rate" as being the proportion of bicycles that encounter a car. In the majority of situations, a cyclist passes through the roundabout without a car being present.

Before PM peak (W, N)	18 May	15 May	7 May	12 May
Cyclist count (W)	73	68	68	47
Car count* (N)	432	469	495	423
Density (cyclists per 100 cars)	16.7	14.5	13.7	11.1
Encounters	21	25	23	15
Encounter rate	29%	37%	34%	32%
Before daily (W, N) excluding PM peak	**15 May**	**7 May**	**12 May**	
Cyclist count (W)	61	46	34	
Car count (N)	2,098*	2,270	2,205*	
Density (cyclists per 100 cars)	2.9	2.0	1.5	
Encounters	24	31	32	
Encounter rate	39%	67%	94%	

*Based on a 20% sample of daily traffic (6 min per half hour) and 33% sample of PM peak traffic (5 min per quarter hour).

Table 1: Cyclist density versus encounters, before situation; west leg cyclists and north leg cars.

Cyclist numbers are small, particularly for peak period encounters. The large difference in cyclist densities between daily and PM peak periods reflects tidal flow in western leg cyclists, most of whom are commuter cyclists whose main travel pattern is eastbound (i.e. away from the CBD) in the PM peak. The tidal flow in cyclists is much higher than the tidal flow in motor vehicles.

An initial observation is that encounter rates are high, with a lack of proportionality in encounter rate versus density between the PM peak and daily periods indicating that different effects are occurring in the two periods. Rather than being proportional to exposure as might be expected, the daily figures indicate a very strong inverse association between exposure and encounters. This relationship is broadly in line with a SiN effect.

For the PM peak, the 18 May figures do not correspond to this pattern. In fact, 'close follow' and 'close entering' results discussed later in this section indicate that quite different conditions occurred on 18 May compared to the other PM peak periods, for unknown reasons. 18 May was a Monday rather than mid-week. Excluding the data from this day, a slight inverse relationship between density and encounter rates is seen in the PM peak periods as for the daily results. Another interpretation is that the pattern is not strong during the PM peak and the 18 May figures are within a range of generally similar results in the period, but atypical of a trend due to small numbers effects. Given the small data set, it may also be true that any patterns are merely coincidental.

The after PM peak results are shown in Table 2.

Cyclist densities are generally higher in the after PM peak situation than the before[51], but the single daily result seems to be in line with the before daily results, in terms of both density and encounter rates.

After PM peak (W, N)	19 Oct	22 Oct	17 Sept
Cyclist count (W)	82	90	76
Car count* (N)	357	447	510
Density (cyclists per 100 cars)	23.0	20.1	14.9
Encounters	40	54	48
Encounter rate	49%	60%	63%
After daily (W, N) excluding PM peak	**17 Sept**		
Cyclist count	52		
Car count*	2,300		
Density (cyclists per 100 cars)	2.3		
Encounters	21		
Encounter rate	40%		

*Based on a 20% sample of daily traffic (6 min per half hour) and 33% sample of PM peak traffic (5 min per quarter hour).

Table 2: Cyclist density versus encounters, after situation; west leg cyclists and north leg cars.

Repetition of an inverse association between density and encounter rate in the after PM period lends some weight to the possibility that a SiN effect is occurring at the roundabout. As with the before results, the lack of proportionality between density and encounter rate implies that

51 Noting that cyclist numbers and hence densities tend to reflect seasonal/weather issues rather than the roundabout changes encouraging additional cyclists.

any relationship is not rigid or direct. Since the relationship is seen in days within the same month in both the before and after conditions, such a SiN effect would be extremely unlikely to be a result of driver behavioural adaptation. This supports the proposition of a probabilistic SiN effect. Given that no empirical evidence of its existence has been previously recorded, finding a probabilistic SiN effect is an exciting possibility. However, given the few data sets and small numbers involved, further study is required to substantiate the possibility and eliminate the potential that the apparent correlation is merely coincidence.

In either case, a SiN effect could not be considered to be a major driver of safety related to radial versus tangential geometry at the roundabout, as the overall level of encounters in the after situation is much higher than the before situation (about 70% higher in the PM peak). Any safety benefit in the after situation must therefore result from a change in the nature of interactions resulting from geometric changes – assuming that encounters are a reasonable proxy for interactions. And this proviso raises a question about the causal chain of an effect.

Thompson et al.'s (2014) proposition is based on exposure of cyclists to car hazards, with a leading cyclist's exposure to a car enabling a close by cyclist to reduce their exposure – for example, for cyclists in a peloton, the first is physically exposed to an approaching car, the others less so[52]. However, the methodology for recording encounters in this case study is that if a cyclist enters the roundabout and a car is located on the approach, then an encounter is recorded i.e. the presence of a lead cyclist does not reduce the number of encounters recorded. Why, then, should increasing density result in reduced encounter rates? One possibility is that cyclist density in relation to northern leg cars is also related to density within the western leg traffic stream – which is likely, given that cyclist numbers are more tidal than vehicle numbers – and the presence of cyclists in that stream introduces non-homogeneity. An encounter with a lead cyclist then enables northern approach cars to 'clear' before a subsequent cyclist arrives, reducing encounter rates. This does not accord to the SiN effect theorised in the thought experiment based on Thompson et al. (2014) but could well describe a different and equally valid probabilistic SiN effect for this roundabout.

As a final point, it is noted that before (tangential) results do not correlate well with Turner, Roozenburg and Smith's (2009) roundabout crash prediction model, which is also based on tangential design. Their work would predict the following results, assuming a 35km/h

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[52] Noting that no pelotons were actually observed.

entering vehicle speed, and noting that the speed on 17 September is expected to be lower and hence the actual cyclist crashes/annum to be lower than calculated.

	May average*	17 Sept
Entering flow, N approach	2,645	2,810
Perpendicular cyclist flow, W approach	108	128
Entering vehicle speed**	35km/h	35km/h
Cyclist crashes/annum	0.039	0.043

*Average of 7, 12, and 15/18 May.

**85th percentile speed in the before situation. Source: Zhang and Ma (2015b).

Table 3: Expected cyclist crash rate, based on Turner et al. (2009).

Given a long-term crash rate at the case study site of about two a year, the crash prediction model vastly under-estimates crash risk. The poor correlation is not surprising. Turner et al.'s model is based on reported crash rates of between about 0.1 and 1 every five years (with an outlier of two). This demonstrates a limitation of safety performance functions based on mass statistical data in application to a particular site.

Close entering

As noted, the preceding analysis does not correlate well with the causal chain for the probabilistic SiN effect proposed by Thompson et al. (2014). However, the presence of the thought experiment mechanism can be tested by observing to what degree cyclists enter the roundabout closely behind another cyclist (and hence follow that cyclist closely), reducing their exposure to car traffic; and whether this varies with cyclist density.

Table 4 presents observations of close entering behaviour from the case study. Here, 'close entering' is defined as the time stamp recorded for an entering cyclist being within 2 seconds of the preceding cyclist. Time stamps were assigned to traffic encounters on a non-exclusive basis and multiple occurrences of a single time stamp could either indicate separate encounters of a subject bicycle to multiple vehicles or separate subject bicycles entering the roundabout simultaneously (side by side). Therefore, each occurrence of a possible close entering was validated by a review of the video recording. Cyclist density could be expressed as either a proportion of traffic on the leg, or (as previously) in terms of interactions with opposing (north and west entering) cars. Both are shown in Table 4.

	Date	Cyclist count	Density (bikes per 100 cars)		Close entering events	Rate of reduced exposures
			Same leg	Opposing leg		
Daily excl PM peak (before)	6&7 May	65	3.0	2.1	1	1.5%
	12 May	44	2.5	1.5	3	6.8%
	15 May	81	4.0	3.3	2	2.5%
Daily excl PM peak (after)	17 Sept	69	5.2	3.7	5	7.2%
PM peak (before)	6&7 May	82	8.9	9.7	3	3.7%
	12 May	53	7.2	7.1	2	3.8%
	15 May	83	10.1	10.3	3	3.6%
	18 May	77	10.2	10.1	1	1.3%
PM peak (after)	17 Sept	84	10.4	9.7	5	6.0%
	19 Oct	88	12.1	12.5	5	5.7%
	22 Oct	100	12.1	11.5	5	5.0%

Table 4: Close entering and density.

The numbers of close entering events are very low, pointing to cyclist density as having little real effect. This should not be surprising, given the low modal share of cyclists. The maximum density of 12.5 cyclists per 100 cars is more than eight times the minimum of 1.5, but an average of eight cars still separate each cyclist and opportunities for close entering would be few and far between.

Nonetheless, a small proportion of cyclists do enter the roundabout closely enough behind another cyclist to reduce their exposure. Higher rates of these events are possibly indicated in after compared to before conditions, as with cyclist density. This (very slightly) supports the idea of the causal chain existing, though the small change in reduced exposures would be too marginal for it to be detectable through even a long-term analysis of crash statistics.

There is evidence that the threshold used to define close entering events does not do justice to the effect. As part of the case study, a note of yield behaviour was made indicating the prior, current and next yield behaviour of object vehicles. When cross-referenced with the close following data, four records were found where an object vehicle yielded to a cyclist and then yielded to a subsequent cyclist, but the distance between cyclists exceeded the two second threshold. (Two occurred on 12 May, one on 7 May and one on 17 September.) As the methodology to find these events was not necessarily exhaustive, those identified have not been added to the results in Table 4. If they were added, the proposition that the rate of reduced exposures is higher in the after compared to the before situation becomes a harder proposition to support, though this was marginal in any case. However, this would point to the single close entering event recorded for the PM peak of 18 May as being slightly less representative of PM peak conditions compared to the other before PM peak results. (The before daily results for 6&7 May also under-represents close entering events, but its density is mid-range while the 18 May results are less obviously in line with other PM peak results.)

Further, studies of this possible exposure effect were not identified in the literature and hence no references were available to inform the methodology, notably in regard to platooning. In the case study situation, Sydenham Road intersects with Magill Road some 330m north of the roundabout at a set of traffic signals. As a result, traffic on the northern approach to the roundabout often platoons. If a vehicle at the head of the platoon yields, following vehicles must slow or stop and are more likely to yield to cyclists encountered at the roundabout. Hence a first cyclist causing a yield can increase the likelihood of a car yielding to a subsequent cyclist even when this cyclist is quite distant in time. Platooning could conceivably increase the risk benefit subsequent cyclists accrue from increased density. However, these more distant yields are difficult to identify, given possible intermediate effects.

From the perspective of causality, the results hint at changed geometric conditions facilitating close entering events. Speed has a likely role, with speed differentials rather than speed itself potentially also having an impact. It is also possible that radial design affects approach behaviour in a facilitative way. The latter two effects are discussed in the following sections. It is reiterated that indication of any effect is very tenuous.

Approach/ entry behaviour

Approach/entry behaviour indicates a greater comfort level for cyclists in the after situation compared to the before. In the context of facilitating close entering events, this could conceivable assist cyclists to focus on other cyclists rather than the behaviour of vehicles on the approach/ entry to the roundabout. In any other respect it is not relevant to the SiN effect and is discussed as an additional observed effect near the end of this chapter.

Close follows

If a cyclist entering close behind another cyclist potentially reduces their exposure, a cyclist closely following a car through the roundabout could also reduce their exposure.

Table 5 presents ‘close follow’ results, where a subject bicycle enters closely behind a preceding car in what would be seen as very close or tail-gating behaviour if exhibited by a car to a car. Apart from a cyclist following a car closely into the roundabout, this occurs in the more common pattern of a cyclist entering very closely behind a car from the cyclist's right – either circulating, or a through vehicle from the previous leg.

Before daily excl PM peak	15 May	6&7 May	12 May	
Close follows	1	3	4	
Period records	84	65	44	
Density (to W vehicles)	2.9	2.0	1.5	
Rate	1.2%	4.6%	9.1%	
After daily excl PM peak	**17 Sept**			
Close follows	6			
Period records	69			
Density (to W vehicles)	2.3			
Close entering rate	8.7%			
Before PM peak	**18 May**	**6&7 May**	**15 May**	**12 May**
Close follows	7	15	18	13
Period records	77	82	83	53
Density (to W vehicles)	16.7	13.7	14.5	11.1
Close entering rate	9.1%	18.3%	21.7%	24.5%
After PM peak	**17 Sept**	**19 Oct**	**22 Oct**	
Close follows	17	19	26	
Period records	84	88	100	
Density (to W vehicles)	14.9	23.0	20.1	
Close entering rate	20.2%	21.6%	26.0%	

Table 5: Close follow events, before and after situations.

Daily results are quite different to PM period results – and something about 18 May seems to be creating quite different conditions in the PM peak. Otherwise, there is no obvious basis on which to suggest that geometric differences have produced any safety effect (assuming that the behaviour has a safety benefit or even disbenefit), nor that there is any correlation to density – measured in terms of west entering vehicles – that might point to a SiN effect.

It is possible that other effects related to geometry obscure any close entering SiN effect. The discussion of approach/entry behaviour later in this chapter notes that 'dual entry' situations that occurred in the before case were virtually eliminated in the after case and that close follows were evident in dual entry situations.

The high rate of close follow events (a fifth in the PM peak, when high traffic volumes facilitate the behaviour) illustrates that this behaviour is considered safe by cyclists, albeit that the discussion on approach/entry behaviour also observes that cyclist have poor understanding about actual crash risks. Observations point to close follow behaviour mainly reflecting the vehicle performance of a bicycle, in terms of dynamic stability and offsetting their lower acceleration rate by getting a 'head start' on cars – giving at best an indirect link to perceived safety issues. What was obvious from the video was the degree to which this behaviour exposed cyclists to risk, when sightlines to entering vehicles were affected (or impeded) by the vehicle the cyclist is following. This is explored at the end of the next section, as part of the LBFS error.

Conclusion

This examination of the Safety in Numbers (SiN) effect has found slight but intriguing indications of SiN operating on a probabilistic rather than cognitive-adaptive basis at the case study site. However, the degree to which this effect changed from before to after conditions is slight and, given the results, is likely to be such a minor effect that its contribution to safety could not be perceived through a statistical crash safety analysis. As such, it is not a driver of safety effects at radial compared to tangential roundabouts.

This observation could indicate that SiN is less effective at roundabouts than other locations on the road network in general, which is fairly likely as the over-representation of crashes at roundabouts indicates that the safety effects in operation at roundabouts are quite distinct to other locations.

In terms of a causal mechanism not linked to speed, SiN does not account for noticeable safety differences between radial and tangential design and hence does not satisfy the proof by contradiction requirements.

Looked But Failed to See

The ‘Looked But Failed to See’ (LBFS) problem is discussed earlier in this chapter, in the literature review for the pragmatic case study. While researchers such as Herslund and Jørgensen (2003), Franklin (2007), Cumming (2012) and Wilke et al. (2014) attribute this effect to bicycles being located outside the field of view, or in drivers’ peripheral vision, there has been little examination of the perceptual rather than cognitive limitation this implies. This opens the possibility that a previously unidentified perceptual effect could be in operation in addition to, and possible exacerbating, a cognitive effect; and that such an effect contributes to the safety performance of radial compared to tangential roundabout design for cyclists.

The visual perception system

To examine an effect based on a visual limitation, some basic theory regarding visual perception first needs to be presented. This theory is well established, with Strasburger, Rentschler and Jüttner's (2011) recap of peripheral vision and pattern recognition research starting in 1840. The following discussion of the visual perception system is drawn from this literature, but also Larson and Loschky (2009), Lewis, Garcia and Zhaoping (2003) and Zhaoping (2014).

There are two types of retinal photoreceptors: rods and cones. The distribution of cones and rods in the human eye was first described by Osterberg (1935). A simplified representation, for a single eye, is shown in Figure 12.

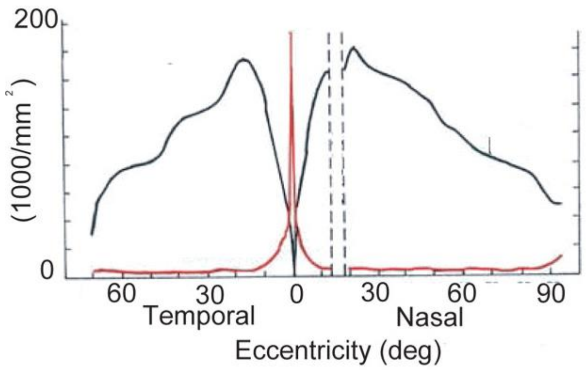


Figure 12: Distribution of cones (red line) and rods (black line) on the human retina. Nasal = nosewards, temporal = templewards, eccentricity = angle away from the centre of vision in the horizontal plane. The dashed line represents the blind spot caused by the optic nerve. Source: Lewis, Garcia and Zhaoping (2003).

Cones (red line) are most densely located in the centre of vision (fovea). They are responsible for colour vision and work best in intense light. Maximum visual acuity is concentrated in a small zone around peak cone density, known as the macular. Rods (black line) are concentrated outside the fovea, in the periphery of the retina, with a peak density at 18° of eccentricity. They do not detect colour but are sensitive to light and motion.

The human field of view produced by binocular vision is presented by Figure 13, which shows the main parts of the field of view in a 'top down' version (left) and as a 'side-to-side' range or visual space (right).

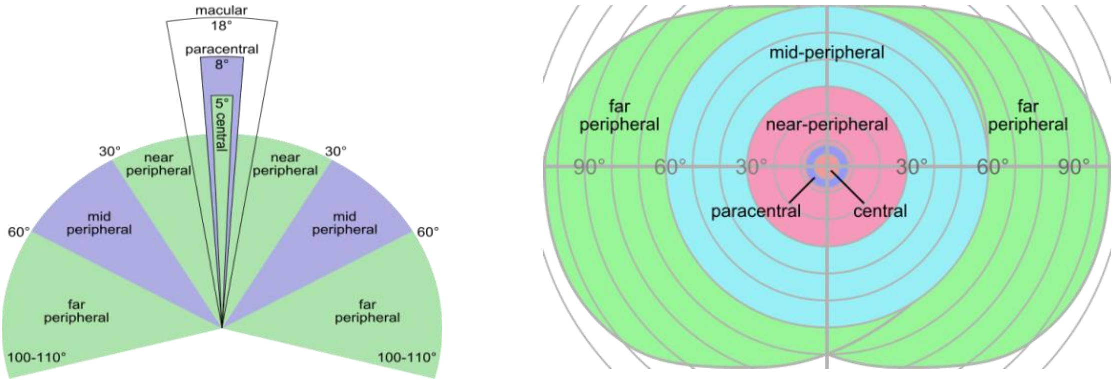
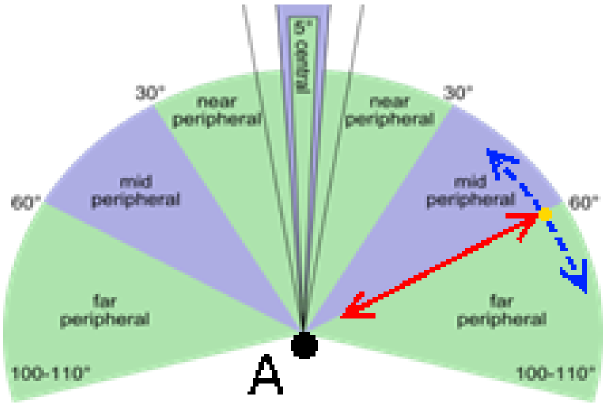


Figure 13: Acuity zones in the human field of view. Source: Wikipedia. Left, image by Zyxwv99, own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=37052186; right: image by Zyxwv99, own work CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=37052106.

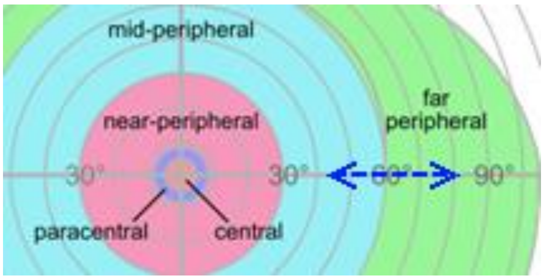
The macular coincides with peak rod density, with peripheral vision commencing outside these limits. Hence peripheral vision is weak at distinguishing detail, colour and shape; relatively good at detecting motion; and better than central (foveal) vision at detecting faint light sources at night. Visual acuity steadily declines from the centre up to 30°, at which point it declines more steeply. 30° is also taken as the dividing line between adequate and poor colour perception and roughly corresponds to the outer edge of good night vision.

In terms of the motion detection of peripheral vision, a speed threshold applies above which motion is detected. This can be further explained with the aid of Figure 14 and the previous field of view diagrams. Basically, any object's motion can be expressed as the sum of three component dimensions but because the observer is essentially standing at the centre of a flattened sphere of sight, these are not experienced as linear motions following a rectangular (Cartesian) coordinate system – the familiar x, y and z. Instead, they are experienced as lateral (i.e. horizontal around the viewer's axis), vertical (up and down) and radial (near versus far) displacements, which each give an effect of motion in isolation or in combination.

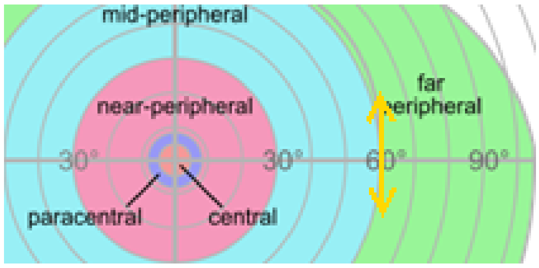


Observer at point A, three motions of an object at 60° from the centre of vision:

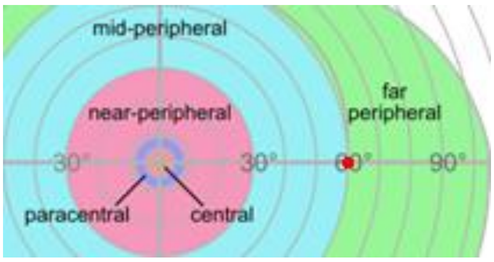
lateral (blue dashed); vertical (yellow dot); and radial (red solid)



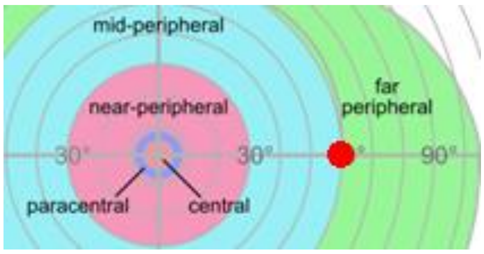
a) Lateral motion across the field of view



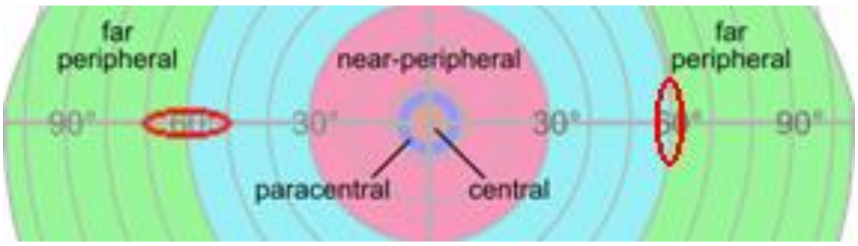
b) Vertical motion



c) Radial motion: object further away



d) Radial motion: object closer



e) Two objects of the same size, contrasting a horizontal aspect ratio (left) to a vertical aspect ratio (right), both centred at the 60° vision angle

Figure 14: Components of motion experienced by an observer at point A.

For most day-to-day activities, lateral movement across the field of view is the major movement indicating motion. Strasburger, Rentschler and Jüttner (2011) cite Basler (1906 and 1908) as being the first to observe that visual acuity is greater in the horizontal compared to other angles. Vertical motion has typically been less relevant to day-to-day human activities, hence our flattened sphere of vision and acuity reduces above and below the horizontal. An object moving radially towards or away from an observer is essentially stationary from the perspective of the observer, with motion indicated by the change in size of the object, as shown in c) and d). The shape of an object also has an impact, as illustrated in e). An object with a horizontal aspect ratio occupies more of the field of view than one with a vertical aspect ratio.

The amount of motion required for an object to be visible has been extensively studied, including aspects such as the target size and duration of exposure required for motion to be detected. Monaco, Kalb and Johnson's (2007) human research for the U.S. Army examined the degree of motion required for an object to be detected in peripheral vision. Figure 15 presents the raw experimental results for Monaco et al.'s two subjects. The subjects' respective responses were different to each other but consistent over different trials.

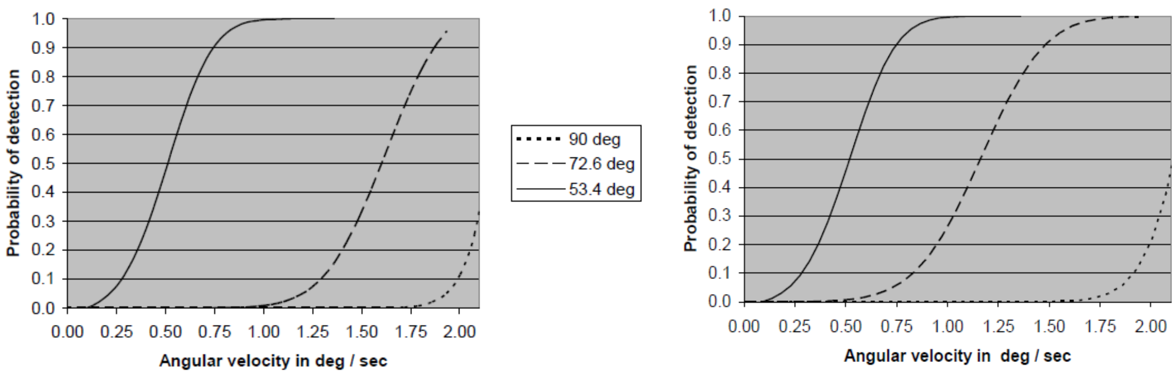


Figure 15: Motion threshold (measured in angular velocity, degrees/second) by probability of detection: results for two subjects and three vision angles. Source: Monaco, Kalb and Johnson (2007).

Because this movement occurs in an arc relative to a central observer, it is expressed as an angular velocity in degrees per second. Monaco et al. report these motion detection thresholds as being similar to those found in other studies using different techniques.

Geometric analysis of peripheral motion detection

Turner et al. (2009) link good sight distance to increased speed and hence increased crash risk, with the greatest correlation being at 10m before the yield line[53]. Turner et al.'s (2009) results are interesting in light of the work of Silvano, Ma and Koutsopoulos (2014). Their

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53 This is based on assessing sight distance at 0m, 10m and 40m from the yield line, and determining correlation coefficients for these points. Other and intermediate points could have higher correlation with increased crash risk but were not assessed.

probabilistic model of drivers yielding to cyclists found that the positions of the interacting subjects are important predictors in a driver's decision to yield, with the decision point being located 10m before the conflict zone[54].

Overlaying a 30° near-peripheral field of view on a car 10m back from the yield line for the case study's before geometry gives Figure 16.

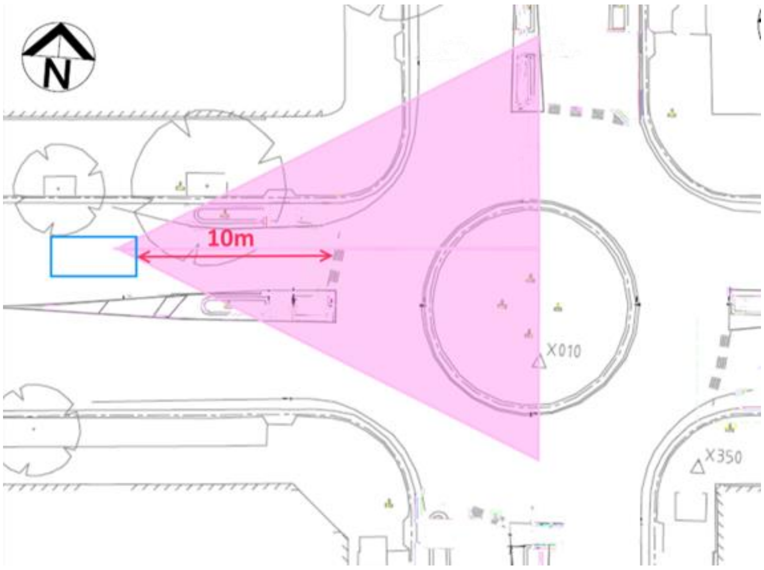

Figure 16: Near-peripheral field of view 10m from the yield line, before situation.

The after situation is slightly more complicated. A car approaching along the before trajectory would collide with the kerb protuberance, hence the after trajectory for a car approaching on the western leg must be slightly further south. In the before case, the yield line is about half a metre closer to the central island than in the after case, so the near peripheral field of view in the after case would also apply from a location about half a metre further away from the roundabout. The before and after situations are compared in Figure 17 by overlaying the car and field of view from Figure 16 onto the after geometry.

54 The conflict zone was defined as per Traffic Conflicts Technique, as a common crossing area where unchanged trajectories would result in a collision.

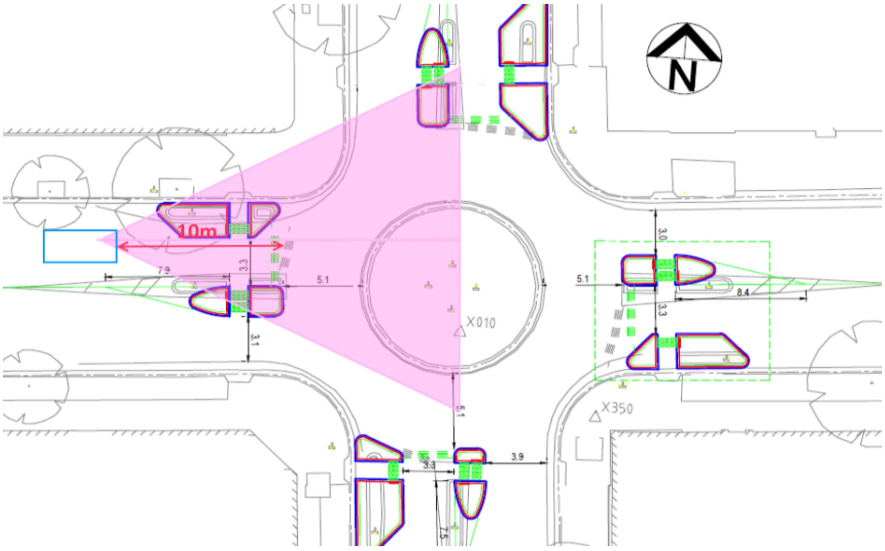

Figure 17: Before near-peripheral field of view overlaid on after geometry.

What is evident from both figures is that a straight-ahead gaze is not realistic. Drivers approaching a roundabout would tend to scan for traffic by moving their heads to use their central field of view. A more realistic situation for a driver approaching the roundabout and a subject bicycle entering the roundabout therefore needs to involve visual scanning strategies.

An indicative situation of an entering car located a car length from its yield line and a bicycle crossing its own yield line and entering the roundabout is shown in Figure 18, for before and after situations.

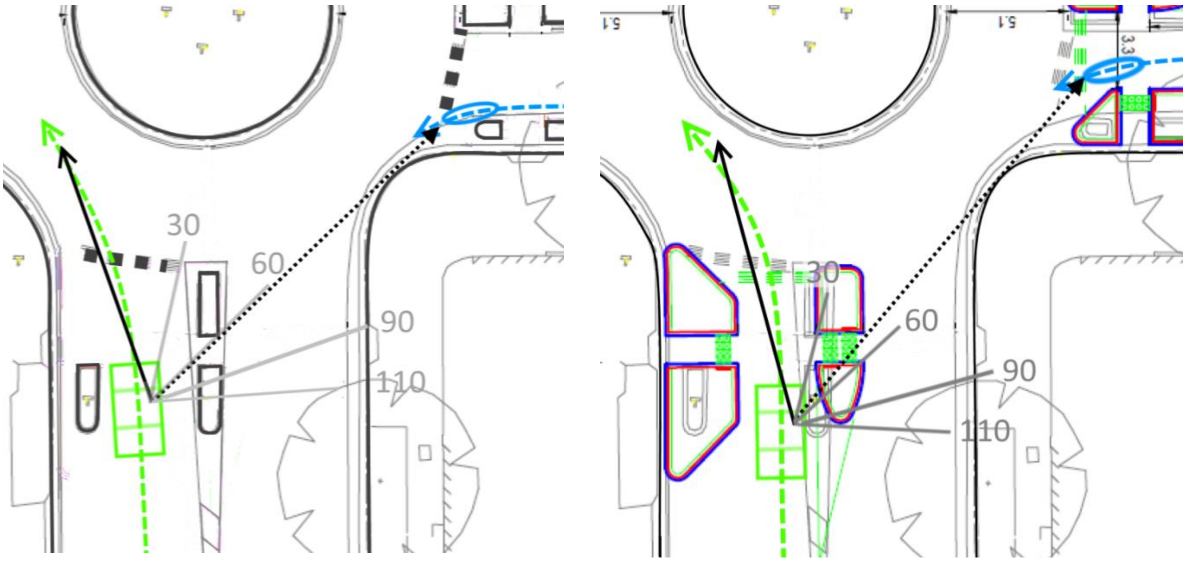

Figure 18: Cyclist location relative to driver's gaze into the roundabout. Left: before; right: after.

The conceptual visual search strategy is that:

- When the driver is approaching the roundabout but further away than shown, the driver scans for traffic to the right (i.e. on or approaching the roundabout) and makes an assessment about whether or not to slow to a stop and yield.
- Assuming the driver does not see opposing traffic at a further distance, the driver continues, modifying speed and trajectory to safely negotiate the roundabout. To do this, they must look in their direction of travel i.e. away from the opposing leg of the roundabout. At this point, any traffic on the opposing leg will be increasingly located away from the central vision and into the driver's mid and far peripheral vision areas.

Hence for a bicycle entering the roundabout while in a driver's peripheral vision, poor vision might contribute to a driver overlooking the bicycle, increasing collision risk. This potential would be greatest when:

- There is no other motor vehicle that could draw the driver's attention to the bicycle or cause the driver to act cautiously to the benefit of the cyclist (as hypothesised by Herslund and Jørgensen, 2002) – but noting that the evidence would suggest that another motor vehicle would instead attract the driver's attention away from the bicycle.
- The entering car is slightly back from the yield line – the bicycle could enter and be in front of the car before the driver detects it, and a collision occur before either party perceives the danger, much less reacts. (If the car were instead at the yield line when the cyclist enters the roundabout, the car would intrude into the roundabout before the cyclist reached it and the cyclist would take evasive action.)

What degree of effect might radial versus tangential design create regarding visual perception and, in particular, positioning in the peripheral field of vision? Figure 18 is based on DPTI's geometric plans for the before and after designs and is hence drawn accurately and to scale. A geometric analysis can be undertaken in the vehicles are also shown at scale and along likely trajectories, with the field of view set at the forward direction for the driver location – which is the basis of this diagram.

In the before case, the bicycle is at roughly 60° from the driver's direction of gaze. This puts the cyclist at the boundary between the driver's mid and far peripheral vision, and at a distance of about 16.5m from the driver's location. In the after case, the bicycle is at about 55° to the driver's gaze, in the driver's mid peripheral vision and around 18m from the driver's location.

Using Monaco et al.'s (2007) results and assuming linear interpolation/ extrapolation is possible, to reach a 95% probability of detection[55], the bicycle would have to have an angular velocity of around 1.1°/s in the before case. In the after case, the angular velocity of the bicycle would have to be about 0.9°/s. These values can be converted to an assessment of required bicycle velocity by considering travel over one second, as per Figure 19.

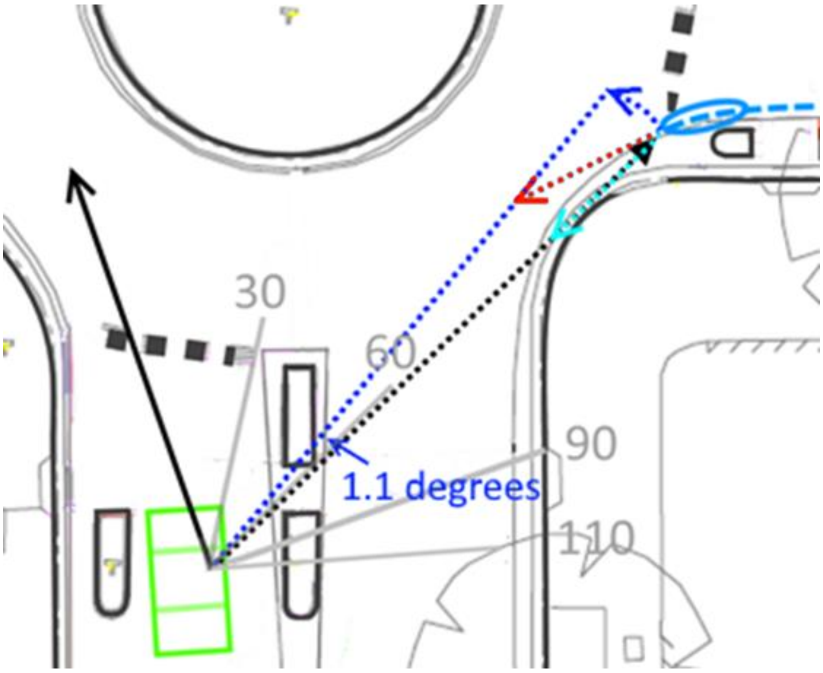

Figure 19: Motion requirement for detection, before case.

Relative to the driver, the onward motion of the bicycle (red dotted arrow) is the sum of a radial motion along the 60° line (light blue arrow) and an angular component of motion (dark blue arrow). We have stated that the red arrow needs to be equivalent to 1.1° over one second for adequate motion detection, excluding any effect of the bicycle's apparent size increasing. The dark blue dotted arrow can be measured at 0.32m. Hence a cyclist would have to travel 0.32m in an angular direction in one second to have a good probability of detection. In the after case, the comparable distance is 0.28m – a very small difference.

However, this represents only the angular component of the cyclist's motion. The same amount of angular motion but different amounts of radial motion can give rise to (or result from) very different travel speeds and trajectories, as shown indicatively in Figure 20.

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[55] 95% is used as Monaco et al.'s graphs become asymptotic at 100% probability.

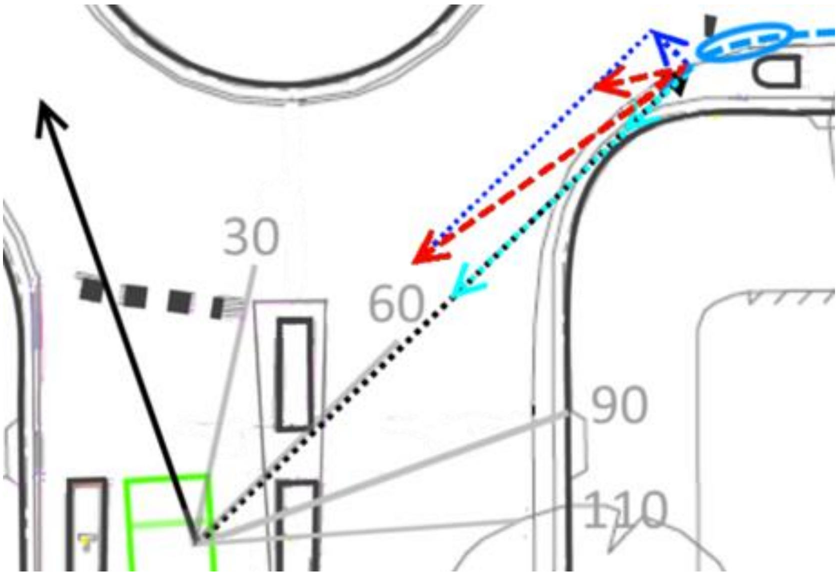

Figure 20: Two cyclist travel paths (red dashed arrows; length indicates cyclist speed) associated with different amounts of radial motion (aqua arrows) for the same lateral motion (dark blue arrow).

Similarly, constant radial motion but different amounts of angular motion gives Figure 21.

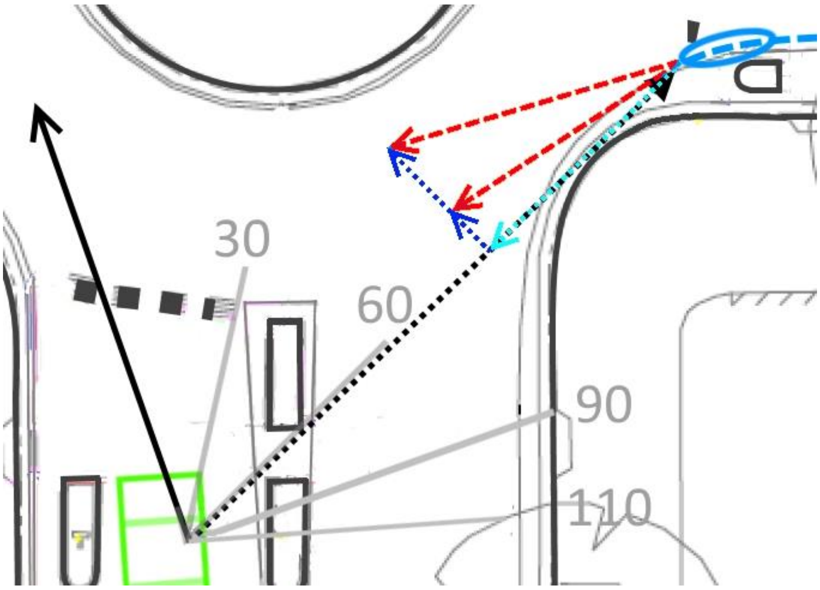

Figure 21: Two cyclist travel paths (red dashed arrows; length indicates cyclist speed) associated with different amounts of lateral motion (dark blue arrows) for the same radial motion (aqua arrow).

From these figures:

- As either radial or lateral motion increases or decreases, so does overall cyclist speed, and in a proportional (though not linear) way.
- Cyclist tracking gives rise to different proportions of lateral and radial motion, and this relationship is not proportional: the further edge-wards a cyclist tracks, the more of their total speed consists of radial rather than angular motion.

Hence for a given cyclist speed, the closer to the central island a cyclist tracks, the more of their speed consists of lateral motion and the higher the likelihood that the minimum angular velocity required for a driver to physically notice the cyclist is achieved; while the closer a cyclist tracks to the edge, the more of their speed consists of radial motion, and the less likely it is that a driver would notice the cyclist.

Whether a cyclist must achieve 0.32m of lateral motion in one second in the before case or 0.28m in the after case could thus be less relevant than the difference in cyclist tracking behaviour in the two cases. To better visualise the potential implications, two extremes of tracking behaviour are shown indicatively for the before case in Figure 22.

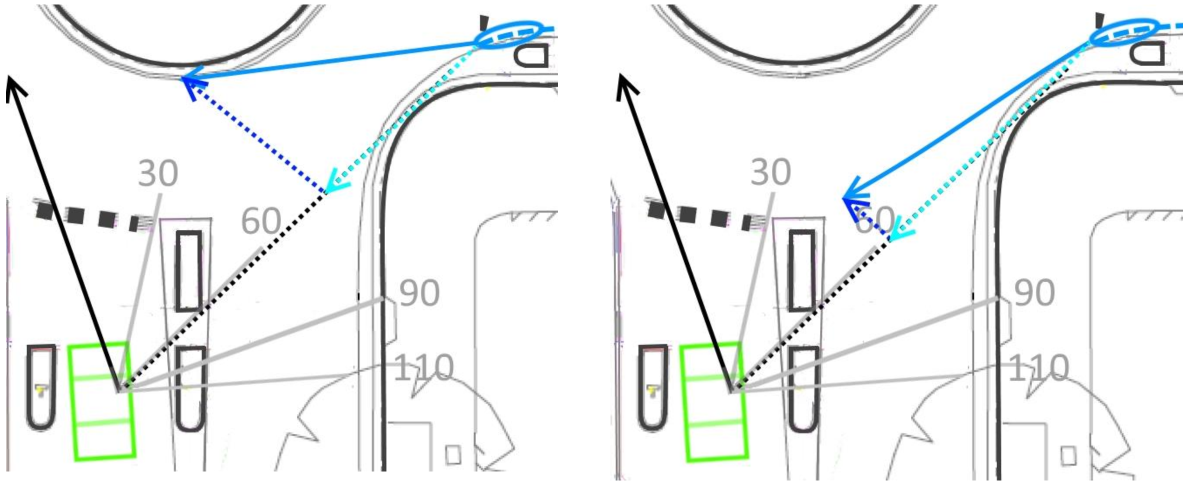

Figure 22: Two simplified tracking behaviours showing component radial and angular components of motion.

When the cyclist tracks close to the central island, the radial motion is about 1.25 times larger than the lateral motion. 0.32m of angular motion per second thus translates to about 1.8km/h of total cyclist speed. For edge-wards tracking, the radial motion could be 4.5 times as great as the lateral motion, with 0.32m of angular motion per second translating to about 5.3km/h – significantly higher, but still an easily achievable cycling speed, especially as the two situations represent the extreme cases. However, this is a simplified representation. Actual edge-wards tracking is not in a straight line, and the entering car is generally only stationary if it has stopped at the yield line. The actual situation will be far more dynamic.

It is difficult to easily characterise relative behaviours for the dynamic situation, where a car's actual approach speed will depend on numerous variables about which assumptions must be made, and similarly for a subject bicycle. Nonetheless, it is necessary for any conclusions to be able to be made and is presented as follows. For this analysis, the bicycle will be assumed to adopt a mid-lane location in both before and after cases to maximise comparability.

It can be observed that as the driver approaches the roundabout, the angle between the driver's gaze and the bicycle will change. As this angle relates to the location of the bicycle in the driver's peripheral vision, it will be termed the peripheral angle. Indicative peripheral angles for a driver at the yield line are shown in Figure 23. Here, the car is shown one car length further forward than previously (a distance of about 5m), i.e. sitting at the yield line. Five bicycle positions are shown for a typical bicycle length of about 1.8m, following fairly typical trajectories as observed in the before and after cases[56]. The trajectory of the first three bicycle lengths is the most consistent in each case, with before cyclists often 'slipping' into the roundabout from a kerbside location and after cyclists prevented from doing so due to the kerb protuberance. However, entering behaviour often responded to the presence of other vehicles; other bicycle positions based on other trajectories can be implied.

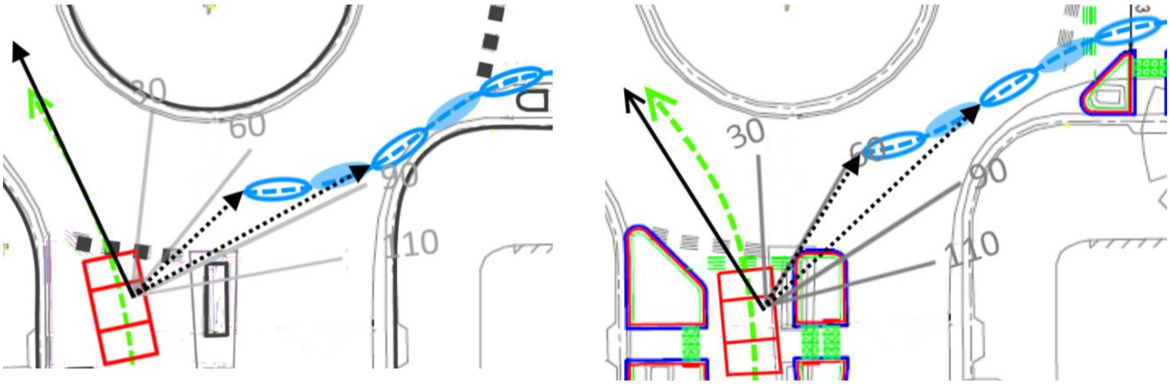

Figure 23: Change in peripheral angles with change in relative vehicle positions. Left: before; right: after[57]. Blue oval indicates bicycle location along its travel path, in bicycle-lengths.

In both before and after cases, the peripheral angle to a subject bicycle increases as the entering car approaches the yield line. I.e. The closer the car is to the roundabout, the further the bicycle moves into the driver's (far) peripheral vision. In Figure 23, the peripheral angle is around 80-90° to a bicycle at its yield line, compared to the 55-60° noted previously. Not explicitly shown, as the driver looks further to the left – for example, to a vehicle entering on the next leg – the peripheral angle would also worsen.

The worst-case scenario in Figure 23 is about two bicycle lengths beyond the subject bicycle's yield line (indicated with a black arrow). Here, the bicycle is about 85° from the driver's direction of gaze in the before situation. At this angle, Monaco et al. (2007) provide

[56] These typical trajectories change between the before and after cases, have been studied as part of the case studies, and are considered in the following section.

[57] This assumes the entering driver is looking to a point roughly in the middle of the circulating lane.

no data for interpolating an angular velocity sufficient to achieve a detection probability of greater than 40%. Extrapolating is fraught, but if this were possible, a 95% probability of a cyclist being detected would require an angular motion of about 2.3°/s. This equates to about 0.44m of lateral motion per second. But as the cyclist is moving almost entirely radially, cyclist speed would have virtually no component of lateral motion, except for increasing proximity to produce an apparent motion, as per Figure 14 e). As the cyclist's aspect ratio is tall and thin, even this would be perceived as mainly as vertical rather than angular motion. As a result, the cyclist would not be able to generate sufficient angular motion to be detected in the driver's peripheral vision, regardless of speed.

In the after situation, the worst-case scenario involves a peripheral angle of close to the 72.6° line shown in Monaco et al. (2007), a required angular motion of about 1.75°/s and an angular travel distance of 0.34m. Here, the tracking shown contains about five times as much radial as lateral motion, but the required travel speed for detection would still only be around 6km/h, which is a quite modest speed for an adult cyclist to achieve on flat ground.

If the situation of an entering car that is moving rather than stationery is now considered, an additional component of angular motion is generated by the car's motion. As the car moves forward, the bicycle appears to the driver to move backwards relative to the car. A component of this relative movement would be lateral. Figure 24 attempts to provide some assessment of the overall effect. Here, the peripheral angle for the car at the yield line (purple line) is relocated (purple arrow) to construct a vector sum with the peripheral angle for the driver a car length back from the yield line (green line). The difference between the purple dotted and green lines is an indication of the effective motion perceived by the driver as s/he travels towards the yield line (red arrow). The red arrow is taken from the initial bicycle position compared to its position when the car is at the yield line, to take account of the bicycle's motion as well. Radial (aqua arrow) and lateral (dark blue arrow) components of the effective motion can then be compared.

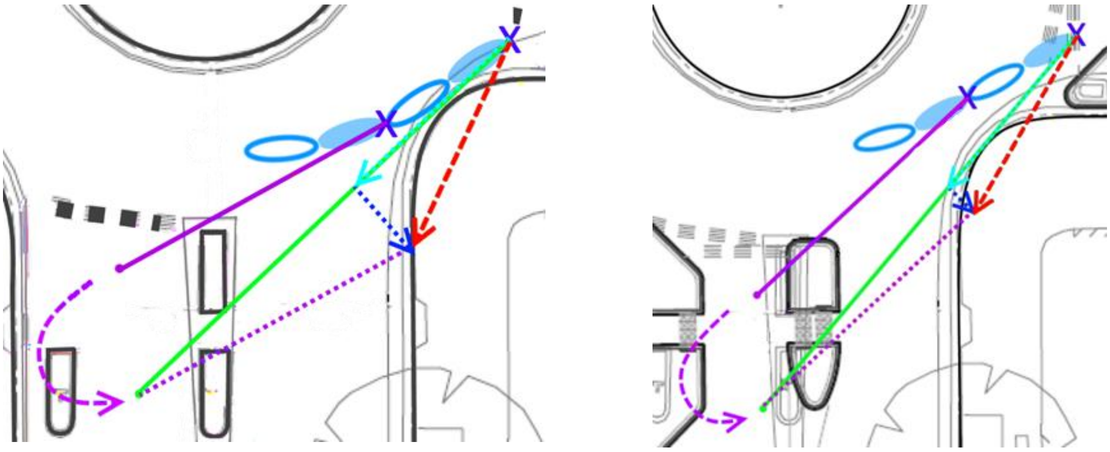

Figure 24: Geometric calculations of relative motion constructed from peripheral angle for a driver at the yield line (purple) and a car length back from the yield line (green). Bicycle at entry point and worst case location shown with X. Left: before; right: after.

The effective motion in the before case indicates a reasonably large component of lateral motion in the negative direction. The effective motion in the after case indicates very little lateral motion, again in the negative direction. The degree of negative motion will in both cases be related to speed: if a slower design speed is assumed, the corresponding driver's location would be located slightly further from the yield line compared to the bicycle's position and the negative lateral motion would reduce. A faster design speed would give a greater negative movement.

An implication of movement in the negative direction is the possibility of this further eroding motion detection. McKee and Nakayama (1984) note that peripheral vision is as good as foveal vision in the fine discrimination of velocity. However, Zhang, Kwon and Tadin (2013) find a strong bias in the visual system towards centrifugal motion i.e. motion travelling away from the centre of view, such that in their study, stationary objects in the visual periphery could be perceived as moving centrifugally away while objects moving as fast as 7°/s toward the fovea could be perceived as stationary[58].

These examples both assume a cyclist tracking that starts close to the kerb and follows a mid-lane position. Tracking closer to the island would produce more positive lateral motion. In the before case, this would be likely to reduce the perceived negative lateral motion. In the after case, this would result in positive lateral motion and, given that the amount of angular

58 The study was undertaken at a 40° peripheral angle and glimpse durations of 10ms, 20ms, 80ms and 240ms. The maximum effect occurred at minimum glimpse duration.

velocity required to capture driver attention is quite modest, the cyclist would probably still achieve sufficient angular velocity to satisfy this requirement.

Overall, this analysis is considered to indicate that geometry is likely to have an effect on perceptual motion detection. Two effects are identified:

- Differing entry angles giving rise to differing minimum angular velocities for detection – the analysis indicates that this effect is small and unlikely to be a major contributor to crash risk per se.
- Differing entry angles giving rise to differing likelihoods of achieving minimum angular velocity for detection – the analysis indicates that this effect can be large, with certain trajectories in the before case leading to the situation that a cyclist could not achieve the minimum angular velocity regardless of overall speed; and with edge-wards positioning of cyclists tending to reduce the probability that a driver would detect a cyclist.

The latter effect can be considered as a geometrically-based perceptual limitation causing an LBFS error. In causal terms, this theorises a driver failing to detect an approaching cyclist – which could be for cognitive reasons or due to visual shielding of the cyclist by another car – and, in the absence of any other hazard, deciding to enter the roundabout. The driver then changes their gaze point from the right (scanning for hazards) to their onwards path into the roundabout, at which point the geometric effects described come into play. This theory reflects a visual search strategy in which drivers rely on a short assessment using foveal vision to detect major hazards, then redeploy foveal vision for the driving task with peripheral motion detection as a ‘failsafe’ for new hazards. Such an effect is compatible with results supporting cognitive/processing LBFS errors.

It is emphasized that this analysis is qualitative and therefore not authoritative. The dynamics of interaction are subject to significant constraints in terms of assumptions and approximations in speeds, tracking, gaze point, etc. Nor was light shed on actual driver behaviour when approaching the roundabout, in terms of when and for how long a driver looks to their right before looking in the direction of travel/left, and hence to what extent they rely on movement in the peripheral visual field to detect approaching hazards. However, Lehtonen et al. (2018) confirm multiple results dating from 1995 that gaze often precedes manual actions with a small, constant lead time, and that this extends to visual control of steering and a visual secondary task. Summala and Räsänen (2000) estimate a glance time of two seconds for similar conditions. Lehtonen et al. also note that as the secondary visual task becomes further from the ahead gaze, glance durations to the secondary task reduce. Again, then, angles involved in tangential design mediate against peripheral visual tasks compared to radial design.

Sight distance for drivers to detect a minimum critical gap of four to five seconds as mandated by Australian roundabout design depends on the speed of an approaching (subject) vehicle, and is designed around cars rather than bicycles. This, plus the differing positioning behaviour of bicycles compared to cars, may well be one driver of at least some LBFS problems. Failure in motion detection could then be a compounding factor when an initial LBFS error has occurred.

In either case, the linking of tracking to angular motion required to detect a cyclist is the first known perceptual/ environmental rather than cognitive/ process explanation for differences in cyclist detection related to cyclist positioning in the roundabout. Since this effect contains some assumptions regarding cyclist tracking, actual cyclist tracking behaviour was examined, as follows. Since tracking is influenced by a number of factors, this examination of tracking behaviour is presented in four parts, under subject sub-headings.

Cyclist tracking

Edge-wards versus island-wards tracking behaviour

A thorough review of tracking was not feasible given difficulties in accurately identifying travel paths manually, the effect of different viewing angles, and lighting conditions. However, tracking behaviour was sampled for 85 cyclists in the before situation (15 May, all day) and 209 in the after situation (90 on 17 September, all day; 67 on 19 October, PM peak; and 52 on 22 October, PM peak). These days were chosen as the video records were taken from similar – though not identical – viewpoints. Cyclists observed were through cyclists coming from the west and excluded cyclists entering two abreast or in tandem, as in these situations the tracking appeared to be affected by the other cyclist. With sunset occurring at 5:21pm on 15 May, the PM period for this analysis was ended at 5:25pm.

The tracking observed in these 294 events was coded as:

A. Close to the island – at his/her closest approach to the island, the rider appears to ride over or adjacent to the 'effective edge line' (a location where the island's concrete edge combines with pavement marks to produce the appearance of an edge line at ground level – a simple indicator for tracking close to the island)

B. Further away than this but not yet at the centre of the traffic lane
C. Roughly centrally within the traffic lane
D. Closer to the edge of the roundabout than the centre of the lane
E. At the outer edge of the lane.

This only captured tracking behaviour in terms of the closest approach to the island, rather than the full tracking envelope and notably the start position. Automated video analysis would better characterise the tracking envelope but was not available. The following discussion considers results in terms of the few studies to also examine cyclist tracking at tangentially designed roundabouts. Given the paucity of these studies, replication of the study for different roundabout sizes under situations of identical viewpoints is indicated to both confirm the results and provide robustness to observed correlations.

In the before situation, the vast majority of cyclists (85%) tracked closer to the island than either central to the lane or closer to the edge, and a comparable amount in the after situation (89% on 17 September, 85% on 19 October and 92% on 22 October). These proportions are slightly higher than Rodergerdts et al. (2007) where 83% of cyclists in the circulating lane tended to ‘take the lane’ rather than ride on the edge of the circle. The seven roundabouts surveyed by Rodergerdts et al. are much larger (average inscribed diameter of 41m) and include two two-lane roundabouts.

These rates are also higher than Cumming (2012) reports. Cumming surveyed 130 commuter cyclists at three single-lane roundabouts in Victoria, all of which had bicycle lanes on the approach, with transitions on most legs directing cyclists towards the roundabout edge at entry. The largest roundabout observed also had segments of bicycle lane marked within the roundabout, again at the roundabout edge. At the two roundabouts without a circulatory bicycle lane, Cumming observed 57% and 76% of cyclists ‘straight-lining’ compared to 41% straight-lining through the roundabout with a bicycle lane, where straight-lining was defined as cyclists entering at a point close to the kerb, moving across the travel lane to a position close to the island and then back close to the kerb. As the term suggests, straight-lining produces an overall straight travel path rather than being deflected by kerb buildouts and the island. Since the current study is based on the closest point of approach to the island, the A and B tracking positions are considered to be analogous to straight-lining, although as the tracking positions for this study are not linked to entry and exit points, the ‘straight-line’ is not necessarily seen in A and B tracking.

Cumming (2012) contrasted straight-lining to edge-riding, where cyclists track closer to the edge of the roundabout than centrally – analogous to D and E tracking positions in the current study. Cumming observed about a third of cyclists displaying this tracking behaviour. This compares the current study's observation of five cyclists (about 6%) in the before daily situation and four (about 4%) in the after daily situation.

The remaining behaviour characterised by Cumming (2012) was 'claiming the lane': entering the roundabout from the middle of the approach lane and remaining central while circulating. This is roughly analogous to the C tracking position in the current study. Cumming did not observe any cyclists circulating centrally, with only five (about 4%) entering from the middle of the approach lane. In comparison, the case study observed seven cyclists (about 8%) located centrally in the before daily situation and 6 (about 7%) in the after daily situation.

While tracking definitions between Cumming (2012), Rodergerdts et al. (2007) and the current case study are not identical, the respective findings suggest that cyclists will naturally tend to track towards the island but engineering treatments directing cyclists towards the edge at entry will affect tracking behaviour. This was found by Wilke et al. (2014) in their study of eight Australian roundabouts. Wilke et al. (2014) express tracking in relation to the roundabout leg the cyclist passes after entering, and particularly its splitter island. Cyclists were observed to track from 2.3m from the island (60% of the roundabout's 3.8m circulatory roadway width) to 4.7m (82% of a 5.7m roadway width) for the seven single-lane roundabouts. Tracking over 60% of the way across the carriageway appears to be roughly analogous to the case study's A and B position. The proportions of cyclists tracking at this location in the current study are similar to the roundabouts with the least edge-wards tracking in Wilke et al.'s (2014) study[59].

This positioning does not accord with Cumming's (2012) proposition that roundabout design should seek to encourage cyclists to track centrally in the travel lane as cyclists thereby avoid the outer edge but are subject to sufficient deflection to ensure that their speeds are moderated, giving drivers a greater opportunity to see them. Cumming's proposition seems to assume that motor vehicles take a central line through the circulating carriageway – which may have been true for the roundabouts observed by Cumming, given the variation in

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[59] Wilke et al. provide their figures as histograms, from which it appears that some 80% to 85% of cyclists tracked in the A and B positions at Canning Street/ Pigdon Street, Melbourne; and Macrae Road/ Reynolds Road, Perth. Neither of these roundabouts had bicycle lanes.

roadway width documented in Wilke et al (2014), but is not true at Beulah Road/ Sydenham Road. Further, while Cumming notes that the faster cyclists tend to straight-line, the current study found that moderate-speed cyclists took a similar travel path to faster cyclists. Hence cyclist speed is not necessarily correlated to tracking behaviour.

St-Aubin et al. (2012) found that drivers tended to drive on the inside of any curved portion of the roundabout, i.e. closer to the island than to the edge. This phenomenon is known in traditional curve design practice and comparable with cyclist straight-lining. In the case study, road wear and tyre patterns indicate that cars typically use about half of the available lane width in the roundabout, being the part of the lane closest to the island. Hence island-wards tracking locates cyclists in a similar area to that which a car would occupy. It is not at all clear that this tracking creates greater risk compared to a more deflected travel path.

Closeness of tracking to the island

There was a noticeable difference in the current study between the proportion of cyclists tracking closer to the roundabout (A) versus slightly further out (B) in the before situation compared to the after, as shown in Table 6. Due to the small numbers, both numbers and percentages are presented in this table. (These results are considered along with C and D tracking in the context of vehicle influence in the next section.)

	A		**B**		**Total Records**	**Proportion, A + B**
	Number	**%**	**Number**	**%**		
15 May, all day (before)	44	52%	28	33%	85	85%
17 Sept, all day (after)	66	73%	14	16%	90	89%
19 Oct, PM peak (after)	43	64%	14	21%	67	85%
22 Oct, PM peak (after)	38	67%	10	19%	52	92%

Table 6: A and B tracking in the case study.

As Rodergerdts et al. (2007) only differentiated between being at the edge, possessing the lane or using the footpath, their results are not comparable to the current study. Cumming (2012) is similarly not comparable. Translating Wilke et al.'s (2014) results into this study's coding, their study found 37% A and 45% B tracking at a Melbourne roundabout and 55% A and 32% B tracking at a Perth roundabout. This indicates that the higher A versus B rates found in the current study are not unprecedented. Wilke et al. ascribed variations in cyclist tracking at roundabouts to geometric differences, with approach conditions significantly affecting cyclist positioning at roundabout entry. It is therefore likely that changes in tracking behaviour observed from the before to the after situation in the current study are related to geometric changes, particularly at the entry.

Table 6 also indicates a slight difference between all day and peak periods in the after situation. This may point to the influence of different patterns of exposure to traffic and cyclist responses to this, which is examined in the next section.

Impact of vehicle presence on tracking

Rodergerdts et al. (2007) found that when there were no vehicles within two car lengths of observed cyclists, 42% of cyclists claimed the vehicle lane. This 'no vehicle' situation accounted for 60% of all cases. When a vehicle was leading the cyclist, the proportion of cyclists claiming the lane decreased to 35%. When a vehicle trailed the cyclist, it decreased further, to 23%. The presence of both gave an effect similar to the leading situation, at 34%.

Rodergerdts et al.'s "within two car lengths" is not compatible with the smaller scale of the Beulah Road/ Sydenham Road roundabout. But the presence (or influence) of vehicles in the case study could be characterised as:

- Vehicle leading – cyclist speed was likely to be responding to a vehicle preceding them. Preceding vehicles were: directly in front on the approach to the roundabout; circulating vehicles; an object vehicle that cut in front of cyclists sufficiently to affect cyclist tracking (these were not frequent, accounting for less than half as many events as the other two preceding vehicle types); and when following a car precipitated stopping at the kerbside.
- Vehicle trailing – a car appears close enough for the cyclist to be aware of its presence. As this was difficult to ascertain, a high threshold was adopted, being: a headway that would suggest cyclists felt they were being tailgated (less than a car length); and/or the trailing car moving out and travelling behind but essentially beside the cyclist (e.g. to assess whether an overtaking manoeuvre was feasible), then moving back behind the cyclist. This last behaviour would be experienced by the cyclist as being 'dogged' by the car.

In the before situation of the case study, 60% of all-day tracking records were associated with 'no vehicle' – as found by Rodergerdts et al. This reduced to 54% in the after situation. In the PM peak, 'no vehicle' levels are about the same for before/after conditions.

Disaggregating the data is hampered by small numbers. Table 7 presents raw numbers rather than percentages to highlight this problem.

	Before (all day)				**After (all day)**			
	A	**B**	**C+D**	***subtotal***	**A**	**B**	**C+D**	***subtotal***
No vehicle	33	14	4	*51*	43	6	0	*49*
Leading only	7	9	4	*20*	18	8	7	*33*
Trailing only	3	4	2	*9*	1	0	0	*1*
Both leading + trailing	1	1	1	*3*	4	1	2	*7*
Total	**44**	**28**	**11**	***83***	**66**	**15**	**9**	***90***

Table 7: Tracking and vehicle influence, all day results.

Very few cyclists tracked right at the outer edge (E) – none in the before situation and only one in the after situation. This is reasonably similar to Wilke et al.'s (2014) findings.

Very similar numbers of tracking events were observed in the before and after situations, but with quite different patterns, both in terms of vehicle influence (leading, trailing or both) and the resultant tracking. In both before and after situations, the presence of motor vehicles was associated with more edge-wards tracking.

In the before situation, 'no vehicle' was associated with about twice as much A as B positioning, while leading/ trailing/ both had about equal amounts of A and B positioning – perhaps slightly more B than A, but not conclusively so.

In the after situation, 'no vehicle' was associated with about the same total rate of A + B positioning as in the before situation. However, the proportion of A to B positioning was markedly different, with far more A positioning, and lower B and C+D positioning translating into greater A positioning. Leading/ trailing/ both were also associated with more A positioning.

These results imply a fairly strong effect caused by the changed geometry. There are also some indications of fewer trailing-only cases in the after situation, and less C+D positioning, but numbers are very small.

The results are quite similar for the PM peak (Table 8). In this case, the after cases have been combined and percentages shown to assist with comparing very different sample sizes.

	Before PM peak (15 May)				**After PM peak (17 Sept, 19 Oct, 22 Oct)**			
	A	**B**	**C+D**	***subtotal***	**A**	**B**	**C+D**	***subtotal***
No vehicle	18	9	0	*27 (61%)*	77	14	5	*96 (60%)*
Leading only	2	4	5	*11 (25%)*	20	12	3	*35 (22%)*
Trailing only	3	2	0	*5 (11%)*	3	5	4	*12 (8%)*
Leading + trailing	0	1	0	*1 (2%)*	6	2	8	*16 (10%)*
Total	**23 (52%)**	**16 (36%)**	**5 (11%)**	***44***	**106 (67%)**	**33 (21%)**	**20 (13%)**	***159***

Table 8: Tracking and vehicle influence, PM peak results.

Rates of C+D tracking seems to be unchanged, but more A tracking is seen compared to B tracking. The 'both leading + trailing' events in the after case are somewhat unreliable in that it is not clear whether influence was actually being exerted. As cyclists cannot sit alongside cars in the after situation, they are more likely to be seen between a leading and trailing vehicle. Otherwise, there is reasonable similarity with daily results.

Overall, though, tracking behaviour does appear to have been influenced by geometric design. The design was therefore reviewed to identify possible causal reasons.

Geometric design impacts on tracking

Firstly, the change in trailing vehicles could reflect the use of tailgating and 'dogging' to indicate trailing vehicle influence. A change in overtaking behaviour was observed, pointing to less of this behaviour being seen in the after situation[60]. Many of the events recorded in the after situation involved cars waiting behind stopped cyclists at the approach, which was not seen in the before situation.

More broadly, because kerb protuberances exist at entry but not exit, the travel line through the Beulah Road/ Sydenham Road roundabout (and most Australian roundabouts) is not symmetrical from entry to exit. An indicative travel path is shown in Figure 25, for the 'no vehicle' situation and A type tracking. Cyclists are closest to the central island on the western (entry) side and slightly further from it on the eastern (exit) side[61].

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[60] This is presented in the context of Approach/entry behaviour at the end of this chapter, as another observed effect.

[61] The yellow travel line is the result of setting an entry point, exit point, deflection point in a graphics editor and using these to achieve a smooth line, and hence represent geometric effects that translate into an adopted travel path.

Figure 25: Before roundabout geometry showing nominal cyclist tracking.

In the before situation:

- Line-marking and a small kerb protuberance create an area protected from vehicles. Cyclists can enter this to maintain dynamic balance alongside a yielding vehicle instead of stopping behind it, and to sit outside the traffic path. But it is an extremely edge-wards location.
- Using this, cyclists can position in front of a dual entry vehicle[62], wait for it to move first, or set off alongside a circulating vehicle while clear of the dual entry vehicle and protected by the circulating vehicle. In these cases, cyclist start their tracking trajectory from an edge-wards position and are not aligned to the A tracking path.
- The further edge-wards that cyclists enter, the less they can claim the lane. When entering alongside a circulating vehicle, or from a strongly edge-wards position, some cyclists will leave space for the circulating or a trailing motor vehicle to occupy.

Hence vehicle presence could be expected to be associated with edge-wards positioning.

In the after situation, the inscribed circle, central island, circulating lane widths and main kerbs are unchanged, but kerb protuberances force vehicles into a more central lane placement at the approach and increase both deflection and asymmetry, as in Figure 26. This is again shown for A type tracking.

Figure 26: After roundabout geometry showing nominal cyclist tracking.

62 As described later under the approach/entry behaviour discussion.

Here:

- The large kerb protuberance forces cyclists further from the roundabout edge at entry.
- Cyclists are forced to ‘claim the lane’ by default due to the straighter approach trajectory and narrow throat.
- The equivalent sheltered area forward of the new kerb protuberance is now inconvenient and away from the natural line of travel. The incentive to use it is significantly reduced as the throat is too narrow for a cyclist to pass a line of waiting cars to reach the area, and dual entry situations no longer need to be avoided.
- Cyclists who have had to stop re-start travel still aligned to the A tracking path, though they can be put off this when re-establishing dynamic balance.
- The more central approach lane positioning creates more deflection and cyclists are naturally directed towards the island.

Overall, then, the radial geometry leads to both more central positioning in the approach lane and less need to track edge-wards. As per Wilke et al. (2014), tracking is affected by the positioning at entry.

Visually, the major effects of tracking close to the island are an increased clearance to entering cars and, for higher speed cyclists, leaning into the curve.

- Maximum clearance of almost a car length to entering cars allows time and space for evasive action within the roundabout.
- A cyclist starting from a stop will not reach normal travel speeds and may not have the momentum to lean in close to the island, leading to more edge-wards tracking. Cyclists forced to stop in the approach lane (after situation) rather than invited to stop forward of the kerb protuberance (before situation) are more likely to attain sufficient momentum to lean in to the island – and hence adopt island-wards tracking. This at lower speed in the after situation due to the greater deflection.
- A cyclist following a slow car – notably right-turning vehicles – must often moderate their speed to suit the car’s pace. The straighter A path is faster, so they will track more centrally in order to proceed more slowly. This demonstrates a very direct effect on tracking created by the presence of a leading car.

And as noted through the geometric analysis, starting further from the kerb and tracking closer to the island translates to a greater possibility of a cyclist being detected in a driver’s peripheral vision if they are not noticed earlier.

Impeded sightlines

If peripheral motion detection presents a failsafe mechanism, the examination of encounters from the Safety in Numbers analysis identifies that close follow events are associated with a potential failure mechanism to which this failsafe (or lack thereof) might apply. These events occur when sightlines between a cyclist and an entering vehicle are blocked (or impeded) by an intermediate vehicle. Impeded sightline encounters clearly have a strong potential to contribute to yield-failure cases. A driver who does not see a bicycle will not yield to it.

As this analysis will indicate, impeded sightline events have the added issue that they tend to be asymmetric, in that a cyclist usually sees the car even if the reverse is not the case. This has the implication that the cyclist knows the driver is obliged to yield, is not aware that the have not been undetected, and approaches the coming encounter with the expectation of being yielded to rather than not. Räsänen and Summala (1998) find that in car/bicycle crashes, 68% of cyclists were aware of a car and 92% believed the driver would yield as required by law. These results are often interpreted as an indication of a LBFS error associated with a lapse in cognitive expectation, but impeded sightlines present a LBFS error due to a perceptual limitation.

A number of factors will affect the result of an impeded sightline, as shielding of a cyclist will occur at different points on the driver's approach. Four general situations are shown in Figure 27. In each of these cases, the proximity or headway between the cyclist and vehicle are also relevant.

1. A motor vehicle entering from the same leg and in front of a cyclist, and travelling through or right, gives a low degree of shielding – the subject cyclist should still be visible to a vehicle entering on the next leg, though they may be briefly shielded from sight and for a longer period if turning right (and therefore positioned further right in the lane).
2. A motor vehicle entering or circulating from the subject cyclist's right and turning right is effectively the same as the above situation, but likely to be travelling more slowly.
3. A motor vehicle entering or circulating from the subject cyclist's right and continuing through gives a high degree of shielding – being reasonably likely to shield the bicycle from drivers entering on the next leg.
4. A motor vehicle entering from the same leg, in front of a subject cyclist and turning left, is effectively the same as the above situation.

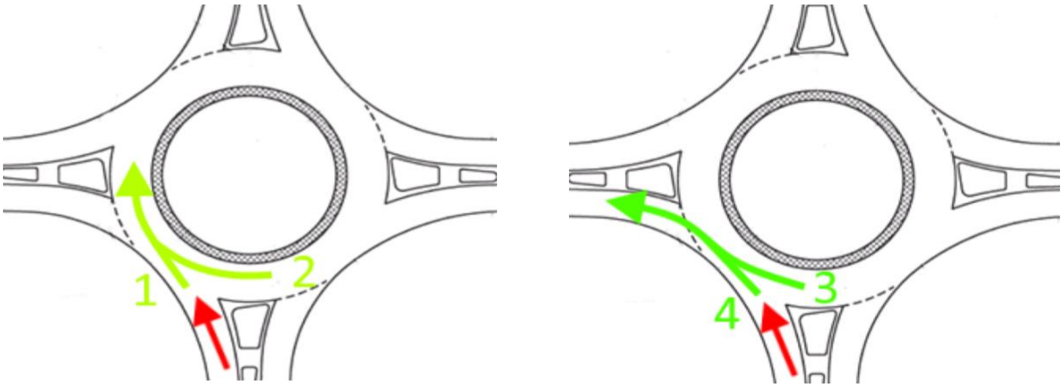

Figure 27: Four types of impeded sightlines giving rise to two severities of shielding (cyclist direction shown in red).

Another effect in the (1) situation is distraction: an object driver's attention is attracted to the motor vehicle and a (relatively small) bicycle escapes notice, especially if the cyclist is positioned towards the edge of the travel lane (which is more common when a cyclist enters with/ closely behind a vehicle). For example, in Figure 28, the object driver's attention may be drawn to the circulating vehicle at the expense of the subject cyclist. This also illustrates that the cyclist would clearly see the object car and expect it to yield.

Figure 28: Possible distraction – a cyclist is first shielded, then the preceding car claims attention.

As noted in the literature review, Pammer, Sabadas and Lentern (2018) find a cognitive-behavioural effect leading to inattention blindness in similar circumstances. This contradicts Herslund and Jørgensen's (2002) hypothesis that a motor vehicle could draw the entering driver's attention to a nearby bicycle or cause the driver to act cautiously to the benefit of the cyclist.

The degree of impeded sightline worsens as the size of the impeding vehicle increases, as shown in Figure 29, albeit that the cyclist may be more aware that sightlines are impeded as s/he will not be able to see past the circulating vehicle.

Figure 29: Impeded sightline resulting from a commercial vehicle.

Less obviously, larger vehicles typically have slower acceleration out of the roundabout and can impede sightlines for a longer period.

To examine the impeded sightline effect, the case study follows Turner et al. (2009) in basing observations on the yield line of approaches. Pragmatically, the yield line is easily identified in video taken from different angles and is a consistent notional point. The yield line also represents a point intermediate between the 10m and 20m distances for which Silvano et al. (2014) correlated the presence of a subject bicycle with the influence over an object driver's decision to yield – although direct comparisons with Silvano et al. (2014) are not possible due to the different methodologies employed. There is also a precedent within Traffic Conflicts Technique, with Van der Horst (1990) using the metric of 'Time to Intersection' to measure the (temporal) proximity to a reference line at the intersection.

Regarding the cyclist point of entry:

a) Cyclists have often low visibility prior to this point (due to buildings, parked cars, etc), so being obscured at entry can mean a cyclist has not had a prior opportunity to be seen.
b) This is when the cyclist commits to negotiating the roundabout and, if relevant, will assume that an entering car should yield.
c) The closer a car is to the roundabout, the less time remains available for the driver to react to the presence of a bicycle.

The before and after yield lines are in similar but not identical locations due to the geometric changes of the redesign. This is illustrated in Figure 30 by overlaying the new design over its predecessor, for the northern leg of the roundabout.

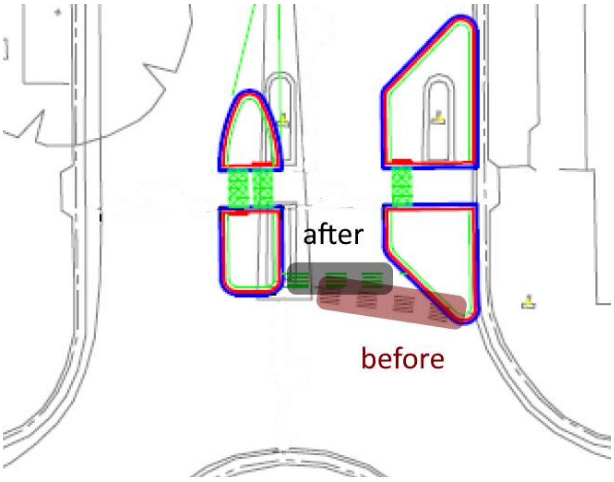

Figure 30: Comparison of before and after yield line position.

The encounter leading to impeded sightlines is seen for west-entering subject bicycles with object vehicles entering from the south or west; or for south-entering subject bicycles with object vehicles entering from the east or south. These events were coded as type '1 or 2' or '3 or 4' as previously defined, with the threshold that the subject bicycle must be within 1 to 2 car lengths of the shielding motor vehicle more than 'momentarily' and with the exception that a subject cyclist following a previous cyclist is not also considered to be shielded, as one of the two should be visible where the other is not[63].

Table 9 presents encounter patterns, ignoring possible distraction effects. (1 or 2) are less likely to contribute to a yield failure and (3 or 4) are more likely to do so. Table 9 also presents the number of records in the period as a basis for comparison, given different sample sizes. To aid readability, numbers of impeded sightline events have been colour-coded by value:

- 1-3: blue
- 4-6: green
- 7-9: orange

63 While 'momentarily' lacks quantitative weight, it is noted that one reason temporal measures became favoured in Traffic Conflicts Technique is that it was easier for human observers to estimate, both reliably and consistently, than distance; and that Traffic Conflicts Technique studies have found consistency by individual observers in their temporal assessments i.e. the assessment of 'momentarily' may be subjective, but it should be relatively consistent throughout. Also, the threshold for a conflict set in Traffic Conflicts Technique reflected agreement between independent observers. 'Momentarily' is a similar human-based assessment.

Before (PM peak)	6&7 May	12 May	15 May*	Average	
1 or 2	4	4	9	5.7	
3 or 4	9	4	3	5.3	
Total impedances	13	8	12	11.0	
Total encounters	*43*	*29*	*45*	*39.0*	
Period records	*82*	*53*	*83*	*72.7*	
After (PM peak)	**17 Sept***	**19 Oct**	**22 Oct**	**Average**	**Expected average****
1 or 2	2	3	3	2.7	7.1
3 or 4	4	2	5	3.3	6.6
Total impedances	6	5	8	6.0	13.7
Total encounters	*53*	*45*	*61*	*53.0*	
Period records	*84*	*88*	*100*	*90.7*	

*A right-turning cyclist encounter comprising both a 1 and 3 is recorded in this period.

**Based on period records. If based on exposure, the higher exposure rate in the after situation would result in a higher expected average.

Table 9: Encounters associated with impeded sightlines, by severity type.

Exposure is slightly higher in the after situation with 58.4% of observed cyclists experiencing an encounter compared to 53.6% in the before situation. In the before situation, some form of impeded sightline event occurs in over a quarter of all encounters (28%). However, fewer encounters in the after situation resulted in impeded sightlines: an average of six compared to 11 in the before situation – less than half of what would be expected based on either cyclist numbers or encounter rates. The reduction is greater in the lower risk (1, 2) pattern than the higher risk (3, 4) pattern, but even the higher risk pattern shows more than a halving in incidence[64].

A larger change was seen in those encounters that resulted in the impeded sightline pattern being observed, but failing the distance and/or time threshold. Introducing a code of '0' to capture this pattern and a new colour code of pink for 10+ observations gives Table 10.

64 'Close follow' and more particularly 'close entering' results indicate quite different conditions on 18 May to other before PM peak periods. The dataset has therefore been excluded from this analysis. If included, the difference in before/after results would reduce slightly but would still be significant.

Before	06&07_05	12_05	15_05*	Average	
0	2	4	7	4.3	
1 or 2	4	4	9	5.7	
3 or 4	9	4	3	5.3	
Total impedances	15	12	19	15.3	
Period records	*82*	*53*	*83*	*72.7*	
After	**17_09***	**19_10**	**22_10**	**Average**	**Expected average****
0	12	14	18	14.7	5.4
1 or 2	2	3	3	2.7	7.1
3 or 4	4	2	5	3.3	6.6
Total impedances	18	19	26	21.0	26.2
Period records	*84*	*88*	*100*	*90.7*	

*A right-turning cyclist encounter comprising both a 1 and 3 is recorded in this period.

**Based on before/after records. If based on exposure, the higher exposure rate in the after situation would result in a higher expected average.

Table 10: Encounters associated with impeded sightlines, including 'momentary' events.

These results point to a significant proportion of expected impeded sightline events failing the minimum time threshold in the after situation. Visually, this is seen as the cyclist path diverging from the motor vehicle path too quickly for an impeded sightline to be anything but 'momentary'.

The change in impeded sightlines events has been explored geometrically in a series of scenarios presented in Appendix E. These scenarios incorporate a number of assumptions regarding relative travel distances and are intended as a thought exercise rather than modelling real-life occurrences. The greatest proviso in these scenarios is that vehicle speeds in the before and after situations have been assumed to be the same, whereas speeds are expected to be lower in the after situation. The quantum of reduction is unknown, with design speeds not necessarily translating to actual speeds, which are difficult to measure due to deceleration giving variable speeds and poor results for methods reliant on distance/time. Zhang and Ma (2015b) put the 85th percentile speed for the tangential (before) design at 35km/h but the after speed is not known to have been assessed.

It is observed that object drivers will tend to wait until a circulating car's motion confirms it is not a hazard before proceeding (i.e. that it is not actually turning right but failing to indicate). A slower circulating car in the after situation would give a subject cyclist more time to travel through and exit visual shielding i.e. improve safety more than the analysis indicates.

An example of a figure from the geometric analysis is given as Figure 31. Here, the object car is shown in green, with its direction of travel shown as a green arrow, and the circulating car is shown in red. The cyclist has entered close to the kerb at the yield line (blue oval) and is tracking along the dashed blue line. S/he is now within the roundabout (second blue oval) and would just be emerging from the area in which s/he is fully shielded from the object driver (yellow/brown triangular area). As the driver enters the roundabout, her/his attention switches to the onwards travel path (black arrow).

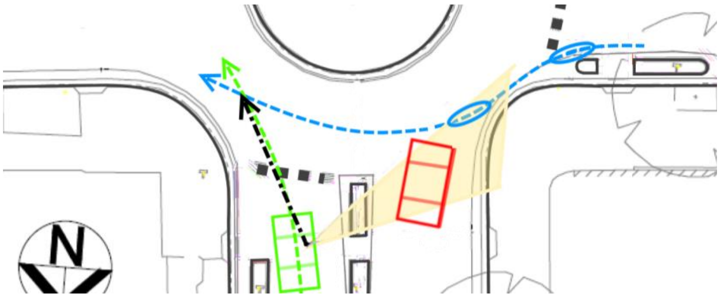

Figure 31: Before case of a subject bicycle shielded from an entering driver by a circulating car (situation 4.2 in Appendix E).

Conclusions from the geometric analysis are:

- The main effect of after geometry is that cyclists enter the roundabout further from the kerb line and follow a path of travel closer to the island, which creates a steeper view angle to cyclists for entering vehicles.
- Shielding conditions are often similar in the before and after cases. However, after cyclists must enter from a point further from the kerb line – they can't enter by 'slipping' through the roundabout close to the kerb. At this point, the circulating (red) car is not as far along its trajectory (it would be further 'up' in Figure 31). This produces a greater headway between a subject bicycle and circulating vehicle. The after bicycle therefore enters the roundabout sooner than a before bicycle would, passes further through any shielded area and is closer to clearing shielding when the entering car is at a similar location. This reduces the time the cyclist spends shielded, and more events are assessed as having their sightlines 'momentarily' impeded in the after case compared to the before.
- The steeper view angles resulting from the impact of geometry on sightlines mean that in the after situation, cyclists are slightly more likely to be shielded from the driver's view for object vehicles that are further from the roundabout, but slightly less likely to be shielded for object vehicles that are closer to the roundabout. The closer events correlate better to the decision point for drivers, contributing to the greater amounts of 'momentary' shielding being noticed in the after case.

  Further, a driver who sees a bicycle at its yield line is slightly more likely to be able to see the bicycle continue into the roundabout in the after situation.

- When bicycles emerge from the shielded area, the after cyclist is slightly closer to the object vehicle in a direction perpendicular to the vehicle but further in a direction parallel to the object vehicle. As the car's path of travel is essentially along the parallel path, this means an overall greater degree of separation between the object car and after bicycle.

Overall, the geometric analysis confirms the importance of roundabout geometry on relative positioning of object motor vehicles and subject bicycles and the resulting conditions of their interaction, as found earlier regarding motion detection.

To put these observations into context, the before situation shown in Figure 31 might well represent the 'perfect storm' against an object driver being able to detect a subject bicycle.

- From Silvano, Ma and Koutsopoulos (2014), this location is close to the object driver's decision point for entering the roundabout.
- Due to an impeded sightline event, the driver has not seen the bicycle cross the yield line and is unaware of the cyclist's presence.
- Having observed and discounted the circulating car as a hazard, and seeing no other vehicles, the driver decides it is safe to enter the roundabout and turns to look at their onwards direction of travel. From Turner et al. (2009), an objectively good sight line is likely to translate to higher approach speed at this point.
- Relative angles and speeds work against the driver noticing the bicycle through peripheral motion detection.
- The cyclist is well within the roundabout, has seen the car, assumes the driver will yield and is not braking or changing course to avoid a collision.

Excluding speed effects, the change from the before to the after case is a reduction in perceptual LBFS errors (by over 50%), better motion detection (from a little to a high likelihood of detection) and an increase in the distance from the front of the object car to the bicycle's travel path. Cumulatively, these changes would be expected to result in a reduced crash risk, especially noting that in this location, expected perceptual LBFS errors from impeded sightlines accounted for over a quarter of all cyclist encounters with an entering car in the before situation.

Conclusion

An examination of the Looked But Failed to See (LBFS) error from a perceptual limitation basis indicates radial design producing tracking and angle effects that support motion detection in the peripheral vision of entering drivers – what might be considered a failsafe mechanism of the human visual system. It also identifies the LBFS failure state of an impeded sightline as being quite common, and also addressed through radial design.

A particular observation is that in certain situations under tangential design conditions, a cyclist could not generate sufficient lateral motion to activate this failsafe. The presence and characteristics of the failsafe is considered an important safety finding and one that causally links edge-wards cyclist tracking to crash risk rather than associating or conjecturing the result. This is believed to be the second study to demonstrate such an effect, after Lund (2008), and the first to identify it as part of a perceptual rather than cognitive LBFS error.

The value of a failsafe is emphasised given the potential frequency of impeded sightline events, and ignoring cognitive LBFS errors not examined in this analysis.

Of course, this analysis is based on a particular roundabout. Is it reasonable to think it might apply to other examples? For the failsafe mechanism, yes, because it is based on relative angles. This is illustrated for Herland and Helmers' (2002) generic roundabouts in Figure 32.

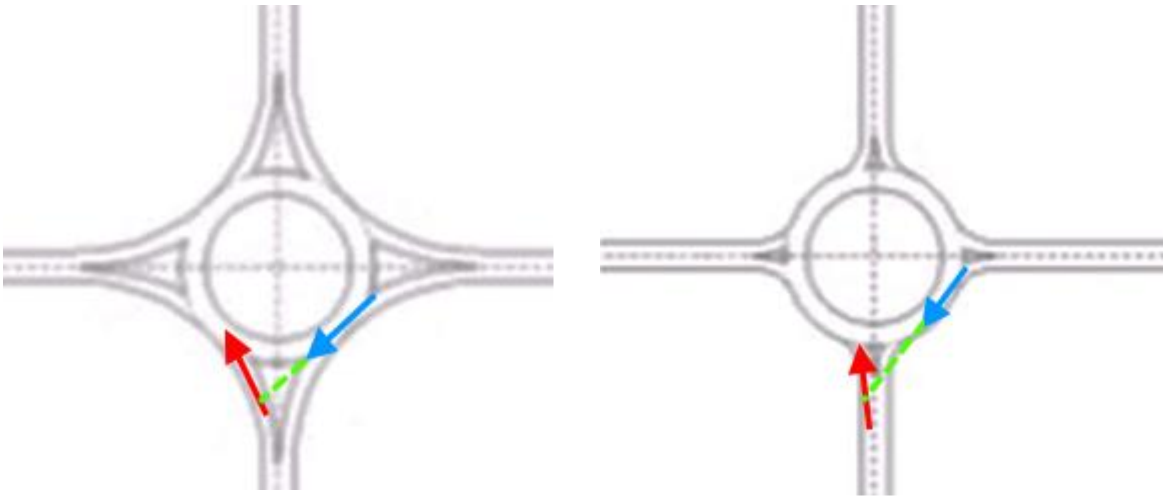

Figure 32: Peripheral vision angles, tangential versus radial roundabouts. Based on Herland and Helmers (2002).

That the angles between an entering car (red arrow) and entering bicycle (blue arrow) are different under the two designs is well recognised. It is the implications for motion detection in peripheral vision that have not been well considered.

Interestingly, Summala and Räsänen (2000) respond to criticism about Räsänen and Summala (2000) by observing that a driver looking left at 45° while a cyclist comes from the right at 22° will overlook the cyclist because approaching at 70° from the fovea:

> "…practically means that the driver cannot detect the cyclist. The drivers themselves therefore "actively mask" the conflicting cyclist out of their view."

While displaying familiarity with search processes, this appears to reference visual acuity rather than motion detection capabilities of peripheral vision. (Their study involved cyclists approaching on a path from the opposite direction to traffic flow and references cognitive LBFS errors but not perceptual LBFS errors.)

Overall, the identified perceptual LBFS mechanisms are considered significant enough to create a noticeable safety difference between radial and tangential design in and of themselves. The examination of perceptual LBFS mechanisms and their relationship to radial and tangential design is based on simple geometric considerations and well-established findings from visual field research. While the geometric features creating this effect may be somewhat compatible to Cumming's (2012) suggestion of greater deflection at roundabouts, the perceptual LBFS mechanisms identified are not based on traffic speed.

Therefore, the proof by contradiction requirements are considered to be satisfied.

Conflict Point Theory

The literature review finds that there is no good evidence supporting Conflict Point Theory, either for vehicles in general or for cyclists in particular. This section makes brief additional notes regarding case study observations.

Cumming (2012) and Wilke et al. (2014) both refer to Conflict Point Theory in the context of bicycle lanes in roundabouts. There is no bicycle lane at the case study site and the observed tracking behaviour does not support the proposition that the number of conflict points is different to that for other vehicles due to edge-wards tracking. Under both tangential and radial designs, few cyclists tracked at the outer edge and cyclists broadly used the same road space as a motor vehicle would use under either design.

Exposure data indicates that the radial design – which due to speed effects is assumed to be associated with lower crash risk – is associated with higher encounter rates than the tangential design it replaced. This points to the number of conflicts increasing rather than decreasing in more safe conditions, in line with other research casting doubt on Conflict Point Theory. This points to the nature of encounters being more important than their frequency, which is an aspect of the safety equation not addressed through Conflict Point Theory.

Approach/ entry behaviour

While the preceding section considered theorised effects, the close observation of the roundabout identified some effects or behaviours at the entry that have not been previously theorised. These are discussed in this section, noting that the LBFS examination has already established safety effects independent of speed sufficient to satisfy the proof by contradiction method. These effects are not necessarily significant but could be expected to increase the safety effect of radial over tangential design.

The before situation in this context is most readily understood by considering an aerial image of the western leg. In Figure 33Figure 33: Approach paths, before situation., the faint white mark at the tip of a street pole's shadow is a bicycle logo, indicating where cyclists should be expected. An indicative expected path of travel for a cyclist travelling along Beulah Road has been sketched in yellow/brown (noting that in this situation, no vehicles are parked alongside the kerb). A kerb protuberance hidden beneath a tree is roughly as outlined in white.

The path of travel for a car is as shown in blue, assuming that no cyclist is present. From its original position clear of the cyclist travel path, the car travel path gets closer to the cyclist travel path until these overlap (red circled zone). In this zone, motorists and cyclists must alter their travel paths to avoid colliding.

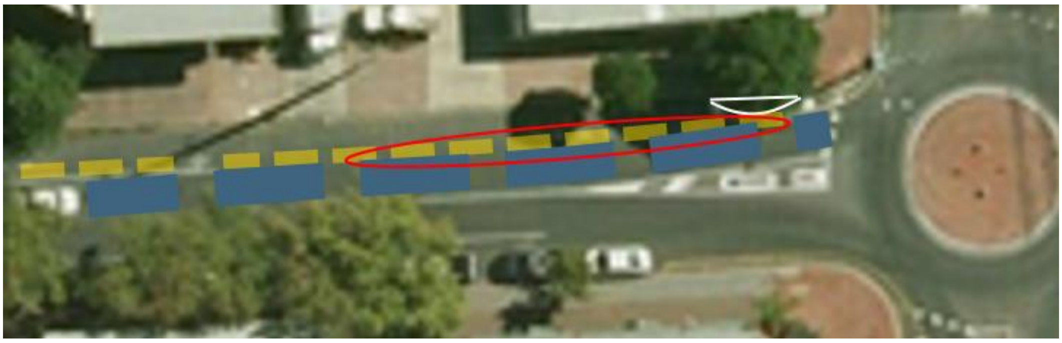

Figure 33: Approach paths, before situation.

While drivers won't usually cut across another vehicle's path, a driver coming upon a cyclist from behind will often attempt to pass the cyclist. Such drivers must complete the manoeuvre before reaching the roundabout as they will otherwise be located in somewhat of a no-man's land, straddling the centreline with the splitter island approaching and vehicles exiting from the roundabout towards them. This leads to two effects, further away and closer to the roundabout.

Further away from the roundabout, cyclists feel 'pressure' to locate closer to the kerb, which may or may not be possible depending on parking (the extent of possible parking is shown in Figure 33 by cars parked on the southern side of Beulah Road). This can place them within the door zone of parked cars. Indeed, the bike logo is roughly the last point where many cyclists would feel comfortable in maintaining their preferred position on the road. But when cyclists ride close to the kerb, drivers are 'invited' to attempt to pass, exacerbating the effect.

Close to the roundabout, car repositioning translates to cutting in on cyclists. In the before situation, this was frequently observed, sometimes required cyclists to adjust speed/ position to maintain safety. Cyclists would find this intimidating. Even cyclists who position centrally in the travel lane in a 'claim the lane' manner (i.e. positioning to prevent a motor vehicle from behind from passing) were subject to this behaviour as the road is too wide for overtaking to be discouraged, even if the cyclist positions so far into the lane that the car can only pass by crossing the centreline.

This approach behaviour is illustrated in the sequence provided as Figure 34.

At the +3 position, the driver is alongside the cyclist and must straddle the centre line to give sufficient clearance.

The driver moves into the lane proper to avoid the splitter island. As clearance to the cyclist reduces, both cyclist and driver could feel pressured.

The driver aligns to enter the roundabout, cutting across the cyclist's travel path. The two are separated by headway rather than clearance and this is small as the car decelerates as it approaches to the roundabout.

The car is well across the cyclist's original travel path, with no clearance remaining. Headway is increasing but would disappear if the car stops at the roundabout.

Figure 34: Example of the typical car-bike interaction on the approach, before situation. Red dot = cyclist headlight, highlighted as a visual aid.

Overall, this pattern of behaviour indicates that drivers have difficulty in judging:

- their speed relative to cyclists;
- what this means for travel distances; and
- the impact on cyclists, given a long and ill-defined overlap in desired travel paths.

The 10-year crash record includes one side swipe of a cyclist. The police found the driver to be at fault, with the crash described as ‘overtaking – on right’ and ‘overtaking without due care’. It is at least possible that the crash reflects this type of situation.

Two design changes affect this behaviour. Firstly, the narrower throat creates the critical difference that a car and bicycle cannot easily fit side by side in the throat of the roundabout. This clarifies to drivers that their vehicles cannot occupy the space alongside a cyclist, and vice versa. Secondly, the straighter (radial) approach gives cyclists protected space. This is as illustrated in Figure 35. The yellow line passes through the centre of the roadways and island, as an aid to appreciating the geometric impacts of the redesign.

Before: small kerb protuberances and symmetrically-aligned splitter islands give a wide throat and a curving travel path on the approach.

After: larger kerb protuberances and larger, offset splitter islands reduce the throat width at entry. This gives a straighter travel path on the approach.

Figure 35: Before and after situations, contrasting travel path and throat width.

The net effect in the after situation is shown in Figure 36.

Figure 36: Approach paths, after situation.

The cyclist’s path of travel (dashed yellow/brown) is separate to a car’s path of travel (blue) up to the kerb protuberance. Cyclists do not feel pressure from passing cars and drivers are no longer pressured to complete passing manoeuvres before the roundabout as neither travel path is affected by passing manoeuvres for most of the approach length. An area of overlapping travel paths still exists (circled in red), but is much shorter and better defined, culminating in a throat that is too narrow to accommodate both a bicycle and a car. Whichever vehicle is in front at the protuberance has clear precedence. A cyclist must knowingly move into the throat, giving the cyclist the opportunity to decide whether or not to move into the lane in front of a car. (In the before situation, this is only true for cyclists who hug the kerb; other cyclists must rely on the judgment of drivers). Poor passing behaviour – a late-arriving car cutting in on a cyclist – is still possible but was only observed on one occasion in some 14 hours of after video, as opposed to quite commonly in the before situation.

Some cyclists did not look comfortable with the new arrangement of essentially being forced to 'claim the lane'. Nonetheless, short of knowingly and deliberately running over a cyclist, drivers must – and do – respect cyclist priority under this configuration.

An additional effect in the before situation of a cyclist and car being able to fit side-by-side in the throat of the approach lane is the likelihood of exactly this occurring. Two main patterns of behaviour related to this were observed in the before situation:

- If a cyclist arrives before a car and must stop to yield to other traffic, s/he typically waits at the kerbside. An approaching driver would then typically position alongside the cyclist.
- If a car is stopped at entry and the cyclist continues to the yield line, the reverse situation occurs, leading to the same outcome. This particularly applies to a cyclist travelling to the left of a queue of vehicles in peak periods, when the minimal headway between cars is not conducive to a cyclist merging into the column of traffic.

Less commonly, a car and bicycle may arrive at the same time, as shown in Figure 37.

Figure 37: Cyclist and driver arriving at the roundabout at the same time, before situation. In this case, the driver, who is turning left, stops at the yield line to allow the cyclist to move off first. Red dot = cyclist headlight, highlighted as a visual aid.

In all cases, having a car to their right means that a cyclist's sightlines to vehicles in or entering the roundabout are more likely to be hindered. In terms of behaviour:

a) the cyclist might try to enter the roundabout before the adjacent car (this assists the cyclist to avoid getting cut off and to use gaps that a car can't)
b) one or other road user might 'encourage' the other to enter first
c) the driver might cut in front of the cyclist – though cutting in per se rarely occurs as cyclists will avoid this situation by either the first behaviour or by ensuring they sit far enough back to not be endangered by the car and waiting for the car to proceed, as per the second behaviour
d) they might set off together, either coincidentally or because the cyclist is using the vehicle (which is travelling through or turning right) as a shield – having a car to their right guarantees that other traffic from the right will not collide with the cyclist without first colliding with the car.

In the type a) behaviour, cyclists often made use of their smaller vehicle size and different dynamics to accept gaps that a driver would not. This involved maintaining dynamic balance as much as possible through deceleration rate, then accelerating while a circulating vehicle was already in the roundabout. This behaviour was associated with locating close to the kerb. This dual entry situation is untidy and could give rise to side swipe crashes or, if the car beside the cyclist unexpectedly turns left, crashes on exit. In the after situation, the throat of the approach lane is too narrow for a bicycle and car to sit beside each other comfortably and few dual entry cases were observed.

The type d) behaviour includes an example of cyclists actively attempting to reduce their exposure to other vehicles during their passage through the roundabout. Apart from being an example of why exposure is not linearly associated with cyclist volumes, this also indicates cyclist concern with a situation that is not the major crash risk. Further, insofar as this positions cyclists further edge-wards, the literature would point to a cyclist's crash risk being increased by the behaviour.

There is some indication that cyclists are not aware of the greatest risks to their safety at roundabouts. Møller and Hels (2007) found correlation between perception and risk in their survey of Danish cyclists, but also that these perceptions were not accurate in terms of risk levels. Some of the wording used in their survey is also potentially ambiguous: what does 'hit by entering car' represent compared to 'hit from the side'? 'Circulating while car enters' would seem clear, but how was this interpreted by the survey respondents? Also, 41% of Møller and Hels' respondents had experienced a near-accident in the roundabout where the interview took place. It is not obvious how this may relate to the experience of cyclists using the case study roundabout.

No other relevant literature was identified regarding cyclist perceptions of risk at roundabouts (Schramm et al. (2014) note three other studies, but these do not address this particular theme). Anecdotally, most Adelaide-based cyclists are concerned about squeeze points on entry at roundabouts rather than driver failure to yield. This was confirmed during a 'Be Safe, Be Seen' session held in 2019[65]. Here, the instructor referred to 'claiming the lane' as a method to avoid being squeezed by vehicles on entry but was unaware of the failure-to-yield risk.

While not frequent, what can best be described as 'messy situations' were also observed in the before situation, especially with heavy vehicles. For example, Figure 38 shows a cyclist (circled) entering to the right of a left-turning heavy vehicle.

[65] 'Be Safe, Be Seen' is a cyclist safety program sponsored by the South Australian state government and now-defunct Motor Accident Commission, and the winner of the 2014 Australian Road Safety Award

Figure 38: Cyclist positioning to the right of a left-turning truck.

This placement may have seemed sensible to the cyclist, compared to positioning to the vehicle's left. But the cyclist is shielded by the truck from the view of the driver of the car on the next leg (who is yielding to a prior cyclist). This car begins to move before the driver sees the new cyclist and yields. A more assertive driver who was not already yielding and who had noted the heavy vehicle's turn indicator might well have collided with the new cyclist.

In the after situation, the throat of the approach lane is too narrow for a bicycle to (easily) pass to the right of a car, much less a heavy vehicle, and these cases did not occur.

Overall, the change from a tangential to a radial design appears to have improved cyclist safety due to approach and entry conditions. The less complicated situation that arises in the radial case could conceivably facilitate cyclist close entering by increasing the ease with which a cyclist can match speeds with a preceding cyclist. Given indications that at least Australian cyclists are not necessarily aware of the crash risks at a roundabout, close entering behaviour is likely to be an incidental effect rather than a cyclist strategy to reduce exposure.

Conclusion

The close study of the conversion of a tangentially designed roundabout to a radial design base identifies that important causal effects are associated with better cyclist safety as radial roundabouts than tangential roundabouts, over and above lower traffic speed. These effects have neither been theorised nor identified through previous safety studies, which tend to rely on mass data for pragmatic reasons. Indeed, the case study notes in passing a lack of correlation between the conditions as the case study site under tangential design (before case) and safety performance functions derived for Australasian roundabouts for the most common cyclist crash type of an entering car failing to yield to a circulating cyclist.

The fact that these causal effects have not been identified earlier is not a result of adopting new approaches or advances in knowledge. The basic analysis was conducted using simple geometric approaches and a consideration of motion detection in peripheral vision based on studies extant for at least a decade.

It must be concluded that the pragmatic use of mass data in safety studies has not optimally informed safety research regarding the well-established safety problem of safety of cyclists at roundabouts. This is notably the case regarding radial versus tangential design, which is ill-suited to examination using statistical safety studies. Regarding the important effect of cyclist tracking on safety, the only study before this one to establish a relationship (Lund, 2008) is an observational study and has not been repeated since it was undertaken.

While cyclist safety at roundabouts represents a specialised field of road safety enquiry, if it is true that this is not optimally informed by statistical safety studies then it is also true that the overall field of road safety has not been optimally informed by statistical safety studies and the thesis hypothesis is thus proven.

The pragmatic case study also refutes Conflict Point Theory, which arguably represents a commitment to paradigm over evidence that only lends further support to the hypothesis.

6. Discussion

Summary of the dissertation

As the Introduction notes, the achievements of traffic engineers and other practitioners in the field of road safety have been truly remarkable, thanks to many decades of considered and concerted action. Nonetheless, there are indications in the road safety literature that in the field of road safety, adverse road safety effects are occurring. These indications range from concerns about lack of methodological robustness in safety studies to direct criticisms that road safety evidence is being ignored in the development of technical guidelines.

These indications have led to the development and exploration of the hypothesis that:

> "Engineering paradigm and pragmatism are having an adverse effect on road safety."

As the literature review in Chapter 2 finds, there is only a small amount of traffic engineering literature that has considered problems in road safety research, or its application, on a systemic basis. Therefore, this dissertation has taken a multidisciplinary approach to examining the hypothesis.

Even so, no literature was identified that considered adverse safety results or effects in the terms of the thesis hypothesis, though Collins and Leathley (1995) come close regarding the negative impact of paradigm, and Mulder (2000) in terms of engineering culture. The literature review instead found evidence across many sociological fields pointing to the types of problems that would lead to paradigm and pragmatism having the adverse effects postulated, and rooted in such factors as the processes of professionalisation, human psychology and self-interest – to name only a few. This is supported by narratives provided by the broader engineering literature. The themes and understandings drawn from this cumulative literature provide a valuable lens through which to view the scant road safety literature that touches upon the subject, enabling a more developed and nuanced consideration of this smaller amount of literature and its relevance to the hypothesis.

To establish that the hypothesised effect exists, typical methodologies from the social sciences were considered inadequate, partly because of the amount of literature in existence that considers factors leading to such an effect. Primary research overlapping with this extant body of evidence might expand the body of knowledge in a particular sociological field, but would not add to an understanding of the hypothesis. A typical engineering methodology for a road safety problem was considered even less well-suited to exploring the hypothesis. Instead, taking a first-principles view of the intent of primary research, and acknowledging the difficulty of trying to disprove a negative statement, the approach of proof by contradiction was selected. Proof by contradiction is a well-established methodology within the scientific tradition. Under this approach, the opposite of the hypothesis is assumed and logical processes are applied to attempt to find a contradiction. If such a contradiction can be found, then the assumed opposite-of-the-hypothesis must be incorrect i.e. the original proposition must be valid.

As this thesis' hypothesis revolves around both paradigm and pragmatism, two case studies of current problems in road safety were chosen, along with the proof by contradiction assumption that in these cases an adherence to paradigm and the application of pragmatic practice (respectively) had optimally produced road safety knowledge. In both cases, 'optimal' potentially implies a level of effectiveness and efficiency that cannot be obtained in real life i.e. represents an artificially high threshold and hence an easy hurdle for the case studies to overcome. To address this, the case studies chosen had to have a sufficient degree of importance within the road safety field and a significant enough 'sub-optimal' result for the contradiction to be proven; and could not rely upon new or innovative techniques (as these would represent an advance on existing research approaches and, by implication, the paradigm and pragmatic practice being tested.) For case studies complying with these conditions, if rejecting accepted paradigm in the first case study and pragmatic practice in the second case study leads to significant new knowledge being produced about these problems, this contradicts the assumption that engineering paradigm and practice are leading to the optimal production of knowledge and having no adverse effect on road safety.

The first case study focuses on Traffic Conflict Techniques (TCT). TCT has been studied for some fifty years due to its potential for enabling crash risk assessment to be undertaken without relying upon reported crash data, which is known to have reliability problems due to the stochastic (rare) and random nature of crashes, crash reporting rates, and so on. Uncommonly for traffic engineering, TCT has a well-established set of definitions, representing the established traffic engineering paradigm. However, numerous conceptual and practical difficulties remain. The main issues relate to the nature of 'conflicts', rating of conflicts by 'severity', the relationship between 'conflicts' and crashes, assumptions explicit and implicit in measuring 'conflict' and the reliability (or otherwise) of indicators used in the field. Most notably, while TCT-based assessments are in use for diagnostic purposes, TCT cannot reliably assess crash risk without recourse to the crash record, despite this being its greatest potential benefit.

After rejecting the paradigmatic elements of TCT, the basic premise remaining is that observations about observed traffic events can be used to provide information about rarer crash events, without waiting for crashes to be observed. The case study therefore takes as a starting point Extreme Value theory. This proven mathematical theory enables predictions of rare events to be made from observations of more common events and is most popularly known through the prediction of (say) 1 in 100-year rainfall events from much shorter rainfall records. It has been applied in TCT studies but as this use has involved it being overlaid on the TCT approach, it has not addressed the outstanding difficulties in TCT's use or overcome TCT's limitations.

When Extreme Value theory is used as its basis, the theoretical method developed – labelled Traffic Events Theory (TET) – is distinctly different from TCT. This is both in terms of the fundamental definitions (e.g. TET does not rely on a defined 'conflict') and the indicators used (in particular, the temporal proximity indicators used in TCT, which the case study shows to be incompatible with Extreme Value theory). In fact, TET addresses all of the known issues with TCT and (theoretically) should have none of the problems and limitations of TCT. This result is considered to demonstrate that rejecting established paradigm can lead to a significant contribution to the understanding and use of TCT (in the form of TET), satisfying the proof by contradiction condition.

The second case study involves the particular safety risk presented to cyclists by roundabouts, and the different safety environments posed by roundabouts designed under a radial base compared to a tangential base. Most researchers consider that the lower speed environment produced by radial design is the generator of its safety benefits. However, this has not been conclusively demonstrated, partly because of the difficulty in using mass data (or statistical) safety studies to analyse roundabout safety. Such safety studies associate mass data in the form of crash rates with geometric design features of a treatment and are favoured for pragmatic reasons regarding data availability, data quality and established analysis methods. However, roundabouts present high levels of complexity and heterogeneity that makes it difficult to gather enough crash data from enough similar roundabouts to confidently be able to associate particular geometric features with crash risk. The task becomes close to impossible for examining cyclist safety in situations in which bicycles have low modal share – which is commonly the case.

The pragmatic case study rejects the use of mass data studies in favour of a before/after observational technique applied to the conversion of a tangential roundabout to a radial design base. If the pragmatic use of statistically-based mass data studies has correctly identified speed as the causal mechanism for safety differences in tangential and radial roundabouts, then no significant non-speed causal mechanisms should be identified by using this alternative methodology. Instead, the case study identifies that the relative angles between a bicycle passing through the roundabout and a car approaching on the next leg have an implication for motion detection in the driver's peripheral field of view. In particular, tangential geometry creates conditions under which an approaching driver, who is obliged by law to yield but is looking at his/her onwards path, is unlikely or unable to detect a cyclist circulating within the roundabout and located in the driver's peripheral field of view. In contrast, successful motion detection is highly likely under conditions of radial design. Further, the relative geometries point to cyclist tracking as being relevant to likelihood of motion detection, and is the first study known to link tracking with crash risk for physical rather than cognitive perception reasons.

The identified motion detection problem becomes particularly relevant if the driver has initially failed to detect a cyclist entering the roundabout. Here, the case study finds that relative angles in the tangential situation are also more likely to contribute to conditions where a circulating car briefly hides the cyclist from the approaching driver's sight (i.e. impedes the driver's sightline.) Such events occurred in over a quarter of all interactions between a cyclist and entering driver under tangential design for the case study roundabout, but roughly half this rate under radial design.

Together, these non-speed related results are considered important contributors to the safety performance of radial versus tangential roundabouts for cyclist safety. This demonstrates that rejecting the pragmatic use of the mass data approach has led to the identification of significant non-speed related safety factors, which satisfies the proof by contradiction condition.

Significance of the case studies

The case studies have significance to this dissertation in demonstrating that paradigm and pragmatic practice are having adverse effects on road safety. This is particularly powerful given that such effects had not been previously theorised for the selected case studies, which examine outstanding questions or issues for the traffic engineering field.

The translation from road safety or traffic engineering research to actual road safety occurs through the guidance and codification of traffic engineering guidelines, practice notes, standards and funding decisions. This is true of both of the case study subject areas. TCT analysis is codified in particular forms of practice in several jurisdictions, such as Sweden and The Netherlands; it forms the basis of safety modelling, such as in the U.S.; and is the subject of considerable academic interest worldwide. The pragmatic use of mass data statistical safety studies to identify cyclist safety issues at sites such as roundabouts is well-established and a standard approach for traffic engineers regarding the road network generally, despite the known limitations in relation to cycling. Applying the approach more broadly to associate safety with geometric features has only been stymied at other infrastructure by the inherent difficulties of doing so, which includes a lack of adequate data. Despite these difficulties, no other observational studies apart from this dissertation's case study are known to have been proposed or undertaken for other installations of radial roundabouts or conversions of tangential to radial roundabouts in Australia[66].

In addition to their contribution to the hypothesis, the case studies have significance in and of themselves, which is discussed as follows.

Paradigmatic case study: Traffic Conflicts Technique

TCT-based safety assessments have been undertaken for many years but have limitations that are particularly acute for mixed traffic situations and active transport modes. For cycling in particular, where the crash record is often based on small numbers and is known to under-report crashes, the inability to realise the full potential of TCT has been a constraint to identifying road safety issues. In more recent years, the development of automated video detection has offered the potential to significantly reduce the resources required for TCT-based studies and enable TCT to be used broadly across traffic networks as a safety diagnosis tool. However, the real-world practice of TCT-based techniques such as the Swedish TCT have been found to incorporate a human 'fudge factor' that cannot be replicated for automated video detection, preventing this application.

The use of Extreme Value theory in TET is expected to require a greater degree of accuracy than human observation can provide and to rely in its practical application on automated

[66] Given a reduction in the cyclist involved crash rate at the case study site, a roundabout along the Rugby-Porter bicycle route in Unley, South Australia, has now been converted from a tangential to a radial design base.

video detection. This potentially limits its use to jurisdictions that can resource this technology, but the pace of technological advancements and rapid reduction in their cost over time is such that this is more to be seen as an opportunity than a constraint.

It should also be noted that this practical reliance of TET on technology does not contravene one of the requirements for the proof by contradiction argument, namely that the outcome is not reliant on innovation or new technology. Neither innovation nor new technology were requirements for the development of TET and, in particular, its theoretical framework. Had TET been developed earlier, this might have led to more labour-intensive examinations of video-taped footage to provide additional accuracy, noting that calibration exercises used in the development of TCT relied on exactly this.

Overall, TET has the potential to redefine understandings in the TCT field and fully operationalise the approach. However, it remains a theory until it is tested and proven. It is still possible that the risk profile of a site is not static. This is perhaps even probable: in the pragmatic case study, differences in cyclist encounters with traffic were certainly evident between peak and non-peak periods, so it is reasonable to assume that this might also extend to crash risks. However, if TET demonstrates dynamism of risk profiles, this would itself be a contribution to the TCT body of knowledge. Further, the use of automated video detection coupled with Extreme Value analysis algorithms gives rise to the possibility of at least semi-dynamic TET safety assessment revolving around risk tolerances and a spectrum of profiles established for types of infrastructure or interactions. With the use of LIDAR, there is some potential that this might help to inform AI decision-making in self-driving car applications.

Pragmatic case study: cyclist safety at radial versus tangential roundabouts

While cyclist safety at roundabouts is an arguably particular field, roundabouts continue to be installed in many jurisdictions as part of speed control and safety amelioration measures due to their positive safety benefits to motorised modes and the advantages they present over traffic signals in many applications. This clashes with the stated intent of Federal, State and local governments of encouraging cycling as a transport mode, to help reduce the negative impacts of motorised modes and/or realise the benefits of cycling as an active transport mode and activity[67], notably on designated cycling routes.

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[67] For example, in Australia, the Australian Bicycle Council, consisting of each state and territory government and the Commonwealth, had a target of doubling the amount of cycling between 2011 and 2016 (Austroads 2010).

While radially based roundabouts favoured in European traffic engineering practice appear to perform better for cyclist safety than the tangentially based roundabouts used in Anglophone countries, the reasons for this have not been well established. In this light, the results regarding impeded sightlines and motion detection in the peripheral field assist in explaining the safety effects of geometric design in terms that are not currently considered in the establishment of design standards worldwide. Apart from supporting the use of the radial design base for cyclist safety, these results potentially open a pathway to developing other safety countermeasures, and using geometric analysis of roundabouts to identify the relative risks posed to cyclists by roundabouts across a network. The case study also established that edge-wards tracking compared to island-wards tracking would exacerbate motion detection problems, and is only the second study known to demonstrate rather than derive a safety/ tracking association. The mechanism identified in this study is distinct from that previously found.

The case study has taken the inferential approach suggested by Noland (2013) by testing SiN, LBFS and Conflict Point theories rather than deterministic cause/effect modelling – the latter approach being one that Noland links with the inherent epistemology of engineering sciences and identifies as not being appropriate to the humanistic field of traffic engineering. This highlights a potential paradigmatic link within pragmatic practice and the difficulty this adds to the use of alternative approaches to the pragmatic, even when such approaches are indicated, as in the case of cyclist safety at roundabouts.

While it could be argued that the case study results are particular to the case study roundabout, which was chosen for treatment because of its poor safety record for cyclists[68], at least the motion detection effect can be seen to be associated with the relative geometric outcomes of the two design bases and can therefore be expected to apply more broadly.

Apart from these significant mechanisms, a few other minor safety effects were observed. These provide additional information about the way in which different aspects of roundabout design affect cyclist safety.

Particularly tantalising but tenuous indications were found supporting the proposition of a probabilistic Safety in Numbers (SiN) effect, where cyclist density in the traffic flow can causally link cyclist numbers to improved safety through statistical effects. Due to the

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[68] Representing a classic issue of reversion to mean, for mass data statistical studies.

characteristics related to cyclist safety at roundabouts, SiN would not be expected to significantly increase cyclist safety at roundabouts compared to the safety problems. However, SiN could do so at other types of infrastructure. As the first empirically reported support for a probabilistic SiN effect, the case study has significance in the implications for understanding what is otherwise a difficult effect to quantify. In particular, Thompson, Savino and Stevenson's (2014) modelling of probabilistic SiN implies that cyclist density rather than absolute numbers of cyclists is an important factor in the safety outcome. Compared to the alternative theory of motorist adaptation and behavioural change, a probabilistic SiN is more obviously quantifiable and independent of local culture. If SiN is expected to be a major mechanism of safety risk reduction, both traffic engineers and cyclists need to be assured that the mechanism will operate as assumed and that the local driver culture will not undermine a safety effect whose expected quantum is based on overseas experience.

Further, probabilistic SiN lends itself to first principles understandings of various underlying SiN mechanisms and possible countermeasures, such as increasing cyclist density through signal phasing and platooning, or establishing vehicular thresholds for given cyclist numbers as a management technique on cyclist routes; and methods to assess these through inferential safety analysis.

Significance of the hypothesis

In many ways, the hypothesis is both small and profound. It is small in that many anecdotes have been presented by various road safety researchers over the years pointing to poor research methodology, incorrect analysis or acceptance/rejection of results based on opinion over evidence. Perhaps, from a human behavioural perspective, that there might be negative impacts from road safety professionals adopting mental models, and the pragmatism of professional practice is more to be expected than presenting any real surprise. Further, any adverse effect of paradigm and pragmatism must be taken in relation to the obvious and considerable advances made in road safety research and its application.

But if the hypothesis is accepted, it has profound implications as a confounding problem within traffic engineering and road safety. Though issues and problems in road safety research and practice are not entirely unheard of, previous literature has not identified an adverse effect systemically linked to paradigm and pragmatism; although human errors are to be expected, the many techniques that have been developed by other disciplines to combat these are not taught to traffic engineers; those tasked with caring about road safety have not yet considered how to off-set incentives to self-interest in order to better develop the broader body of road safety knowledge. And while the road safety field has achieved a tremendous amount over the years, while a systemic problem in the field remains unacknowledged, the degree of adverse effect that may be occurring is unknown. Traffic engineers and road safety practitioners do not presently know how much more effective their efforts could be.

To expand on these implications, acknowledging the systemic adverse effect of the hypothesis creates a framework for interpreting examples that are otherwise presented as isolated anecdotes. Kant and Kerr (2018) note that engineers are not often interested in philosophical discussions. This might be extended to self-reflection in general. In the absence of a structured way of interpreting case studies such as those presented by Hauer (2019a, 2019b) or Noland (2013), the issues raised are too easily ignored or set aside as troubling but otherwise isolated problems rather than stimulating an imperative for action.

This being the case, the broader significance of the hypothesis can be seen in several other levels, by critically examining some elements of traffic engineering through the lens of the themes and perspectives established by the literature review. In this regard, practice across jurisdictions is not uniform. Australian examples will be considered for pragmatic reasons of sourcing literature and the author’s familiarity with the field.

The national road safety research agenda

In Australia, Austroads leads the road safety research agenda as a formalised program (compared to the individual-led interests displayed in academic research.) Austroads is a member organisation involving government-based road and transport agencies. Austroads’ (2019) annual report for 2018-19 highlights a research program “…focusing on key crash types that contribute to fatal and serious injury on our road networks” in order to “…support both system-wide and targeted responses to the highest trauma risks identified by road and transport authorities.” Projects within this multi-year program include a pilot linking crash data and hospital admission data, a new Infrastructure Risk Rating (IRR) tool, and update of road safety audit guidance.

Narratives from the sociological and engineering perspectives can be applied to the safety program to derive road safety related traffic engineering paradigm and signs of pragmatic effects. So, while the linking of crash data with hospital admission data will arguably improve data quality, it will also encourage availability and hence use of mass data in safety studies. Meanwhile, the IRR and road safety audit guidance arguably encourage the application of deterministic approaches rather than proposing agenda-setting and encouraging inferential hypothesis testing. Austroads professes commitment to the Safe Systems approach, but there is no mention of the defence-in-depth fallacy described in the examination of engineering psychology, or how to combat this.

Meanwhile, the terms of reference for Austroads' research agenda specifically exclude it from considering policy decisions undertaken by state and national governments or the negative safety results of road-building. The terms of reference would exclude, for example, a review of the factors used in cost-benefit analysis of motor vehicle projects versus active transport projects, and to what extent the predicted benefits of road building actually materialise. Indeed, its road safety program is described in Austroads (2019) as: "Improving the efficient, reliable and safe operation of the road network." That is, even road safety is framed in terms of other priorities, despite the natural human behavioural response to increasingly "efficient, reliable" car travel being to drive more, which undermines the efficiency and reliability of the road network via congestion effects, as well as its road safety.

In contrast, Roads Australia (2018) found that Australia's most populous cities should be actively discouraging private car use and investing heavily in mass transit systems. A difference between these peak organisations is that Roads Australia represents major contractors and consultants, motoring clubs, service providers and other industry groups in addition to the government-based road and transport agencies that comprise Austroads' membership. It could be considered that Austroads has greater pragmatic reason not to be seen as criticising political decisions regarding transport infrastructure, either explicitly or implicitly through its research agenda. A more generous interpretation is that the organisation is subject to group think and, like most of its constituents, lacks the multi-disciplinary outlook that would enable it to consider road safety in a broader way.

In either case, in failing to inhabit this broader traffic engineering domain, Austroads excuses itself from influencing public discourse on holistic road safety impacts and limits itself to subjects that are politically acceptable to its masters. Whatever the intent and however unconscious this may be, the result is an adverse influence of engineering paradigm and/or pragmatism on road safety research.

Effects of traffic engineering paradigm and pragmatic practice can also play out in the guidance Austroads produces. Here, it should be noted that Austroads can and will consider the safety of active transport users within its established paradigm. Austroads responded to concerns about bicycle lanes in roundabouts raised by Patterson (2010) by commissioning Wilke et al. (2014) and then incorporating the findings into Austroads (2015) design guidance. But it is less successful in identifying and addressing more implicit examples of adverse influences of paradigm and practice that affect active transport modes in particular. So, while Austroads (2013) mentions the limitations of crash data in road safety evaluation and that:

> “Effective understanding of a problem often requires deeper investigation than routine examination of the data bases, drawing on theoretical understanding of social, economic, behavioural and medical issues and more detailed analysis which usually relies on additional data sources.” (p.9)

the only actual advice offered in undertaking such deeper investigation is that:

> “The importance of this scientific appraisal lies both in the more precise definition of problems and the identification of appropriate solutions.”

While this in itself arguably only a weakness of advice, expecting a multi-disciplinary approach from road safety researchers without providing any guidance on how to achieve this is a surprising lapse from an organisation with intimate knowledge of Australia’s traffic engineering profession. Notably, Austroads (2013) is roughly contemporary with the research report prepared for Austroads by Cairney, Turner and Steinmetz’ (2012). The latter presents guidance in how to evaluate the effectiveness of road safety treatments – and is based exclusively on mass data approaches.

In fact, Cairney et al. (2012) reference Austroads’ *Guide to Road Safety, Part 2: Road Safety Strategy and Evaluation* (Austroads, 2006) as providing advice regarding behavioural measures when there is insufficient crash data to support outcome evaluation. Austroads (2006) states:

> “Problem analysis involves developing a detailed appreciation of the road safety issues in the area covered by the strategy. This appreciation should be based primarily on the road crash data base, interpreted with caution due to under-reporting of crashes (particularly those involving pedestrians or two-wheel vehicles), to the fact that some information is frequently not reported (e.g. BAC information for drivers and riders), and to the fact that some important information is generally not recorded at all (e.g. BACs for pedestrians). Other relevant

> information sources are hospital records, and public opinion regarding road safety issues."

Again, mass data is the base, and this does not seem to be particularly helpful advice in relation to Cairney et al.'s (2012) referencing of it. Austroads (2006) itself references "Section 5 and Appendix 2 of Part 9 of the *Guide to Road Safety*", however there does not appear have been a *Guide to Road Safety Part 9* prior to 2008. Austroads Part 9 (2008) addresses roadside hazard management and has neither a Section 5 nor any appendices. It is possible that Austroads (2006) intended a reference to a soon-to-be-published document, but if so, the reference remains unclear.

With both Austroads and Roads Australia representing those whose careers revolve around building roads, rather than a diverse view of how well those roads satisfy community needs, it is not surprising that more nuanced road safety agendas are not developed. Hauer (2019a) has concerns regarding the researcher-practitioner relationship, that:

> "It is the 'State' that produces and operates the road network and road-user safety is affected by how this is done. This is why those who on behalf of the 'State' plan, design and operate the road network should take road-user safety into account. However, in my view, their consideration of safety is too often based on opinion rather than evidence."

Apart from opinion rather than evidence, issues of how "road-user safety" is interpreted by communities outside the traffic engineering profession are also relevant. This is most obviously the case through considerations of road safety and population health, which is discussed in the following section.

Population health and Cost Benefit Analysis

As has been noted in this dissertation, cycling is a valid mode of transport but one that does not fit motor vehicle-centric research paradigms, and for which significant issues exist in terms of the quantity and quality of data underpinning pragmatic practice. Robinson's (1998) conclusion that mandatory helmet laws in Australia appear to have increased the crash risk for cyclists is an example of confounding, where a focus on crashes as a symptom of risk has produced contrary effects[69].

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[69] Despite these findings, there has been little movement on Australia's helmet laws: the paradigms of increasing exposure increasing risk and head protection saving lives are so self-evidently true that actual evidence to the contrary is more likely to be dismissed than accepted. Indeed, this paradigm was so self-evident that the data collection that would support a before/after analysis of results was not undertaken.

Assumption of increasing numbers of vulnerable road users resulting in increasing numbers of crashes is also a paradigm-satisfying intuition subject to confounding. Elvik (2009) contends that a large transfer of trips from motor vehicles to walking and cycling would reduce overall risk due to both a Safety in Numbers effect for vulnerable road users and reduced exposure to motor vehicles. This appears to have played out in countries that have achieved relatively high cycling modal share. Hence Andersen et al.'s (2018) finding that cycling in Denmark increased by 10% over the last two decades but cycle-related injuries declined by 55%; de Hartog et al.'s (2010) finding that if the risk presented to other road users is included, the risk of a fatal traffic accident is virtually the same for cyclists and car drivers; or Andersen et al.'s (2018) estimate that the health benefit of physical activity associated with cycling are 21 times higher than the risk of injuries.

But considering only those killed or injured on our roads as defining 'road safety' overlooks the societal context that is set by the safety risk of the transport environment. Would the average Australian feel that our roads are safe enough for parents to allow children to walk and cycle to school? Or that our transport network presents a safe environment for cycling to work, for shopping, to visit friends? Considering walking and cycling in the 1970s and currently, most Australians would perceive the truly remarkable reduction in road crash deaths that has occurred since then as being associated with a deterioration in road safety. And the impact of the resultant increase in deaths from preventable causes arguably outweighs the benefits generated by traffic engineering and road safety practitioners. The degree of adverse effect from paradigm and pragmatism is not a small matter of convenience for certain minor modes; it is a population health result that involves the leading causes of death in Australia[70].

For example, in 2016, compared to the 1,293 road deaths that are the focus of the road safety field, there were 45,392 deaths from cardio-vascular disease and 44,100 from cancer. Given that inactivity is a leading contributor to cancer, cardio-vascular disease and other preventable health problems, it is arguable that the road safety field would achieve the greatest reduction

[70] According to the Australian Institute of Health and Welfare (2019), the leading underlying cause of death in Australia is coronary heart disease, followed by dementia and Alzheimer disease, and cerebrovascular disease (which includes stroke). Physical activity has a protective effect for all of these.

in deaths if they focused on encouraging active transport to the disadvantage of private car travel[71].

Of course, the prioritisation and assessment of road projects by traffic engineers includes more than just absolute numbers of deaths, or road safety in isolation from other effects. Here, the Australian Transport Assessment and Planning (ATAP) Guidelines[72] for economic appraisal provide an exemplar for Australia. The ATAP Guidelines were developed as the single, definitive national source of guidance on transport planning, assessment and appraisal. A mode-specific guidance exists for active travel, including Cost Benefit Analysis.

While the current ATAP Guidelines were updated in 2016, the cost assessments underestimate cycling benefits because they use now-dated information (updated in 2016). The ATAP Guidelines adopts the methodology adopted by Genter et al. (2008) in valuing the health benefits of active travel in New Zealand to the Australian adult population. As Genter et al. (2008) found inadequate evidence supporting the association between active transport and reduced sick days, the methodology does not include a cost estimate for reduced absenteeism. Subsequently, Hendriksen et al. (2010) assessed absenteeism for two Dutch ministries and found that regular commuter cyclists experienced, on average, over a day less absenteeism than non-cyclists – but this remains outside the methodology set by Genter et al. (2008). This is similarly the case for mental health. Most recently, a 2020 study indicates that the active travel risk may be over-estimated, at least for projects primarily aimed at commuter travel[73].

These issues reflect the problems associated with sourcing adequate data quality, and the inevitable lag that occurs between studies being undertaken and advice being updated.

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71 For example, Celis-Morales and Gill (2017) cite Celis-Morales et al. (2017) as finding that cycling to work in the UK is associated with a 41% lower risk of dying overall compared to commuting by car or public transport, with cycle commuters having a 52% lower risk of dying from heart disease and a 40% lower risk of dying from cancer. Andersen et al. (2018) estimate that for Denmark, cycling may prevent over 6,000 deaths each year. This is for a country with a population of some 6 million, compared to Australia's 25 million.

72 https://www.atap.gov.au/mode-specific-guidance/active-travel/5-estimation-of-benefits

73 Fatality rates for motorists and active travellers in Australia, based on data from 2002 to 2006, has been used to determine that active travel risk is up to eight times riskier than private motor vehicle travel. However, estimates of crash risk had to exclude Queensland and New South Wales data due to data incompatibilities as used different data sources in estimating travel. Queensland's fatality and injury rates were higher for car drivers and passengers than the estimates used by ATAP, and the active travel rates generally lower.
In one of the largest studies of its kind in the world, Shaw et al. (2020) have found no increase in injury deaths in association with walking and cycling to work compared to driving to work, in a car-dominated transport system (New Zealand, based on a 1996-2006). This implies that for projects aimed at commuting, no additional crash risk should be assumed for active travel compared to driving.

However, the focus on data quality could also be seen as reflecting an engineering culture where information is quantified as much as possible and non-quantified information ignored. To appreciate the adverse impact of this, it can be noted that as late as 2010, no health benefits could be incorporated into Cost Benefit Analysis for cycling projects by most Australian government agencies, even though health benefits of cycling were acknowledged, because these benefits could not be quantified. An alternative approach might have been to use a sensitivity analysis framework to estimate possible benefit ranges that at least reflected this known but unquantifiable benefit. After all, most major infrastructure projects include a contingency sum to account for the likely variation of actual costs to estimated costs, and actual costs of projects are frequently at major variance to the predictions.

There are other weaknesses in the ATAP Guidelines. For example, these reference accident prediction models (or Crash Modification Factors) developed by Turner et al. (2006), but exclude the Safety in Numbers effect as this is considered unreliable. As previously mentioned, both are empirically determined, and given the potentially poor correlation between accident prediction based on mass statistical data and the actual crash risk for cyclists, it is questionable whether one is more accurate than the other. The difference in treatment appears to reflect, at least in part, the paradigmatic acceptability of accident prediction models and unacceptability of Safety in Numbers.

Similarly, Cost Benefit Analysis for road projects rarely incorporates induced car travel, although this is an empirically established phenomenon. Nor does it consider the health costs of projects that encourage more or longer trips, or driving instead of active travel. Other costs and benefits that may be poorly incorporated into Cost Benefit Analysis include amenity, tourism, housing value capture from new paths, urban revitalisation, the ability for self-actualisation associated with self-mobility of children, the social costs of severance, and so on. And in Australia, road projects are rarely compared with travel demand management or planning alternatives that ameliorate the need to travel at all. These all jar with a traffic engineering paradigm based on supply, demand, predictable traffic units, quantifiable values and a single-discipline view; though entirely compatible with road user reflexivity, social values and a multi-disciplinary view.

At least some of these other costs/benefits have found their way into Cost Benefit Analysis methodologies and other ways of valuing cycling infrastructure overseas (such as satisfying social inclusion/ social justice goals). Apart from the conclusion that Australia's road safety practitioners are more firmly placed within a traffic engineering paradigm than their overseas counterparts, it has been argued[74] that investment in major cycling infrastructure in other countries is partly a pragmatic response to the fact that few road projects can demonstrate a high enough benefit to cost ratio to support their implementation. Small changes in Cost Benefit Analysis have had a large impact, including incentivising traffic engineers to develop cycling infrastructure to satisfy their professional practice.

Changing paradigm and ceding professional domain as part of embracing multi-disciplinary approaches are not simple to achieve. However, a broader issue for road safety practitioners might be the difficulty in effectively achieving the desired road safety results at all. This is discussed in the context of adaptive leadership, as follows.

Adaptive leadership

It is notable that the major road safety advances from the peak death rates of the 1970s occurred in conjunction with, according to McLean (1988), the road safety field concluding that road safety could not be considered solely from an engineering perspective. The road safety profession of the time identified that it needed to change established road user behaviours in a way that would curtail the accepted norms of the majority of the community. The profession's response successfully challenged and re-set the socio-political environment as a key to facilitating the road safety result.

As interpreted according to Heifetz and Linsky's (2002) views on leadership, this narrative reflects problem specification that differentiates between technical and adaptive problems. Under their theory of adaptive leadership, technical problems can be addressed by a technician or expert who fine tunes existing ways of getting things done. In comparison, adaptive problems require deeper transformation by more people in the community who have to change their values, behaviour, or attitudes. Menzel, Aaltio and Ulijn (2007) might quibble about the characterisation of all technical problems in this singular way and argue for the methods of innovation, entre- and intrapreneurialship as presenting a distinct problem/ solution type compared to Heifetz and Linsky's (2002) typology. Nonetheless, the road safety initiatives of the 1970s – introducing mandatory seat-belts, blood alcohol limits, random breath testing, etc – are all examples of solutions to adaptive problems. Many current imperatives in road safety also reflect adaptive problems, such as introducing lower speed

[74] Author's personal communications.

limits, improving motorist attitudes and behaviour towards active transport modes, or generating modal shift away from private car use. However, the most recent road safety strategies in South Australia and Federally have generally failed to generate the community interest that would allow socio-political change[75]. This to some extent reflects an incorrect problem specification for road safety that positioned it as a technical rather than adaptive problem, and a focus on the road system at the expense of considering the greater socio-political environment as a subject for road safety practice.

Effective approaches to solving adaptive problems are different to those that will be successful for technical problems. They lie outside technical competencies generated by a paradigmatically defined engineering education, or the established methods used in the traffic engineering profession. A variety of theoretical frameworks apply, but are not relevant in terms of this thesis' hypothesis. It is notable, however, that adaptive problems were not beyond the ability of the traffic engineers of McLean's time to develop and apply, with the help of a Human Factors Committee. Difficulty in developing the techniques that would allow greater success has occurred after the disbandment of the Human Factors Committee and a withdrawal from the multi-disciplinary approach that was then prevalent, and a solidification of pragmatic/paradigmatic approaches involving quantifying and ignoring the less quantifiable. Achieving the effectiveness of previous road safety practitioners arguably requires a return to adaptive leadership philosophies and an appreciation for the socio-political environment.

This dissertation posits that paradigm and pragmatism are having an adverse effect on road safety, an hypothesis that has been previously identified in these terms. Rather than being taken as a criticism, it could be considered in the same way that the road safety field of the past took the conclusion that road safety could not be considered solely from an engineering perspective: as a challenge to be met with creativity, innovation and collaboration. These are, after all, the hallmarks of the successful engineer.

Further research

The two case studies provide fertile ground for further research.

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[75] Feedback received from the South Australian Road Safety Strategy Working Group via the author's personal involvement, 2020.

As noted, the paradigmatic case study has the potential to redefine understandings in the TCT field and fully operationalise the approach. However, this potential needs to be tested through practical safety studies. This will no doubt involve methodological considerations and include considerations of the complexities in applying Extreme Value theory. Obvious areas to be explored include data requirements for TET-based studies; whether risk at a site is static or dynamic and the drivers of this; the use of the Block Maxima method or the Peaks-Over-Threshold method; refinement of a severity indicator linked to delta-V; comparative 3D risk shapes for different treatment types; and so on.

The pragmatic case study of cyclist safety at radial versus tangential roundabouts reflects the conditions at a single site. Although at least the motion detection effect would seem to be generalisable across typical radial or tangential designs, repeating the analysis at roundabouts of different sizes and operating conditions would add robustness to the case study results. This should include confirming (or otherwise) cyclist tracking impacts on safety effects.

In fact, due to the geometric element of the motion detection effect, a desktop analysis of roundabouts on the basis of expected relative positioning of subject bicycles and entering cars would form a relatively quick and inexpensive first-pass analysis of how widespread and severe the effect is at different roundabouts across a network. This would give an indication of safety risk to cyclists associated with this effect and, depending on the results, enable the examined roundabouts to be prioritised for treatment. There may also be some element of the motion detection effect applying to subject cars against entering cars, particularly for larger roundabouts.

The confirmation of the identified radial versus tangential design safety effects would justify a review and update of Australian design standards for roundabouts – including removal of commentary regarding Conflict Point theory.

The tenuous indications of a probabilistic Safety in Numbers effect warrant further exploration through inferential testing at types of infrastructure more conducive to the SiN effect. This could lead the way for SiN to be applied as a safety measure in well-understood circumstances, and for measures to be designed to maximise the SiN effect. A more robust, quantifiable understanding of SiN would also pave the way for the effect to be incorporated into cost-benefit analysis.

In terms of the broader hypothesis, including the themes and perspectives developed through the literature review, it is more appropriate for experts in education, research, sociology and so forth to identify appropriate future research directions.

7. Conclusions

By pointing out the adverse effects of engineering paradigm and pragmatism on road safety, and ascribing causes to such human frailties as cognitive psychology, resource limitations and self-interest, this dissertation will no doubt be seen as being critical of traffic engineers and the profession at large. In fact, the profession has a justifiably proud history and by raising issues related to the current modes of thinking and ways of doing things, the dissertation could instead be seen as encouraging reinvigoration for the field.

The literature review points to engineering as a profession that has been at its most productive when technical know-how is matched by social skills. From Lloyd et al. (2001), the most significant competencies an engineering student needs are not just represented by "…an excellent understanding of societal needs*"* but also the capacity to be an innovator and entrepreneur. While not explicitly stated, this involves communication and negotiation skills, a firm understanding of economic principles, and human skills of project management and leadership – all 'non-technical' skills under the current engineering education paradigm. From McLean (1988), the leadership of a Human Factors Committee led to a productive period of the Australian traffic engineering research. And the case studies indicate the value of adopting a multi-disciplinary approach, regarding Extreme Value theory in the paradigmatic case study and optics in the pragmatic case study.

Commentary by engineering educators points to multi-disciplinary skills being eroded by academic education through the pragmatic pressures of professionalisation. However, Lloyd et al. (2001) also note the changing face of engineering practice in the dominant employee-based workforce that existed for engineers up until the 1970s-80s being replaced by a workforce having greater emphasis on private practice. Arguably, the development of these large public workforces actually worked against the tradition of "The famous engineers of the Industrial Revolution…." Public sector employees are isolated from the market economics integral to entrepreneurialism, and if trained up through cadetships into job-for-life positions, do not bring additional multi-disciplinary experience to the organisation. Increasing specialisation at earlier and earlier ages would only exacerbate a narrowing of knowledge base.

The current-era appreciation of innovation and entrepreneurs therefore offers an opportunity to revisit academic curricula to produce more rounded professionals and, it is acknowledged, many academic institutions appear to be responding to this. Whether universities will find the same difficulties in attracting appropriately qualified and experience lecturers to be able to transmit information more successfully than noted by Lloyd et al. (2001), Hilburn and Humphrey's (2002) or Rojter (2004) remains to be seen.

The literature in engineering judgment and engineering psychology points to a particular need for an engineer's non-technical skills to include knowledge of cognitive biases and techniques such as reflective practice developed to help counteract these. If not covered by academic institutions, government agencies could require certain competencies of employees and consultants as a condition of contract, coupled by making appropriate instruction available such that this does not become an exclusionary gate-keeper requirement. Standards, guidelines and requirements for continuing professional development could also incorporate information on common types of internal bias, to help ensure these have been considered.

However, while the case studies demonstrate the value of bringing multi-disciplinary understandings to problems in road safety, the almost exponential expansion of knowledge occurring in modern times renders infeasible the idea that engineers could be conversant in all fields relevant to their practice. Here, McLean's (1988) Human Factors Committee might provide a useful template for organisations such as Austroads in developing multi-disciplinary research agendas. The agenda developed by such a Committee would arguably consider the broader social benefits of modes such as cycling[76].

These considerations of engineering conform to Whitley's (2000) and Jacobs and Frickel's (2009) observations about engineering as a dynamic rather than static discipline. Within engineering, its sub-branches (engineering fields or disciplines) are aligned with particular technologies and describe a domain of knowledge based on fundamental units related to the area of practice. That engineering responds to technology is obvious in engineering disciplines such as aeronautical or even traffic engineering, as deriving from new technologies and hence technological change.

For traffic engineers, advances in driverless cars or Internet of Things technologies will affect their practice. In this future, Traffic Events Theory could provide a method by which automated technologies can assess safety and risk in complex traffic environments.

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[76] An early committee tasked with considering the most cost-effective approaches to mitigating carbon emissions pointed out that cycling should be encouraged due to the benefit-cost ratio from health alone. (Author's personal experience.)

Pragmatically, technology in the form of the Internet of Things and Edge computing[77] may offer a future pathway for collecting exposure data for cyclists and pedestrians by providing an inexpensive, distributed network of counters based on automated video analysis.

What is less well recognised than the impact of technological change is the way in which engineering responds to community needs and social change. This is evident in the preceding descriptions from McLean (1988) and Lloyd et al. (2001), or Moore and Hughes' (1991) comments about their traffic engineering practice "…[being] driven by public opinion…" or that "…we [traffic engineers] are obliged to accept the values of the day." Law and Callon (1988) also argue that engineers are practical sociologists enforcing their paradigm on multiple aspects of a system through pragmatic responses to other engineer-sociologists. Investment in even the inexpensive network of Internet of Things-based counters mentioned above requires a decision to be made within a practice that currently under-values active travel modes, but also the non-technical understandings that generate socio-political change. This political decision to fund a distributed data collection network for pedestrians and cyclists could be made for reasons of efficiency compared to commissioning counts of these road users, or filling a paradigm gap by including active modes in collected traffic data, or to satisfy public demands that active modes be included in traffic engineering decision-making. It will not be made under current business-as-usual conditions.

If the vision of engineering as a dynamic, politically-engaged and socially-aware profession challenges the picture of engineers as staid technologists objectively applying learned truths to predictable systems, then it is also a more honest characterisation of engineers and engineering than typically promulgated. And it offers engineers the opportunity for their work to be recognised as possessing social relevance. Such recognition only enhances the standing of engineers, as can be seen in developing countries where the results of engineering practice in providing clean drinking water, working sanitation and supporting economic systems in a myriad of ways translates to engineers having amongst the highest standing of all professionals, vying only with doctors at the pinnacle of regard. Increasing the breadth of professional engineering education is likely to reap benefits regarding the ongoing issue of low female representation in engineering. And in considering the future, professionals who display complex social understanding in a field catering to human needs will be less

[77] Edge computing refers to the ability for computational analysis to be undertaken at the collection point, enabling the transmission of pre-processed data via low range, wide-area networks (LoRaWANs) rather than transmitting large amounts of raw data over higher capacity networks.

vulnerable to replacement with AI than technologists who faithfully apply heuristic-driven decision-making in a model-driven environment.

Traffic engineers and road safety researchers should not, then, regard the statement that “Engineering paradigm and pragmatism are having an adverse influence on road safety” as representing mere criticism and rebuke. They should instead regard it as a call for the profession to acknowledge that, fundamentally, engineers are as human as anyone else.

To err is human. To recognise sources of error in our thinking, to incentivise research against self-interest, and to embrace methods to improve both our research and social performance is a struggle against human nature that is worth pursuing.

8. References

Adams J, Hillier-Brown F, Moore H, Lake A, Araujo-Soares V, White M and Summerbell C (2016), Searching and synthesising 'grey literature' and 'grey information' in public health: critical reflections on three case studies. *Systematic Reviews*, Volume 5, Article 164. doi:10.1186/s13643-016-0337-y.

Al-Omari B, Ghuzlan K and Al-Heloa L (2014), Modeling through Traffic Speed at Roundabouts along Urban and Suburban Street Arterials. *Journal of the Transportation Research Forum*, Volume 53, No. 2 (Summer 2014), pp7-19.

Allott and Lomax Ltd (1991), Cyclists and Roundabouts: A Review of Literature. *Cyclists' Touring Club Technical Report*, Cyclists' Touring Club, Godalming, UK.

Alrutz D, Angenendt W, Draeger W and Gündel D (2002), 'Verkehrssicherheit in Einbahnstraßen mit gegengerichtetem Radverkehr' (Traffic safety on one-way streets with contraflow bicycle traffic). *Straßenverkehrstechnik*, Issue 6, 2002, translated by John S Allen c2003 at www.bikexprt.com/research/contraflow/gegengerichtet.htm.

Amundson F and Hydén C (1977) Traffic conflicts technique-status in Norway. *Proceedings of first workshop on traffic conflicts*, Institute of Economics, Oslo.

Andersen H and Hepburn B (2016), Scientific Method. *The Stanford Encyclopedia of Philosophy* (Summer 2016 Edition), Zalta E (ed.), https://plato.stanford.edu/archives/sum2016/entries/scientific-method/.

Andersen L, Riiser A, Rutter H, Goenka S, Nordengen S and Solbraa A (2018), Trends in cycling and cycle related injuries and a calculation of prevented morbidity and mortality. *Journal of Transport and Health*, Vol 9, pp217-225.

Andreassend D (1985), Letter to the Editor. *Australian Road Research Board*, Volume 15, Issue 1, pp58-59.

Aumann P, Pratt K and Papamiltiades A (2017), *Bicycle Safety at Roundabouts*. Austroads Research Report AP-R542-17, pub. Austroads, Sydney, N.S.W.

Australian College of Road Safety (2010), *ACRS Fact Sheet: Safe Systems Approach*. Pub. Australian College of Road Safety, ACT.

Australian Institute of Health and Welfare (2016), *Australian burden of disease study: impact and causes of illness and death in Australia 2011*. Pub. Australian Institute of Health and Welfare (AIHW), Canberra, ACT.

References

Australian Institute of Health and Welfare (2019), *Deaths in Australia*. Web report, cat. no: PHE 229, https://www.aihw.gov.au/reports/life-expectancy-death/deaths-in-australia/contents/leading-causes-of-death. (Accessed 14 December 2019).

Austroads (2006), *Guide to Road Safety, Part 2: Road Safety Strategy and Evaluation*. Austroads publication no. AGRS02-06, pub. Austroads, Sydney, N.S.W.

Austroads (2007), *Guide to Traffic Management Part 6: Intersections, Interchanges and Crossings*. Austroads publication no. AGTM06/07, pub. Austroads, Sydney, N.S.W.

Austroads (2008), *Guide to Road Safety Part 9: Roadside Hazard Management*. Austroads publication no. AGRS09-08, pub. Austroads, Sydney, N.S.W.

Austroads (2009), *Guide to Road Design – Part 4B: Roundabouts*. Austroads publication no. AGRD04B/09, pub. Austroads, Sydney, N.S.W.

Austroads (2012), *Managing Asset Management Related Civil Liability Risk*. Austroads publication no. AP-R412-12, pub. Austroads, Sydney, N.S.W.

Ausroads (2013), *Guide to Road Safety – Part 2: Road Safety Strategy and Evaluation*. Austroads publication no. AGRS02-13, pub. Austroads, Sydney, N.S.W.

Austroads (2015), *Guide to Road Design – Part 4B: Roundabouts*. Austroads publication no. AGRD04B-15, pub. Austroads, Sydney, N.S.W.

Austroads (2019), *Austroads Annual Report 2018-19*. Austroads publication no. AP-C20-19, pub. Austroads, Sydney N.S.W.

Azevedo C and Farrah H (2015), Using Extreme Value Theory For the Prediction of Head-On Collisions During Passing Maneuvres. Intelligent Transportation Systems Conference (ITSC), *Proceedings of the 2015 IEEE 18th International Conference on Intelligent Transportation Systems*, 15-18 September 2015, Gran Canaria, Spain, pp268-273.

Bachmann C, Roorda, M and Abdulhai B (2011), Improved time-to-collision definition for simulating traffic conflicts on truck-only infrastructure. *Transportation Research Record, Journal of the Transportation Research Board*, Issue 2237, pp31-40.

Bagdadi O (2013), Estimation of the severity of safety critical events. *Accident Analysis and Prevention*, Issue 50, pp167-174.

Barber B (1963), Some Problems in the Sociology of the Professions. *Daedalus*, Volume 92, Number 4, pp669-688. JSTOR, www.jstor.org/stable/20026806.

Beddoes K, D Montfort and S Brown (2017), Squaring Philosophy of Engineering Through Personal Epistemologies Research. *Philosophy and Engineering: Exploring Boundaries, Expanding Connections*, Michelfelder D, Newberry B, Zhu Q (eds), published by Springer Nature, Switzerland.

Bergh T (1997), Roundabouts – Current Swedish practice and research. *Third International Symposium on Intersections Without Traffic Signals*, 21–23 July 1997, Portland, Oregon, Transportation Research Board, Washington DC, pp. 36–44.

Bhatia R and Wier M (2011), “Safety in Numbers” re-examined: Can we make valid or practical inferences from available evidence? *Accident Analysis and Prevention*, Volume 43 (2011), pp235–240.

Boell S and Cecez-Kecmanovic D (2015), On being ‘systematic’ in literature reviews. In: Willcocks L, Sauer C, Lacity M (eds), *Formulating Research Methods for Information Systems*, pub Palgrave Macmillan, London. Chapter 11, pp48-78.

Bommier E (2014), *Peaks-Over-Threshold Modelling of Environmental Data*, U.U.D.M. Project Report 2014:33, pub. Uppsala Universitet.

Boon M (2011), In Defense of Engineering Sciences. *Techné* 15:1, pp 49-71, Winter 2011.

Brilon W (2011), Studies on Roundabouts in Germany: Lessons Learned. *3rd International TRB-roundabout Conference*, Carmel, Indiana, May 2011.

Brindle R (1984), *Town planning and road safety*. ARRB Special Report, SR No. 28.

Brüde U and Larsson J (2000), What roundabout design provides the highest possible safety? *Nordic Road & Transport Research*, Swedish National Road and Transport Research Institute, Number 2, pp17-21.

Buyruk H (2013), “Professionalization” or “Proletarianization”: Which Concept Defines the Changes in Teachers’ Work? *Procedia – Social and Behavioral Sciences*, Issue 116, pub. 2014, pp1709-1714.

Cairney P, Turner B and Steinmetz L (2012), *An Introductory Guide for Evaluating Effectiveness of Road Safety Treatments.* Austroads Research Report AP-R421-12, pub. Austroads Ltd, Sydney, N.S.W.

Campbell D, Jurisich I and Dunn R (2006), *Improved multi-lane roundabout designs for cyclists,* Land Transport New Zealand Research Report 287, 140 pp.

Campbell D, Jurisich I and Dunn R (2011), Improved multi-lane roundabout designs for all road users. *Technical Conference of the Institution of Professional Engineers New Zealand Transportation Group (IPENZ-TG)*, Auckland, New Zealand, 2011.

Campbell K, Joksch H and Green P (1996), *A Bridging Analysis for Estimating the Benefits of Active Safety Technologies.* Report No. UMTRI-96-18, University of Michigan, Transportation Research Institute, Ann Arbor, Michigan.

Carter (ed.) (2017), *Road Safety Fundamentals: Concepts, Strategies, and Practices that Reduce Fatalities and Injuries on the Road.* Publication No. FHWA-SA-18-003, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

Cascio W (2015), Industrial–Organizational Psychology: Science and Practice. *International Encyclopedia of the Social and Behavioral Sciences (Second Edition),* Volume 11, Wright D (ed.), pub. Elsevier Health Sciences, London, pp879-884.

Celis-Morales and Gill J (2017), Cycling to work: major new study suggests health benefits are staggering, *The Conversation*, 20 April 2017. http://theconversation.com/cycling-to-work-major-new-study-suggests-health-benefits-are-staggering-76292

Celis-Morales C, Lyall D, Welsh P, Anderson J, Steell L, Guo Y, Maldonado R, Mackay D, Pell J, Sattar N and Gill J (2017), Association between active commuting and incident cardiovascular disease, cancer, and mortality: prospective cohort study. *BMJ* 2017;357:j1456, http://dx.doi.org/10.1136/bmj.j1456.

Chapman C, Bicca-Marques J, Calvignac-Spencer S, Fan P, Fashing P, Gogarten J, Guo S, Hemingway C, Leendertz F, Li B, Matsuda I, Hou R, Serio-Silva J and Stenseth N (2019), Games academics play and their consequences: how authorship, h-index and journal impact factors are shaping the future of academia. *Proceedings of the Royal Society B*, Biological Sciences Practices, 286.

Chen Y, Persaud B, Sacchi E and Bassani M (2013), Investigation of models for relating roundabout safety to predicted speed. *Accident Analysis and Prevention*, Volume 50, January 2013, pp196-203.

Chin H and Quek S (1997), Measurement of Traffic Conflicts. *Safety Science,* Volume 26, Number 3, pp169-185, 1997.

Coles S (2001), *An introduction to statistical modeling of Extreme Values*. Springer-Verlag, London, UK, 2001.

Cropp N, Banks A and Elghali L (2011), Expert Decision Making in a Complex Engineering Environment: A Comparison of the Lens Model, Explanatory Coherence, and Matching Heuristics. *Journal of Cognitive Engineering and Decision Making*, Volume 5, Issue 3, pp255-276. https://doi.org/10.1177/1555343411415795.

Crotty M (1998), *The Foundations of Social Research: meaning and perspectives in the research process*. Pub. Allen & Unwin, Crows Nest, NSW.

Cumming B (2010), *Roundabout Design: Minimising Conflicts for Bicycle Riders*. Swinburne University of Technology.

Cumming B (2012), A bicycle friendly roundabout: designing to direct cyclists to ride where drivers look. *4th Australian Cycling Conference*, Bonham J and Lumb P (eds.), pub. Australian Cycling Conference Inc., Adelaide.

Cunningham C and Kelly G (2016), Epistemic Practices of Engineering in Education. *Annual Meeting of NARST*, 2016 in Baltimore, MD.

Daniels S and Wets G (2005), Traffic Safety Effects of Roundabouts: a Review with Emphasis on Bicyclist's Safety. *Proceedings of the 18th ICTCT Workshop*, 27-28 October 2005, Helsinki, Finland.

Daniels S, Brijs T, Nuyts E and Wets G (2009), Design types of cycle facilities at roundabouts and their effects on traffic safety: Some empirical evidence. *Velo-City 2009 Cycling Conference*, 14 May 2009, Brussels.

Davis M (1992), Professional Judgment. *Perspectives on the Professions*, Volume 11, Number 2.

Davis M (2012), A plea for judgment. *Science and Engineering Ethics*, Volume 18, Issue 4, pp789-808. https://doi.org/10.1007/s11948-011-9254-6.

Debnath A, Wilson A and Haworth N (2014), Proactive safety assessment in roadwork zones: a synthesis of surrogate measures of safety. *Proceedings of the 2014 Occupational Safety in Transport Conference*, Crowne Plaza Surfers Paradise, Queensland, Australia.

de Brabander and Vereeck L (2007), Safety effects of roundabouts in Flanders: Signal type, speed limits and vulnerable road users. *Accident Analysis and Prevention*, Volume 39, Issue 3, May 2007, pp 591-599.

de Geus B, Vandenbulcke G, Int Panis L, Thomas I, Degraeuwe B, Cumps E, Aertsens J, Torfs R and Meeusen R (2012), A prospective cohort study on minor accidents involving commuter cyclists in Belgium. *Accident Analysis and Prevention*, Issue 45, pp 683-93, March 2012.

de Hartog J, Boogaard H, Nijland H and Hoek G (2010), Do the Health Benefits of Cycling Outweigh the Risks? *Environmental Health Perspectives*, August 2010, Volume 118, Issue 8, pp1109-1116.

Delattro E (1992), Judgment in Police Work. *Perspectives on the Professions*, Volume 11, number 2.

de Vries M (2003), The Nature of Technological Knowledge: Extending Empirically Informed Studies into What Engineers Know. *Techné: Research in Philosophy and Technology*, Volume 6, Number 3.

Dozza M (2017), Crash risk: How cycling flow can help explain crash data. Accident Analysis and Prevention, Issue 105 (2017), pp21-29.

Edwards J, Ross L, Wadley V, Clay O, Crowe M, Roenker D and Ball K (2006), The useful field of view test: Normative data for older adults. *Archives of Clinical Neuropsychology,* Issue 21, pp275-286, 2006.

El-Basyouny K and Sayed T (2013), Safety performance functions using traffic conflicts. *Safety Science*, Volume 51, pp160-164.

Elstein A (1992), Balancing Risks and Benefits in Clinical Decision Making. *Perspectives on the Professions*, Volume 11, number 2.

Elvik R (2003), Effects on road safety of converting intersections to roundabouts: review of evidence from Non-U.S. studies. *Transportation Research Record: Journal of the Transportation Research Board*, Issue 1847, pp1-10, 2003.

Elvik R (2004), 'To what extent can theory account for the findings of road safety evaluation studies?'. *Accident Analysis & Prevention*, Volume 36, Issue 5, September 2004, pp841-849.

Elvik R (2009), The non-linearity of risk and the promotion of environmentally sustainable transport. *Accident Analysis and Prevention*, Volume 41 (2009), pp849–855.

Elvik R and Vaa T (2004), *The handbook of road safety measures*. ISBN-13: 978-0-08-044091-0; Institute of Transport Economics, Norway, 2004.

Evans L (1985), Human behavior feedback and traffic safety. *Human Factors*, Issue 27, pp555-576.

Evans L (1991), *Traffic safety and the driver.* Van Nostrand Reinhold, New York, NY.

Ewing R and Dumbaugh E (2009), The built environment and traffic safety: a review of empirical evidence. *Journal of Planning Literature*, Volume 23, Issue 4, pp347-367.

Farah H and Azevedo C (2016), Safety analysis of passing maneuvers using extreme value theory. *IATSS Research*, http://dx.doi.org/10.1016/j.iatssr.2016.07.001

Ferrari R (2015), Writing narrative style literature reviews. *Medical Writing*, Volume 24, Number 4, pp230-235.

Ferreira A and de Haan L (2015), On The Block Maxima Method In Extreme Value Theory: PWM Estimators. *The Annals of Statistics 2015*, Volume 43, No. 1, pp276–298.

Ferroff C, Mavin T, Bates P and Murray P (2012), A case for social constructionism in aviation safety and human performance research. *Aeronautica*, Issue 3, 2012.

Foster J, Rzhetsky A and Evans J (2013), Tradition and Innovation in Scientists' Research Strategies. *CoRR*, abs/1302.6906, n page.

Feynman R (2001), *''What Do You Care What Other People Think?": Further Adventures of a Curious Character.* Leighton, R. (Ed.). Reprint ed. W. W. Norton & Company.

Fouad N, Singh R, Cappaert K, Chang W and Wan M (2016), Comparison of women engineers who persist in or depart from engineering. *Journal of Vocational Behavior*, Issue 92, pp79-93.

Gabbay D, Meijers A, Woods J and Thagard P (Eds), (2009), *Philosophy of Technology and Engineering Sciences*, 1st Edition. Pub. New Holland, New York.

Gårder P (1985), Theory for strong validation, application of Swedish results. *Proceedings from Evaluation 85: International Meeting on the Evaluation of Local Traffic Safety Measures*. Paris, France: Organisation National de Securite Routiere, 1985.

Genter J, Donovan S and Petrenas B (2008), *Valuing the health benefits of active transport modes.* New Zealand transport agency research report No. 359, Wellington, N.Z.

Gettman G, Pu L, Sayed T and Shelby S (2008), *Surrogate Safety Assessment Model and Validation: Final Report.* U.S. Department of Transportation Federal Highway Administration, Washington, D.C.

Glauz W and Migletz D (1980), *Application of Traffic Conflict Analysis at Intersections.* NCHRP Report 219, Transportation Research Board, Washington, D.C., 1980.

Glover I and Kelly M (1987), Introduction: Sociology and Engineering. *Engineers in Britain*, pp3-9, Springer, Boston, MA.

Gössling S and Choi A (2015), Transport transitions in Copenhagen: Comparing the cost of cars and bicycles. *Ecological Economics*, Issue 113, pp106-113. DOI: 10.1016/j.ecolecon.2015.03.006.

Gray C and Fernandez T (2018), When World(view)s Collide: Contested Epistemologies and Ontologies in Transdisciplinary Education. *International Journal of Engineering Education*, Volume 34, Issue 2B, pp574-589.

Grayson G, Hydén C, Kraay J, Muhlrad N and Oppe S (1984), *The Malmö Study: A Calibration of Traffic Conflict Techniques.* Report R-84-12, ed Grayson G, Institute for Road Safety Research SWOV, Leidschendam, The Netherlands, 1984.

Green E (2016), "What are the most-cited publications in the social sciences (according to Google Scholar)?" *LSE Impact Blog*, retrieved December 14, 2019.

Green F and Harrison W (2002), *Investigation of Cyclist Safety at Intersections*. Austroads publication no. AP-R206-02, pub. Austroads Sydney, N.S.W.

Grimson W and Murphy M (2015), Chapter 9: The Epistemological Basis of Engineering, and Its Reflection in the Modern Engineering Curriculum. *Engineering Identities, Epistemologies and Values – Engineering Education and Practice in Context*, Volume 2, Christensen S, Didier C, Jamison A, Meganck M, Mitcham C and Newberry B (eds), pub Springer International, Switzerland.

Guido G, Saccomanno F, Vitale A, Astarita V and Festa D (2011), Comparing safety performance measures obtained from video capture data. *Journal of Transportation Engineering*, Volume 137, Issue 7, pp481-491.

Haddaway N, Woodcock P, Macura B and Collins A (2015), Making literature reviews more reliable through application of lessons from systematic reviews. *Society for Conservation Biology*, Volume 29, Issue 6, pp1596-1605.

Hamilton, J (2000), *The Engineering Profession: A comparison between the operation of the engineering profession in the United Kingdom and other countries*. Pub Engineering Council, London UK.

Hauer E (1978), Design Considerations of Conflict Survey. *Transportation Research Record,* Transportation Research Board, Issue 667, pp57-66, 1978.

Hauer E (1997), *Observational Before-After Studies in Road Safety: Estimating the Effect of Highway Traffic Engineering Measures on Road Safety*. Pub. Emerald Group Publishing Limited, Bingley, United Kingdom.

Hauer E (2005), Cause and Effect in Observational Cross-Section Studies on Road Safety. Unpublished manuscript.

Hauer E (2019a), On the relationship between road safety research and the practice of road design and operation. *Accident Analysis and Prevention*, Volume 128, pp114-131.

Hauer E (2019b), Engineering judgment and road safety. *Accident Analysis and Prevention*, Volume 129, pp180-189.

Hawse S and Wood L (2017), Fostering wise judgment: professional decisions in development programmes for early career engineers. *Journal of Vocational Education and Training*, Volume 70, Issue 2. Https://doi.org/10.1080/13636820.2017.1410723

Hayward J (1971), *Near misses as a measure of safety at urban intersections*. Ph.D. thesis, Department of Civil Engineering, Pennsylvania State University.

Heifetz R and Linsky M (2002), *Leadership on the Line: Staying Alive Through the Dangers of Leading.* Harvard Business School Press, Boston, Massachusetts.

Hendriksen I, Simons M, Galindo Garre F and Hildebrandt V (2010), The association between commuter cycling and sickness absence. *Preventive Medicine,* Issue 51, 2010, pp132-135.

Herland L and Helmers G (2002), *Cirkulationsplatser – utforming och funktion* (Roundabouts – design and function. Swedish and foreign recommendations and design rules with analyses and comments), Swedish National Road and Transport Research Institute, 2002.

Herslund M-B and Jørgensen O (2003), Looked-but-failed-to-see-errors in traffic. *Accident Analysis and Prevention,* Issue 35, 2003, pp885-891.

Hilburn T and Humphrey W (2002), Teaching Teamwork. *IEEE Software*, Volume 19, Issue 5, pp72-77.

Hitzemann M (2003), Reconstruction of low speed rear-end collisions – Technical means of assessing cervical spine injuries. Republished article, *Pain Research and Management*, Volume 8, Number 1, pp28-29.

Hudson L (1975). *Human beings: An introduction to the psychology of human experience*, pub. Cape Publishing, London.

Hughes B (2017), *A Comprehensive Framework for Future Road Safety Strategies.* Doctoral thesis, Curtin University, School of Occupational Therapy and Social Work.

Hydén C (1987), *The development of a method for traffic safety evaluation: the Swedish traffic conflict technique*. Doctoral thesis, Lund University, Department of Traffic Planning and Engineering.s

Hydén C and Várhelyi A (2000), The Effects on Safety, Time Consumption and Environment of Large Scale Use of Roundabouts in an Urban Area: a Case Study. *Accident Analysis and Prevention*, Issue 32, 2000, pp11-23.

IVA (2019), *Teknisk obalans? Kvinnor och män i teknik*. Kungl. Ingenjörsvetenskapsakademien (IVA), Stockholm 2019.

Jacobs J and Frickel S (2009), Interdisciplinarity: a critical assessment. *Annual Review of Sociology*, Volume 35, 2009, pp 43-65.

Jacobsen PL (2003), Safety in numbers: more walkers and bicyclists, safer walking and bicycling. *Injury Prevention*, Volume 9, Issue 3, pp205-9.

Jensen S (2012) Safety Effects of Converting Intersections to Roundabouts. *Transportation Research Record Journal of the Transportation Research Board*, Volume 2389, pp22-29, 2013.

Johnsson C, Laureshyn A and De Ceunynck T (2018), In search of surrogate safety indicators for vulnerable road users: a review of surrogate safety indicators. *Transport Reviews*, Volume 38, Issue 6, pp765-785. DOI: 10.1080/01441647.2018.1442888.

Jonasson J and Rootzén H (2014), Internal validation of near-crashes in naturalistic driving studies: a continuous and multivariate approach. *Accident Analysis and Prevention*, Volume 62, 2014, pp. 102–109.

Jurewicz C, Sobhani A, Woolley J, Dutschke J and Corben B (2015), Proposed vehicle impact speed-severe injury probability relationships for selected crash types. *Proceedings of the 2015 Australasian Road Safety Conference*, 14-16 October, Gold Coast, Australia, Peer Review stream.

Kant V and Kerr E (2018), Taking Stock of Engineering Epistemology: Multidisciplinary Perspectives. *Philosophy & Technology*. https://doi.org/10.1007/s13347-018-0331-5.

Kennedy J, Peirce J and Summersgill I (2005). Review of Accident Research at Roundabouts. *Transportation Research Board National Roundabout Conference*, Vail, 2005.

Killi D and Vedagiri P (2014), Proactive Evaluation of Traffic Safety at An Unsignalized Intersection Using Micro-Simulation. *Journal of Traffic and Logistics Engineering*, Volume 2, No. 2, June 2014, pp140-145.

King J (2011), Restructuring Engineering Education: Why, How and When? *Research & Occasional Paper Series: CSHE.12.11*, Center for Studies in Higher Education, University of California, Berkeley.

King B and Magun-Jackson S (2009), Epistemological Beliefs of Engineering Students. *Journal of Technology Studies*, Volume 35, Issue 2, pp 56-64. ERIC.

Koehn E and Koehn J (2006), Professional Body of Knowledge requirements for civil engineers in the 21st century. *9th International Conference on Engineering Education*, San Juan, PR, Session R2F, pp19-24.

Koen B (1992), Professional Judgment in Engineering. *Perspectives on the Professions*, Volume 11, Number 2.

Koskela L, Pikas E, Niiranen J, Ferrantelli A and Dave B (2017). On Epistemology of Construction Engineering and Management. *LC3 2017 Volume II – Proceedings of the 25th Annual Conference of the International Group for Lean Construction (IGLC)*, Walsh K, Sacks R, Brilakis I (eds.), Heraklion, Greece, pp169-176 DOI: https://doi.org/10.24928/2017/0336.

Kotz S and Nadarajah S (2000), *Extreme Value Distributions: Theory and Applications.* Pub Imperial College Press, London, UK.

Kruijff E, Orlosky J, Kishishita N, Trepkowski C and Kiyokawa K (2018), The influence of label design on search performance and noticeability in wide field of view augmented reality displays. *IEEE Transactions on Visualization and Computer Graphics*.

Kruysse H and Wijlhuizen G (1992), Why are experts not better in judging the danger of filmed traffic conflicts? *Accident Analysis and Prevention,* Volume 26, March 1992, pp227-235.

Kuhn T (1962), *The Structure of Scientific Revolutions*. Chicago, University of Chicago Press, 1962.

Lackey R (2016), Keep science and scientists credible: avoid stealth policy advocacy. *Bulletin of the Ecological Society of Australia,* Volume 46, number 3, pp14-15.

Langham M, Edwards G, Holt J and O'Neill C (2002), An analysis of `looked but failed to see' accidents involving parked police vehicles. *Ergonomics,* 2002, Volume 45, number 3, pp167-185.

Larson A and Loschky L (2009), The contributions of central versus peripheral vision to scene gist recognition. *Journal of Vision*, September 2009, Volume 9, Issue 6. doi:https://doi.org/10.1167/9.10.6.

Latour B (1990), On actor-network theory. A few clarifications plus more than a few complications. English version: in *Soziale Welt,* Volume 47, pp. 369-381, 1996.

Laureshyn A, Svensson Ǻ and Hydén C (2010), Evaluation of traffic safety, based on micro-level behavioural data: Theoretical framework and first implementation. *Accident Analysis and Prevention,* 2010, doi:10.1016/j.aap.2010.03.021.

Laureshyn A, De Ceunynck T, Karlsson C, Svensson Ǻ and Daniels S (2017a), In search of the severity dimension of traffic events: Extended Delta-V as a traffic conflict indicator. *Accident Analysis and Prevention*, Volume 98, 2017, pp46-56.

Laureshyn A, De Goede M, Saunier N and Fyhri A (2017b), Cross-comparison of three surrogate safety methods to diagnose cyclist safety problems at intersections in Norway. *Accident Analysis and Prevention,* Volume 105, August 2017, pp11-20.

Laureshyn A, Jonsson C, De Ceunynck T, Svensson Ǻ, de Goede M, Saunier N, Włodarek P, van der Horst R and Daniels S (2016), Review of current study methods for VRU safety, Appendix 6 – Systematic quantitative review: surrogate measures of safety in site-based road traffic observations (draft). *InDeV: In-Depth understanding of accident causation for Vulnerable road users*, pub Warsaw University of Technology, Poland.

Laureshyn A and Várhelyi A (2018), *The Swedish Traffic Conflict Technique Observer's Manual*. Lund University, Lund.

Law J and Callon M (1988), Engineering and Sociology in a Military Aircraft Project: A Network Analysis of Technological Change. *Social Problems*, Volume 35, Number 3, pp284-297, June 1988.

Le Coze J (2018), Managing the Unexpected. *Wiley Handbook of Safety Principles*, Möller N, Hansson S, Holmberg J and Rollenhagen C (eds), pub. Wiley & Sons Inc, Hoboken, New Jersey.

Leahey E, Beckman C and Stanko T (2017), Prominent but Less Productive: The Impact of Interdisciplinarity on Scientists' Research. *Administrative Science Quarterly*, volume 62, Issue 1, pp105–139.

Lehtonen E, Lappi O, Koskiahde N, Mansikka T, Hietamäki J and Summala H (2018), Gaze doesn't always lead steering. *Accident Analysis and Prevention*, Issue 121 (2018), pp368-278.

Leonardi P (2003), *The Mythos of Engineering Culture: A Study of Communicative Performances and Interaction.* Master of Arts thesis, Department of Communication, Graduate School of the University of Colorado.

Lewis A, Garcia R and Zhaoping L (2003), The distribution of visual objects on the retina: connecting eye movements and cone distributions. *Journal of Vision*, December 2003, Volume 3, Issue 21. doi:https://doi.org/10.1167/3.11.21

Li S, Xiang Q, Ma Y, Gu X and Li H (2016), Crash Risk Prediction Modeling Based on the Traffic Conflict Technique and a Microscopic Simulation for Freeway Interchange Merging Areas. *International Journal of Environmental Research and Public Health*, Issue 13, pp1157-1171.

Liu Q (2010), *Development of A Methodology to Compare and Select an Appropriate Crash Surrogate for Freeways Safety Analysis: A Case Study on Truck Lane Restriction Strategies.* Doctoral Thesis, University of Virginia, pub. ProQuest LLC, Michigan, USA.

Lloyd B, Ferguson C, Palmer S and Rice M (2001), *Engineering the Future: Preparing Professional Engineers for the 21st Century*. Pub Association of Professional Engineers, Scientists and Managers Australia in association with Histec Publications, Melbourne Aus, 2001.

Lo J and Kennedy M (2015), Approval in nanotechnology patents: Micro and macro factors that affect reactions to category blending. *Organization Science*, Volume 26, Issue 1, pp119-139.

Lund B (2008), *Driver behaviour towards circulating cyclists at roundabouts*. Pub. Trafitec, Lyngby, Denmark.

Mackenzie J, Kloeden C and Hutchinson T (2015), Reduction of speed limit from 110 km/h to 100 km/h on certain roads in South Australia: a follow up evaluation. *Proceedings of the 2015 Australasian Road Safety Conference*, 14-16 October, Gold Coast, Australia.

Madheswari S and Mageswari S (2019), Changing Paradigms of Engineering Education – An Indian Perspective. Paper of the 9th World Engineering Education Forum 2019 (WEEF 2019), in *Procedia Computer Science*, Issue 172, 2020, pp215-224.

Mandavilli S, McCartt A and Retting R (2009), Crash patterns and potential engineering countermeasures at Maryland roundabouts. *Traffic Injury and Prevention*, March, Volume 10 Issue 1, pp 44-50.

Martin J (2002), Relationship between crash rate and hourly traffic flow on interurban motorways. *Accident Analysis and Prevention*, Volume34, Issue 5, pp619-29.

McKee S and Nakayama K (1984), The Detection of Motion in the Peripheral Visual Field. *Vision Research*, Volume 2, number 1, pp25-32.

McLean J (1988), An Australian Perspective on Traffic Engineering Research, *Proceedings of the 14th ARRB Conference*, Volume 14, Issue 1, pp145-155, Canberra.

Menzel H, Aaltio I and Ulijn J (2007), On the way to creativity: Engineers as intrapreneurs in organizations. *Technovation*, Issue 27, pp732-743.

Millar M and Dillman D (2012), *Trends in Interdisciplinary Dissertation Research: An Analysis of the Survey of Earned Doctorates*. Working Paper NCSES 12-200. Arlington, VA: National Science Foundation, National Center for Science and Engineering Statistics. Available at www.nsf.gov/statistics/ncses12200/.

Møller M and Hels T (2007), Cyclists' perception of risk in roundabouts. *Accident Analysis and Prevention,* Volume 40 (2008), pp1055-1062.

Monaco W, Kalb J and Johnson C (2007), *Motion Detection in the Far Peripheral Visual Field.* Pub U.S. Army Research Laboratory, Human Research and Engineering Directorate, Aberdeen Proving Ground MD 21005-5425 ARL-MR-0684, December 2007.

Montella A, Turner S, Chiaradonna S and Aldridge D (2013), International overview of roundabout design practices and insights for improvement of the Italian standard, *Canadian Journal of Civil Engineering*, Volume 40, Issue 12, pp1215-1226.

Moore J and Hughes B (1991), User Initiated Research into Traffic Accident Frequency at Signalised Intersections. *16th Australasian Transport Research Forum*, Hobart.

Mulder K (2000), Engineering in an increasingly complex world. How to train engineers for integrated problem solving? Lessons from some experiments. *IFAC Proceedings*, Volume 33, Issue 12, pp183-188.

Mullakkal-Babu F, Wang M, Farah H, van Arem B and Happee R (2017), Comparative Assessment of Safety Indicators for Vehicle Trajectories on the Highway. *Transportation Research Record: Journal of the Transportation Research Board*, Number. 2659, 2017. DOI: 10.3141/2659.

Nersessian N (2008), *Creating Scientific Concepts.* Pub. Cambridge: MIT Press.

Newton I (1675), *"Letter from Sir Isaac Newton to Robert Hooke".* Historical Society of Pennsylvania. Source: Wikipedia.

Noland R (2013), From theory to practice in road safety policy: Understanding risk versus mobility. *Research in Transportation Economics*, volume 43 (2013), pp71-84.

Noland R and Oh L (2004), The effect of infrastructure and demographic change on traffic-related fatalities and crashes: a case study of Illinois county-level data. *Accident Analysis and Prevention*, Volume 36, Issue 4, pp525-532.

Nordback K, Marshall W and Janson B (2014), Bicyclist safety performance functions for a U.S. city. *Accident Analysis and Prevention*, Volume 65, April 2014, pp114–122.

Numbers R and Kampourakis K (eds.) (2015), *Newton's Apple and Other Myths About Science. Pub*. Harvard University Press.

OECD (1998), *Safety of Vulnerable Road Users*. Organisation for Economic Co-Operation and Development, Paris.

OECD/International Transport Forum (2013), *Cycling Health and Safety*. Research Report, OECD Publishing/ITF. http://dx.doi.org/10.1787/9789282105955-en

Orsini F, Gecchele G, Gastaldi M and Rossi R (2019), Collision prediction in roundabouts: a comparative study of extreme value theory approaches. Transportmetrica A: Transport Science, Volume 15, Issue 2, pp556-572.

Oxford English Dictionary (2019), *OED Online*. Oxford University Press, June 2019. Web. 2 September 2019.

Ozturk O, Ozbay K and Yang H (2015), Investigating the Impact of Work Zones on Crash Severity by Comparative Analysis. *Transportation Research Board 94th Annual Meeting Compendium of Papers*, pub Transportation Research Board, 2015.

Pammer K, Sabadas S and Lentern S (2018), Allocating Attention to Detect Motorcycles: The Role of Inattentional Blindness. *Human Factors*, Volume 60, Number 1, February 2018, pp5-19.

Parker M and Zegeer C (1989), *Traffic conflict techniques for safety and operations-observers manual.* Publication No. FHWA-IP-88-027, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

Patterson F (2010), Cycling and roundabouts: An Australian perspective. *Road and Transport Research*, Volume 19, Issue 2, June 2010, pp 4-19.

Patterson F (2013), The evidence for contra-flow cycling. *Road and Transport Research*, Volume 22, Issue 1, March 2013, pp51-60.

Perkins S and Harris J (1967), *Traffic conflict characteristics; accident potential at intersections.* General Motors Corporation Research Laboratories, Warren, Michigan, USA. Research publication GMR-632 also Highway Research Record No 225, Washington, DC. 1968.

Persuad B and Lyon C (2006), Empirical Bayes before–after safety studies: Lessons learned from two decades of experience and future directions. *Accident Analysis and Prevention*, Volume 39 (2007), pp 546–555.

Pickering C and Byrne J (2014), The benefits of publishing systematic quantitative literature reviews for PhD candidates and other early career researchers. *Higher Education Research and Development*, Issue 33, pp534-548.

Pinch T and Bijker W (1987), The Social Construction of Facts and Artifacts: Or How the Sociology of Science and the Sociology of Technology Might Benefit Each Other. *The Social construction of technological systems,* Wiebe B, Hughes, T and Pinch J (eds). Papers of a workshop held at the University of Twente, The Netherlands, July 1984. Pub Massachusetts Institute of Technology Press, Cambridge Massachusetts/ London England, 1987.

Rae A and Alexander R (2017), Forecasts or fortune-telling: When are expert judgments of safety risk valid? *Safety Science*, Issue 99 (2017), pp156-165.

Ranney T (1994), Models of Driving Behavior: A Review of Their Evolution. *Accident Analysis and Prevention*, Volume 26, Number 6, pp733-750.

Räsänen M and Summala H (1998), Attention and expectation problems in bicycle-car collisions: an in-depth study. *Accident Analysis and Prevention,* Volume 30, Issue 5, September 1998, pp657-66.

Räsänen M and Summala H (2000), Car Drivers' Adjustments to Cyclists at Roundabouts. *Transportation Human Factors*, Volume 2, Issue 1, pp1-17.

Rasmussen J (1997), Risk management in a dynamic society: A modelling problem. *Safety Science,* Volume 27, Issue 2, pp183-213.

Reason J (1990), *Human Error.* Cambridge University Press, Cambridge.

Retting R, Ferguson S and McCartt A (2003), A Review of Evidence-Based Traffic Engineering Measures Designed to Reduce Pedestrian–Motor Vehicle Crashes. *American Journal of Public Health*, Volume 93, Issue 9, September 2003, pp1456-1463.

Roads Australia (2018), *Cities for the Future Report 2018.* Pub. Roads Australia, Melbourne, Vic.

Robertson J, Mclean A and Ryan G (1966), *Traffic Accidents in Adelaide, South Australia (1963-1964).* Australian Road Research Board Special Report No. 1 – 1966.

Robinson B, Rodergerdts L, Scarborough W, Kittelson W, Troutbeck R, Brilon W, Bondzio L, Courage K, Kyte M, Mason J, Flannery A, Myers E, Bunker J and Jacquemart G (2000), *Roundabouts: An Informational Guide.* Federal Highways Administration report FHWA-RD-00-067, pub. U.S. Department of Transportation, Virginia.

Robinson D (1998), Accidents at Roundabouts in New South Wales. *Road and Transport Research,* Volume 7, Issue 1, pp4-13, March 1998.

Robinson D (2005), Safety in numbers in Australia: more walkers and bicyclists, safer walking and bicycling. *Health promotion journal of Australia*, Volume 16, Issue 1, pp47-51, May 2005. DOI: 10.1071/HE05047

Roda F (2013), Systems engineering and modeling: some epistemological remarks. Proceedings of the Posters Workshop at CSD&M 2013.

Rodergerdts L, Blogg M, Wemple E, Myers E, Kyte M, Dixon M, List G, Flannery A, Troutbeck R, Brilon W, Wu N, Persaud B, Lyon C, Harkey D and Carter D (2007), *Roundabouts in the United States.* NCHRP Report 572, National Cooperative Highway Research Program, Transportation Research Board, Washington DC, 2007.

Rojter J (2004), The Role of Humanities and Social Sciences in Engineering Practice and Engineering Education. *Proceedings of the 2004 International Conference on Engineering Education and Research "Progress Through Partnership",* pp395-401.

Rumar K (1990), The basic driver error: late detection. *Ergonomics,* Volume 33, pp1281-1290.

Rzhetsky A, Foster J, Foster I and Evans J (2015), Choosing experiments to accelerate collective discovery. *PNAS,* Volume 112, Number 47, pp14569-14574, November 2015.

Saavedra L, Araújo A, de Oliveira J and Stephens C (2014), Looking through glass walls: Women engineers in Portugal. *Women's Studies International Forum*, Issue 45, pp27-33.

Satterthwaite S (1981), *A Survey of Research into Relationships Between Traffic Accidents and Traffic Volumes.* Publication of the Transport and Road Research Laboratory, Wokingham, Berkshire, UK.

Sayed T, Zaki M and Autey J (2013), Automated safety diagnosis of vehicle–bicycle interactions using computer vision analysis. *Safety Science*, Volume 59, November 2013, pp163-172.

Schepers P, Hagenzieker M, Methorst R, van Wee B and Wegman F (2014), A conceptual framework for road safety and mobility applied to cycling safety. *Accident Analysis and Prevention,* Volume 62, January 2014, pp331-340.

Scase R (2005). Circle of influence: How France has used roundabouts to cut casualties. *Traffic Technology International*, Case 5, Road Sense, International Road Assessment Program, Basingstoke.

Schramm A, Haworth N, van den Dool D, Murphy J, Qu X and McDonald M (2014), Roundabout design and cycling safety. *3rd International Cycling Safety Conference (ICSC2014),* 18-19 November 2014, Göteborg, Sweden.

Schryen G (2015), Writing Qualitative IS Literature Reviews—Guidelines for Synthesis, Interpretation, and Guidance of Research. *Communications of the Association for Information Systems*, Volume 37, Article 12, pp286-325.

Sharma J, Yarlagadda T, Sharma S and Yarlagadda P (2018), Vertical segregation: Issues and challenges of women engineers in Australia. Paper of the 14th Congress on Manufacturing and Management (GCMM-2018), in *Procedia Manufacturing*, Issue 30, pp 671-676.

Shelby S (2011), Delta-V as a Measure of Traffic Conflict Severity. *International conference on road safety and simulation,* 2011, Indianapolis, USA, Transportation Research Board, Washington, DC, USA, 20pp.

Silvano A and Linder A (2017), *Traffic safety for cyclists in roundabouts: geometry, traffic, and priority rules. A literature review*. Technical report VTI notat 31A-2017.

Silvano A, Ma X and Koutsopoulos H (2014), A Hierarchical Modelling Framework for Vehicle-bicycle Interactions at Roundabouts, *Proceedings, International Cycling Safety Conference 2014*, 18-19 November 2014, Göteborg, Sweden.

Simons D and Chabris C (1999), Gorillas in our midst: sustained inattentional blindness for dynamic events. *Perception*, 1999, Volume 28, pp1059-1074.

Smeed R (1949), Some statistical aspects of road safety research. *Journal of the Royal Statistical Society, Series A (General),* Volume 112, Issue 1, pp1-34.

Songchitruksa P and Tarko A (2004), *Using Imaging Technology to Evaluate Highway Safety.* Final report, TRB Subject Code: 54-9 Traffic Performance Measure, Publication No.: FHWA/IN/JTRP-2004/27, SPR-2663.

Songchitruksa P and Tarko A (2006), The extreme value theory approach to safety estimation. *Accident Analysis and Prevention*, Volume 38, Issue 4, August 2006, pp811-822.

Spacek P (2004), Basis of the Swiss Design Standard for Roundabouts, *Transportation Research Record Journal of the Transportation Research Board*, Volume 1881, Issue 1, pp27-35.

Srinivasan R and Bauer K (2013), *Safety Performance Function Development Guide: Developing Jurisdiction-Specific SPFs.* Federal Highways Administration report FHWA-SA-14-005, pub. U.S. Department of Transportation.

St-Aubin P, Saunier N, Miranda-Moreno L and Ismail K (2012), Detailed Driver Behaviour Analysis and Trajectory Interpretation at Roundabouts using Computer Vision Data. *Transportation Research Record, Journal of the Transportation Research Board*, Volume 2389, December 2013.

Staughton G and Storie V (1977), *Methodology of an in-depth accident investigation*. Survey Report No. 672, Transport and Road Research Laboratory, Crowthorne, Berkshire UK.

Stoet G and Geary D (2018), The Gender-Equality Paradox in Science, Technology, Engineering, and Mathematics Education. *Psychological Science*, April 2018, Volume 29, Issue 4, pp581-593.

Strasburger H, Rentschler I and Jüttner M (2011), Peripheral vision and pattern recognition: A review. *Journal of Vision*, December 2011, Volume 11, Issue 13.

Summala H and Räsänen M (2000), Response: Top-Down and Bottom-Up Processes in Driver Behavior at Roundabouts and Crossroads. *Transportation Human Factors*, Volume 2, Issue 1, pp29-37.

Svensson Å (1998), *A Method for Analysing the Traffic Process in a Safety Perspective.* Doctoral Thesis, University of Lund, Lund Institute of Technology, Department of Traffic Planning and Engineering.

Tarko A and Songchitruksa P (2005), Estimating the Frequency of Crashes as Extreme Traffic Events. *84th Annual Meeting of the Transportation Research Board*, January 9-13, 2005, Washington D.C.

Tageldin A and Sayed T (2015), Can Time Proximity Measures Be Used As Safety Indicators In All Driving Cultures? *Transportation Research Record, Journal of the Transportation Research Board*, Volume 2520, pp165-174, January 2015.

Tageldin, Sayed and Shaaban (2017), Comparison of Time-Proximity and Evasive Action Conflict Measures: Case Studies from Five Cities. *Transportation Research Record, Journal of the Transportation Research Board,* Volume 2661, pp19-29, January 2017.

Thompson J, Savino G and Stevenson M (2014), Reconsidering the Safety in Numbers Effect for Vulnerable Road Users: An Application of Agent-Based Modeling. *Traffic Injury Prevention,* DOI: 10.1080/15389588.2014.914626.

Timpe K, Giesa H and Seifert K (2004), Engineering Psychology. *Encyclopedia of Applied Psychology*, Volume 1, Spielberger C (ed.), pub Elsevier Academic Press, Oxford, pp777-787.

Tin Tin S, Woodward A and Ameratunga S (2014), The role of conspicuity in preventing bicycle crashes involving a motor vehicle. *European Journal of Public Health*, 2014, pp1-5.

Tiwari G, Mohan D and Fazio J (1998), Conflict analysis for prediction of fatal crash locations in mixed traffic streams. *Accident Analysis and Prevention*, Volume 30, Issue 2, pp207-215, March 1998.

Trevelyan J (2013), Towards a theoretical framework for engineering practice. *Engineering Practice in a Global Context: Understanding the Technical and the Social,* Williams B, Figueiredo J and Trevelyan J (eds), CRC Press/Belkema, Leiden, The Netherlands, 2013.

Trevelyan J (2014), *The making of an expert engineer.* CRC Press/Balkema, Leiden, The Netherlands.

Turner S, Roozenburg A and Francis T (2006), *Predicting Accident Rates for Pedestrians and Cyclists.* NZ Transport Agency Research Report 289.

Turner S, Roozenburg A and Smith A (2009), *Roundabout crash prediction models.* NZ Transport Agency Research Report 386.

Turner S, Wood G and Roozenburg A (undated), *Accident Prediction Models for Roundabouts,* Beca Infrastructure Ltd technical paper, 14pp.

Turner S, Wood G, Hughes T and Singh R (2011), Safety Performance Functions for Bicycle Crashes in New Zealand and Australia. *Transportation Research Record*, Volume 2236, Issue 1, pp66-73.

Vanderbilt T (2008), *Traffic: why we drive the way we do (and what it says about us).* Pub. Alfred A. Knopf, New York, USA.

Van der Horst A (1990), *A Time-Based Analysis of Road User Behaviour in Normal and Critical Encounters,* TNO Institute for Perception, Delft, The Netherlands.

Van Minnen J (1994), *Voor- en nastudies op rotondelocaties (Before and After Studies at Roundabout Locations).* Report R-94-61, Stichting Wetenschappelijk Onderzoek Verkeersveiligheid (Foundation for Road Safety Research), Leidschendam, The Netherlands.

Van Minnen J (1998), Rotondes en voorrangsregelingen II. Uniformering voorrangsregeling op oudere pleinen, veiligheid fietsvoorzieningen en tweestrooks rotondes. (Dutch roundabouts and priority intersections II. Standardizing right-of-way on older plazas, bicycle safety and two-lane roundabouts.) *Roundabouts in a sustainably safe infrastructure*, Research Report R-98-12, Stichting Wetenschappelijk Onderzoek Verkeersveiligheid (Foundation for Road Safety Research), Leidschendam, The Netherlands.

Van Minnen J and Schoon C (1993), *Accidents on roundabouts II. Second study into the road safety aspects of Dutch roundabouts, in particular with regard to cyclists and moped riders.* Research Report R-93-16, Stichting Wetenschappelijk Onderzoek Verkeersveiligheid (Foundation for Road Safety Research), Leidschendam. the Netherlands.

Vanparijs J, Int Panis L, Meeusen R and de Geus B (2015), Exposure measurement in bicycle safety analysis: A review of the literature. *Accident Analysis and Prevention,* Volume 84, 2015, pp9-19.

Van Zandt D (1992), How Do Judges Think? *Perspectives on the Professions,* Volume 11, Number 2.

Wang J, Veugelers R and Stephan P (2017), Bias against novelty in science: A cautionary tale for users of bibliometric indicators. *Research policy*, Volume 46 (2017), pp1416-1436.

Wang J, Wu J, Zheng X, Ni D and Li K (2016), Driving safety field theory modeling and its application in pre-collision warning system. *Transportation Research Part C: Emerging Technologies*, Volume 72, 2016, pp306-324.

Washington S, Lord D and Persaud B (2009), The Use of Expert Panels in Highway Safety: A Critique. *Transportation Research Record*, 2102, pp101-107.

Watson A, Watson B and Vallmuur K (2015), Estimating under-reporting of road crash injuries to police using multiple linked data collections. *Accident Analysis and Prevention,* Issue 83, pp18-25, October 2015.

Weedon J (2016), Judging for Themselves: How Students Practice Engineering Judgment. *Conference Proceedings of the 2016 ASEE Conference & Exposition*, New Orleans, LA, paper ID 15775.

White M (2006), "Sorry mate, I didn't see you". A plausible scientific explanation. *Proceedings of the Australasian road safety research, policing and education conference*, Volume 10, Monash University, Clayton, VIC, Australia.

Whitley R (2000), *The Intellectual and Social Organization of the Sciences (second edition).* Pub Oxford University Press, Oxford UK.

Wilke A, Lieswyn J and Munro C (2014), *Assessment of the Effectiveness of On-road Bicycle Lanes at Roundabouts in Australia and New Zealand.* Austroads Research Report AP-R461-14, pub Austroads Sydney, N.S.W.

Williams M (1981), Validity of the Traffic Conflicts Technique. *Accident Analysis and Prevention,* Volume 13, pp133-145.

Willmott H (1986), Organising the Profession: A Theoretical and Historical Examination of the Development of the Major Accountancy Bodies in the U.K. *Accounting Organizations and Society,* Volume 11, Number 6, pp555-580.

Wood K (1999), *Bicycle Crashes in New Zealand*. Masters Thesis, Lincoln University. 84pp.

Yannis G, Weijermars W and Kauppila J (2012), A review of international sources for road safety measures assessment. *Procedia - Social and Behavioral Sciences*, Volume 48 (2012), pp2876-2886.

Zhang B and Ma Z (2015a), Revolutionise Roundabout Design on Bicycle Routes. *AITPM National Conference*, Brisbane Australia 2015.

Zhang B and Ma Z (2015b), Revolutionise Roundabout Design on Bicycle Routes. Powerpoint slides to the presentation, AITPM National Conference, Brisbane Australia 2015.

Zhang R, Kwon O and Tadin D (2013), Illusory Movement of Stationary Stimuli in the Visual Periphery: Evidence for a Strong Centrifugal Prior in Motion Processing. *The Journal of Neuroscience*, March 6, 2013, Volume 33, Issue 10, pp4415-4423.

Zhaoa N, Chen W, Xuan Y, Mehler B, Reimer B and Fu X (2014), Drivers' and non-drivers' performance in a change detection task with static driving. *Ergonomics*, 2014. http://dx.doi.org/10.1080/00140139.2014.909952.

Zhaoping L (2014), *Understanding Vision: Theory, Models and Data.* Pub. Oxford University Press, Oxford, UK.

Zheng D, Qin X, Tillman R and Noyce D (2013), Measuring Modern Roundabout Traffic Conflict Exposure. *Journal of Transportation Safety & Security,* Volume 5, Issue 3, pp208-223.

Zheng L, Ismail K and Meng X (2014a), Traffic conflict techniques for road safety analysis: open questions and some insights. *Canadian Journal of Civil Engineering*, Volume 41, pp633-641.

Zheng L, Ismail K and Meng X (2014b), Freeway safety estimation using extreme value theory approaches: a comparative study. *Accident Analysis and Prevention*, Volume 62, January 2014, pp32-41.

Zheng L, Ismail K and Meng X (2016), Investigating the Heterogeneity of Postencroachment Time Thresholds Determined by Peak over Threshold Approach. *Transportation Research Record: Journal of the Transportation Research Board*, Volume 2601, Issue 3.

Zhou M and Sisiopiku V (1997), Relationship Between Volume-to-Capacity Ratios and Accident Rates. *Transportation Research Record: Journal of the Transportation Research Board*, Volume 1581, Issue 1, pp47-52.

Appendix A: Approach to the literature

This section presents some background to qualitative and quantitative literature reviews in general, before detailing the approach to the qualitative literature review presented in Chapter 2 of the thesis. It also covers other examinations of literature that occur throughout the thesis and is therefore broader than the qualitative literature review per se.

In terms of what a qualitative literature review is or aims to be, Schryen (2015) describes two types of qualitative literature review:

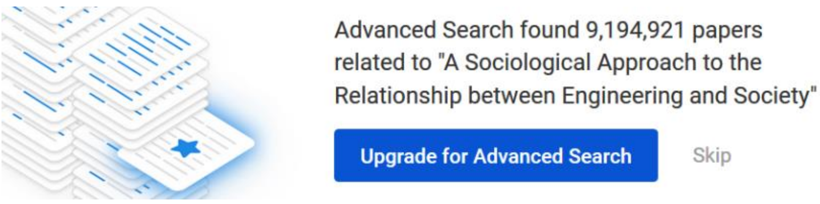
> "A narrative review (e.g., Powell, Piccoli, & Ives, 2005) presents verbal descriptions of studies focusing on theories and frameworks, elementary factors, and their roles and/or research outcomes regarding a hypothesized relationship. A descriptive review (e.g., Riedl, Leimeister, & Krcmar, 2011) analyzes to what extent the existing literature supports a particular proposition or reveals an interpretable pattern."

The difference between a narrative and descriptive literature review can be subtle and most other authors refer to 'narrative' literature reviews in the same sense as Schryen's (2015) 'qualitative' – especially as the term 'qualitative' invites comparison with 'quantitative', where a quantitative literature review has a markedly different approach, method and aims.

Compared to the qualitative approach of synthesizing information from the content of individual sources, quantitative literature reviews take a rigorous, systematic approach to published literature, identifying how frequently themes, topics or characteristics of interest occur within a sample of publications to derive understandings about the body of literature as a whole. Ferrari (2015)'s comparison between narrative and systematic literature reviews and Pickering and Byrne's (2014) discussion of systematic quantitative (SQ) literature reviews compare quantitative to narrative literature reviews. Haddaway et al. (2015) follow many others in comparing 'systematic' with 'traditional' literature reviews, where the former are quantitative and the latter qualitative.

The interest in quantitative literature reviews in such papers reflects an increasing popularity of SQ literature reviews in line with the increasing amount of literature being published, plus technological advances (e.g. access to database programs) that facilitate use of the SQ approach. As a practical example of an SQ literature review, early on in the research for this thesis, an SQ literature review was undertaken examining research into cyclist safety at infrastructure. The SQ literature review was aimed at exploring the extent of the field, how research was formulated and undertaken, identifying current and emerging themes, and to help frame the hypothesis. The SQ literature review subsequently enabled a different perspective to be taken to the available literature by allowing this to be analysed in terms of the themes emerging from the narrative literature review. Relevant results from the SQ literature review are referred to in the literature review and the thesis in general. A report on the SQ literature review is included as Appendix B.

From Ferrari (2015), the major limitation of a qualitative literature review is that the selection and evaluation biases used in the literature review are not known. This is particularly true when the amount of literature available to be interpreted and synthesised is considered. The SQ literature review presented in Appendix B notes an almost exponential growth in literature over the last few decades. The following screenshot provides some nuance to the “large, unbounded and continuously growing body of literature” mentioned by Boell and Cecez-Kecmanovic (2015) – and relates to only a single on-line source (Academia.edu):



A helpful email alert presents a much more constrained data set by advising that “59,941 papers on Academia discuss ‘Philosophy of Technology’.”

While there may be some possibility of an SQ literature review being able to synthesis data from over 9 million sources using filtering strategies, heuristics, etc., it is not at all realistic that the abstracts of even a modest 60,000 articles could be read as part of preparing a qualitative literature review, even ignoring the additional papers being published every day. The qualitative literature review’s author instead reads, interprets and synthesises selected sources to fit with theories and arguments without justifying to the reader the sources chosen (or how they were identified) versus those rejected. Hence Ferrari’s “selection and evaluation bias” is a small term for a potentially very large effect.

In the current qualitative literature review, the general approach to the literature has been to:

- Search on keywords that attempt to encapsulate the essence of the topic, such as “impact of engineering practice on research” (noting that the advice from Academia about ‘A sociological approach to the relationship between engineering and society’ reflected the title of a viewed paper, not a keyword search). This relies on the algorithms used by search engines to deliver results by relevance, with the returned articles examined by title and abstract to the point where papers appear to lapse into irrelevance. Those identified as the most relevant were read first.

- Follow references within texts where context suggested that these might provide more information on the topic, and also use these as the basis of identifying new phrases or terms for further keyword searching.
- Where terms refer to a field or sub-discipline, to undertake a general search on this term to gain a feel for its history and hence seminal authors/ papers/ other sub-fields. This also produced a feel for keywords with which to further explore the field, if relevant.
- Revisit the literature at periods and from different angles reflecting drafting, editing and (where relevant) feedback on the emerging literature review, and understandings stimulated by the process.

As the last point implies, the adopted approach has been applied in an iterative way. (A cut-off date of 1 June 2019 can be assumed.) The approach used has also balanced breadth against depth, i.e. the more literature available and hence the larger the theme being examined, the less detail sought through the literature review. This is because the hypothesis is based around engineering paradigm and pragmatism, but the actual focus of the hypothesis is about the effect of these on road safety. By their nature, engineering paradigm and pragmatism are much broader and more mature fields of (sociological) enquiry than a focus on their implications on road safety. That is, the topic of engineering paradigm is a larger field than that of traffic engineering paradigm; and the topic of professional pragmatism is a larger one than engineering professional pragmatism. The implications of these on road safety then lies at the intersection of road safety and subsets of paradigm and pragmatism, hence is a smaller field.

One result of this is that the amount of literature produced on different aspects of the thesis topic tends to be inversely proportional to the relevance of that literature to the overall topic. This has been reflected in the approach to framing and scoping the qualitative literature review. The literature review essentially triangulates in from the breadth of engineering paradigm (notably through the sociological literature), through an Australian traffic engineering perspective, and into paradigmatic and pragmatic issues identified in road safety. This triangulation is also reflected in the structuring of the literature review, where literature from a (broad) sociological perspective is presented first, followed by evidence from the Australian engineering perspective. The latter literature is limited to Australian sources for two reasons.

Firstly, given Whitley’s (2000) and Jacobs and Frickel’s (2009) observations about engineering as a dynamic rather than static discipline, the development of the engineering profession cannot be considered to have progressed equivalently in all countries. This is supported by the Finniston report in that the Commission of Enquiry examined the progression of engineering education and accreditation in various countries and found the UK lagging European professional development. This is particularly true of traffic engineering, which is a younger field than many other engineering fields (its establishment having followed the widespread adoption of the automobile.) Mixing literature from different countries where engineering developed along different timeframes and under different influences runs the risk of confusing rather than illuminating[1].

Secondly, literature that is written by engineers for engineers is not necessarily aimed at academic research – particularly for historic literature that was not produced in an electronic version. Of the substantive pieces examined in the literature review, only Rojter (2004) was identified using academic databases. The others represent what might be termed ‘light-grey’ literature, where grey literature is defined as per the Pisa Declaration on Policy Development for Grey Literature (2014) as "…not controlled by commercial publishing" and therefore (as observed by Adams et al., 2016) difficult to search for and retrieve. Two of these pieces of literature were identified through the SQ literature review methodology of interrogating holdings of the Australian Road Research Board and Australasian Transport Research Forum, which are not indexed in academic databases but represent freely accessible, searchable data sources for those aware of them – typically Australian traffic engineering practitioners. Finding such literature in other countries is a difficult task and was not attempted beyond a general observation that little similar literature was returned through other literature searches.

Another exercise undertaken during the research for this thesis was an on-line survey of road authorities. This sought to identify research, research needs and practice involving cyclist infrastructure. Amongst other things, this identified attitudes and barriers to innovative practice, as well as opportunities to undertake primary research on new cycle infrastructure (i.e. supporting a before/after study methodology). A report on the results of the survey is included as Appendix C; results from it are referenced as relevant.

This, then, provides the context for the qualitative literature review.

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[1] The reader interested in understanding how the U.K. and U.S. engineering professions have progressed compared to the Australian situation is referred to Lloyd et al. (2001), Chapter 13: International Comparisons, pp110-117. This chapter contrasts in particular accreditation and formation processes, and also presents representative samples from engineering and technology courses as a broad benchmarking of engineering education.

Appendix B: Systematic quantitative (SQ) literature review

Contents

1. Introduction

Appendix A provides background to both qualitative literature reviews and systematic quantitative (SQ) literature reviews.

A systematic quantitative (SQ) literature review was undertaken early in the research for the thesis in order to scope the literature available within the broad topic of on-road cyclist infrastructure. A second purpose of this early literature review was to help refine the topic for the dissertation. In particular, it assisted in identifying:

- How knowledge about bicycle infrastructure is constituted
- An appreciation of the literature as a body of knowledge
- General themes in the research: types of infrastructure, particular design considerations, focus areas and emerging research agendas
- Sources of further information for application to the proposed case study.

As such, the SQ literature review was exploratory, but it did reveal evidence that was used in the dissertation.

What follows is an edited version of an original working paper summarizing the results. This version focuses on the evidence embodied in the hypothesis: engineering paradigm and pragmatism, and the impact of each on road safety. However before doing so it explains the methods by which the review as undertaken, and provides broad a broad, quantified outline was what was found.

A ‘snapshot’ date for the SQ literature review was set as 1 August 2014.

This SQ literature review was intended to provide an overview of the breadth of relevant research and the extent of the Australian contribution to this body of knowledge. It is not intended to be comprehensive, exhaustive or to establish an authoritative view on the safety performance of all types of on-road infrastructure for cyclists.

2. Methodology

The SQ literature review was undertaken by developing a database of research based on using on-line search engines (referred to as the on-line database), and augmenting this with an overview of major Australian sources. The two types of data sources used very different approaches and are described separately in the following sections, but the on-line search led to some 3,900 articles being reviewed at abstract level.

The on-line search was supplemented with examination of major holdings of Australian research, totalling over 5,000 pieces of Australian transport and traffic research and identifying eleven items relating to the topic in addition to the literature identified through the on-line search.

Three on-line data bases were interrogated: Science Direct, PubMed and Google Scholar. An initial search in Science Direct using the phrase “safety of cycle infrastructure” (and then excluding the keyword “life”, to exclude articles related to life-cycles) did not yield relevant research within the top five results (and, indeed, only one or two within the first twenty-five results). Using PubMed, the fifth article was relevant. Using Google Scholar, the first and fifth results were relevant. This in itself pointed to one issue in undertaking a broad literature review: that the framing of the current research focus does not necessarily reflect the framing of other researchers’ work. Keywords ascribed by other researchers might focus on methodological aspects (e.g. naturalistic studies, questionnaire surveys), statistical methods (e.g. Bayesian models), data types used (e.g. accidents), population groups studied (e.g. elderly), particular infrastructure types (e.g. roundabouts), or conclusions drawn (e.g. risk). Another issue is that the keyword used may not be intuitive for the searcher (e.g. roads – design and construction).

For this reason, it was considered that in the first instance, the search feature of on-line databases that returns recommended or related articles might provide better results than relying on an individual’s conception of relevant keywords. As this appears to have yielded adequate results, the approach is described as follows. It is illustrated as a “search tree” in Figure 1 on page B5.

As the highest ranking result of relevance, the Google Scholar result (McClintock and Cleary, 1996) was selected as a start point for exploring the field. Since Google Scholar does not constrain itself to peer-reviewed research, this article was located in Science Direct and the “recommended articles” feature of that database was used to identify one hundred potentially relevant articles. Similarly, the “cited by” feature was used to identify articles that cited this initial article. (The latter feature is limited to twenty results.)

The abstracts of each returned result were reviewed. If the result was related to the safety of cycle infrastructure, it was entered into a simple database and the degree of relevance assessed.

The following explanation of the ranking used includes an example article title. The example article titles give some flavour of the article but do not fully convey the content of the abstract leading to the classification decision.

Two classifications were used to characterise the state of practice regarding the specific theme of the safety of on-road cycle infrastructure[1]:

A. The article is directly focused on the safety of on-road cycle infrastructure (e.g. "Evaluation of bike boxes at signalized intersections"); or the safety of cyclists at infrastructure

B. The article includes information about the safety of cycle infrastructure but is not directly focused on this (e.g. "Aggravating and mitigating factors associated with cyclist injury severity in Denmark").

Two other categories were used to classify articles that fell outside these main classifications but that arguably contributed to characterising the broader field of research:

C. The article is not on the safety of on-road cycle infrastructure per se but could be described as research on secondary aspects to the main topic. For example, "Characteristics of multimodal conflicts in urban on-street bicycle lanes" examines obstructions of rather than cyclist safety in bicycle lanes; "Riding through red lights: The rate, characteristics and risk factors of non-compliant urban commuter cyclists" examines red-light running but does not evaluate the safety of the actual behaviour; "Cycling in the City: An in-depth examination of bicycle lane use in a low-income urban neighbourhood" is clearly about socio-demographics, but a detailed reading of the article may reveal information on the main topic.

D. The article is not on the safety of on-road cycle infrastructure per se but could be described as oblique research on secondary topics. For example, research such as "Who uses new walking and cycling infrastructure and how? Longitudinal results from the UK iConnect study" relates cycle infrastructure design with use and a detailed reading may find an association between safety and design; "Safety in numbers? Investigating Australian driver behaviour, knowledge and attitudes towards cyclists" looks at drivers and behavioural aspects in its examination of the safety in numbers effect; "The analysis of roundabouts through visibility" considers motor vehicles and infrastructure. Category D also formed a broad "catch-all" category for papers describing theoretical/ methodological issues and papers revealing emerging research agendas.

A note was also made if the research or data originated in Australia and if articles specifically covered methodological or analytical issues, although articles that only covered

[1] It should be stressed that this categorisation was based on the search term. This is not the same as the later thesis topic.

methodological or analytical issues and did not include the target theme were excluded (such as "Age, gender, mileage and the DBQ: The validity of the Driver Behavior Questionnaire in different driver groups").

Abstracts were not available in four cases (one being an editorial response to criticism of an apparently contentious piece of research). In one case, a presentation was identified and added to the database in lieu of the missing article. A few citations were for a book, book review or special journal issue where all articles were on the same theme. In none of these did the table of contents or review indicate relevant Australian research

Figure 1is an illustration of the way that each of the fourteen "A" articles was subjected to the same search methodology i.e. recommended/ related articles and citing articles identified as relating to the safety of cycle infrastructure were added to the database and the relevance of these assessed.

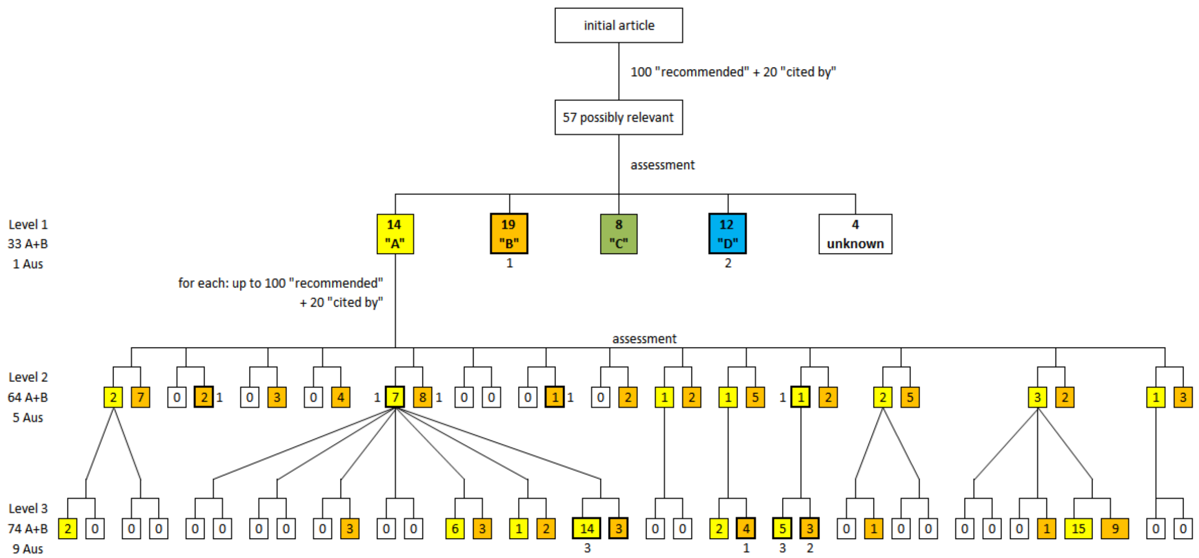

Figure 1: The search tree

Where the article was not available through Science Direct, PubMed was then searched to attempt to find the article (the "related articles" function in this case returns one hundred and twenty articles) and if still not found, searched in Google Scholar.

The search was then repeated on the new "A" articles. To ensure that a good coverage was provided through the use of "A" articles only, after the "A" article search was completed the search method was conducted on the first two "B" articles. These returned no new relevant research. The final database was sorted by title to enable any duplicated records to be identified and removed.

From some 3,900 articles reviewed, 385 articles were identified of potential relevance, with 172 articles classified as "A" or "B" articles.

The classification of relevance of articles as judged by abstracts is subjective and not always clear-cut. For example, “on-road cycle infrastructure” was used to differentiate infrastructure aimed at transport (commuter and utility) purposes from that associated with leisure and recreation purposes. But in Germany, Denmark and Holland, off-road bicycle paths are a key piece of cycle infrastructure used for transport purposes. Articles referencing this type of infrastructure were classified as “A” (directly relevant) if the research focused on bicycle-motor vehicle interactions and the infrastructure contribution to this, and “B” (less relevant) if it focused on single-vehicle, pedestrian-bicycle or bicycle-bicycle interactions and was not obviously linked to infrastructure. “D” articles in particular could be quite unrelated to the topic of safety at cycle infrastructure and the broader database should be considered very cautiously in terms of its relationship with the safety of on-road infrastructure treatments for cyclists.

In terms of the topic of the dissertation, a dominant research approach affecting knowledge produced is revealed through the recurrence of themes in the approaches adopted by research into cyclist safety and infrastructure. To provide rigour to impressions of how commonly these themes occurred, a textual review of abstracts in the database was undertaken. Excluding articles for which no abstract was available and adding the Australian content, a data subset of 176 “A” or “B” articles and 211 “C” or “D” articles were used as the basis of the textual analysis.

Up to six (though more commonly, two to four) textual terms were allocated to each abstract, with 143 “A” or “B” articles and 113 “C” or “D” having one or more terms associated with them.

The choice of terms used reflected how frequently these occurred in abstracts and comprised describing:

- Methodology, e.g. Gamma, Poisson, regression analysis, exposure
- Data sources, e.g. crash data, hospital admission data, death records
- Study design, e.g. observational, case crossover, conflict study, before/after
- Infrastructure of interest, e.g. roundabouts, bike tracks, intersections
- Safety factors (or in the engineers’ jargon “mechanisms”), e.g. speed, Safety in Numbers effect, Looked But Failed to See error.

In practice, data sources were closely aligned with statistical terms, to the extent that data sources and methodology were combined in the analysis and reporting. “Safety factors” mentioned in abstracts as a limitation rather than being addressed by the methodology were considered to represent a subset of a larger field term “common issues/ concerns”, which included exposure.

3. Basic results

Research age

As on-line databases were used, results are only for articles with content enabling on-line searching, which excludes hard-copy articles unless these have been scanned and processed.

So while the earliest relevant article dated from 1975, very few date from before 1990. This has particular implications for cycling because an interest in cycling emerged at an earlier date in parts of continental Europe (notably Holland, Denmark and Germany) than in countries such as Australia, and access to seminal research could become more difficult over time as early researchers and practitioners still in possession of hard copy research or aware of its existence retire.

Further, while some of the Australian sources have undertaken the task of digitizing older holdings, as these papers have not been republished in searchable journals they are still not available through on-line search engines. A method to make these searchable would be useful.

This should not be an ongoing effect: as production of information is now almost exclusively digitally-based – assuming that search engines can maintain their growing databases as accessible and that the economic rationale for their existence continues. It might be wise to consider what backstop might apply should these conditions change, but the research database would arguably continue to form a valuable asset and would be retained in the event of a changeover process being required.

More recent articles are more likely to have been produced using word processing software and thus be accessible to digital searching. Apart from improved access to research, this leads to the available research base increasing significantly since 1975, as illustrated by Figure 2**.** (This presents the full database, which gives a better overview than only “A” and “B” publications).

The fewer articles published in 2014 reflect the fact that the database exercise was undertaken during and completed before the end of this calendar year.

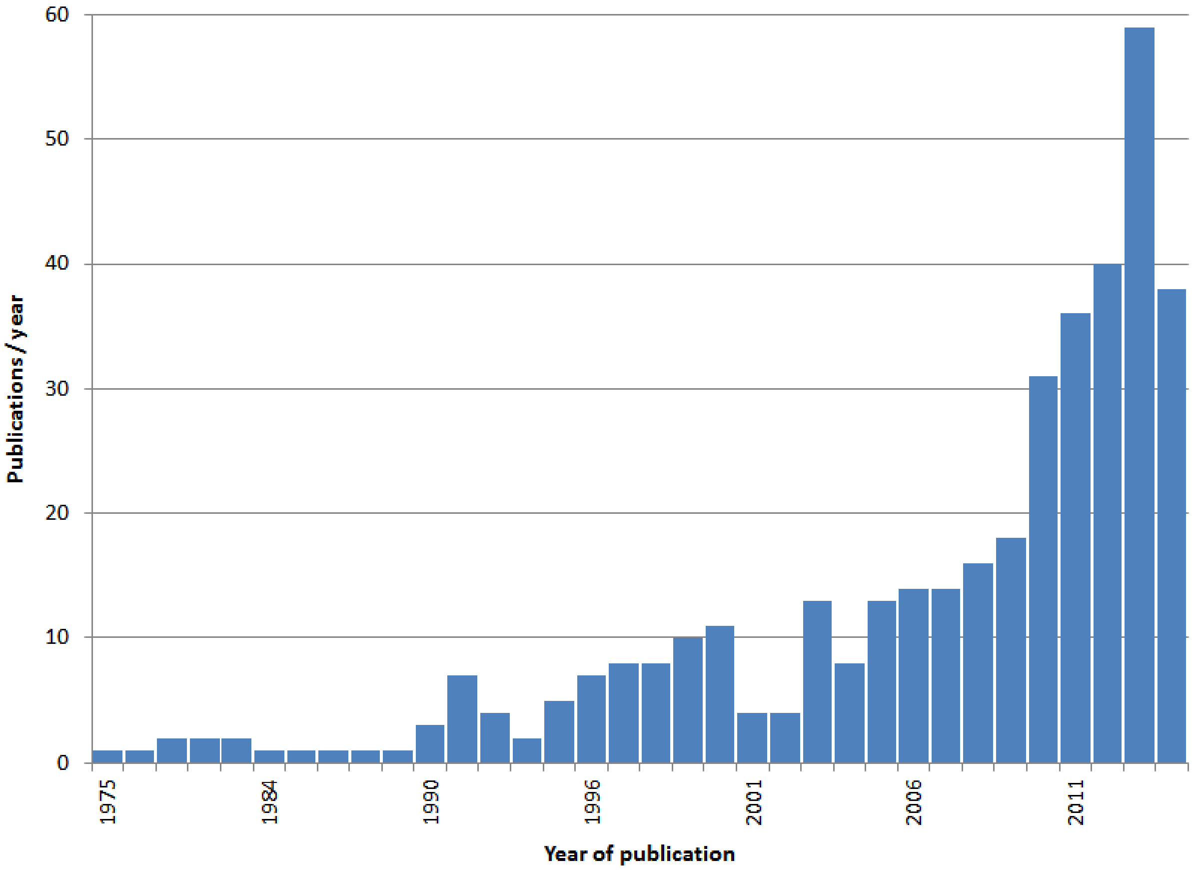

Figure 2: Number of potentially relevant articles by year of publication

An exponential growth in the potentially relevant research is evident, more likely because of the rise of on-line publishing (and journals that make this research available to others) than accelerating interest in the safety of cycle infrastructure. This supposition could be confirmed by contrasting this graph with similar searches for other subject areas, but it is not a critical point for the SQ literature review. What this does point to is the high frequency with which new literature is now published, and which partly gives rise to the snapshot approach used in the SQ literature review.

Not obvious from the process described is the geometrically expanding amount of material that must be reviewed to return relevant results. The initial item generated 120 articles, of which 33 were assessed as “A” or “B” (a success rate of 27.5%), The fourteen “A” articles produced gave rise to some 1,600 articles, of which 64 were assessed as being “A” or “B” articles (a success rate of 4%). To identify the 74 “A” and “B” articles at the next level, around 2,150 articles had to be reviewed – with a slightly lower success rate of some 3.5%, though this falls to some 3% if the overly productive search noted earlier is stripped of its non-scholarly results. To continue the search at another level down would require over 5,000 articles to be reviewed. As searching takes time to undertake, additional articles could be expected to be published at the same time that searches are being conducted, hence there is no real feasibility in conducting a search to the point that no new information is revealed.

The approach taken balanced the return of relevant articles with the amount of effort involved. It is considered that a future SQ literature review following the adopted methodology could be limited to the 4% success rate limit and still provide good insight into the research topic while reducing the number of articles reviewed by some two-thirds. This is made with the knowledge that the SQ literature review was intended to be followed by a traditional literature review enabling a more thorough examination of issues of interest.

Research language

Linguistic diversity compounds the skew of results away from earlier research as older literature is less likely to be available in English. For example, seminal German research into contra-flow cycling undertaken by the Federal Road Research Institute was completed in 2000. Alrutz et al (2002) summarised the results. This paper was later translated by John S Allen and posted on his website. As this has not been published as English-language research, it is not available through scholarly databases operating in the English language, instead being identified by Google Scholar.

While language barrier effects exist in other fields, this plus the skew against older research have particular implications for cycling because an interest in cycling emerged at an earlier date in parts of continental Europe (notably Holland, Denmark and Germany) than in Anglophone countries, giving rise to more advanced research agendas often being pursued in these countries compared to Anglophone topics.

Only three non-English references were identified in the database, with two further papers found on a French-only website. Obtaining full papers would be difficult without competency in these languages, much less understanding the results if these are not available in English. Japan and China also have long traditions of providing cycle infrastructure and their research history is even more opaque for the English-only speaker.

The rise of English as an international language and the growing interest of Anglophone countries in cycling research appear to be eroding the language issue. When coupled with improvements in machine translation, the language barrier is expected to diminish in the future. A cautionary proviso may be that increasing amounts of research produced in large population non-Anglophone countries – China would be the standout example at present – could present an increase in the language barrier over time. This would particularly be the case for symbolic written languages such as Chinese where users of Latin scripts have difficulty in inputting characters to conduct keyword searches for subsequent machine translation. However, the development of voice-controlled IT coupled with better machine translation should also minimise this as an emerging problem.

Impact of keywords and search engines

The variation in keywords indicated by each search engine could skew the snapshot presented by the SQ literature review. While the initial search article generated fourteen related "A" articles, the first of these articles generated only nine "A" and "B" articles, while the last search article generated none. However, it should be noted that the search tree as represented in Figure 1 is misleading in this aspect, as search results have been presented with consideration to readability rather than in strict chronological order. Further, one or two search items were initially missed, while the removal of duplicate records did not necessarily follow a chronological searching sequence. Given the impact of duplication on records identified and kept for assessment, the search tree results are therefore best understood in the aggregate and as illustrative of the types of results found rather than as an accurate portrayal of the actual results by search term.

After the initial search article, the most prolific generators of relevant research were the sixth, which generated seventeen "A" and "B" articles, and the thirty-third, which produced twenty-four articles but should be treated with some caution due to the use of Google Scholar as the search engine. Looking at the actual keywords being used by the search engines:

- Initial article: obtained by searching on "safety of cycle infrastructure" and generated fourteen "A" results from the keywords "cycle facilities", "safety", "Greater Nottingham" and "traffic planning"
- First related search: keywords of "bicycle accidents", "accident risk", "Bayesian framework", "case-control strategy", "risk factors" and "cycling"
- Sixth (and most prolific) related search: keywords of "cyclists", "roads – design and construction", "traffic circles", "cycling- safety measures", "crash injuries" and "statistics". "Traffic circles" is an alternative term for a roundabout.
- Thirty-third article: Google Scholar did not return the keywords used in its search algorithm. However, the Google algorithm is not limited to keywords but also considers the frequency with which a website is referenced as an indicator of its relevance.
- Thirty-fourth (last) related search: keywords of "safety", "bicyclist", "safety performance" and "intersection".

It also appears that the keyword of "bicycle" will return results involving "cycle" or "cyclist", albeit perhaps in different orders. As a keyword, "cycle" tends to pick up research involving construction management (via "life-cycle") and, to a lesser extent, research from the life sciences.

A few test follow-up searches (e.g. “cycling”, “safety”, “roads – design and construction” and “bike boxes”, based on the sixth related search; and searches undertaken on high level “B” articles) have identified very little additional research of relevance, indicating that the methodology has identified most relevant material and that further searching for relevant literature should involve a different methodology.

It should be noted that the 3,900 articles reviewed were not unique records. Given similarities in keywords, it should not be surprising that results overlapped in the search results. Indeed, this effect provides some indication that the methodology was providing a reasonably thorough overview of the literature: if the results being returned had been entirely unique, the search methodology would have been altered to continue into the result tree to the point that an overview could have been considered to have been obtained. Instead, Figure 1 illustrates the number of searches at the third level returning no new “A” or “B” material.

The number of times a particular article was returned in different searches was not recorded but would reduce the number of reviewed articles. It is difficult to disaggregate this effect from the relevance of the topic being searched. Assuming perhaps 25 per cent of articles were not unique, this means that under 3,000 unique articles were reviewed. Even at a 50 per cent recurrence rate – which is considered higher than observed – a sample of slightly under 2,000 should still be large enough to assume that the proportion of Australian research to international research is representative.

In terms of the breadth of search provided, there are limitations to using on-line databases.

- Science Direct is available by subscription and references Elsevier’s 3,454 journal titles in four subject areas: physical sciences and engineering, life sciences, health sciences, and social sciences and humanities. These titles include conference proceedings in twenty subject-areas. Science Direct can be used without a subscription to conduct initial searches and return abstracts. SCOPUS is also a subscription service provided by Elsevier.
- PubMed is a free resource developed and maintained by the National Center for Biotechnology Information at the U.S. National Library of Medicine and makes use of the MEDLINE bibliographical database. This references life sciences articles in some 5,600 journals and forty languages[2].
- Google Scholar is a free resource provided by Google and uses Google’s search algorithm.

[2] MEDLINE fact sheet: http://www.nlm.nih.gov/pubs/factsheets/medline.html

Science Direct has a broad subject scope within its journal titles compared to the medical focus of PubMed. Google Scholar has a much broader scope but this comes at the cost of a poorer focus on published peer-review research. As Google does not maintain a research database, abstracts or publication information may not be available. Google Scholar results will also reference Science Direct or PubMed results, creating some overlap with searches using these engines. In all cases, few full text papers are freely available (rendering most research returned by academic search engines as 'black' literature).

Journal sources

Almost 100 journals and other sources contributed to the 385 potentially relevant research references in the broader data base. Student theses are considered as a single source, though originating from different universities. As mentioned, the sources included a few books and book reviews, as well as special journal issues on a single topic. Books on cycle infrastructure do not seem to be common – apart from standards and guidelines issued by national bodies, which are not referenced by the major scholarly databases. Where books have been found through other means, these more typically focus on policy, perhaps because of the primacy of technical standards and guidelines. Scholarly articles may also be of less interest to readers in book form due to their role as part of a body of research because journals enable a more rapid dispersion of research, which can be soon cited by the next piece of research.

The journal generating the overwhelming majority of references was *Accident Analysis and Prevention,* which accounted for 126 articles or almost a third of the full database. This far exceeded the contribution by the next most significant source, *Transportation Research Record: Proceedings of the Transportation Research Board* (18 articles, excluding three records of Annual Meetings), Apart from the dominance of *Accident Analysis and Prevention*, there is no major pattern in the contribution of articles from journals, which gradually reduce as shown in Figure 3. This figure labels these two mentioned journals plus the only other journals to have more than ten articles:

- *Transportation Research Part A: Policy and Practice* (16)
- *Transport Policy* (13)
- *Transportation Research Part F: Traffic Psychology and Behaviour* (11)
- *Transportation Research Part D: Transport and Environment* (11).

Together, these six journals account for just over half of the potentially relevant research – again noting the loose boundaries applied to the assessment of "potentially relevant".

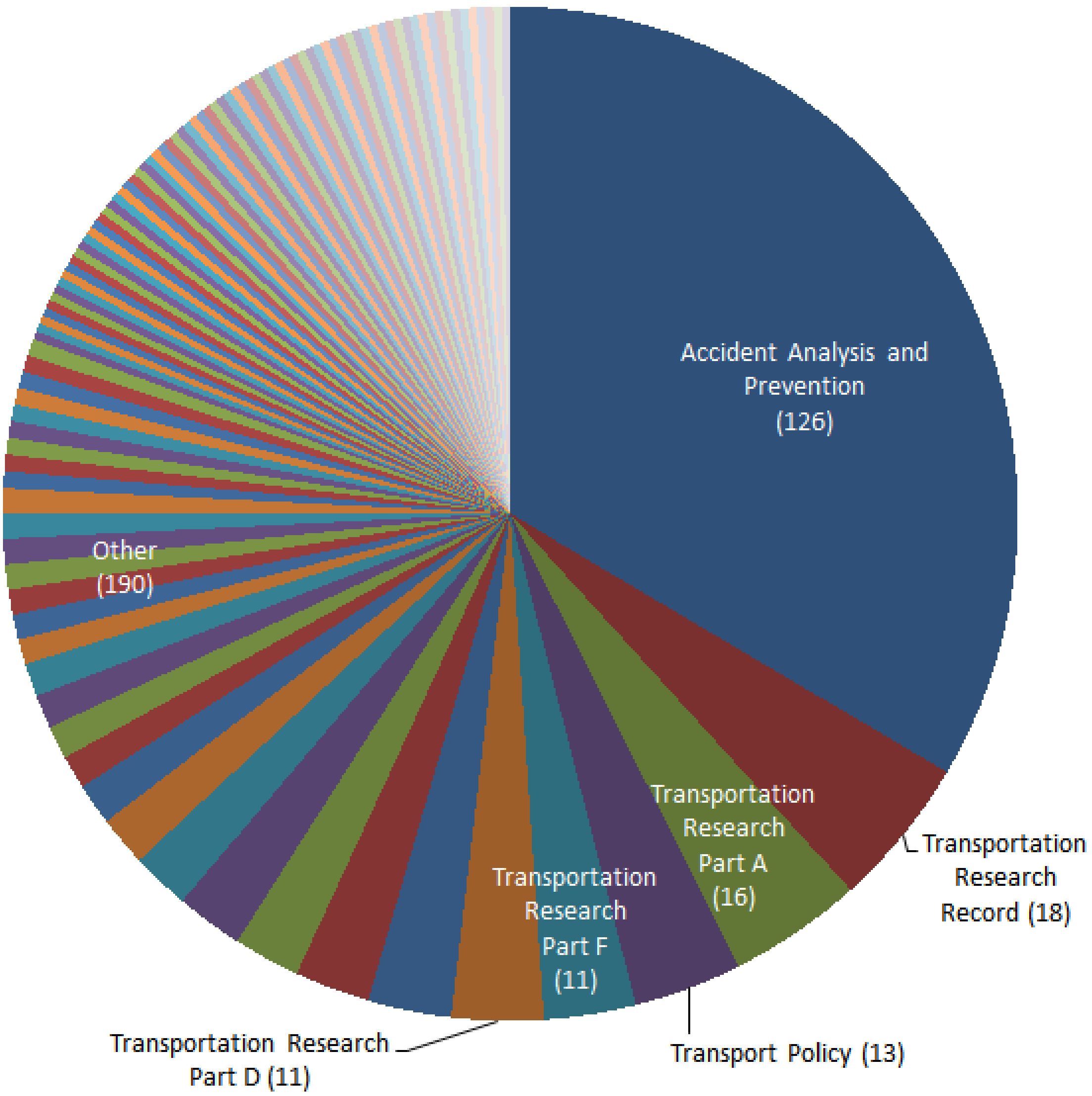

Figure 3: Journal contributions to the full on-line database, largest to smallest

When considering only “A” or “B” articles, the number of journals is reduced as many only generated single “C” or “D” articles. *Accident Analysis and Prevention* maintains its dominance but there is little to differentiate the remaining journals.

Australian research can be found in these journals and, not surprisingly, in Australian journals and proceedings of peer-reviewed conferences: *Australian and New Zealand Journal of Public Health*, *Australasian Transport Research Forum*, *Australian Cycling Conference*, *Health Promotion Journal Australia*, *Journal of the Australasian College of Road Safety*, *Road and Transport Research*, *Transport Engineering in Australia*. Two references were not peer-reviewed per se: *Australia: Walking the 21st Century Conference Proceedings* and an Austroads project report. A further article was contained in the Institution of Professional Engineers New Zealand Transportation Group Conference proceedings rather than in an Australian-based publication.

Given small numbers, there is little to differentiate these sources in terms of contribution to the field of study.

4. Australian content

Of the 172 “A” and “B” articles identified by the academic search engines, Australian research was represented in fifteen. As the SQ literature review is being undertaken as part of Australian research, Australian content in the dataset was of particular interest and additional sources were consulted to confirm a reasonable capture of Australian research. The results of this grey literature review are discussed in this section.

In total, a search of over 5,000 pieces of Australian transport and traffic research identified nine additional items relating to the safety of infrastructure for cyclists. Even including part of the New Zealand research, the actual number of articles is small. It is arguably over-representative of Australia’s population compared to the rest of the world, though this could reflect the dominance of English and hence Anglophone research in the on-line literature. By way of comparison, a search on “Canada” identified eleven A and B classified articles in the on-line database. Nonetheless, the amount and scope of relevant research found is modest given the potential types of infrastructure that could be considered, especially as three papers focused on roundabouts as a particular type of infrastructure and as Anglophone countries have some distinctive engineering practices compared to other countries. For example, in non-Anglophone countries separated bicycle tracks/paths are prevalent (with Anglophone countries having “bicycle boulevards” and “sharrows” as alternative treatments). Also, non-Anglophone countries often allow contra-flow cycling in one-way streets through signage only, and use radial rather than tangential roundabout design.

It may be the case that what is actually reflected by these results is an overall lack of research into the safety of infrastructure for cyclists. This SQ literature review could not confirm this proposition.

Sources

Australasian Transport Research Forum (ATRF)

All papers from 1975 to 2013 ATRF conferences are available at the ATRF website and conference papers are peer-reviewed. These have been graphed as Figure 4, again demonstrating an increase in research over time, but not the exponential growth noted for research identified using search engines.

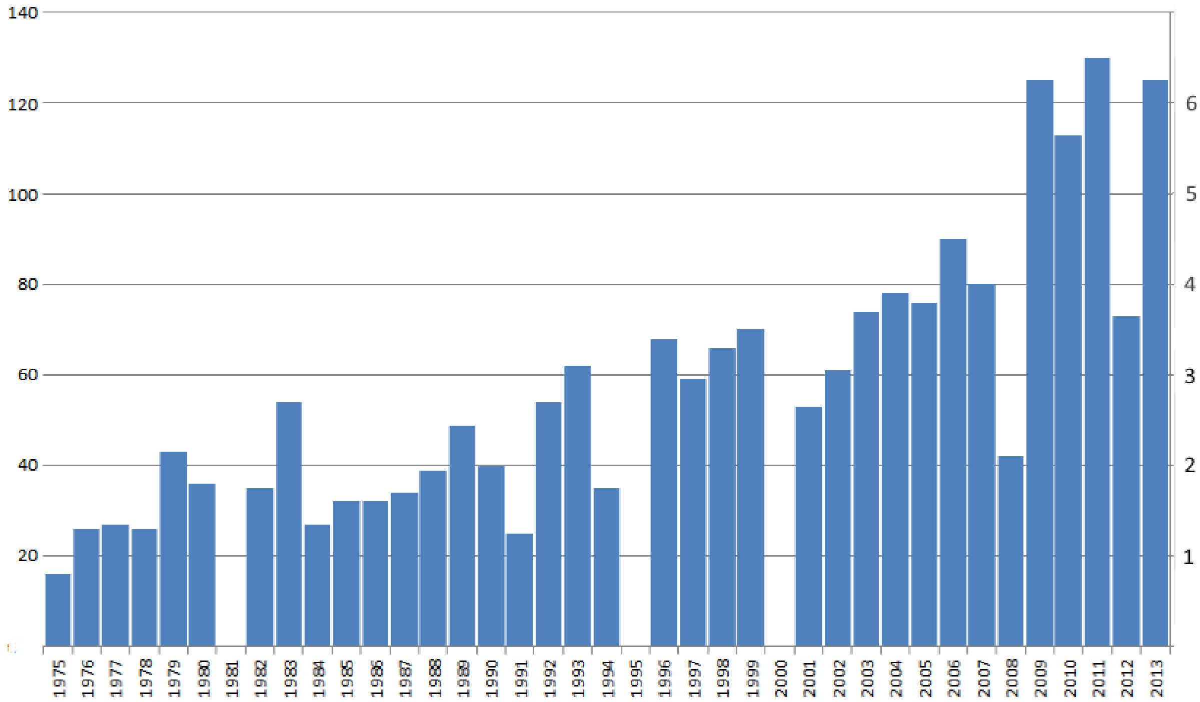

Figure 4: ATRF papers by conference year

Conferences were not held in 1981, 1995, 2000 or 2014; the total number of ATRF papers is 427.

Six papers were identified relating safety to cycle infrastructure, and a further three New Zealand papers – Walton, Dravitzki and Cleland's (2003) examination into the effects of line markings for wet/night visibility on cycle safety, Harper and Dunn's (2003) study into accident prediction at urban roundabouts and Turner and Wood's (2009) study into crash prediction modelling at intersections. Turner and Wood (2009) encompasses the literature review associated with the ATRF article and was captured in the on-line database, where it is classified as being Australian research.

Austroads

Austroads is the peak organisation of Australasian road transport and traffic agencies. Austroads' purpose is to support its member organisations to deliver an improved Australasian road transport network, which it achieves in part by undertaking leading-edge road and transport research, which it uses to underpin policy development and its published guidance on the design, construction and management of the road network and associated infrastructure.

A search of Austroads research publications using the keyword "bicycle" and excluding practitioner guidelines found eight reports whose titles indicated potential relevance, all published between 2000 and 2014. (The date parameters of its search engine and the overall size of the database searched are not obvious.) However, when the research embodied in the reports was taken into account, four of these could not be considered to add to the research topic. One of the remaining four articles would, under the methodology adopted for the on-line database, rate a "C" assessment, while another – AP-R410-12 (2012) *Cycling on Higher Speed Roads* (Eady and Daff, 2012) – cited only a single study linking crash severity with factors on undivided roads in North Carolina and otherwise reviewed practice and guidelines rather than empirical evidence. This leaves two publications of relevance:

- AP-R461-14 (2014) *Assessment of the Effectiveness of On-road Bicycle Lanes at Roundabouts in Australia and New Zealand* (Wilke, Lieswyn and Munro, 2014)
- AP-R157-00 (2000) Pedestrian and Cyclist Safety — *Investigation of Accidents in Different Road Environments.* (Austroads 2000).

Australasian Road Research Board (ARRB)

The Australasian Road Research Board (ARRB) was formed in 1960 as a national transport research organisation tasked by its members (Australian and New Zealand state road agencies) with commissioning or undertaking research in the field of traffic and transport in Australasia – albeit that the way in which it delivers on its primary goal is, as of 2017, undergoing some changes.

ARRB holdings include:

- ARRB special reports (1961-2013, comprising 768 reports). These are not peer-reviewed
- ARRB conferences (1962-2012, comprising 3,583 articles). Papers undergo peer-review but can include practical topics not conducive to a scholarly level of review
- ARRB's *Road and Transport Research Journal* (2005-2014). These are generally peer-reviewed but can include invited papers considered to be of particular value that may not have been peer-reviewed.

A search using "bicycle" as a keyword identified:

- Two special reports, both of such vintage (1966 in the case of Robertson, Mclean and Ryan and 1984 in the case of Brindle) that while the intent may have been to examine the association between safety and infrastructure, the methodology and results would not in modern times warrant an "A" or "B" rating because of the very tenuous associations established.
- Four conference papers of potential relevance.
  Two of these – Taylor (1980) and Brindle and Andreassend (1984) – are also of a sufficient vintage for the results to lack rigour in more modern terms.
  The abstract for Wadhwa (2003) mentions an international review of intersection

treatments, but the evidence is not presented in the full paper. This paper may be based on Wadhwa and Faichney (2002), which developed a catalogue of technologies for improving bicycle safety and was presented at an ATRF conference and identified in the examination of ATRF proceedings.

White and Daff (1990) observed cyclists and motor vehicle interaction at five sites to observe how cyclist comfort and safety varied with kerbside lane widths. Their results correlate to current Australian technical guidance for wide kerbside lane treatments.

- Four journal papers of direct relevance, two of which represented Australian research. One had already been identified through the on-line database. In the remaining piece of Australian research not previously, Patterson (2013), provided a literature review on the safety of contra-flow cycling enabled through “bicycles excepted” signage rather than bicycle lanes.

A follow up search using “cycling” as a keyword identified that the keyword search was sophisticated enough to associate “bicycle” with “cycling” and no additional research was identified.

Influence of Australian research on local practice

So how well does the Australian research influence Australian practice? This is difficult to ascertain from the SQ literature review, however a first indication might be made by highlighting Australian research in the graph of ATRF papers over time, as in Figure 4, albeit that Stevenson et al (2014) describes the approach and protocols for a future study rather than reporting on the study itself, and that the SQ literature review only covers the first 9 months of 2014. (ATRF papers are used as a basis as these did not display the exponential growth in literature present in the full database, and which confuses the picture somewhat.)

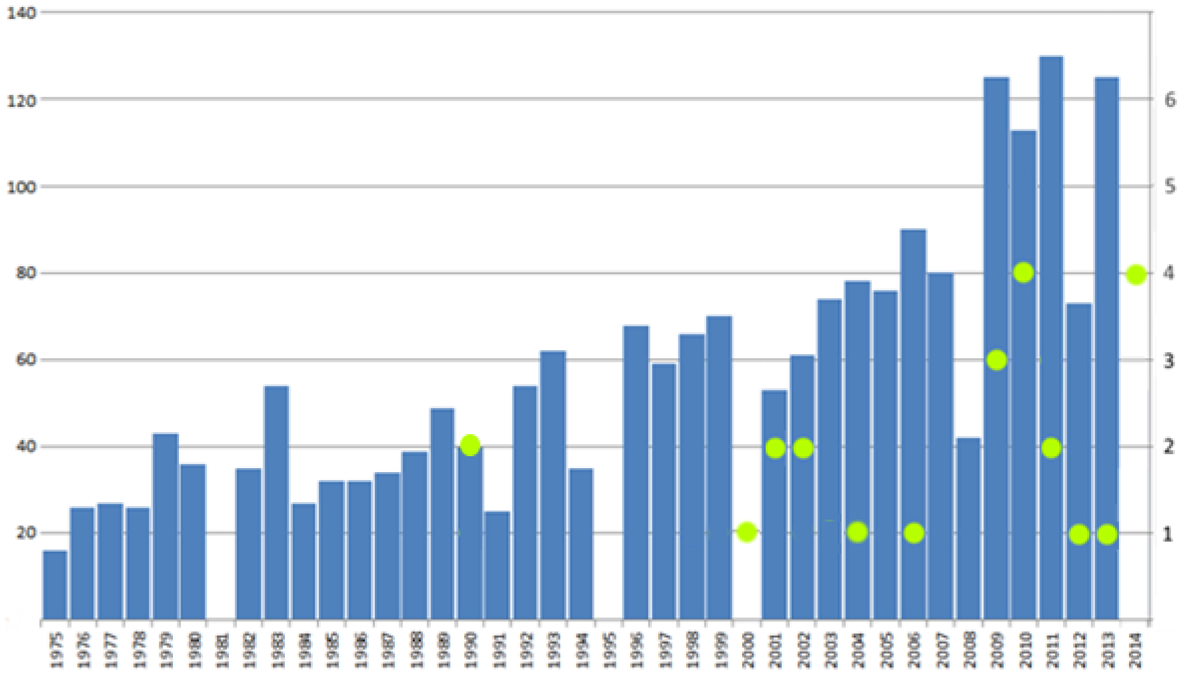

Figure 5: ATRF papers (left hand scale) by year; total Australian research papers dealing with cycling and infrastructure by year shown in green (right hand scale)

The small numbers caution against drawing firm conclusions, but it can be observed that research into infrastructure safety appears to have mainly occurred after publication of national practitioner guidance: Austroads' *Guide to Traffic Engineering Part 14: Bicycles*, first published in 1993 with a second edition published in 1999; and the series of Austroads *Guide to Road Design* in 2008, which superseded the *Guide to Traffic Engineering Part 14*. The association that could be drawn, then, is not that research has guided the development of practical guidance, but rather that the practical guidance has coincided with interest in cycle safety or, indeed, spawned research. Figure 5 also gives an impression of two main clusters of research, a small cluster around 2000-2002 and a larger cluster around 2009-2011, with a small outlier in 1990 and another peak emerging in 2014. This impression is only strengthened by noting that the 2006 paper by Garrard, Rose and Lo (2006) was not related to the 2008 *Guide to Road Design*. (It researched the role of infrastructure for encouraging women to cycle.)

Another way to interpret Figure 5 is to say that the release of national guidance stimulated interest in research on the topic of the safety of cycling infrastructure, and that the trend of increasing research regarding cycle infrastructure is also in line with a general trend of increasing amounts of transport research being presented at ATRF conferences. However, this does not contradict the observation that research follows rather than leads national practitioner guidance.

Of course, other cycle-related publications, such as AS 1742.9 – 2000, *Manual of uniform traffic control devices: bicycle facilities* (Standards Australia, 2000) and AS 2890.3 – 1993, *Parking facilities: bicycle parking facilities* (Standards Australia, 1993), as well as state-based guidance, could be a stimulus for research that did then become incorporated into the national guidelines. But the proposition that research lags the published guidance is supported by Patterson (2010). This literature review attempted (and failed) to find a research base for the inclusion of bicycle lanes in roundabouts, which were a new treatment included in the 2008 *Guide to Road Design.* Prior to this new national guidance, bicycle lanes in roundabouts were included as an option in New South Wales and (with some provisos) Victorian guidance, but neither of these state-based publications provided a research base for the treatment**.**

Overall, Australian research does not seem particularly influential in regard to national practitioner guidance. This still leaves open the possibility that jurisdictions are commissioning and responding to research that has not been published. The SQ literature review does not lend itself to exploring this topic in further detail.

Researcher/ practitioner collaboration

Moore and Hughes (1991) express the desirability of collaboration between engineering managers, practitioners (users) and researchers. They express the view that the most useful role the engineering manager can play is as an interface between users and researchers. The extent of collaboration is difficult to identify in the literature. But while not always easy to ascertain, author affiliations provided lend themselves to a loose classification of:

- Academic
- Advocate-based
- Consultant, with authors being either professional researchers or practitioners
- Government agencies, as commissioning authorities or practitioners
- Research agencies, typically associated with either universities or government – but in Australia at least, facing increasing pressure to adopt a consulting role.

Author affiliations are time-consuming to establish. A first cut at a comparison is to simply compare the number of authors for Australian versus international research.

The on-line database plus ATRF and ARRB papers were examined by author number, with research classified as being of the “A” and “B” type deemed as being most likely to influence practice. The two Austroads publications were excluded as these identified the people who prepared the work separately to a working group/ project manager and it is not clear how the latter should be considered compared to authors identified in peer-reviewed research.

Numbers of papers are presented along with proportion by author number in Table 1. The paper numbers are provided to illustrate that caution is needed in interpreting the results because of the small absolute amount of research covered.

# of Authors	Australian ("A" and "B")		International ("A" and "B")	
	# papers	proportion	# papers	proportion
1	8	33%	29	19%
2	6	25%	40	26%
3	3	13%	46	30%
4	4	17%	17	11%
5+	3	13%	20	13%
	24		*152*	

Table 1: Number of authors by research source, "A" and "B" classified research

The clearest difference is that Australian research shows a larger proportion of single authors compared with overseas. A secondary observation is that in overseas research, authorship proportions increase from one to three and then reduce to four, whereas in Australian research, authorship proportions fall from one to three, with a slight uptick for four authors. The proportion of papers having five or more authors is similar between Australian and overseas research.

Adding in "C" and "D" classified articles to increase the amount of Australian research considered gives Table 2.

# of Authors	Australian (all classifications)		International ("A" and "B")	
	# papers	proportion	# papers	proportion
1	14	30%	29	19%
2	10	22%	40	26%
3	6	13%	46	30%
4	11	24%	17	11%
5+	5	11%	20	13%
	46		*152*	

Table 2: Number of authors by research source, extended Australian research

This essentially confirms the observations established by "A" and "B" classified research[3].

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[3] As a proviso, the two excluded ARRB papers were prepared by three main authors. If it could be assumed that these represent the total authorship, this would give a steady reduction of author proportions from one

The larger proportion of single author papers in Australian research indicates less collaboration, and by a considerable amount: almost one in three Australian papers are written by an individual, while only one in five overseas papers have a single author. It is possible that this reflects more practitioner-researcher authors in Australia than overseas, but there is little reason to assume that this is the case[4].

The secondary trend may lend weight to collaboration in research being valued more highly overseas than in Australia as the higher proportion of single authors in Australia resulted in a lower proportion of three-author papers rather than papers with two authors. However the number of listed authors is not necessarily a good indicator of collaboration between rather than within fields. For the relatively few items of Australian research, it is feasible to establish author affiliations to test collaborations in multi-author articles.

Of the twenty-four pieces of “A” or “B” ranked Australian research in the database only Hatfield, Murphy, Job and Du (2009) had authors from more than one field of affiliation, being university and government agency. The remainder of multi-author papers involved collaborations within a single field of affiliation (usually academic).

Comparing this with the international research is time consuming, difficult and less feasible to establish with certainty, especially given the complicating factor of overseas agencies having relationships/ functions that may not be directly analogous to the Australian context. For example, of the seven papers for which Paul Schepers was principal author, the Dutch government employee:

- was the only author in one case
- collaborated with consultants in one case
- collaborated with a research agency in two cases
- collaborated with a government agency in three cases, with an author being from a different Ministry to Schepers’ in one of those cases

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to five in Table 1 and a smoother progression of proportions in Table 2. If the project manager/ working group were instead added to the authorships, making these into four and seven authorship papers, these would instead emphasise the small proportion of three-author papers and the increase in proportion of four-author papers. In neither case would the Australian authorship proportions reflect those of the overseas research.

4 There is some evidence in support of this proposition. Patterson (2010) and Cumming (2010) focused on roundabouts due to the inclusion of bicycle lanes in roundabouts in national guidance released in 2008 and the lack of research underpinning this guidance. These authors are both practitioners who applied research to a treatment of concern. Alan Parker, conducted significant research in areas which he felt were not otherwise covered. The larger question is whether this type of practitioner research is represented in the overseas literature.

- collaborated with a university in five cases.

Clearly, papers typically included a combination of affiliations in their authorship. Less obviously, these backgrounds included an author from a university department of psychology in one case; some co-authors held positions in both university and a research agency; the government collaboration *may* indicate practitioner involvement in addition to management; and the above listing of collaborations assumes that the Dutch Consumer and Safety Institute (which holds Netherlands Injury Surveillance System records) is classified as a government rather than a research agency.

A comparison with New Zealand is both feasible and reasonable, given the high levels of cultural similarity and even practitioner guidance shared between the two countries. A search on “New Zealand” in the on-line database identified ten pieces of New Zealand research (including “C” and “D” articles), A subsequent examination of authors revealed:

- two sole authors (one paper being a student thesis)
- a partnership between two authors from the same university, but one author was also a consultant
- a partnership between two government employees
- a partnership between two different consultant companies
- a collaboration between government and university
- a collaboration between university and consultants
- three collaborations between government and consultants.

While not definitive, this points to collaborations between affiliation fields being more common in our near neighbours’ authorship than in our own.

A similar exercise using the term “Canada” returned 23 results – a reasonably similar level of research to Australia, if the additional literature derived from Australian sources is omitted. No single author papers are represented in the literature. All research included at least one university affiliation, with other authors including:

- a consultant only in one case
- a consultant plus government in one case
- a health research institute apparently not affiliated with universities in one case, plus the Emergency Department, University Health Network, Toronto (assumed to describe a university type of interest rather than a hospital practitioner interest)
- two health research institutes apparently not affiliated with universities, plus a hospital in one case

- government only in six cases.

Here, the Directeur de Santé Publique de Montréal (Integrated University Health and Social Services Centre) and Occupational Cancer Research Centre, Cancer Care Ontario, have been classified as research institutes. Hospitals have been added as it is unclear how else to categorise the affiliation as in this case 'practitioner' describes a non-practitioner for the purposes of traffic engineering. (Luckily, the BC Injury Research Prevention Unit, "…a core research program within the Evidence to Innovation research theme at BC Children's Hospital, serving as a student training centre, and whose staff may hold faculty appointments at the University of British Columbia", was collaborating with both a university and research institute, making a judgment of which of these best represented its operations unnecessary.)

Overall, the examples of New Zealand, Canada and the case of Paul Schepers paint a picture of broader inter and intra- field collaboration in overseas research compared to Australian research. This arguably reflects different cultural attitudes towards research, as evinced by all research from Canada involving universities; is related to the higher modal share of cycling in many overseas countries than Australia; and reflects ease of access to collaborators in areas of denser population. However, neither of the latter two explanations apply to New Zealand and we are left with no clues as to why a different cultural attitude exists towards research overseas compared with Australia.

Moore and Hughes (1991) point out that in traffic engineering, the more removed the researchers are from the traffic management practitioners, the more likely that the results of research will not be put into practice. Research involving practitioners from non-transport fields arguably represents research removed from traffic engineering users. But when considering active transport, the cross-sector impacts rather than the transport function can be a driver of infrastructure development. The corollary to Moore and Hughes (1991) is surely that *traffic engineering* research that does not address the needs of *other* users may result in research that is not put into practice. In this light, the nature of specific research collaborations is important, as is the mechanism(s) for non-transport research to be incorporated into the transport agenda. This is a much larger topic than this SQ literature review can address.

5. Common features of the database literature

The results of the textual analysis are documented in Table 3. They are discussed by subject field following this table. Here, results for the 143 more relevant ("A" and "B") articles are shown separately to the 113 less relevant "C" and "D" articles.

	"A" and "B"		"C" and "D"	
Subject field	# papers	%	# papers	%
1. Data sources				
Police crash record	68	48%	42	37%
Hospital admission data	6	4%	21	19%
Mortality data	0	0%	6	5%
Prospective survey	0	0%	6	5%
2. Study design				
Observational study	22	15%	38	34%
Before/ after study	14	10%	4	4%
User survey	9	6%	23	20%
Comparison study (case control, case crossover design)	9	6%	3	3%
3. Common issues/ concerns				
Exposure	18	13%	19	17%
Crash or injury severity model/s	16	11%	22	19%
Safety in numbers	13	9%	9	8%
Speed	11	8%	5	4%
Conflict/s	6	4%	3	3%
Looked but failed to see				
4. Infrastructure theme				
Roundabout/s	24	17%	10	9%
Bike tracks/ bike lanes	24	17%	2	2%
Intersections	7	5%	5	4%
Bike boxes/ advanced storage areas/ advanced stop lines	4	3%	2	2%
Red light running	1	<1%	5	4%

Table 3: Article themes of the quantitative literature review

Data sources

Police crash data is by far the most common data source used. As the textual review method used allowed articles to have more than a single keyword ascribed to them, the use of data sources as shown is not exclusive. That is, a study may have examined police records but is not necessarily reliant on them. Indeed, some research compared data sources to identify to what degree crashes captured in police crash records also appeared in hospital admission data as part of understanding the limitations of police crash records. What is evident, though, is that in research directly focused on the safety performance of cycle infrastructure, police data is particularly relied upon. This reflects researchers' ability to both easily access and trust the quality of this. In particular, while hospital admission data is arguably of a better quality in terms of capturing actual injury information, this is typically less useful to traffic engineers as it is rarely linked to a crash location or conditions. However, use of police data raises some issues given known under-reporting of cycle crashes to police.

Prospective surveys, which recruit and follow a cohort to observe outcomes over time, can provide better quality data than mass data approaches, but require extensive resourcing to obtain and to recruit a very large cohort if statistical associations are to be drawn between crash risk or injury severity and particular types of infrastructure, design features or behaviours – as when developing crash and injury severity models. Observational studies can be used to address data issues, although many of these also included an examination of police crash data. Observational studies are discussed in more detail under study design, below.

Although single-vehicle crashes account for the majority of cyclist crashes, Schepers and den Brinker (2011) was one of few studies to specifically examine causal factors for these, by considering the visual characteristics of bicycle facilities in avoiding such crashes. Apart from the generally greater severity associated with cyclist-vehicle crashes, the lack of such research could be explained by the difficulty in examining factors contributing to a crash type poorly represented in police crash data, compared to examining a spatially-defined location for its crash history – an example of pragmatism. Other ways to overcome the limitations of data are captured through study design, as follows.

Study design

Broad scale analyses of crash statistics and/or injury statistics follow a premise that relevant information about crash locations (including aspects such as infrastructure characteristics, speeds, geometric design features, etc), crash characteristics (type, severity, etc) and road user characteristics (age, experience, training, type of cyclist, alcohol use, etc) can be analysed using different statistical approaches to identify factors contributing to crash incidence and outcomes, either for all cyclists in the population or particular groups such as children. Minikel's (2012) examination of Berkeley's bike boulevards, which included analysing police collision data for arterial roads as well as bike boulevards and undertaking bicycle counts to assess comparative risk, is an example of this type of study, and the conceptual underpinning has obvious application to infrastructure. The statistical modelling used is often reported in these studies. A list of commonly mentioned approaches gives a good impression of the statistical manipulation used: negative binomial, Poisson, ordered probit, multivariate regression, Bayesian, empirical Bayes, multilevel Poisson regression, gamma and multinomial logit.

Compared to the prevalence of the data source of “police crash record”, however, crash or injury severity modelling was only mentioned about a third as often in the A and B articles and half as often in the C and D articles. To a large extent, this indicates an assumed acceptance for the methodology. However, in their simplest forms, these statistical analyses do not control for cyclist volumes, much less the demographics or social determinants of the cycling population – the latter of which can be significant in cultures that confine cycling to the socially marginalised. As such, the results of such studies can be a de facto measure of exposure/demographic driven factors rather than reflect the performance of the infrastructure being examined. For example, as Bíl, Bílová and Müller (2010) note, the significance of finding that more male cyclists are involved in crashes than female cyclists is difficult to evaluate when their relative participation rates are unknown – this finding would have very different implications if Czech cycling participation rates are similar to Dutch, with more women cycling than men, than if similar to Australian, with more men cycling than women.

More sophisticated studies survey injured cyclists for contributing factors or examine other factors related to risk. An example is Tin et al.’s (2011) study, which computed average time spent cycling or driving as part of assessing and understanding regional variations in rates of traffic injuries to pedal cyclists. (The paper’s title, “Regional variations in pedal cyclist injuries in New Zealand: Safety in numbers or risk in scarcity?”, gives some indication of the results). Again, however, the lack of explicit commentary on the modelling used points to some issues regarding an understanding of data limitations and potential implications. A particular example of this is given by Komanoff’s (2001) letter to the editor of Injury Prevention (A British Medical Journal publication), where a thought experiment shows that the reduction in cyclist numbers caused by helmet legislation can lead to safety disbenefits (due to the non-linearity of risk) that more than outweigh the benefits gained by helmet wearing – an effect Robinson (2005) confirms for the Australian experience. (Both of these are classified as “D” articles as they do not look at infrastructure.)

It is not surprising then, that “exposure” is mentioned as a common issue/ concern – but this is still at ratios similar to crash or severity models, in comparison to mentions of police data sources. Given that a lack of exposure data undermines any conclusions being reached, this again points to an under-appreciation of the severity of the exposure issue. Conversely, in a number of these cases, “exposure” was mentioned in terms of the lack of exposure data and inability to control for exposure effects in the research itself.

Apart from the pure understanding about the limitations of a lack of exposure data, the lack of data generally becomes obvious where data is insufficient to support statistical analysis. This is especially clear in before-after studies, unless a long "before" and "after" period can be accepted; and in spatially broad (e.g. network-wide) studies. Study design to overcome this type of data limitation, or provide alternative approaches to the data problem, include video observation, naturalistic studies and video simulation. These methodologies have been categorised as "observational study design". No category for broad statistical study was assigned as studies were generally not described as being such in the abstracts – a further indication of the assumption of the validity of this type of study design. In the absence of "broad statistical study", "observational study" was the most popular study design explicitly identified.

Research directly focused on the safety performance of cycle infrastructure significantly favoured police crash data over observational study with slightly over three times as many articles noted to be using police data than noted as being observational studies. Again, the study design and data type are not exclusive and the results of observational studies were generally correlated to crash data when this was possible. Only one or two studies specifically mentioned applying a Traffic Conflicts Technique, though several more mentioned conflicts more broadly. (All mentions of "conflict" or "conflicts" were recorded as a common issue/ concern.) Of the observational studies, naturalistic techniques were specifically mentioned when used, as were the few involving video simulation. The remainder – which were the majority – occasionally mentioned behaviour but more often simply mentioned observation. Similarly to broad statistical studies, the use of the methodology seems sufficiently well accepted as to not warrant particular comment regarding its methodological or theoretical underpinnings. Concerns about these underpinnings are better illustrated through the common issues/ concerns identified in the articles.

Common issues/ concerns

As already mentioned, exposure is (or should be) a particular concern in statistical studies because of the difficulty in assigning significance to results without an understanding of what these results are actually measuring. "Exposure" as an issue/concern could relate either to an attempt in the article to determine exposure, or theoretical issues related to the consideration of exposure. Exposure estimation is relatively straight forward. Theoretical issues and how these are addressed from a methodological perspective are less so.

Schepers et al. (2014) allude to a higher-level approach to their understanding of the literature in noting the lack of a model linking exposure-to-risk with risk itself, or how these are related.

Their research proposes a conceptual road safety framework to remedy this. The authors review travel behaviour theory, mainly in terms of utility maximization; theories explaining the link between exposure and risk, with substantive consideration of the non-linearity of risk; crash risk theories, based on physics and social science theories linking vehicles, road infrastructure and road users; and injury risk theories, mainly based on physics. They then propose a road safety framework incorporating all of these elements. The paper is arguably distinct in proposing a theoretical framework for safety research rather than for the actual interaction being examined – the more common approach evident in, for example, Strauss, Miranda-Moreno and Morency (2014), who use statistical approaches to develop safety performance functions for each mode at signalised and un-signalised intersections. The distinction between Schepers et al.'s framework and the implicit conceptual frameworks adopted by (for example) Vandenbulcke, Thomas (et al.) (2009) – who link differences in the use of the bicycle to get to work to the urban hierarchy in their attempt at predicting cycling accident risk for an entire network; or the examination of crashes at intersections by Gårder, Leden and Thedéen (1994) – which is based on applying a Baysian method to meta-analysis – seems mainly to be in the awareness of a framework integrating different elements, rather than in its application.

A broader shortcoming of statistical studies not often mentioned as part of the study results is the validity of the underlying assumptions regarding crash risk. As alluded to above, the relationship between risk and exposure cannot be assumed to be linear (that is, and x% increase in exposure equals and x% increase in risk) – but this often seems to be an implicit assumption in the literature, particularly in the absence of exposure data. This non-linearity has been captured as Smeed's Law or the 'power law' of exposure, but is now most commonly understood as the "safety in numbers" effect: the more cyclists there are, the lower the crash risk per cyclist[5]. This was a reasonably common issue/ concern, with much of the research exploring this undertaken by US practitioners seeking to confirm European research. In particular, an aim in US research about "safety in numbers" was to justify providing cycling infrastructure rather than regarding such infrastructure as creating a safety risk by increasing cycle participation rates – a logical conclusion if linearity of risk with exposure is assumed.

"Safety in numbers" could, however, be somewhat of an ancillary effect for research focusing on the safety of infrastructure. Hence although "safety in numbers" was apparently of more

[5] Smeed's Law and the Safety in Numbers effect are discussed in detail in the qualitative literature review contained in Chapter 5 of the thesis, for the pragmatic case study.

interest than vehicle speed, this could reflect authors failing to mention "speed" as a safety issue of concern. If not mentioned by a paper, "speed" would then not occur as a keyword through the textual search.

Infrastructure themes

The infrastructure examined in the research varied from broader examinations to very specific topics. Leden, Gårder and Pulkkinen (2000) took a broad approach to estimating the safety effect of "a bicycle facility", developing a risk model enabling safety impacts of different features to be analysed separately – but then followed this with the case study of a raised crossing treatment. Greibe (2010) reported on two studies examining urban junction and urban road link characteristics, in order to establish accident prediction models.

Other research contrasted the performance of different types of infrastructure, such as mixed traffic versus cycle lanes versus cycle paths (De Rome et al (2014)). The large number of articles focusing on bike "tracks" and bike "lanes" similarly reflected, in many cases, an effort of US author/s to confirm European experience with infrastructure (acknowledging inconsistencies in terminology). In fact, the focus on these facilities under-reports actual subject matter in that the keyword search only picked up articles assessing bike tracks and bike lanes in particular. Those examining the effect of multiple types of bicycle infrastructure, or simply the presence of "bicycle facilities", were not considered to be examining bike tracks or bike lanes in particular.

In terms of "A" and "B" articles, secondary research is typically included as an introduction to primary research, such as Arnold et al (2013), which followed a literature review regarding cyclist safety at multi-lane roundabouts with case studies, in-field counts and surveys, focus groups and video analysis. Relatively few articles involved secondary research only. Thomas and De Robertis (2013) examined the published literature for evidence regarding the safety of cycle tracks without then undertaking primary research. Zador (1984) is a little unusual in re-analysing data previously published by Zador et al. to confirm that right-turn-on-red laws increase cyclist crashes, but this was in response to criticism of the conclusions drawn from the previous paper.

Theory based around statistical analysis of crash and injury – such as Eluru, Bhat and Hensher's (2008) proposed econometric structure for injury severity analysis – was not sufficiently common to warrant an "A" or "B" rating unless some analysis of infrastructure was included. Schepers et al. (2014) applied their framework to link safety research with land use and infrastructure to gain a "B" level rating.

Roundabouts featured prominently in the “A” and “B” research. While few researchers had the same opportunity to evaluate before/after conditions as Daniels, Nuyts and Wets (2008), and allowing that the authors concede that changed traffic volumes could not be controlled for in the significant increase in injury crashes they identified for cyclists, the contrast between increased risk for cyclists and improved safety for motorists caused by roundabouts is a consistent theme emerging from the research – especially as roundabouts have become an increasingly popular traffic control device internationally. Roundabouts appear in the literature both as a specific topic, such as in Daniels, et al (2010) and their examination of 90 roundabouts in Flanders-Belgium; and as a form of intersection control in broader studies, such as Green and Harrison’s (2002) examination of intersection type and crash risk in Melbourne and Sydney. European studies such as Daniels et al (2010) tend to compare the safety impacts of different approaches to accommodating cyclists at roundabouts.

Apart from roundabouts and the question of on-road versus off-road facilities, studies that focused on one particular form of treatment tended to be specialized, such as Gårder, Leden and Pulkkinen’s (1998) study into the safety effects of raised cycle crossings. Zhang and Wu’s (2013) study of the effect of sunshields on red-light running behaviour was one paper that looked at infrastructure provided for other reasons than to improve cyclist safety.

6. Summary and conclusion

This SQ literature review has examined the state of the field of research relating to the safety of infrastructure for cyclists rather than generating a detailed understanding of all research in this broad field. It has addressed methodological limitations of an on-line review by augmenting results generated by on-line search engines with a review of major sources of Australian research.

Up to 3,900 records returned via on-line search engines identified fifteen pieces of Australian research, while a review of over 5,000 pieces of Australian transport and traffic research identified eleven items relating to the safety of infrastructure for cyclists. The snapshot produced has been examined against several different criteria. In summary, the major findings of the SQ literature review are:

- Much of the foundational research underpinning European and Asian practice is difficult to find through databases biased towards English-language and more recent publications. While the amount of Australian research produced seems reasonable on a population size basis, the augmented research obtained through major Australian sources points to no similar under-representation in Australian foundational research. Australian research may therefore under-support our specific research needs.

- Police crash records clearly provide the main source of data used for safety diagnosis, for pragmatic reasons of quality, availability and compatibility with research aims. However, as Vanparijs, Int Panis, Meeusen and de Geus (2015) note, good exposure data is often lacking, which makes results hard to interpret and compare. The limitations of using police crash data, including methodological issues related to data collection or exposure and risk relationships – currently termed the "safety in numbers" effect – are poorly accounted for in the literature. Indeed, very little commentary on theoretical frameworks is provided overall.
- The recording of video footage, use of naturalistic techniques and advances in technology enabling quantitative data to be derived from observational studies are providing new opportunities for observational studies to contribute to safety diagnosis, including as a surrogate for analysis of collision data and to overcome the lack of exposure data. In particular, as Sayed, Zaki and Autey (2013) note, traffic conflicts can provide insight into the failure mechanisms leading to road collisions without requiring long observation periods, overcoming a major limitation of broad statistical approaches in before/ after situations in particular. Nonetheless, the use of observational studies is not widespread. Traffic Conflicts Technique was explicitly mentioned only twice.
- Roundabouts and bike tracks/ bike lanes have been the types of infrastructure of most interest to researchers. Both remain emerging areas of practice in the Australian context.
- Only one paper examined the causes of cyclist-only crashes. Apart from the generally greater severity associated with cyclist-vehicle crashes, the lack of such research could be explained by the difficulty in examining factors contributing to a crash type poorly represented in police crash data, compared to examining a spatially-defined location for its crash history – an example of pragmatism.
- Australia does not have published primary research providing key evidence on which standards and policies can be based.
- Australian research does not appear to guide practice. On the contrary, publication dates suggest that Australian research lags rather than leads new practitioner guidance.
- Considering Moore and Hughes (1991), a collaborative approach between researchers and users could be highly beneficial. While there is evidence of this occurring overseas, it appears that very little Australian research involves collaborations across academic, bureaucratic and practitioner fields, much less involving inter-disciplinary collaborations with areas such as health.

The SQ literature review identified very little commentary on theoretical frameworks in the literature in general. But if the limitations of data, its use and interpretations are not well represented, then the potential exists for the safety effects to also be poorly – or at least sub-optimally – represented. As the conceptualisation of a safety effect influences our understanding, this can in the worst case lead to a contrary understanding. Robinson (2005) makes this point in regard to helmet legislation by demonstrating that the introduction of compulsory wearing of helmets in Australia appears to have increased the fatality risk for cyclists, as measured per kilometre travelled. This is because the benefit to individual cyclists from wearing helmets must be balanced by the disbenefit of a reduction in cyclist numbers, with Australian data indicating that the disbenefit outweighed the benefit.

Robinson's (2005) conclusions could be drawn because the theory of non-linearity of risk (as identified empirically by Smeed (1948) and currently more popularly known as "Safety in Numbers") was already in place, as demonstrated for active transport users by Jacobsen (2003). By contrast, the theoretical frameworks applicable to traditional or observational safety studies are, as noted by both Elvik (2004) and the SQ literature review, poorly treated in the literature. Partly, this may be for the pragmatic reasons highlighted by Moore and Hughes (1991). This may also reflect a lack of cross-disciplinary collaboration in Australian research compared to international research, also identified by the SQ literature review. McLean (1988) notes that a demarcation between research and practice was not allowed in the early days of the Australian professional traffic engineering community because these two roles had been so closely interwoven in the development of the discipline. In effect, traffic engineers saw themselves as researchers who allowed practice to lead research, while the pure researcher monitored the field of practice closely so that opportunities to examine changes of practice were not lost and, with them, the chance to better understand their effects on the traffic system. From the results of the SQ literature review, this degree of collaboration, almost verging on symbiosis, has not been in evidence for some time.

Of course, this SQ literature review does not cover much of the research to which engineering practitioners would be exposed: non-peer-reviewed work presented at conferences and in seminars, and explored but not published by road authorities. For example, Pattison (1977) notes the provision of 1.4m wide bicycle lanes but that 2.0m is preferred for comfort, indicating some reference to research underpinning practice, though a source is not cited; while Campbell and Adams (1989) mention unpublished research undertaken in Western Australia regarding conflicts on paths and footpaths. Research may also be embedded in guidelines, with the potential that this research is sufficiently obscured that it is either "forgotten" or advances in understanding are not applied to update the research – such as the guidance in Austroads' *Guide to Engineering Practice Part 14: Bicycles* that bicycle lanes should not be provided in roundabouts. The difficulty is in assessing the quality of unpublished or unreviewed research, and that is a task outside the scope of this literature review.

Overall, the SQ literature review provides a foundation for understanding the current state of the field of research into the safety performance of on-road infrastructure for cyclists.

7. References

Alrutz D, Angenendt W, Draeger W and Gündel D (2002), 'Verkehrssicherheit in Einbahnstraßen mit gegengerichtetem Radverkehr' (Traffic safety on one-way streets with contraflow bicycle traffic). *Straßenverkehrstechnik,* Issue 6, 2002. (Translated by John S Allen c2003, available at www.bikexprt.com/research/contraflow/gegengerichtet.htm.)

Arnold, L. S., Flannery, A., Ledbetter L (et al.) (2013), *Identifying Factors that Determine Bicyclist and Pedestrian-Involved Collision Rates and Bicyclist and Pedestrian Demand at Multi-Lane Roundabouts.* UC Berkeley: Safe Transportation Research & Education Center. Research Report RR-2013-2.

Austroads (1999) *Guide to Traffic Engineering Part 13: Bicycles*. AP-11.14/99.

Austroads (2000) *Pedestrian and Cyclist Safety – Investigation of Accidents in Different Road Environments.* AP-R157-00

Bíl M, Bílová M and Müller I (2010), Critical factors in fatal collisions of adult cyclists with automobiles. *Accident Analysis & Prevention* Volume 42, Issue 6, November 2010, pp1632-1636.

Brindle R and Andreassend D (1984), Low cost infrastructure solutions for bicycle safety. *Proceedings of the 21st ARRB and 11th REAAA Conference,* Cairns.

Campbell R and Adams T (1989), The bicycle as an effective transport mode. *14th Australian Transport Research Forum,* Perth, 20-22 September.

Daniels S, Brijs T, Nuyts E and Wets G (2010), Explaining variation in safety performance of roundabouts. *Accident Analysis and Prevention,* Volume 42, Issue 2, March 2010, pp393-402.

Daniels S, Nuyts E and Wets G (2008), The effects of roundabouts on traffic safety for bicyclists: An observational study. *Accident Analysis and Prevention*, Volume 40, Issue 2, March 2008, Pages 518-526.

De Rome, L., Boufous, S., Georgeson, T., (et al.) (2014), Bicycle Crashes in Different Riding Environments in the Australian Capital Territory. *Traffic Injury Prevention*, Volume 15 Issue1, Pages 81-88.

Eady J and Daff M (2012), *Cycling on Higher Speed Roads.* Austroads AP-R410-12.

Eluru N, Bhat C and Hensher D (2008), A mixed generalized ordered response model for examining pedestrian and bicyclist injury severity level in traffic crashes. *Accident Analysis and Prevention*, Volume 40, Issue 3, May 2008, pp1033-1054.

Elvik, R (2004), To what extent can theory account for the findings of road safety evaluation studies?. *Accident Analysis and Prevention*, Volume 36, Issue 5, September 2004, pp841-849.

Gårder P, Leden L and Pulkkinen U (1998), Measuring the safety effect of raised bicycle crossings using a new research methodology. *Transportation Research Record*, Volume 1636 issue 1, January 1998, pp64-70.

Gårder P, Leden L and Thedéen T (1994), Safety implications of bicycle paths at signalized intersections. *Accident Analysis and Prevention*, Volume 26, Issue 4, August 1994, pp429-439.

Garrard J, Rose G and Lo S (2006), Promoting transportation cycling for women: The role of bicycle infrastructure. *Preventative Medicine*, Volume 46, Issue 1, January 2008, pp55-59.

Green F and Harrison W (2002), *Investigation of cyclist safety at intersections*. Austroads, AP-R206/02.

Greibe P (2010), Accident prediction models for urban roads. *Accident Analysis and Prevention*, Volume 35, Issue 2, March 2003, pp273-285.

Harper N and Dunn R (2003), Accident Prediction at Urban Roundabouts in New Zealand- Some initial results. *26th Australasian Transport Research Forum*, Wellington.

Jacobsen P (2003), Safety in numbers: more walkers and bicyclists, safer walking and bicycling. *Injury Prevention*, Volume 9, Issue 3, pp205-209.

Komanoff C (2001), Safety in numbers? A new dimension to the bicycle helmet controversy. *Injury Prevention* (letter to the editor, http://dx.doi.org/10.1136/ip.7.4.343-a.)

Leden L, Gårder P and Pulkkinen U (2000), An expert judgment model applied to estimating the safety effect of a bicycle facility. *Accident Analysis & Prevention*, Volume 32, Issue 4, July 2000, pp589-599.

McClintock H and Cleary J, (1996), Cycle facilities and cyclists′ safety: Experience from Greater Nottingham and lessons for future cycling provision. *Transport Policy,* Volume 3, Issues 1-2, January–April 1996, pp67-77.

Minikel E (2012), Cyclist safety on bicycle boulevards and parallel arterial routes in Berkeley, California. *Accident Analysis and Prevention*, Volume 45, March 2012, pp241-247.

Moore J and Hughes B (1991), User Initiated Research into Traffic Accident Frequency at Signalised Intersections. *16th Australasian Transport Research Forum*, Hobart.

Patterson F (2010), Cycling and Roundabouts: An Australian Perspective. *Road & Transport Research: A Journal of Australian and New Zealand Research and Practice,* Volume 19 Issue 2, June 2010, Pages 4-19.

Patterson F (2013), 'The evidence for contra-flow cycling'. *Road and Transport Research*, Volume 22, Issue 1, March 2013, pp51-60.

Pattison, W (1977), Bicycle facilities for Australian capital cities. *3rd Australasian Transport Research Forum*, Melbourne.

Robertson J, Mclean A and Ryan G (1966), *Traffic Accidents in Adelaide, South Australia (1963-1964).* Australian Road Research Board Special Report No. 1 – 1966.

Robinson D (2005), Safety in numbers in Australia: more walkers and bicyclists, safer walking and bicycling. *Health promotion journal of Australia*, Volume 16, Issue 1, pp47-51, May 2005.

Schepers P and den Brinker B (2011), What do cyclists need to see to avoid single-bicycle crashes? *Ergonomics*, Volume 54 Issue 4, pp315-327.

Schepers P, Hagenzieker M, Methorst R, van Wee B and Wegman F (2014), A conceptual framework for road safety and mobility applied to cycling safety. *Accident Analysis and Prevention,* Volume 62, January 2014, pp331-340.

Standards Australia (1993), *Parking facilities: bicycle parking facilities.* Australian Standard AS 2890.3 – 1993.

Standards Australia (2000), *Manual of uniform traffic control devices: bicycle facilities* and *AS 2890.3 – 1993, Parking facilities: bicycle parking facilities.* Australian Standard AS 1742.9 – 2000.

Strauss J, Miranda-Moreno LF, Morency P (2014), Multimodal injury risk analysis of road users at signalized and non-signalized intersections. *Accident Analysis and Prevention*, Volume 71, October 2014, pp201-209.

Taylor M (1980), Soft, slow and going places: pedestrians and cyclists in urban transport. *10th Australian Road Research Board (ARRB) Conference*, 1980, Sydney.

Thomas B and De Robertis M (2013), The safety of urban cycle tracks: A review of the literature. *Accident Analysis and Prevention*, Volume 52, 28 March 2013, pp219-227.

Tin S, Woodward A, Thornley S and Ameratunga S (2011), Regional variations in pedal cyclist injuries in New Zealand: Safety in numbers or risk in scarcity?. *Australian and New Zealand Journal of Public Health*, Volume 35, Issue 4, August 2011, pp357–363.

Turner S and Wood G (2009), Accident prediction modelling down-under: a literature review. *Transportation Research Board Conference,* January, Washington DC.

Vandenbulcke G, Thomas I (et al) (2009), Mapping bicycle use and the risk of accidents for commuters who cycle to work in Belgium. *Transport Policy*, Volume 16, Issue 2, March 2009, pp77-87.

Vanparijs J, Int Panis L, Meeusen R and de Geus B (2015), Exposure measurement in bicycle safety analysis: A review of the literature. *Accident Analysis and Prevention*, Volume 84, 2015, pp9-19.

Wadhwa L and Faichney M (2002), Enhancing safety for cyclists through infrastructure design. *25th Australasian Transport Research Forum*, October, Canberra.

Wadhwa, L (2003), Roundabouts and pedestrians with visual disabilities: How can we make them safer. *Transportation Research Board Conference*, January, Washington, DC.

Walton D, Dravitzki B and Cleland, BS (2003), The effects of line markings for wet/night visibility on cycle safety. *26th Australasian Transport Research Forum*, Wellington.

White F and Daff M (1990), On-road observations of wide kerbside lanes for cyclists. *15th Australian Road Research Board Conference*, 1990, Darwin.

Wilke A, Lieswyn J and Munro C (2014), *Assessment of the effectiveness of on-road bicycle lanes at roundabouts in Australia and New Zealand*. Austroads Project NS1722.

Zador P (1984), Right-turn-on-red laws and motor vehicle crashes: A review of the literature. *Accident Analysis and Prevention*, Volume 16, Issue 4, August 1984, pp241-245.

Zhang Y and Wu C (2013), The effects of sunshields on red light running behavior of cyclists and electric bike riders. *Accident Analysis and Prevention*, Volume 52, 28 March 2013, pp210-218.

Appendix C Road and traffic authority survey

Contents

1. Introduction

An on-line survey was undertaken during early 2015 of representatives from local and State government road and traffic authorities across Australia. May (1998) describes the use of questionnaire surveys as a method of broad-level data gathering and further describes the logic and processes of different types of questionnaire surveys.

The survey sought to:

1) catalogue the range of on-road cycling infrastructure currently being implemented across Australia
2) determine the problems local and State governments are seeking to address with the infrastructure
3) gain an understanding of the research informing bike-related treatments and any barriers to the use of research
4) identify sites for the conduct of case study research.

The survey was thus broad rather than being focused on any particular type of infrastructure. A detailed analysis of the road and traffic authority survey is presented in the next section.

The self-completion survey involved a broad approach to road agencies. Although this included some New Zealand agencies, the distribution via local networks was poorer and responses essentially relate to Australian respondents. The variability of each jurisdiction is such that no sampling frame exists and the respondents represent a non-probability sample: their responses are of value without representing a statistical selection of all road agencies across Australia. The issue of sample size is not relevant and the data is better described through summary statistics such as frequencies, means and ranges, rather than more sophisticated statistical analyses.

Key outcomes of the survey are:

- Number of responses: 72 people attempted the survey but only half this (approximately 36) fully completed it. This demonstrates level of interest but often that non-road authority people attempted to respond in the first instance – e.g. a health worker in local government.
- Types of infrastructure being used: no pattern of a predominant type of infrastructure with all respondents using a wide variety of treatments.

- Infrastructure requiring further research: a range of infrastructure was suggested with little agreement on any one type. However, sharrows and bike path priority over side streets were mentioned on more than a few occasions.
- Research need: there was a consensus in responses that there is a lack of research into and evaluations of cycling infrastructure.
- Case studies: A number of road authorities were interested in partnering in primary research on road infrastructure treatments.

In particular, the survey identified that South Australia's Department of Planning, Transport and Infrastructure (DPTI) was intending a trial redesign of a tangential roundabout to a radial roundabout, and that DPTI would be amenable to involvement in a before/ after case study.

As Schramm et al. (2014) note, while it could be assumed that radial roundabouts perform better for cyclist safety compared to tangential roundabouts, this has not been examined in a before/ after case study. Wilke, Lieswyn and Munro (2014) confirm the difficulty of pair-wise comparisons between roundabouts by failing to find appropriate pairs in their work. The South Australian trial is therefore an ideal candidate for study.

Focusing on the safety of roundabouts, it is notable that while no respondents nominated roundabouts as a design feature of interest, under types of infrastructure used, thirteen respondents (18%) nominated radial roundabouts. This is a surprisingly high number as there were no Australian guidelines for designing radial roundabouts in existence at the time of the survey and no mention of such roundabouts being used in Australia in either the academic or grey literature.

Aumann, Pratt and Papamiltiades (2017) observe that on local roads, the alignment of the tangential roundabouts to achieve an entry speed of 30km/h was similar to the alignment of a radial roundabout, and one roundabout they examined could be characterised as being radial. However, it is not clear that the roundabout was designed with cyclist safety in mind or recognised as being radial before Aumann et al. identified it as such.

Nor were radial roundabouts identified when respondents were asked what infrastructure treatments the respondent's organisation was using/ considered using/ planning to use that were not covered by the Australian standards or Austroads guidelines. Further, the understanding of radial versus tangential design philosophies does not have a good historical underpinning in Australia, only gaining traction after being described by Patterson (2010), Cumming (2010) and the resulting discussion in Wilke et al. (2014). The identification of radial roundabouts could hence reflect a lack of understanding on what this actually entails, at least amongst some respondents; or a 'claiming' of roundabouts identified after the fact as radial where these might be thought to meet radial design standards (which had not yet been set), perhaps in response to the then-recent Wilke et al.

As a treatment, use of radial roundabouts was also out-numbered by the fourteen respondents who indicated use of bicycle lanes in roundabouts – a treatment type not supported by evidence, as discussed by Patterson (2010), Cumming (2010) and Wilke et al. (2014), and for which radial roundabouts are seen as an alternative. Different respondents also made contradictory comments regarding the safety of bicycle lanes in roundabouts.

Overall, then, the responses were considered to indicate that cyclist safety at roundabouts remains an unresolved issue, with potentially poor understanding regarding radial roundabout design and its application for cyclists. This represents a large knowledge gap given the well-documented safety problem that roundabouts pose for cyclists.

2. Analysis

The first part of the survey sought to understand respondents, their responsibilities and types of treatments used. This set of questions was answered by the most respondents – 72. The fall-off in responses after this is attributed to the fact that the survey was very much targeted at road authorities with an understanding of how their authority functions. Respondents who did not represent this sector would find themselves increasingly unable to answer questions.

Q1. Please tick the cell that would best describe your position/ role.

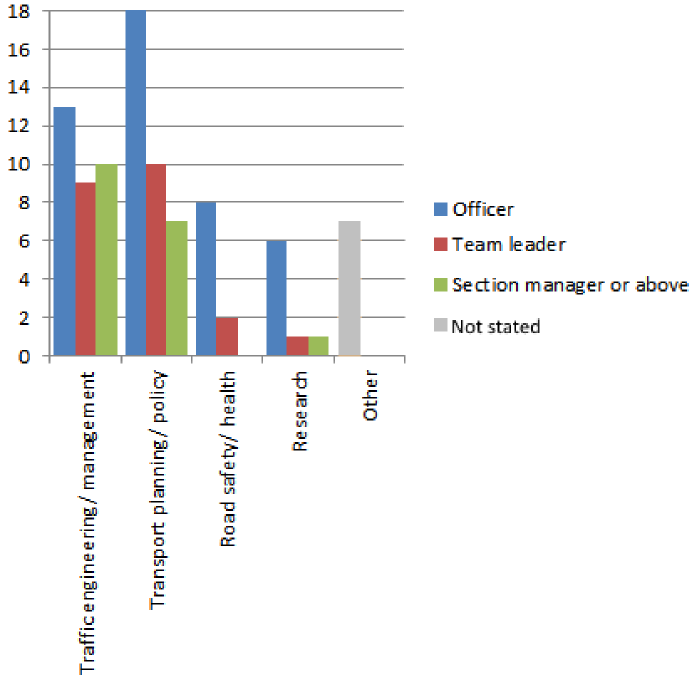

Figure 1: Roles and responsibilities.

Respondents mainly came from the traffic and transport areas – many with overlap between these two fields – and mainly at officer level, which is not surprising given that there are more people employed at this level than at higher levels.

'Other' respondents self-nominated as:

- Academic
- Advocate
- Council Officer
- Engineering
- Environmental engagement
- Road Maintenance - Manager
- Strategic projects management
- Recreation officer
- TravelSmart.
- Capital works planning and delivery

The 'TravelSmart' and 'Capital works planning and delivery' responses were provided in addition to other information and these respondents are included in Figure 1.

Q2. Which of the following best describes the geographical location/s applicable to your role?

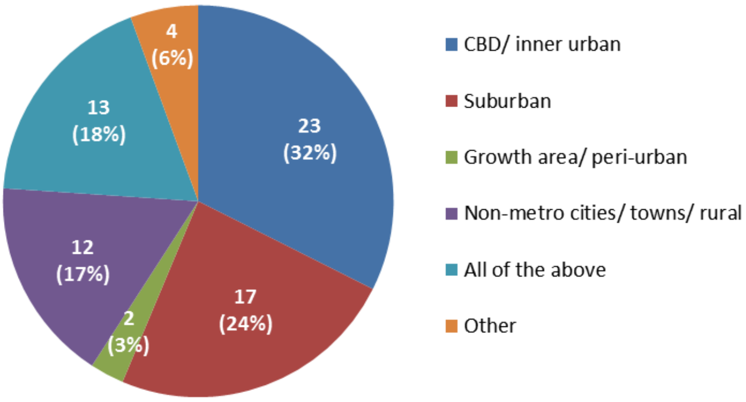

Figure 2: Geographical location of work

'All of the above' was not an option but comprised the majority of 'other' responses and is shown in Figure 2.

Most respondents work in metropolitan areas, especially CBD/ inner urban, although there would be far fewer CBD/ inner urban councils in Australia compared to other council types. This would be expected, in that the highest rates of commuter cycling in Australia occur in CBD/ inner urban councils, which are also those councils most likely to be able to resource staff having a particular focus on cycling.

Given that few councils would encompass all location types, the 'all of the above' nominations are likely to be indicative of State/territory government responsibility, and people in non-government positions (consultants, NGOs, etc).

The location types intended to include most types of areas in Australia, so there were few 'other' nominations apart from 'all of the above'. Not surprisingly, these four responses indicated a combination of areas:

- Inner regional
- CBD/suburban/rural
- Metropolitan
- CBD inner urban, suburban and peri-urban.

Q3 Is your role in…

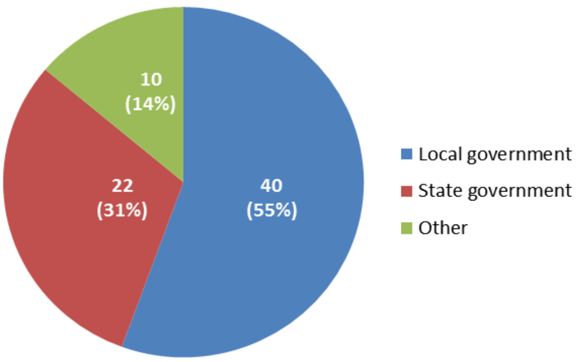

Figure 3: Work role

A slight majority of respondents were from local government. While this was significantly more than the number from State government, there are far fewer State government authorities – but these typically have a responsibility for cycling, with specific resourcing for this, which is less often the case with councils.

While 22 respondents were from State government, only 13 respondents indicated a role across all geographical types, pointing to some specialisation within State government roles.

The ‘other’ respondents were:

- Consultants (three, one mainly consulting to local government, one mainly to State government, one to both)
- NGOs (three)
- University (two)
- ACT (having both local and State government roles)
- Not specified.

Q4 What types of on-street treatments do you currently use?

This question captured an impression of the current State of practice around Australia and it was well-answered, with 72 respondents indicating treatments. However, there are several factors against this forming an inventory of treatments:

- Differences in terminology.
  It is very difficult to be completely unambiguous in the terminology applying to treatments. For example, what is a ‘cycle track’ compared to a ‘cycleway’, when neither are defined in technical guidance? To the extent possible, listed treatments included some description to convey what was intended, but these descriptions could not be completely unambiguous.
- Technical differences in applying treatments.
  This is an extension of the preceding point. For example, given that sharrows are not included in national guidance, the same nomination could refer to very different technical applications, so to what degree can they be considered to be the same treatment?
- Respondents are not exclusively linked to treatments.
  More than one person from any agency could respond, and if a council has installed a treatment in conjunction with State government, this could be listed by both council and State government respondents.
- Selection bias.
  As survey respondents can be expected to be those most interested in cycling infrastructure, their responses cannot be considered to be representative of road agencies in general. Conversely, people who did not respond could represent a larger body of knowledge excluded from the survey – notably with regard to consultants.
- Presence versus effectiveness.
  The nomination of a treatment does not necessarily point to the potential for further use of the treatment, the extent of its use, restrictions on its use, or the contribution this treatment makes to cycling safety. For example, a council that nominates contra-flow lanes as being

used could be referring to a single example or widespread implementation, with very different results for cycling safety.

- Crossed purposes.
  The question wording did not specifically ask about the purpose behind the treatments being used. For example, radial design of roundabouts is not incompatible with the deflection method of design which underpins tangential design. However, the presence of radial roundabouts does not necessarily mean they were installed in order to improve cyclist safety, although that may be a side-effect.

For this question, a list of treatments was provided, along with the opportunity to add more. Responses are listed in Table 1 from highest to lowest frequency of nominations, except for ‘other’.

Treatment	
Kerbside bike lanes (full-time)	46
Coloured pavements	39
Bike boxes/ forward storage areas	30
Bicycle signals at traffic lights	28
Bicycle lanes separated from traffic using more than paint (e.g. using car parking, kerb, landscaping, etc)	28
Bicycle buttons to call bicycle signals	28
Bike path/ shared path at footpath level as part of providing priority over a street	27
Bicycle/ car parking lanes (NSW: shoulder lanes) (full-time)	21
Kerbside bike lanes (part-time)	20
Continuous footpaths at side streets	19
‘Hook turn from left’ markings	16
Bicycle-specific detectors at signals (e.g. SCOOT loops)	15
Bicycle lanes in roundabouts	14
One-way contraflow using contraflow lanes along the full-length of the street	14
Continental/ radial roundabouts	13
One-way contraflow using threshold treatments only (no full-length bike lanes)	13
Mini-roundabouts (central island up to 4m in diameter)	11
One-way contraflow using signage only (no bike lanes or threshold treatments)	10
Bicycle signals with release in advance of other traffic	9
Sharrows	7
Bicycle Friendly Zones (Qld)	6
Bicycle/ car parking lanes (NSW: shoulder lanes) (part-time)	5
Low speed zones ≤ 30km/h, excluding schools zones	5

Table 1: Cycle treatments

Only full-time kerbside bicycle lanes and coloured pavements were used by a majority of respondents. ‘Low speed zones ≤ 30km/h’ was the treatment used by the fewest respondents. These appear to be as shared zones (nominated by four respondents, with the fifth advising “some treatments used on a trial basis”) involving discrete or short sections of streets. This contrasts to their use in Europe, where extensive amounts of residential streets in many countries have a speed limit of 30km/h (20 mph)[1] or less.

(For example, Edinburgh has 20mph zones in 80% of its streets, including the entire city centre[2].) Attitudes and education approaches about lower speed limits in residential streets might be a rewarding field of enquiry.

The thirteen nominations of ‘Continental/radial roundabouts’ is a surprisingly high number (at 18% of respondents) as there are currently no Australian guidelines for designing radial roundabouts. Further, the understanding of radial versus tangential design philosophies has not been well understood in Australia, gaining traction after being described by Patterson (2010), Cummings (2010) and in subsequent discussion in Wilke et al. (2014). The nomination of ‘Continental/ radial roundabouts’ may therefore reflect a lack of understanding on what this actually entails, at least amongst some respondents; or a ‘claiming’ of roundabouts identified after the fact as radial, where these meet radial design standards (which have not yet been set). These would be in addition to practitioners who had identified the radial/ tangential issue earlier and set about installing radial roundabouts for cyclist safety reasons, without publicising this through the literature. There is anecdotal evidence of this having happened and a potential impetus after the safety issues were raised by Patterson and Cummings. Even so, the 18% of respondents seems high, although this could reflect self-selection bias and the potential for multiple respondents to reply about this type of treatment.

Q5 Please describe any bicycle infrastructure treatments not included in the previous question which your organisation has introduced or is considering introducing, and which you think we should be aware of.

Of the 23 responses and 30 treatments, only a few treatments received multiple nominations. The most frequent of these was off-road paths or cycleways (with a further response being for the lighting of paths). While these are clearly not on-street treatments, descriptions such as “bi-directional bicycle path (within existing kerbs)” indicate a facility provided specifically to remove cyclists from traffic flow. In this sense, off-street facilities can be a means of addressing on-street issues, and the four respondents who also use ‘bicycle lanes separated from traffic using more than paint’, this is probably the case. (However, for the two respondents whose only form of cycle treatment was an off-road cycleway, and a further two whose only other treatments were bicycle lanes and coloured pavement, it is likely that their bicycle paths/ cycleways are recreational facilities rather than a means of addressing on-street issues per se.)

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1 As well summarised under ‘living street’ in the road hierarchy at http://wiki.openstreetmap.org/wiki/OSM_tags_for_routing/Maxspeed, accessed 8 July 2015, and supported by https://en.wikipedia.org/wiki/Speed_limits_by_country, also accessed 8 July 2015.

2 As noted by Polis: www.polisnetwork.eu/publicnews/781/45/Increased-acceptance-across-Europe-for-30-km-h-speed-limits, accessed 8 July 2015.

Bicycle boulevards were mentioned three times, one of these specifically without trying to reduce the volume of motor vehicle traffic to safe levels; and allowing footpath cycling was mentioned twice.

Other treatments were:

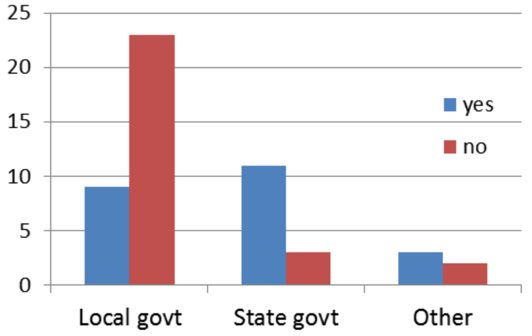
- Bicycle slip lanes at traffic signals
- Bicycle storage boxes at roundabout approaches with coloured green treatments and no bike lanes continuing through the roundabout [specifically, no support for putting bicycle lanes through roundabouts]
- Bike corrals [parking] on-street
- Copenhagen bicycle lanes with raised island separators [this would arguably be covered by ‘Bicycle lanes separated from traffic using more than paint (e.g. using car parking, kerb, landscaping, etc)’]
- Honeycomb surface treatment instead of a green paint at intersections where traffic wears out the paint too quickly
- Mountain bike skills park
- Narrow (2.5m) wide traffic lanes
- Non-standard use of cyclist guidance pavement marking (to guide cyclists around tram platforms)
- "Orca" cycle lane separators now being trialled in Camden Council, UK (under investigation, not yet used)
- “Share the road 1m” signage
- Shared bike and left turn lane treatment (now a DTMR standard)
- Sharrows at the entrance to roundabout and on streets where there is no room for a wide bike lane
- Sub-standard (<1.2m) bike lanes where no other facility can be provided
- Splitter islands at roundabouts to slow traffic and give more protection to cyclists [relating to existing bicycle lanes in roundabouts]
- Weave right/ change lanes to overtake (TMR TC2003).

Two contradictory comments regarding the safety of bicycle lanes in roundabouts highlights ongoing differences of opinion regarding this treatment.

The next questions explore the relationships between road authorities, innovation and safety research.

Q6 Does your organisation use, has it considered using, or is it planning to use, any infrastructure treatments not covered by the Australian standards or Austroads guidelines?

This question was answered by 51 respondents, with a small majority only using treatments covered by Australian standards or Austroads guidelines (28 ‘no’ to 23 ‘yes’).



It could be expected that State government authorities would have a greater capacity to depart from existing standards than local councils, and this is indeed the case.

Although the question asked about Australian standards and Austroads guidelines in particular, the question could be slightly ambiguous for councils in that they would generally follow State guidance, which may depart from national guidance.

One implication for councils of the reliance on a State lead in departing from national guidance is the capacity for staff within State government to be aware of treatments of interest/ issue with local governments and the capacity for State government to take a lead. If the State level authority is insufficiently resourced or skilled to undertake relevant research, based on their record, councils are not well placed to fill this void, and especially not if they oppose an approach taken at State level (which is possible, given that State government responsibilities are more focused on arterial than local level roads).

If yes, please describe this treatment/ these treatments

Generally, these descriptions added information to the treatments mentioned in Q5, indicating that the treatments respondents considered of interest were those outside the existing guidance. Some State authorities noted their departures from national guidance, with reference made to this guidance.

Treatments detailed at this question were (roughly sorted into subject areas):

Contra-flow cycling	Shared contra-flow lanes Considered use of signage only contra-flow lanes Contra-flow cycling allowed on low-traffic one-way street
Additional separation	Riley kerb (didn't work and dangerous to cyclists) Vibraline Bicycle lanes separated by rubber strips Fully separated bicycle lanes (two respondents)
On-road lanes	Two-way one-sided bike lane with only an edge line cf kerb separation Replacing a left turn lane with a 3.0m wide bicycle lane then allowing vehicle traffic to use the bicycle lane for left turn manoeuvres Parallel bicycle lanes with treatment between to allow bicycles to transition across of a left turning lane to continue straight. Back of kerb bicycle lanes
Paths, tracks, cycleways (incl. thresholds, transitions)	Mid-block transition from off-road Brisbane City Council style path threshold treatments (considered only) Shared zone threshold treatments at low traffic intersections of bidirectional separated cycleways Bicycle boulevard shared environment intersection (footway/ cycleway continuation at footpath level across side street) Separated cycleways, priority crossings of side streets Cycle tracks at all intersections. See TMR Separated Cycleways Guideline

	2.5m wide segregated cycle paths; 3.5-4.0m wide two-way segregated cycle paths. These would be on arterial roads.
Miscellaneous	Various, refer to Qld technical standards Any innovative devices Permanent bicycle counters (as an example) Narrow bridge “Do not overtake cyclists” signs & large BAZ symbols. Sharrows

Q7 How have you, or the officer who authorises bicycle treatment/s, gained an understanding regarding the safety performance of the treatment/s you use? (This can refer to any treatment listed in questions 4 to 6).

The 33 responses to this question highlighted different approaches between local and State government authorities, and non-government respondents. As the responses were open-ended, these were reviewed and common responses categorised, in Table 2 for local government responses and Table 3 for State government responses.

The two non-government responses are listed separately.

	Safety audit/ assessment	Site review; experience	Monitoring	Feedback (cyclist, public)	Crash data	State govt advice	Standards, guidelines	Review research	Not done	Not specified
Local government respondents	✓			✓		✓				
										✓
									✓	
										✓
			✓	✓	✓					
	✓	✓	✓	✓		✓			✓	
		✓		✓						
					✓					✓
	✓							✓		✓
						✓	✓			
							✓			
		✓								
										✓
			✓	✓	✓					
	✓	✓	✓							
				✓						
		✓						✓		
										✓
	✓		✓							

Table 2: Local government responses

	Safety audit/ assessment	Site review; experience	Monitoring	Feedback (cyclist, public)	Crash data	Local govt involvement	Standards, guidelines	Review research	Not done	Not specified
State government respondents		✓	✓	✓				✓		
										✓
		✓					✓	✓		
			✓			✓				✓
								✓		
										✓
			✓							
		✓								
										✓
					✓					
										✓
		✓			✓					

Table 3: State government responses

Non-government respondents:

- Review research ("Contacted UK engineers who are involved in trial")
- Review research ("Research of what other jurisdictions or countries do to solve problems").

'Monitoring' in this sense includes traffic counts, video observation, and unspecified monitoring of rider and driver behaviour. One respondent also mentioned sound levels.

The tabulation is quite loose due to the degree of differences in responses, which makes it slightly misleading. For example, the State government responses tended to have less information about detail, but often indicated a higher level of assessment involving teams of people e.g. "Developed State guidelines", "reliant upon technical expertise of team members" and "Trial undertaken with the City of Sydney. Technical direction developed" were all classified as 'not specified', compared to local government responses such as "In general but not in terms of before and after safety performance measurement of facilities in our LGA" and "Undertake review after implementation".

Still, there are differences between the respondents' approaches, notably in looking at previous research, monitoring and user feedback. This is considered to reflect the State government respondents focusing on a higher level of assessment, for example related to developing technical guidance for general application, while council authorities are more likely to be examining individual cases. It is stressed that this is a generalisation: State and council authorities do work together in some trials, though the use of 'State government advice' shows that in many of these situations, the State road authority would have a leading role in deciding safety performances.

Council authorities are more reliant on standards and guidelines (including State government knowledge/advice). Two local government respondents mention these as their only forms of developing safety understanding, compared to none of the State government respondents.

The high degree of reliance by councils on feedback may open the way for perception to influence assessment, while a complete lack of assessment points to fewer resources and a lack of political interest in independent assessment. (A comment from State government: “Not really my area” points to the greater specialisation at a State versus local government levels.)

Q8 If any treatment/s have been implemented as a trial, what research has been/ will be undertaken to assess safety performance?

The 29 responses included one ‘unknown’ from a local government respondent.

Tabulating in a similar way to the previous question, but excluding ‘standards and guidelines’ and ‘review research’ as not applicable, gives Table 4 and Table 5. (One State government respondent noted that research was undertaken by the University of NSW and the Australasian Road Research Board. This has been classified as ‘not specified’.) In four cases, ‘not done’ for local governments means that no trial treatments have been undertaken. (As with one of the two responses from State government respondents, an additional council response is ambiguous on this point.)

	Safety audit/ assessment	Site review; experience	Monitoring	Feedback (cyclist, public)	Crash data	State govt involvement	Not done	Not specified
Local government respondents			✓	✓		✓		
							✓	
			✓					
	✓		✓					✓
							✓	
	✓				✓	✓		
	✓							
							✓	
							✓	
				✓	✓			
	✓	✓	✓		✓			
	✓			✓			✓	
								✓

Table 4: Local government responses

Road and traffic authority survey

	Safety audit/ assessment	Site review; experience	Monitoring	Feedback (cyclist, public)	Crash data	Local govt involvement	Not done	Not specified
State government respondents			✓	✓	✓			✓
			✓					
						✓		✓
						*		✓
							✓	
							✓	
			✓					
				✓	✓			
			✓	✓				
	✓			✓	✓			
								✓
	✓							✓

Table 5: State government responses

* The response detail refers to side streets, possibly suggesting the treatment involved local government jurisdiction.

Two responses were also received from non-government respondents:

- “There is a two year trial of the overtaking exemptions in Queensland together with mandated minimum passing distances.”
- [Re: separators.] “Trial currently proceeding. Includes vehicle impact tests and cyclist impact tests on test track.”

The responses from local and State government respondents were more similar than the previous question, which probably reflects shared approaches to assessing trials.

Several respondents mention safety reviews or reports, but without specifying the content to be covered in this process. A few respondents mentioned that they would continue to monitor crash data over time, but as one pointed out, “…because we have such low reported crash data it may not be very meaningful.”

Q9 When your organisation considers installing new infrastructure, to what degree do barriers exist to using designs not covered by the Australian Standards or Austroads Guides?

Respondents were asked provided with a set of potential barriers, as follows, and asked to rate these as high, medium or low. They could also nominate other barriers.

- Lack of documented impacts on the safety performance of the proposed infrastructure
- Lack of understanding of how to use a risk management approach to satisfy legal liability exposure issues
- Lack of a template/ formal guidance for undertaking trials of infrastructure not covered by standards or guidelines

- Public understanding/ acceptance
- Lack of design guidance
- Lack of practitioner skills in designing new infrastructure
- Lack of in-house skills to assess new design concepts (e.g. adequacy of features, comparison with best practice, design adequacy re: the particular location being considered)
- Political risk
- Cost.

A few respondents identified issues as being not applicable. It is not clear whether this implies that trials and innovation aren't attempted, or that barriers are not encountered. The responses have been sorted from low to high and are presented in Table 6.

Documented impacts	Risk exposure	Trials template	Public acceptance	Design guidance	Design skills	In-house skills	Political risk	Cost
N/A	N/A	N/A	Low	N/A	Low	N/A	N/A	N/A
N/A	N/A	N/A	Low	Low	Low	Low	Low	N/A
N/A	N/A	N/A	Low	Low	Low	Low	Low	N/A
Low	Low	Low	Low	Low	Low	Low	Low	Low
Low	Low	Low	Low	Low	Low	Low	Low	Low
Low	Low	Low	Low	Low	Low	Low	Low	Low
Low	Low	Low	Low	Low	Low	Low	Low	Low
Medium	Low	Low	Low	Low	Low	Low	Low	Low
Medium	Low	Medium	Low	Low	Low	Low	Medium	Low
Medium	Low	Medium	Low	Low	Low	Low	Medium	Low
Medium	Low	Medium	Low	Low	Medium	Low	Medium	Low
Medium	Low*	Medium	Medium	Medium	Medium	Low	Medium	Low
Medium	Medium	Medium	Medium	Medium	Medium	Low	Medium	Low
Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Low
Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Low
Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Low
Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Low
Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Medium	Medium	Medium	Medium	Medium	High	Medium	Medium	Medium
Medium	Medium	Medium	High	Medium	High	Medium	High	Medium
Medium	Medium	Medium	High	Medium	High	Medium	High	Medium
Medium	Medium	Medium	High	Medium	High	High	High	Medium
High	Medium*	High	High	Medium	High	High	High	Medium
High	High	High	High	High	High	High	High	Medium
High	High	High	High	High	High	High	High	High
High	High	High	High	High	High	High	High	High
High	High	High	High	High	High	High	High	High
High	High	High	High	High	High	High	High	High
High	High	High	High	High	High	High	High	High
High	High	High	High	High	High	High	High	High
High	High	High	High	High	High	High	High	No answer

Table 6: Importance of barriers

*Associated ‘other’ responses were “Concern for engineer who signs designs that are not in accordance with Australian Standards and [guidance]” and (paraphrasing) “Internal staff who aren’t cyclists and don’t understand the current risks vs proposed risk profiles”. Risk management nominations arguably be increased for these.

Given 36 responses, a mid-point of responses (thick line) and quantiles (double lines) can be applied. With the applied rating system, an environment in which innovation is easy would involve most barriers being assessed as low. This is not the case.

Cost is clearly the lowest barrier. As one respondent noted, “Cycle infrastructure is comparatively cheap.”

‘Lack of documented impacts’ had the fewest nominations as being a low degree barrier, followed by ‘lack of a trials template’ and ‘political risk’ (complicated slightly by N/A nominations). These are therefore considered the greatest barriers to innovation. Of these, ‘political risk’ was a higher degree barrier to more respondents.

Design skills had the largest skew toward being a high barrier and the greatest level of disagreement between respondents about the degree of barrier it represents. ‘In-house skills’ had a similar skew level of disagreement, skewed toward being a low barrier.

Breaking the responses into the 23 council responses (Table 7) and 10 State government responses (Table 8) enables opinions to be contrasted. A mid-point has been shown for council respondents only.

Documented impacts	Risk exposure	Trials template	Public acceptance	Design guidance	Design skills	In-house skills	Political risk	Cost
N/A	N/A	N/A	Low	Low	Low	Low	Low	N/A
Low	Low	N/A	Low	Low	Low	Low	Low	Low
Low	Low	Low	Low	Low	Low	Low	Low	Low
Low	Low	Low	Low	Low	Low	Low	Low	Low
Low	Low	Low	Low	Low	Low	Low	Low	Low
Medium	Low	Medium	Low	Low	Low	Low	Low	Low
Medium	Low	Medium	Low	Low	Low	Low	Low	Low
Medium	Low*	Medium	Low	Medium	Low	Low	Medium	Low
Medium	Medium	Medium	Medium	Medium	Low	Low	Medium	Low
Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Medium	Medium*	Medium	Medium	Medium	High	High	Medium	Medium
High	High	High	High	Medium	High	High	High	Medium
High	High	High	High	High	High	High	High	High
High	High	High	High	High	High	High	High	High
High	High	High	High	High	High	High	High	High
High	High	High	High	High	High	High	High	High
High	High	High	High	High	High	High	High	High

Table 7: Local government responses

Road and traffic authority survey

Documented impacts	Risk exposure	Trials template	Public acceptance	Design guidance	Design skills	In-house skills	Political risk	Cost
N/A	N/A	N/A	Low	N/A	Low	N/A	N/A	N/A
N/A	N/A	Low	Low	Low	Medium	Low	Medium	N/A
Medium	Low	Medium	Low	Low	Medium	Low	Medium	Low
Medium	Medium	Medium	Medium	Low	Medium	Low	Medium	Low
Medium	Medium	Medium	Medium	Medium	High	Medium	Medium	Low
Medium	Medium	Medium	High	Medium	High	Medium	Medium	Low
Medium	Medium	Medium	High	Medium	High	Medium	High	Low
Medium	Medium	Medium	High	Medium	High	High	High	Medium
Medium	Medium	Medium	High	High	High	High	High	Medium
High	High	High	High	High	High	High	High	High

Table 8: State government responses

Design skills and political risk are of more concern to State government than councils, with the former nominated as a high barrier almost as often by the ten State government respondents as the 23 council respondents. Risk exposure and documented impacts are also of higher concern to State government, probably reflecting that councils can (and do) rely on State government guidance, but State government has no similar recourse.

The fairly consistent medium nominations for ‘lack of a documented trials template’ from State respondents in interesting as State authorities could arguably develop a template for the use of councils requiring State government sign-off for trials – which is the case in Queensland, for example. The State government responses could refer to the lack of a similar format when applied to the national situation.

Cost is seen as a greater barrier by councils.

While this question arguably referred to the authority the respondent represents, one council respondent raised the difficulty in getting State government approval for something not covered in existing guidance.

Q10 If there is a treatment/s you currently do not use but would like to use, please list the treatment/s and barriers to their use.

This question was intended to identify treatments that could be researched to overcome barriers, but also the cultural norms that might prevent such research from being effective. It gained responses from nine local government respondents, eight State government respondents and one non-government respondent. The treatments identified can be loosely classed together, as follows.

Separation	• Segregated bike lanes (Copenhagen style) • Separated bike lanes • Safer methods for separating cycles from traffic e.g. Orca lane separators (used in UK) • Replace slip lanes with basic left and separated cycle track at urban signalised intersections • Narrower traffic lanes to allow space for bicycle lanes

Crossings, intersections	• Bicycle crossing (shared crossing) • Priority for walking and cycling at intersections (signals or raised tables), especially when arterial active transport routes cross minor road intersections. • All directions green for cyclists. • Bicycle-specific signals • Bike boxes
Integration	• Contraflow lanes / signs without lanes. • Bicycle symbols in the middle of junctions • Advisory treatments (e.g. sharrows) • The bicycle boulevard or shared zone

Non-specific treatments were:

- Low standard of driving skills.
- Some of the treatments listed in previous question.
- Low cost, quick to install temporary treatments.

The barriers raised reveal some frustration and difficulties in practice.

A lack of guidance exists for certain treatments, which would be expected for innovative treatments:

- Australian Standards and guidance on their use is out of date
- Not used because not recommended in Australian Standards
- Not recognised within the road rules.

This is where good quality research should facilitate trials and developing new guidance, and allowing the risk of a new treatment to be assessed and managed.

- We can never make the roads perfectly safe… but we can do things to reduce risk.

However, responses point to risk aversion rather than risk management, potentially coupled with some ignorance of the cycling field:

- New treatments that have not been implemented before tend to take a long time to gain staff and management acceptance, due to lack of understanding.
- Management and designers always driving to work in council cars… is another major issue because they don't really understand the existing risks cyclists have to deal with that [we] are trying to reduce with new infrastructure.
- [Engineers] are too scared of being blamed, sued and/or being jailed… to do anything that doesn't already have Austroads or State level guidance.
- Unfortunately many practitioners rely on [Austroads documents] to cover all scenarios and forget how to think for themselves, or become too scared of not following Austroads that they dare not make a decision of their own.

This has safety implications:

- Austroads publications are written as a guideline for suggested improvements and do not suit all applications.

- ... there are some treatments [in] Austroads… that [overseas evidence has] proven to be dangerous. Yet practitioners use the treatments because Austroads States you can. [E]very site and location must be looked at based on its own individual circumstances and with a view to achieving the highest level of safety for all road users.

This points to research needing to be framed in a risk management paradigm to be most effective, and/or road safety, research and professional bodies providing training in how to use research to satisfy risk concerns.

Other barriers include challenging the current traffic paradigm:

- The need to reallocate road space from either kerbside parking or general traffic lane.
- Reluctance from traffic engineers to give priority to walking or cycling in any situation in case they might get run over (even in situations where road rules require drivers to give way but there are no visual cues provided).
- Perceived reduction in efficiency for left turning vehicles/not understanding safety benefits.
- Road speed reduction required
- The political and/or community acceptance of changing a road environment to give bicycles priority.

Attitudes and education approaches about traffic management might be a rewarding field of enquiry.

Other responses were:

- Not enough cyclists due to unsafe roads and streets
- Mandatory helmet law deters many trips that could be made by bike
- Availability of funding.

The next few questions were seeking potential partners with whom to undertake primary research.

Q11 was a query as to whether the respondents' organisation would/ could be interested in being involved in primary research.

39 responses were received, as shown in Figure 4.

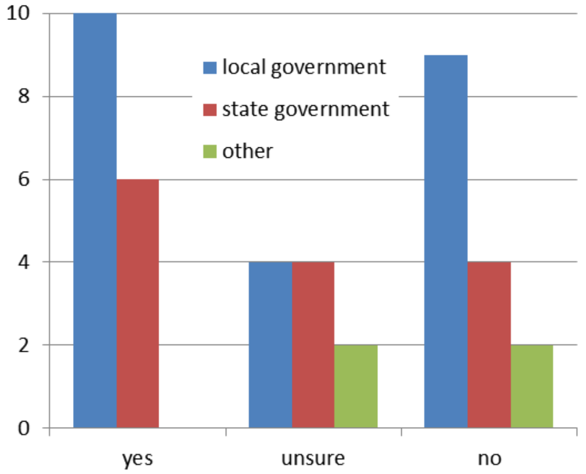


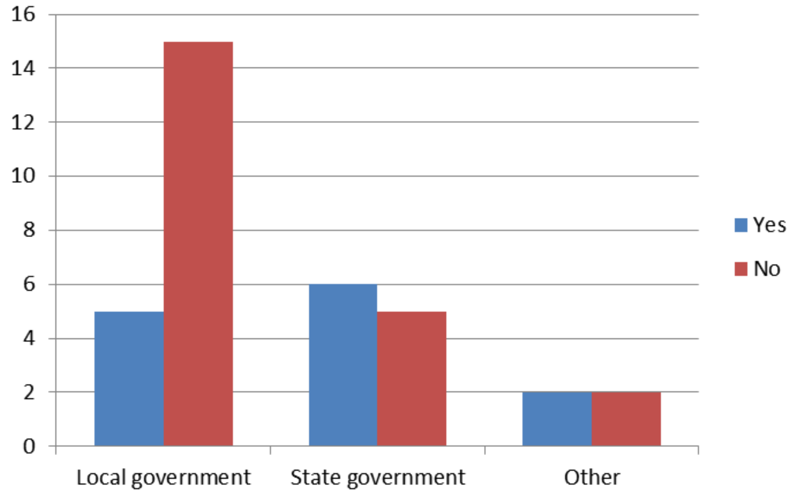
Figure 4: interest in further research

The large number of 'yes' or 'unsure' responses is considered to indicate the level of interest in research.

Q12 was a request for contact details and is not reported. Q13 enquired whether the organisation could assist in costs of data collection, which elicited 4 'yes' responses and 15 'unsure' responses.

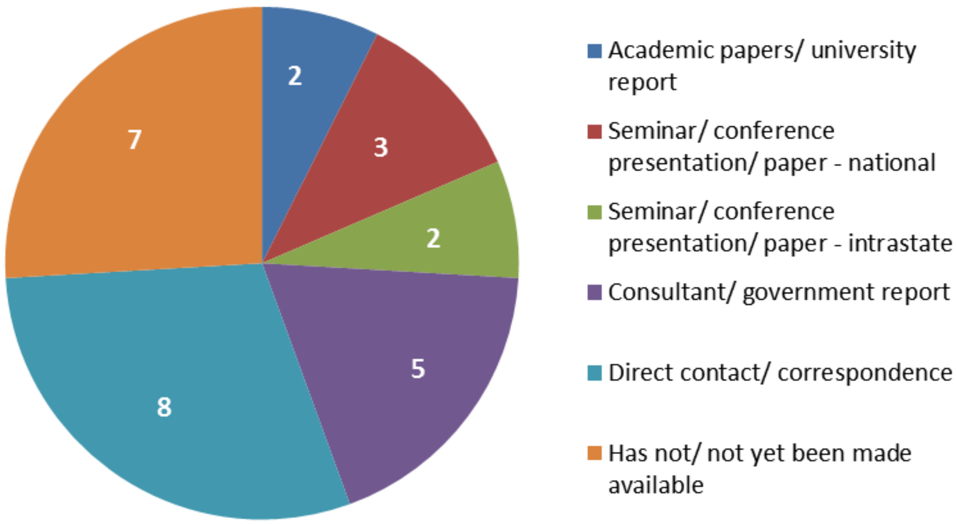
The second section of the survey asked about respondents' use of research, other than Australian standards and guidelines. Q15 and Q16 ask about the production and dissemination of research.

Q15 Has your organisation undertaken any research on the safety performance of infrastructure treatments within the last 18 months?



This indicates that there are modest levels of research being undertaken around Australia, more at State than council level. There are too few 'other' respondents to generalise regarding their responses.

Q16 How has this been made available to other agencies, if at all?



The high level of unpublished research and grey literature points to issues with the ability to learn about or build on research being undertaken.

- Only two pieces of research were made available via academia (where other researchers could find this through academic search engines).
- A significant number weren't (or hadn't yet) been made available in any form, with 'direct contact/correspondence' likely to be similarly inaccessible.
- Presentations to seminars/ conferences would not be included within academic databases unless these have been peer-reviewed – which is unlikely for the intra-State conferences, and questionable for many national conferences. Papers that are not peer reviewed but are published as part of proceedings could be identifiable through a generic search engine, however seminar and conference presentations often do not generate a published paper.
- The case is similar for consultant/ government reports, in terms of whether these are made publicly available.

This also points to a need for practitioners to have well-developed professional networks to identify new research.

The next questions were intended to reflect (and enable comparison against) work undertaken by Mulley and Reedy (2013) into how evidence-based research is used by transport policy makers in New South Wales. This approach was based on the fact that transport planners and traffic engineers are often also the policy makers and that similar factors would affect the use and barriers to use of translating research into practice. Hence the current survey results could be compared with previous research. Some changes were necessary to make the policy-related questions more relevant to traffic management practice.

Q17 Considering the evidence you use to inform your work, what is the order of importance of the following sources for you?

(This question compares to Mulley and Reedy's wording: "If you look at evidence to inform your work, order the importance of these sources for YOU?")

36 respondents answered this question by ranking five sources from 1 (most important) to 5 (least important). Mulley and Reedy weighted responses by awarding a score of 5 to the most important, 4 to the second most important, etc, and comparing weighted values for responses. The weighted results of the two surveys are shown in Table 9.

	Cycle infrastructure survey		**Transport policy survey**	
	Raw ranking	Weighted ranking	Raw ranking	Weighted ranking
Government reports	4	19%	1	28%
Academic papers/ University reports	3	20%	2	27%
Peak body reports	1	31%	3	22%
Consultant reports	2	21%	4	21%
Other	5	9%	5	2%

Table 9: Weighted importance of research sources

Mulley and Reedy found 'government reports' and 'academic papers' to be very closely ranked, and similarly for 'peak body reports' and 'consultant reports'. In comparison, the infrastructure survey found 'peak body reports' to have a clear importance, and 'other' to have a clear lack of importance, with the remaining sources closely ranked.

A major difference between traffic practitioners and transport policy makers is that traffic practitioners are required – including by legislation – to use State and/or national standards. (For example, the authority to install traffic devices on roads is generally vested in the Minister for Transport for each jurisdiction and delegated down to council and State government staff level through legislative means, which require compliance with certain guidance. Certain pathways are provided to step outside this guidance, but this can be onerous and uncertain.) Two 'other' responses refer to this working environment:

- [State road authority] guidelines and technical directions, speed surveys, traffic pedestrian and cyclist surveys.
- Relevant standards.

Since Austroads publishes the main guidance for traffic engineers, including for cycling, 'peak body reports' would have a crucial role in traffic practice. It is perhaps interesting, then, to observe that only 25 respondents ranked 'peak body reports' as 'most important'. In this respect, one respondent's comment is revealing: "Peak bodies tend to be less reliable these days, re-publishing existing research done by others. It's much better to go to the source." This was also reflected in another comment which explained that their ordering of priority reflected the importance of sources for getting things done rather than faith in the content of the sources.

Q18 In your work, about how often are you called upon to use evidence-based research regarding the safety of infrastructure for cyclists?

37 respondents answered this question. Despite only have 29 participants in their interviews, Mulley and Reedy presented results on a percentage basis, as in Table 10.

	Cycle infrastructure survey	Transport policy survey
More than once a week	8%	65%
About once a week	14%	16%
About once a month	24%	13%
About once a year	46%	6%
Never	8%	0

Table 10: Frequency of research use

Again, the results demonstrate the difference between transport policy and traffic practice, and again, the infrequency of use of research is indicative of the need to comply with standards and guidelines – which could, in themselves, be considered to be based on good quality research, potentially obviating the need for additional research.

However, an effect of relying on a peak body’s research would be a tendency to stagnation:

- The respondent is dependent on the peak body’s research agenda, which may not suit the respondent’s situation.
- The respondent doesn’t develop critical skills in undertaking and interpreting research, or applying research on treatments outside of current guidance.
- Standards, guidelines and relevant legislation (notably the Australian Road Rules) require Australia’s jurisdictions to reach a large degree of agreement on content and therefore change only slowly. The respondent would not lead in this process.

In comparison, policy-makers could be expected to be closer to the leading edge of practice.

This assumes that there is nothing inherent in being a traffic engineer that would affect the use of research compared to transport policy makers. As the cycle infrastructure survey had earlier asked about the field of practice of respondents, this can be verified.

The breakdown of research use by role is shown in Table 11 and, on small numbers, appears to confirm that the it is the subject of work (cycle infrastructure vs policy) rather than the person undertaking the work that drives the differences in research use (and that researchers have a different pattern of research use, as would be expected.) As this includes multiple nominations – nine respondents were both traffic engineers and transport policy/planners – the results are slightly skewed, showing a more even use of research either once a month or once a year, but are generally similar to Table 10.

Road and traffic authority survey

	More than once a week	About once a week	About once a month	About once a year	Never
Traffic engineers	2	4	7	6	2
Transport policy/ planning	1	3	4	4	1
Road safety/ health	0	1	2	2	1
Research	1	2	1	1	0
	9%	***22%***	***31%***	***29%***	***9%***

Table 11: Frequency of research use by role

Mulley and Reedy further noted in their survey that "…a majority of stakeholders at a senior level are considering evidence based research on a regular basis. This is encouraging for research into policy transfer and for research as part of the policy diffusion mechanism, particularly if these stakeholders, central to the research and policy environment, promote an evidence based culture in their teams."

The cycle infrastructure survey found the opposite. Examining responses by responsibility levels gives Table 12.

	More than once a week	About once a week	About once a month	About once a year	Never
Officer	3	2	5	6	1
Team leader	0	3	2	4	1
Manager	0	0	2	7	1

Table 12: Frequency of research use by responsibility level

As a corollary to Mulley and Reedy, when seniority is associated with less consideration of evidence-based research, this could form a barrier to transfer of practice and to research as part of the diffusion of new infrastructure treatments, particularly if these stakeholders, central to the research and practice environment, fail to promote an evidence-based culture in their teams.

It is therefore perhaps not surprising that two comments received regarding this question, one at officer level and one at team leader level, exhibited some cynicism and frustration:

- "It depends which decision-maker needs to be satisfied"
- "On almost every project the designers still argue against doing things even when we have done it before."

Q19 What are the greatest barriers you face to using evidence-based research?

This repeats Q9 but in a format compatible with Mulley and Reedy's research, with the exception that an option for 'other' was included in the cycle infrastructure survey.

	Cycle infrastructure survey		Transport policy survey	
	Raw ranking	**Weighted ranking**	**Raw ranking**	**Weighted ranking**
Not enough time to consider the research that exists	2	13%	1	22%
Swamped with information	9	8%	2	21%
Irrelevant research (does not address actual problems)	3	13%	3	13%
Poor dissemination of research results	4	12%	4	12%
Poor communication of research results	6	11%	5	11%
Lack of evidence available	5	11%	6	10%
Quality of research (sample sizes, skewed evidence)	1	13%	7	9%
Difficulty in transferring evidence from other contexts	7	11%	7	2%
Other (e.g. organisational culture)	8	8%	n/a	n/a

Table 13: Barriers to using research, by ranking

Mulley and Reedy classified responses into three main bands: time to consider research, problems with research, and difficulty in transferring research.

The cycle infrastructure survey isn't quite comparable due to the inclusion of 'other', but does illustrate more issues with the available research. The low ranking of 'swamped with information' could be considered a corollary to the high ranking of 'quality of research': traffic practitioners aren't flooded with research from amongst which they can find good quality research. Nor do they appear to have the time to sift through the research that does exist. It is not surprising, then, that they have greater difficulty in transferring the research from other contexts.

For those who nominated 'other' as being the greatest barrier, responses mentioned more than once included organisational change and comments around risk.

Q20 What are [the] most important factors encouraging your use of research in designing, developing and implementing infrastructure?

The question responses were varied from Mulley and Reedy to reflect the different nature of traffic practice versus transport policy. In the trialling of the survey, a suggestion was made that this question differentiate between the existing situation and an ideal situation, and this was incorporated. Also, while Mulley and Reedy asked what was THE most important factor, the cycle infrastructure survey requested a ranking, in line with previous questions.

The results for the existing situation are presented in Table 14.

Cycle infrastructure survey			Transport policy survey	
	% most important	Weighted ranking		% participants
Training/ masterclasses	21%	3	Training/ masterclasses	16%
Professional networks	18%	2	Transport research and policy network	26%
External research bodies (e.g. ARRB, Austroads, ABC)	33%	1		
Access to research clearinghouses (e.g. Cycle Research Centre)	6%	4	Greater use of clearing house evidence	13%
Strategic plan for research	3%	5	Strategic research plan for policy formulation	32%
In-house positions/ units devoted specifically to research	9%	6		
Other	9%	n/a*	None of these	13%

Table 14: Factors encouraging research

* Only four responses were received for 'other', so this is not comparable in a weighted ranking.

For traffic practitioners, external research bodies are of greatest importance, while a strategic research plan is of least importance. This may point to these professionals relying on the research bodies to set the research agenda, with research bodies then performing the same role as a strategic research plan. (Indeed, the inclusion of 'external research bodies' as an option was to address this expected behaviour.) While traffic practitioners rank 'training/ masterclasses' slightly more highly than transport policy practitioners – perhaps reflecting the lack of a corollary group to the research and policy network per se – this was reversed when a simple weighted average was used.

Overall, both groups can be considered to have quite similar responses, especially given the very small numbers involved.

Only 13 respondents provided an answer for the ideal situation, and a percentage of more important nominations is not considered appropriate with such small numbers. The weighted ranking again prioritised 'external research bodies', with the weighted score increasing for this, and was again followed by 'professional networks'. 'Training/ masterclasses', 'access to research clearinghouses' and 'strategic plan for research' were then roughly equally valued. This perhaps indicates that respondents would like to rely more heavily on outside bodies to conduct research.

3. References

Aumann P, Pratt K and Papamiltiades A (2017), *Bicycle Safety at Roundabouts,* Austroads Research Report AP-R542-17, pub Austroads Sydney, N.S.W.

Cumming B (2010), *Roundabout Design: Minimising Conflicts for Bicycle Riders*. Swinburne University of Technology.

May, T. (1998), *Social Research: Issues, methods and process, 2nd edition.* Pub. Open University Press: McGraw, Berkshire, U.K.

Mulley C and Reedy L (2013), Research into Policy: Improving the research evidence base for transport policy makers in NSW. *Australasian Transport Research Forum 2013 Proceedings*, 2-4 October 2013, Brisbane, Australia.

Patterson, F (2010), Cycling and roundabouts: An Australian perspective. *Road and Transport Research*, Volume 19, Issue 2, June 2010, pp 4-19.

Schramm A, Haworth N, van den Dool D, Murphy J, Qu X and McDonald M (2014), Roundabout design and cycling safety. *3rd International Cycling Safety Conference (ICSC2014),* 18-19 November 2014, Göteborg, Sweden.

Wilke A, Lieswyn J and Munro C (2014), *Assessment of the Effectiveness of On-road Bicycle Lanes at Roundabouts in Australia and New Zealand.* Austroads Research Report AP-R461-14, pub Austroads Sydney, N.S.W.

Appendix D: Roundabout case study

Contents

1. Beulah Road/Sydenham Road roundabout

Introduction

Beulah Road/Sydenham Road roundabout is located on an east-west bicycle route from the Adelaide CBD to the eastern suburbs, as shown in Figure 1. The roundabout is about 2km from the CBD and is the western-most and largest of four roundabouts that lie along a 1.6km section of Beulah Road, between the arterial Fullarton and Portrush Roads. Beulah Road is a local collector in the City of Norwood Payneham and St Peters, running parallel to and between Magill Road, an arterial road to the north; and The Parade, a main-street to the south.

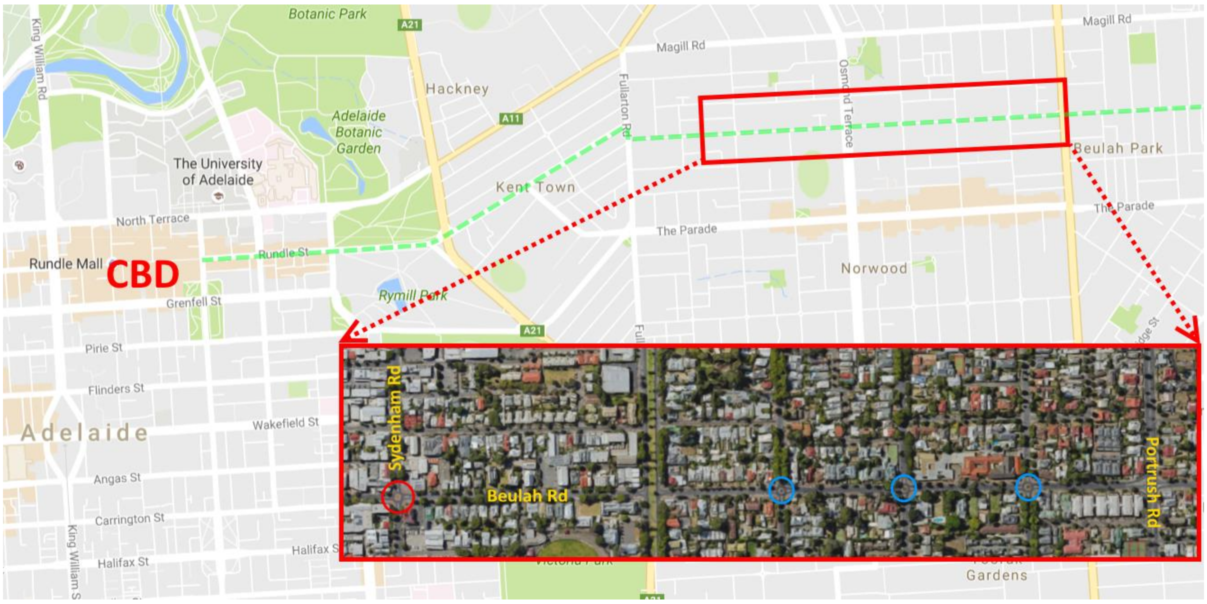


Figure 1: Case study locality plan – Beulah Road/ Sydenham Road roundabout is circled in red and other roundabouts in blue.

The Beulah Road/Sydenham Road roundabout was identified for trial conversion from a tangential to a radial design due to its poor safety record for cyclists.

In 2013, Beulah Road/Sydenham Road was identified as a Black Spot location, having the 3rd highest number of cyclist-involved road crashes in the state based on 2008-12 data – albeit that it was one of three that fitted this description. With the Department of Transport, Planning and Infrastructure (DPTI) seeking to improve Beulah Road as a strategic cycle route to the east of the City (the Norwood-Magill Bikeway), the poor safety conditions posed by the roundabout for cyclists were a key problem to be addressed. (The worse and second worst locations were also addressed.)

As part of the Beulah Road/Sydenham Road roundabout upgrade, the other three roundabouts located between Fullarton Road and Portrush Road were also changed to a radial design.

Although some of these smaller roundabouts had poor cyclist crash histories, none were in the top ten of worst cyclist safety locations.

Background data in the form of traffic flow, crash statistics and before/after geometries of Beulah Road/ Sydenham Road roundabout are presented as follows. This is presented before the results and analysis as it will be referred to in these later sections.

Engineering design approach

In considering the before and after case, the detailed geometric design for the intersection is informative. Zhang and Ma (2015) have provided the radial design developed as an overlay to the original tangential design, reproduced as Figure 2.

From the before to after design, and referring to typical roundabout elements:

- the inscribed circle is unchanged at 21m, measured to face of kerb
- the central island diameter is unchanged at 10.5m
- the circulating roadway width is unchanged at 5.1m
- entry lane widths are reduced from 3.9m to 3.3m
- exit lane widths vary but are reduced from 5.0m-6.0m to 3.0m-3.9m.

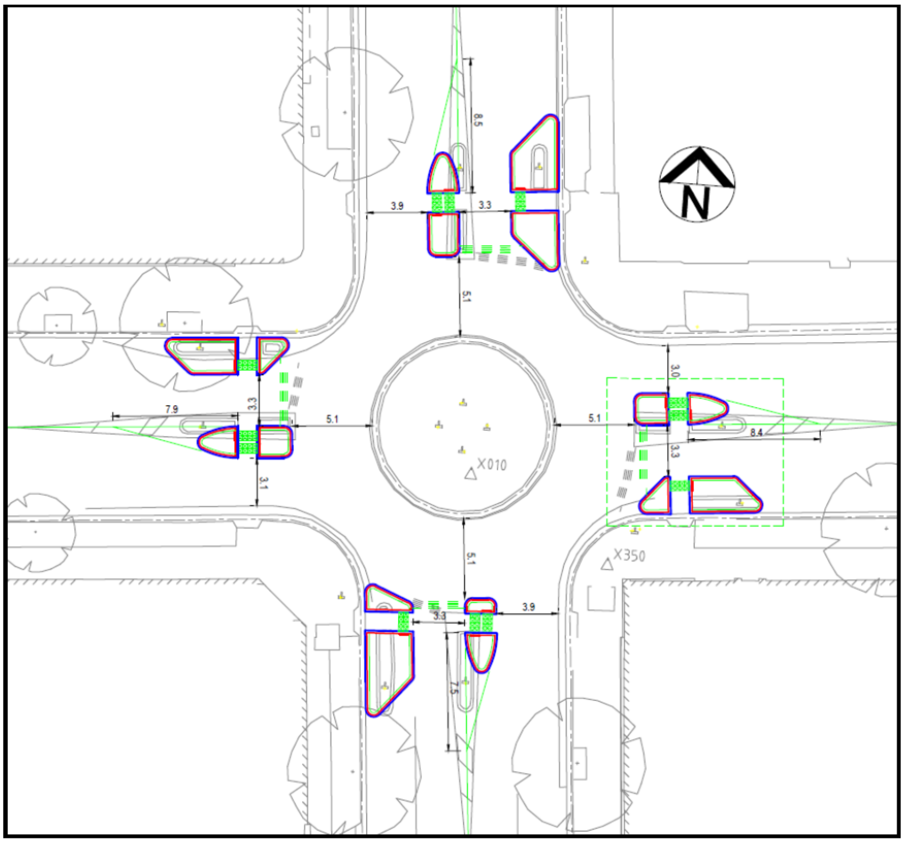


Figure 2: Before and after design, Beulah Road/ Sydenham Road roundabout

Traffic flow

Traffic data was sourced for the intersection from DPTI. An 11-hour turning traffic count of motor vehicles is shown in Figure 3. While this represents conditions on a particular day, it is assumed/ expected that this is representative of general numbers and patterns experienced at this location in both before and after conditions.

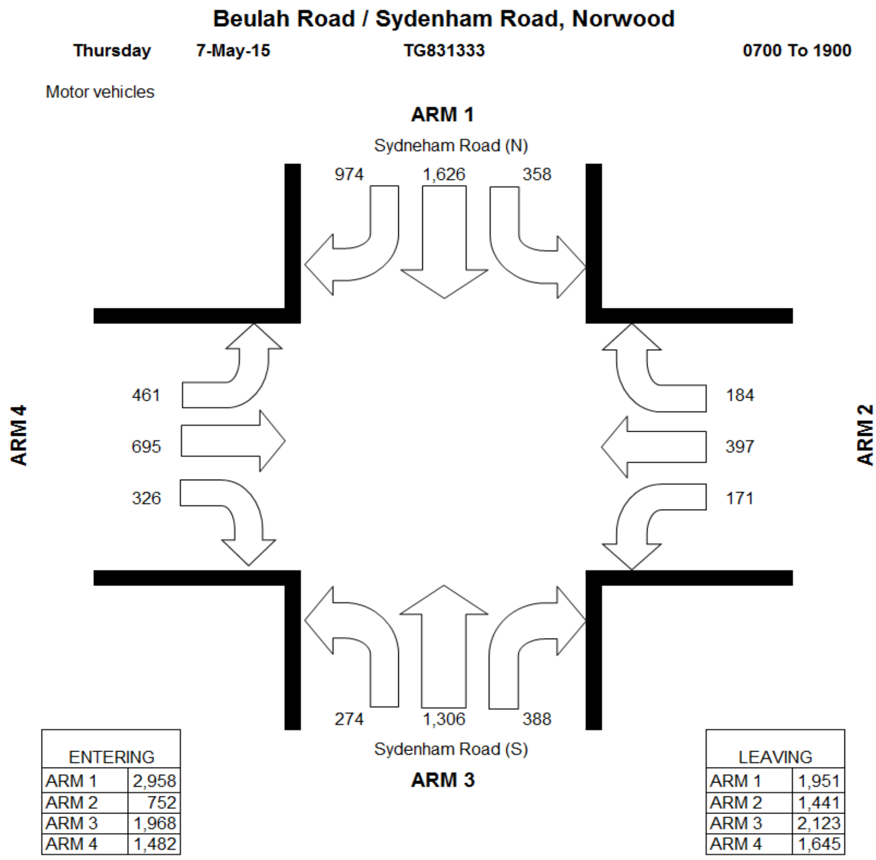


Figure 3: 11-hour (7am-7pm) turning traffic count of motor vehicles, 7 May 2015. Source: DPTI.

Motor vehicle traffic flows are asymmetric, with the highest volume of traffic entering the intersection from Sydenham Road (north), then Sydenham Road (south), Beulah Road (west) and least from Beulah Road (east). The major north-south flows are much higher than the minor east-west flows, with volumes entering from Beulah Road (east) at about a quarter of the volume entering from Sydenham Road (north).

The two north-south roads also have unequal flows compared to each other: while the through movement from Sydenham Road (north) is about 25% higher than that from Sydenham Road (south), and its left turn movements slightly greater, its right turn movements are two and a half times higher – a significant difference.

Leaving traffic volumes are more equal but the north-south legs still attract the majority of flows.

Overall, this leads to unequal interactions between vehicles on each leg.

Bicycle traffic was also counted on 7 May 2015 (Figure 4).

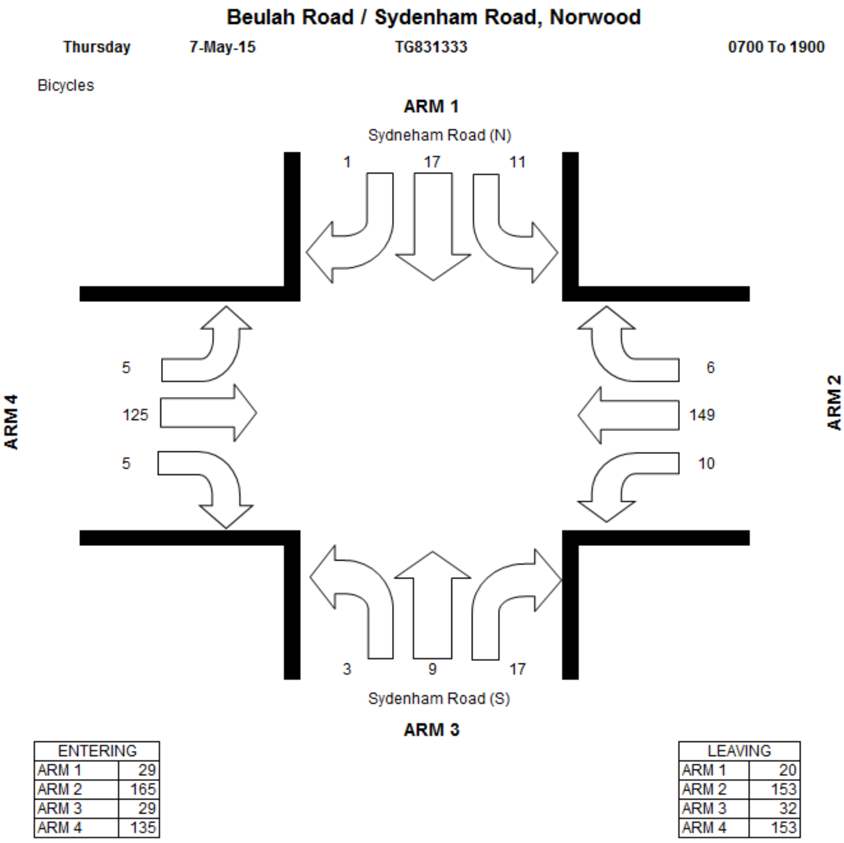


Figure 4: 11-hour (7am-7pm) turning traffic count of bicycles, 7 May 2015. Source: DPTI.

This count is not broadly representative of bicycle traffic for Beulah Road in that the count was undertaken in winter, during wet weather. In Adelaide, cyclist numbers follow strong seasonal variation; mid-spring and mid-autumn numbers are considered more representative. Nonetheless, while cyclist numbers are low, the travel patterns (proportions of turning cyclists) are considered to be representative.

On 7 May 2015, bicycle flow showed similar characteristics as for motor vehicle flow, but with an opposing pattern: the flows are overwhelmingly in an east-west direction, compared to north-south for motor vehicles. The east-west flows show few turning movements. The (small) north-south flows have proportionally significant turn movements into Beulah Road (east). Leaving traffic flows are biased to the east-west direction, but relatively balanced.

Adding these cyclist travel patterns to quite distinct motor vehicle traffic flows would result in very different interactions being experienced by cyclists entering from different legs.

Considering the situation for the PM period, Figure 5 compares traffic volumes observed on 7 May 2015 with cyclist volumes on the same day, as recorded between 4pm and 5:45pm[1].

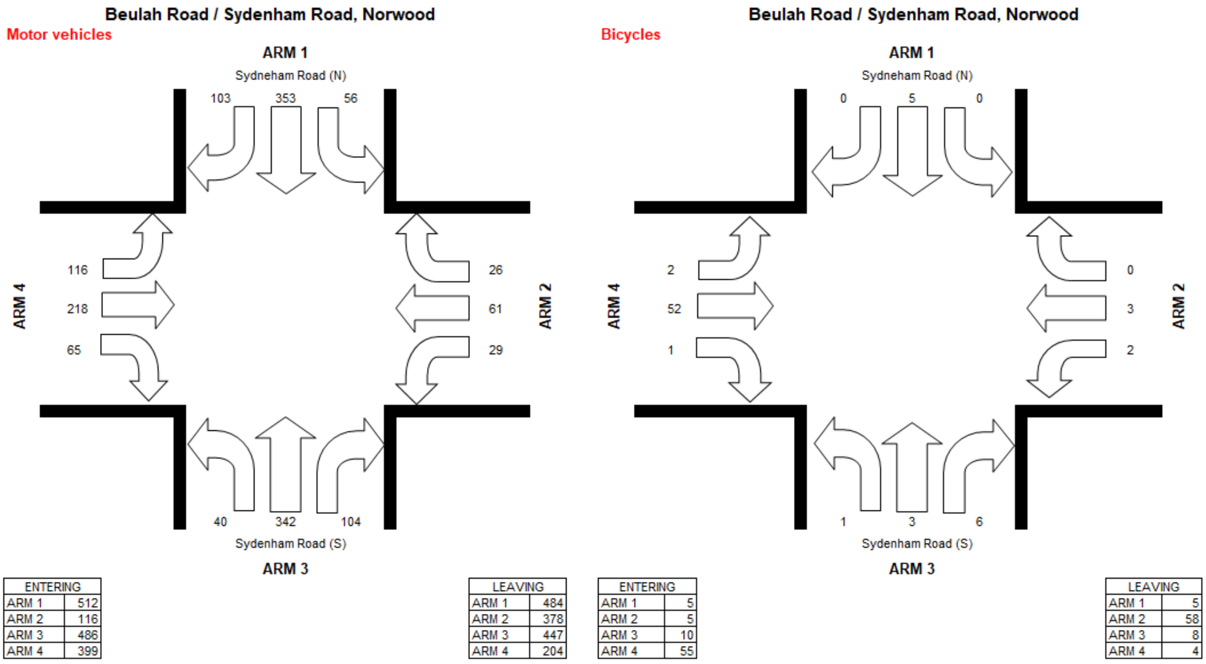


Figure 5: PM period (4pm-5:45pm) turning traffic counts, 7 May 2015. Source: DPTI.

More balanced motor vehicle traffic flows in this period implies that strong tidal flow must occur in the morning period in order to give the overall asymmetry noted for the 11-hour period. This is not the case for bicycles, where tidal flow is stronger in the PM period than the 11-hour period.

Traffic flows clearly change on each leg throughout the day and it can be expected that interactions also change. Hence in considering traffic interactions, it cannot be assumed that every hour is equal. Small numbers problems for cyclists can also be noted, especially on the minor legs.

Crash statistics – motor vehicle/ cyclist crashes

Zhang and Ma (2015) reported cyclist crash involvement at the four roundabouts on Beulah Road, based on 2004-2013 data. From west to east, and with cyclists the injured unit in the reported casualty crashes:

- Beulah Road/ Sydenham Road: 21 cyclist-involved crashes; 13 of these casualties. This was one of the highest recorded crash figures for a roundabout intersection in South Australia over this time period.

[1] Although video observations for 7 May 2015 have been used in the current study, inadequate view angles led to this being supplemented by data from 6 May 2015 to provide a usable data set and count numbers are not strictly comparable with video observation results.

- Beulah Road/ Edward Street: 8 cyclist-involved crashes; 4 of these casualties
- Beulah Road/ George Street: 14 cyclist-involved crashes; 4 of these casualties
- Beulah Road/ Queen Street: 6 cyclist-involved crashes; 4 of these casualties.

Eighty percent of the recorded crashes involved a driver entering the roundabout failing to give way to a cyclist circulating the roundabout.

DPTI has provided a copy of the 20-year crash record for Sydenham Road/ Beulah Road to 2015. The most recent ten years of crash statistics are presented in Table 1. Bicycle involvement and apparent error of the cyclist have been highlighted as an aid to readability.

		unit no	unit type	crash type	dir. of travel	unit movement	apparent error
1	17-Jul-15	1	station wagon	right angle	west	left turn	fail to give way
		2	pedal cycle	right angle	east	straight ahead	no errors
2	7-Feb-15	1	motor cars - sedan	right angle	south	straight ahead	fail to give way
		2	pedal cycle	right angle	east	straight ahead	no errors
3	14-Jul-13	1	station wagon	right angle	north	left turn	fail to give way
		2	pedal cycle	right angle	west	straight ahead	no errors
4	28-Mar-13	1	pedal cycle	right angle	west	straight ahead	no errors
		2	station wagon	right angle	north	right turn	fail to give way
5	18-Oct-12	1	motor cars - sedan	right angle	south	straight ahead	fail to give way
		2	pedal cycle	right angle	east	straight ahead	no errors
6	28-Feb-12	1	pedal cycle	right angle	east	straight ahead	no errors
		2	motor cars - sedan	right angle	south	straight ahead	fail to give way
7	22-Feb-12	1	motor cars - sedan	right angle	south	straight ahead	fail to give way
		2	pedal cycle	right angle	east	straight ahead	no errors
8	######	1	station wagon	right angle	north	left turn	fail to give way
		2	pedal cycle	right angle	west	straight ahead	no errors
9	29-Jun-11	1	motor cars - sedan	right angle	north	straight ahead	fail to give way
		2	pedal cycle	right angle	west	straight ahead	no errors
10	17-Mar-11	1	motor cars - sedan	right angle	east	straight ahead	no errors
		2	motor cars - sedan	right angle	n-west	straight ahead	fail to give way
11	13-Mar-11	1	motor cars - sedan	hit fixed object	north	straight ahead	excessive speed
		2	tree	hit fixed object			
12	11-Jun-10	1	pedal cycle	right angle	east	straight ahead	no errors
		2	station wagon	right angle	south	straight ahead	fail to give way
13	17-Mar-10	1	pedal cycle	right angle	west	straight ahead	no errors
		2	station wagon	right angle	north	left turn	fail to give way

		unit no	unit type	crash type	dir. of travel	unit movement	apparent error
14	######	1	motor cars - sedan	right angle	south	straight ahead	no errors
		2	motor cars - sedan	right angle	west	straight ahead	fail to give way
15	8-Jul-09	1	pedal cycle	right angle	west	straight ahead	no errors
		2	motor cars - sedan	right angle	north	straight ahead	fail to give way
16	29-Oct-09	1	station wagon	side swipe	east	overtaking - on right	overtake w/o due care
		2	pedal cycle	side swipe	east	straight ahead	no errors
17	######	1	motor cars - sedan	right angle	north	straight ahead	fail to give way
		2	pedal cycle	right angle	west	straight ahead	no errors
18	29-Oct-09	1	pedal cycle	rear end	east	straight ahead	no errors
		2	station wagon	rear end	east	straight ahead	follow too closely
19	######	1	motor cars - sedan	right angle	south	straight ahead	fail to give way
		2	pedal cycle	right angle	east	straight ahead	no errors
20	6-Mar-09	1	station wagon	right angle	north	straight ahead	fail to give way
		2	pedal cycle	right angle	west	straight ahead	no errors
21	######	1	pedal cycle	right angle	west	straight ahead	fail to give way
		2	station wagon	right angle	east	right turn	no errors
22	22-Oct-07	1	pedal cycle	right angle	west	straight ahead	no errors
		2	station wagon	right angle	north	straight ahead	fail to give way
23	9-Nov-05	1	motor cars - sedan	right angle	north	straight ahead	fail to give way
		2	pedal cycle	right angle	west	straight ahead	no errors
24	######	1	pedal cycle	right angle	east	straight ahead	no errors
		2	motor cars - sedan	right angle	south	left turn	fail to give way

Table 1; Beulah Rd/ Sydenham Rd crash statistics, 2005-2015. Source: DPTI.

Of the 24 crashes recorded, 21 involved cyclists and the police assigned fault to the cyclist in only one of these cases[2].

In all cases, the cyclist was proceeding straight ahead: 10 east-bound and 11 west-bound. In 19 of the cases, the crash type was right angle. This indicates the classic ‘entering car hits through cyclist’ crash type found to account for the majority of cyclist/motor vehicle crashes at roundabouts both Australia-wide and internationally, as discussed in the thesis literature review for the pragmatic case study (Chapter 5). The exact proportion of crashes this crash

[2] The crash recorded on 17 July 2015 occurred soon after the roundabout was altered (works were completed at the end of June 2015) and arguable before road users had adjusted to the new geometry. While the crash record in Table 1 extends to October 2015, DPTI advised that as at 6 May 2016, no further crashes had been recorded.

type accounts for depends on the types of roundabouts included in the reported studies. The next most frequent crash type is generally side swipe.

At the Sydenham Road/ Beulah Road roundabout, the entering-car-hits-through-cyclist crash type represented 90% of cyclist-involved crashes and 79% of all recorded crashes. According to Zhang and Ma (2015), for the recorded cyclist right angle crashes, the AM peak crashes were all between cyclists travelling towards the city (west) and motor vehicles travelling south while the PM peak right angle crashes showed the reverse i.e. crashes between cyclists travelling east and motor vehicle travelling north. This would match tidal cyclist flows.

The other two cyclist-involved crashes were a side swipe and a rear end. Both involved east-bound cyclists.

It is apparent why the entering car hits through cyclist crash type would be of concern to DPTI, especially on a strategic bicycle route. This concern directly led to the trial of a radial roundabout design at this location.

Crash statistics – motor vehicle/motor vehicle crashes

Given the very limited number of motor vehicle crashes with motor vehicles in the crash record, this record does not shed light on those types of crashes that occur at roundabouts but do not involve cyclists.

While crash statistics of roundabout have been reported from overseas studies, many of these must be read with caution due to the different yielding rules that apply, particularly in relation to pedestrian crossings on roundabout legs.

In this regard, Turner, Roozenburg and Smith's (2009) work on crash prediction models for roundabouts is relevant due to the similarity of New Zealand and Australian practice in roundabout design, although in their study of 104 roundabouts, 65 were four-leg single-lane urban roundabouts, 4 were three-leg single-lane roundabouts and the remaining 35 were two-lane roundabouts.

Turner et al. (2009) report that 51% of all crashes at urban roundabouts are of the 'entering vehicle versus circulating vehicle' type, i.e. the broader case of the classic entering-car-hits-through-cyclist crash type.

Turner et al. do not disaggregate motor vehicle-motor vehicle crashes from these entering-vehicle-versus-circulating-vehicle crashes. However, a technical paper by Turner, Wood and Roozenburg (undated) on the same subject and based on the same data presents predicted annual accidents by different forms of control based on the accident prediction models developed. These accident rates place entering-vehicle-versus-circulating-vehicle crash types at the highest rate of motor vehicle-motor vehicle only crashes, on a par with loss-of-control crashes and with rear-end as the only other major crash type. Their predicted crash rate for the entering-motor-vehicle-versus-circulating-motor-vehicle crash type is slightly less than half the entering-car-hits-through-cyclist crash rate.

Similar patterns were found by Cumming (2012) in an analysis of Victorian roundabouts. The entering-vehicle-versus-circulating-vehicle crash type was the most common type of car-only crash, accounting for about a third of these, closely followed by loss-of-control crashes. Rear-end was the next major crash type, accounting for about a quarter of car-only crashes. In comparison, entering-car-hits-through-cyclist accounted for 82% of car-cyclist crashes, with no other crash type dominating in the remaining crashes.

Although the inclusion of multi-lane roundabouts in both of these studies means that these crash patterns do not necessarily characterise a small single-lane roundabout such as at Beulah Road/ Sydenham Road, these studies point to the entering-vehicle-versus-circulating-vehicle crash type as being relevant to motor vehicle safety as well as to cyclist safety.

2. Case study method

The proposal for the case study was to undertaken an observational safety study in order to identify safety mechanisms not captured through traditional safety studies or by follow up on those observational safety studies already undertaken.

This section details some of the issues encountered in the data capture, how these issues affected the method, and summarises the data sets achieved.

Video data has been uploaded into the University file recording/sharing system, Figshare. DOI for these are provided in Table 5 and Table 6 along with thumbnail pictures of the viewing angles.

Timing issues

The roundabout upgrade was scheduled for late June 2015 but an exact date was not known due to weather variability and weather impacts on works timetables, etc. Funding for the video data collection was secured less than two weeks before works started. A major impact of this, in conjunction with funding constraints, was that trial data capture/ analysis could not be developed before works occurred, hence there was no opportunity to refine the method used for data capture and analysis prior to use.

Videoing occurred during winter, with minimum cyclist volumes and poor weather conditions involving cold, rain and wind gusts – albeit that selection of days on which to video attempted to avoid the worst forecast weather within the (short) window of opportunity. Cautionary signage erected some weeks prior to the works starting may have had an impact on the behaviour of drivers in the before situation (though no indication of this was observed).

It was initially hoped that some automated video analysis would be possible. A single day of video collection was undertaken and sent to confirm its suitability before the remaining video collection occurred. The use of this fell through and the window for undertaking videoing was reduced by some days.

The potential days for videoing were also reduced by a decision to exclude weekends. It was known that weekend traffic flows would be very different to weekdays due to the role of Beulah Road as a commuter route during the week and there were insufficient resources to examine both types of conditions.

Preliminary works, including removal of splitter islands and replacing these with bunting, occurred before construction work began and during the video observation period. This may have had an impact on driver behaviour. Again, no indication of this was observed in the recorded video except in relation to one period in which a vehicle with flashing lights was parked by the side of the road. This was excluded from the usable data sets.

The after data is not strictly comparable in terms of seasonal and weather effects. Traffic and cyclist flows in the after situation would also be slightly different due to the installation of a signalised cycle crossing at the intersection of Beulah Road with Portrush Road, about 1.2km east of the subject site, which occurred concurrently with the roundabout reconfigurations.

Video collection

DPTI undertook a day each of video observation before and after reconstructing the roundabout. This research project supplemented the DPTI data with additional video collection.

A major factor in the methodology is that a commercial videoing service was used by both DPTI and the researcher to collect video data. In the traffic engineering industry, such videoing is mainly for purposes of traffic volume and vehicle classification counts and involves installing a camera before the start of the period of interest and removing it after the end of the count period. The raw data is then sent to a third party who converts it into a readable format and divides it into consecutive one-hour segments (in order for the files to be of a usable size) before sending it back to the service provider to pass on to the client.

Use of a commercial videoing service had three significant impacts.

- Under this practice, the camera angle is fixed throughout the day rather than varied to match dominant traffic flows. The view angle adopted is kept low to minimise wind effects and the viewpoint is into the roundabout to enable movements to be assigned. This had implications on the view angles collected, the visibility of traffic events and comparability between angles, particularly for the DPTI data collection.
- Collection must be scheduled within the provider's other commitments, while processing takes time. The DPTI video was not available prior to the researcher video collection and as already discussed, no preliminary analysis and refinement of view angles was possible.
- The cost of data collection was a constraint. The research budget was fully expended on collecting before data, with after data eventually obtained by borrowing equipment from a service provider and the researcher undertaking data collection. Under this arrangement, however, the equipment could not be left on-site all day and only peak period data collection was possible.

Site and traffic flow

The site itself constrained camera fixing points and resulting viewpoints. The camera used must be securely affixed to an anchoring point for security and to minimise camera shake, with the availability and suitability of anchoring points varying with location and over time. For example, the post that provided the best view angle was removed as part of works and not replaced.

As noted, the DPTI video and before data involved a fixed camera position throughout the day. The cameras used do not have a wide-angled (or fishbowl) lens, so camera angles do not allow for all legs of the roundabout plus approach roads to be viewed. This means that the data collected is not of equal quality for eastbound versus westbound traffic (or north and southbound traffic), except for the after data, where the camera location was varied to suit.

Given the traffic and cyclist flows on Beulah Road and the major crash risk of an entering driver hitting a through cyclist, the optimal view would be one that shows cyclists from the east (in the morning) or west (in the afternoon) interacting with vehicles entering at north or south respectively. Meanwhile, camera angles that allowed views along one or more roads would allow approach/ departure behaviour to be examined.

Researcher video collection attempted to locate cameras to collect such data, within the constraints of the site, communication with the commercial videoing service and limited ability to view the data being collected in detail. Further refinement was achieved by examining the data obtained to identify the best views as part of the achievable data sets.

Data sets

The overall result of the data capture constraints is that data was captured for the period 7am to 7pm over five days in the before situation but only one in the after situation, with the captured video having varying degrees of usability; plus AM and PM peak periods on two days in the after situation. These are identified by date in Table 2.

Before	After
2015_05_06 (partial angle) 2015_05_07 (partial angle) 2015_05_12 2015_05_15 (partial day) 2015_05_18 (partial day)	2015_09_17 2015_10_19 (peak only) 2015_10_22 (peak only)

Table 2: Video data captured

Usable data sets have been developed based on pragmatic factors, such as daylight hours; and methodological issues related to data analysis through manual observation and coding of traffic events. Coding issues are discussed in the following sections. A key decision made early on was to examine traffic events using the trigger of a vehicle passing through the roundabout, which may or may not encounter another vehicle. As the trigger vehicle was considered the main subject of the encounter and as encountered vehicles were nominally expected to react to (i.e. be acted upon by) the subject vehicle, the grammatical allegory of subject (trigger) vehicle and object (encountered) vehicle. This terminology was adopted in preference to terminology used in the crash reconstruction field of 'bullet' and 'target' vehicles, which differentiates between the 'striking' and 'struck' vehicle (for example, Hitzemann 2003) and describes collision mechanics rather than characterising the traffic event.

On passing through the roundabout, the subject vehicle could:

- complete its passage without encountering an object vehicle
- encounter an object vehicle, in which case the characteristics of the encounter were recorded
- encounter more than one object vehicle, in which case characteristics for each vehicle encountered were recorded.

A practical limit had to be made as to which object vehicles would be recorded and how the encounter would be characterised. This is discussed further on. At this stage, it is sufficient to note that:

1) such vehicle encounters could be conflicts but did not have to be conflicts: vehicle paths did not have to intersect/ overlap in order for characteristics of the encounter to be recorded
2) subject vehicles were only recorded on the southern or western legs and for ease of reference are referred to as 'south subject vehicles' and 'west subject vehicles'
3) in a similar way, encountered (object) vehicles mainly occurred on the northern and western legs and are referred to as 'north object vehicles' and 'west object vehicles' respectively.

Comparison periods

Given low cyclist numbers compared to motor vehicles, comparison periods used attempt to maximise data quantity, but also quality.

Of the two comparison periods possible, the all-day situation would allow three days of before data to be compared with one day of after data. From the DPTI count data already presented, the peak half-hour for bicycle traffic occurs between 5:00pm and 5:30pm. For an afternoon (PM) period, four days of before data could be compared with three days of after data, but with less data on any one day.

Considering these periods:

- All day observations commence between 5:25am and 7:00am, with nominal sunrise on the shortest day being at 7:05am. This gives 7:00am as the earliest start time for an all day period.
- PM observations commence between 3:23pm and 3:56pm, with potentially disruptive works on 18 May ending at 4:00pm. This gives 4:00pm as the earliest start time for PM peak periods.
- All day and PM observations finish at 7:00pm to 8:30pm, giving 7:00pm as the latest finish time for all observations. However, evening light conditions vary significantly from May (before) to September/October (after).
    - The nominal sunset for the shortest day, both in the before situation and overall, was at 5:18pm[3] on 18 May, with full dark by about 6:00pm. On the longest day in the before situation (6 May), the nominal sunset was at 5:29pm.
    - The nominal sunset for the shortest day in the after situation was at 6:08pm on 19 September, but dusk-like conditions had not been reached by 6:00pm on this day. On the longest day in the after situation (22 October), the nominal sunset was at 7:36pm.
    - In order to maximise data, capture the peak period indicated by DPTI data and give the greatest comparability between data sets, a cut-off of 5:45pm has been used as the all day and peak period finish time. This does extend observations into twilight periods for the before data, to varying extents depending on the day length.
    - As a check, while the 1.75-hour PM period is significantly shorter than the 10.75-hour all-day period, 59% of daily cyclist observations occurred in this PM period. (Varying from 53.7% on 12 May to 65.6% on 15/18 May in the before situation to 54.9% on 17 September in the after situation).

[3] SA government website, https://www.sa.gov.au/topics/transport-travel-and-motoring/sunrise-and-sunset-times. The times of sunrise and sunset are the instant the upper edge of the sun appears to lie on the horizon for an observer at sea level. They are calculated rather than observed and assume certain ideal conditions rather than reflecting actual conditions at any particular place or time.

Vehicles and interactions examined

In response to camera angles and viewpoints, this study initially focused on subject vehicles from the western leg and their encounters with object vehicles on the northern leg, which captures the major cyclist flow in the PM peak period. To provide a statistical grounding to this focus, observations included the pure traffic event case i.e. where the subject vehicle did not encounter another vehicle.

However, the before data in particular was captured during the low season for cycling, creating a small numbers problem. This was partially addressed by also looking at subject vehicles entering on the southern leg and their encounters with object vehicles entering on the western leg.

For subject vehicles from the south travelling through, right or U-turning, encounters with object vehicles entering from the north were also captured on video but have the potential to introduce an asymmetry to the data (the matching data for subject vehicles entering on the west in terms of their encounters with object vehicles on the east was not available from the video collected). This is dealt with through the data analysis by excluding these interactions, where relevant.

Partial and effective periods

View angles on 6 May and 7 May were not optimal. For 6 May, encounters between south subject vehicles and west object vehicles were visible but not encounters between west or south subject vehicles and north object vehicles. For 7 May, encounters between west or south subject vehicles and north object vehicles were visible, but not encounters between south subject vehicles and west object vehicles.

6 and 7 May data sets have been combined to create one effective full day of data. This was not a simple summation of the data captured. Some vehicle movements are visible in both data sets (e.g. left turns of south subject vehicles) and a summation would over-represent these. To avoid such double-counting, dominance for particular movements was assigned to each day and only data from the relevant day was used.

Other movements could be over-represented due to multiple possible encounters. For example, south subject vehicles proceeding through could encounter object vehicles from the west (captured in the 6 May record) or north (captured in the 7 May record) or neither. These movements were calibrated against data from each day to ensure that these were not over-represented in the final data set.

Finally, the view angle on 15 May did not allow adequate vision on one leg prior to 9:40am, at which point it was adjusted, while works undertaken on 18 May potentially influenced results between 12:45pm and 4:02pm, so data from this period is not considered reliable. Each of these data sets provides usable PM peak data. While neither provides a full day of data, they could be combined to create one effective day of data.

Assessment against target quantity

In order to be able to characterise cyclist behaviour, the approach for the study was to collect as much data as possible within resourcing limits – similarly to a statistical study, but not using crash mass data as a basis. Given that resources were very limited, the literature review for the paradigmatic case study concerning data needs for Traffic Conflicts Technique studies was referred to as a basis for assessing the adequacy of the data acquired. It is acknowledged that this considers very different conditions, but this provided at least some information.

Hauer (1978) proposes that three days of observation is a reasonable practical limit providing sufficient data for impacts from the roundabout changes to be evident. Retting, Ferguson and McCartt (2003) cite Gårder (1985) as showing that a one-day conflict count provides a more accurate estimate of the expected number of crashes than a one-year crash history if the expected number of crashes is less than five per year. The crash rate at the roundabout is about two a year and three days of all-day observation would be more than adequate.

However, William Gauz’s response in Hauer (1978) was that three days may be a ‘pessimistic’ assessment of the amount of data needed for results to characterise conditions, and also that partial counts may be more practical than daily counts. Noting further comments about inter-observer reliability, Gauz’s observation is considered to apply to the case study as a single observer coded the case study data. For manual coding, focusing on partial counts certainly aided analysis when considering coding every traffic movement for multiple days of data.

Overall, then, the approach was to focus resources on gathering three days of all-day data in the before situation, with a supplemental fourth PM peak period providing additional surety; followed by three days of PM peak data in the after situation for comparative purposes, with all day data collected if possible. The focus on before data also reflects the fact that it is possible to collect after data at any point after the roundabout has been constructed, if more resources become available, but it is not possible to revisit the before situation.

In the event, three effective days of all-day data and four PM peak periods were collected in the before situation, however this was slightly undermined by the inability to trial and review the data prior to the data collection phase. One all-day and three PM peak periods were videoed in the after situation.

In coding results, all bicycle events and a sample of motor vehicle events were coded, as discussed in the following sections.

The three effective all-day data sets of before data would fully satisfy Hauer's (1987) goal, but not the single all-day data set in the after situation. Hence the daily data can be considered to provide additional indicative information about daily patterns, but this is subject to lower confidence in before/after comparisons due to the single day of after sampling. This after data might also satisfy Gauz. This is not guaranteed, but data patterns displayed in the all-day after situation did not seem unreasonable in more situations, except that small numbers issues are greater for disaggregated data and certain types of enquiry.

Overall, the PM data sets are considered to provide the best before/ after comparisons and the most representative information. In all cases, data validity is subject to the understanding of its limitations.

Motor vehicle sampling

One element of the research hypothesis is that a comparison can be made between motor vehicle-motor vehicle interactions and bicycle-motor vehicle interactions.

To examine this, encounters between motor vehicles and bicycles need to be compared to encounters between motor vehicles and other motor vehicles, and the characteristics of both sets of encounters compared between the before and after situations. However, the large numbers of motor vehicle-motor vehicle observations is both potentially overwhelming for manual analysis and represents an amount of data far in excess of the comparable data involving cyclists. Therefore, a sampling methodology has been applied to subject motor vehicle observations to reduce this to more manageable levels.

As noted, different traffic flows lead to variations in exposure. Hence a sampling based on, say, one hour in the PM peak could not be extrapolated to other periods. Therefore, the sampling methodology used has been to take small samples frequently throughout the period being examined.

- Six-minute samples were taken every half-hour for the one before and one after all-day situations in which motor vehicle traffic was examined (i.e. a 20% sample for each 11-hour count, or 264 minutes of video data overall); and

- Five-minute samples were taken every fifteen minutes for the four before and three after PM peak periods (i.e. a 33% sample for each 1.75 hour count, or 245 minutes of video data in total).

For the 18 May data, a works vehicle may have influenced behaviour until 4:02pm. To address this, the first motor vehicle sampling period for the PM peak on this day was adjusted to start at 4:02pm instead of 4:00pm and end at 4:07pm instead of 4:05pm. However, for bicycle observations, a 100% sample rate meant that a 4:02pm start would result in the end time also being two minutes later. As this was the shortest day and evening lighting conditions were already becoming marginal, it was considered that adopting a similar adjustment would be undesirable. In fact, it was observed that between 4:00pm-4:02pm and after 5:38pm, no encounters occurred involving cyclists and the impact of an adjustment was purely hypothetical.

As combining the two partial angles involved additional data examination and calibration tasks, and as only one all-day after data set was available, the 20% sample of motor vehicles was undertaken in the before situation only on the single full day of data.

Data sets achieved

The usable data sets are given below.

	Before	After
100% sample of bicycles 20% sample of motor vehicles	2015_05_12	2015_09_17
100% sample of bicycles	2015_06_06 & 07 (two partial angles combined)	
100% sample of bicycles	2015_05_15 & 18 (two partial periods combined)	

Table 3: All-day (7:00am-5:45pm) data sets

	Before	After
100% sample of bicycles 33% sample of motor vehicles	2015_05_06 & 07 (two partial angles combined)	2015_09_17
100% sample of bicycles 33% sample of motor vehicles	2015_05_12	2015_10_19
100% sample of bicycles 33% sample of motor vehicles	2015_05_15	2015_10_22
100% sample of bicycles 33% sample of motor vehicles	2015_05_18	

Table 4: PM period (4:00pm-5:45pm) data sets

Summaries of the data by collection date are provided in Table 5 and Table 6, over the following pages. These summaries include thumbnails from the video that illustrate the viewpoints. Sunrise and sunset times are as provided by the SA government.

Table 5: Data collection sets with thumbnail views: before.

BEFORE		
Wednesday 6 May 2015		
Partial south 6:58am – 20:13pm *Sunrise 6:55am* *Sunset 17:29pm* Rain affected, AM and interpeak.		View to south and west legs, i.e. only encounters with vehicles on these legs could be examined. Used to augment 7 May data by giving west encounters with south vehicles. Due the low viewing angle, distances were difficult to judge.
Bicycle subject vehicles (partial view)	7:00am-15:59pm 16:00-17:45pm	
Motorised subject vehicles (partial view)	16:00-17:45pm	5 minutes every quarter hour = 33% sample
DOI: 10.6084/m9.figshare.14564697		
Thursday 7 May 2015 (DPTI video)		
West and partial south 7:00am – 19:00pm *Sunrise 6:54am* *Sunset 17:28pm* Half-hour shower period, interpeak.		View to north and east legs. Visibility poor to west stop bar; entry position for west subject vehicles is estimated. Used for north encounters with west vehicles and north encounters with south vehicles, but 6 May has been used as a substitute source for west encounters with south vehicles.
Bicycle subject vehicles (partial view)	7:00am-15:59pm 16:00-17:45pm	
Motorised subject vehicles (partial view)	16:00-17:45pm	5 minutes every quarter hour = 33% sample
DOI: 10.6084/m9.figshare.14564754		
Tuesday 12 May 2015		
West and south 5:54am – 19:39pm *Sunrise 7:00am* *Sunset 17:24pm* Rain affected, AM and early interpeak.		View down west leg, with limited view to east, south and north legs. Direction and limited distance information is available for all legs. The post to which the camera was fixed was removed and could not be used again.
Bicycle subject vehicles	7:00am-15:59pm 16:00-17:45pm	
Motorised subject vehicles	7:00am-17:45pm 16:00-17:45pm	6 minutes every half hour = 20% sample 5 minutes every quarter hour = 33% sample
DOI: 10.6084/m9.figshare.14564937		
Friday 15 May 2015		
West and south View 1: 5:25am – 9:39am View 2: 9:40am – 20:30pm *Sunrise 7:02am*		View to west and north legs, splitter islands removed. Before 9.39am, only encounters for west entering vehicles could be examined. Data from 2015_05_18 has been used to augment this. South subject vehicles are visible, but

Sunset 17:21pm		not the stop bar. Entry position for south subject vehicles is estimated.
Bicycle subject vehicles	9:39am-15:59pm 16:00-17:45pm	
Motorised subject vehicles	16:00-17:45pm	5 minutes every quarter hour = 33% sample
DOI: 10.6084/m9.figshare.14565897		
Monday 18 May 2015		
South 7:20am – 20:19pm *Sunrise 7:05am* *Sunset 17:18pm* Rain affected, PM peak.		View to west and north legs, splitter islands removed. South subject vehicles are visible, but not the stop bar. Entry position for south subject vehicles is estimated. Workers were present at/beside the carriageway from about 12:45pm to 14:03pm, with warning flashing lights. This may have affected road user behaviour. Data from 7:00am to 10:40am was used to supplement the data for 2015_05_15.
Bicycle subject vehicles	7:00-9:39am 16:00-17:45pm	
Motorised subject vehicles	16:00-17:45pm	5 minutes every quarter hour = 33% sample
DOI: 10.6084/m9.figshare.14566140		

Table 6: Data collection sets with thumbnail views: after.

AFTER		
Thursday 17 September 2015		
South and west 6:21am – 20:27pm *Sunrise 6:13am* *Sunset 18:08pm*		View to west and north legs. South subject vehicles are visible, but not the stop bar. Entry position for south subject vehicles is estimated. Glare reduced visibility in the late afternoon.
Bicycle subject vehicles	7:00am-15:59pm 16:00-17:45pm	
Motorised subject vehicles	7:00am-17:45pm 16:00-17:45pm	6 minutes every half hour = 20% sample 5 minutes every quarter hour = 33% sample
DOI: 10.6084/m9.figshare.14564664		
Monday 19 October 2015		
Not used 7:05am – 8:04am *Sunrise 6:29am*		View to south and west legs, i.e. only south subject vehicles could be examined. Given lack of compatibility, not used.
DOI: 10.6084/m9.figshare.14566242		

South and west 15:23pm – 19:22pm *Sunset 19:33pm*		View to west and north legs. South subject vehicles are visible, but not the stop bar. Entry position for south subject vehicles is estimated.
Bicycle subject vehicles	16:00-17:45pm	
Motorised subject vehicles	16:00-17:45pm	5 minutes every quarter hour = 33% sample
DOI: 10.6084/m9.figshare.14564604		
Tuesday 20 October 2015		
Not used 6:49am – 9:48am *Sunrise 6:28am* No matching afternoon data.		View to south and west legs, i.e. only south subject vehicles could be examined. Given lack of compatibility, not used.
DOI: 10.6084/m9.figshare.14566269		
Thursday 22 October 2015		
Not used 8:23am – 2:22pm *Sunrise 6:25am*		View to south and west legs, i.e. only south subject vehicles could be examined. Given lack of compatibility, not used.
DOI: 10.6084/m9.figshare.14566374		
South and west 15:56pm – 18:55pm *Sunset 19:36pm*		View to west and north legs. South subject vehicles are visible, but not the stop bar. Entry position for south subject vehicles is estimated.
Bicycle subject vehicles	16:00-17:45pm	
Motorised subject vehicles	16:00-17:45pm	5 minutes every quarter hour = 33% sample
DOI: 10.6084/m9.figshare.14564646		

Iterative development of the coding system

To enable encounters to be recorded and examined, a system of coding was developed in an exploratory and iterative process. This section presents a general overview of how the coding system developed.

Given the dominance of the circulating cyclist/ entering motorist crash type, the focus of the study was on circulating vehicles and the behaviour of entering vehicles when circulating vehicles were present.

An initial observation of the stream of entering vehicles on the northern leg provided insight into this traffic flow as a whole – including the frequency with which north-entering vehicles stopped in case a south-entering vehicle might turn right across their travel path, and the difference in behaviour of individual vehicles to a platoon of vehicles. However, this did not enable individual vehicle movements to be well characterised or compared.

A coding system was instead trialled based on a vehicle entering the intersection (the subject vehicle). All subject vehicles were recorded whether or not these encountered another vehicle on the roundabout. In terms of coding vehicles encountered, a practical limit had to be made as to which vehicles would be recorded and how the encounter would be characterised.

As the known safety issue between motor vehicles and cyclists is of an entering vehicle with a circulating cyclist, the behaviour of vehicles entering on the leg to the left of the subject vehicles was adopted as the focus of the study. As any vehicle approaching the roundabout can be entering the roundabout, the vehicle to the subject vehicle's left has been termed the 'object vehicle' for clarity and ease of reference. (This uses an analogy with grammatical structure: the subject of a sentence acts upon the object; the object vehicle reacts to a subject vehicle, so the subject vehicle can be considered to act upon the object vehicle.) In fact, other vehicles were also characterised in some encounters and became 'object vehicles' for the purpose of the encounter. These could be further differentiated as circulating vehicles (those already on the roundabout) or by approach leg.

The coding is described under sub-headings at the end of this section.

The coding system was first applied to the western leg, capturing the major flow for bicycles in the PM peak encountering the major motor vehicle flow from the north; then the southern leg, capturing a minor flow for bicycles encountering a minor motor vehicle flow from the south. Given that south subject vehicles also frequently encountered vehicles entering from the north, these traffic events were also captured. As already noted, this introduces asymmetry to the data that is dealt with through data cleansing.

The coding system was developed as an iterative process, with the addition of new codes in some instances requiring the video data to be re-examined. For example, additional codes capture observations about circulating vehicles and situations leading to impeded viewpoints.

Upon observation of the video data. some behaviours regarding vehicles on the approach, cyclist tracking through the roundabout and times to pass through the roundabout became of interest and were examined, but a thorough quantitative examination of these would be intensive and was not always supported by the available data. Instead, samples were used to provide indicative rather than statistically robust information and are highlighted as such in the discussion of results.

As traffic events recorded for subject vehicles included events where no encounter with another vehicle occurred, exposure risks could be determined from the data.

A limitation of a manual analysis system is the amount of data that can be examined on a realistic basis, with the much greater number of motor vehicles in particular precluding coding of all movements and related encounters.

At least one all-day data set was created for the before and after situations, but the goal of three days of data was not achieved for both bicycles and motor vehicles. (Indeed, three full days of data were not collected in the after situation. However, unlike the before situation, there is potential for additional video observation to be undertaken at a later date.)

The coding system

The actual coding used is detailed as follows, grouped into similar variables.

Time record

The time records are essentially administrative codes that enable observations to be assigned and uniquely identified.

- **Period**: video observations taken from commercial recording services must be decoded into a usable video format. The video is provided to the researcher in consecutively numbered 1-hour segments, to ensure the video size is small enough to be manageable. The period is a record of which segment is being examined.
  For example, 0621_07 is the 7th one-hour period for a recording that started at 6:21am, i.e. contains data for 12:21pm-13:20pm.
  Each video run continues until a timer function for recording ceases or the recording is manually stopped, hence the last period would not normally be for an entire hour.
- **Time within the period**: this is based on elapsed time according to video viewing software.
  For example, in the 0621_07 period, the observation at 12.26 was one of nine recorded for the minute between 11 and 13 minutes elapsed time, for a subject vehicle entering at 26 seconds after the start of the minute.
  Not all times represent unique subject vehicles: two observations were recorded at 12.29 for the same vehicle, one being in relation to an object vehicle and one for a circulating object vehicle. Up to five observations were recorded for a single subject vehicle, but

these were rare.

Where more than one subject vehicle entered at a given time (e.g. from the south and west), differences in other codes relating to vehicle characteristics (e.g. entering leg) can be used to differentiate vehicles. A one-second difference was applied to prevent confusion when the subject vehicles were entering from the same leg (e.g. two cyclists travelling abreast), since times are approximate and most observations were at least two seconds apart.

- **Real time**: uses the period and time within the period to convert to a time of day. For example, in the 0621_07 period, the observation at 12.26 occurred 12 minutes and 26 seconds into the 7th hour after 6:21am, i.e. at about 12:33pm. This was a useful check.

  The time record was also used to speed up manual processing as it enabled video to be viewed at two or four times speed to identify when subject vehicles or encounters occurred, which could then be viewed at normal speed. This capability was useful for cyclist encounters where long periods might exist between observations, and as part of the iterative process where additional data was being collected from video that had already been examined. When counting vehicles, video could be viewed at eight times normal speed.

Subject vehicle characteristics

The subject vehicle is a vehicle entering the roundabout from the south or west. Basic characteristics assist with identification and metrics (such as exposure risk) that are based on the traffic event.

- **Type**: motor vehicle (car, motorbike, heavy vehicle) or bicycle
- **Entering direction**: west or south
- **Movement:** left, through, right or U-turn.

Codes in all fields must be present for a record to be valid, forming a cross-check that data has been properly recorded.

Object vehicle characteristics

Given the dominance of the circulating cyclist/ entering motorist crash type, the focus of the study was on a subject vehicle entering the roundabout and circulating, and the behaviour of entering object vehicles encountering this subject vehicle.

The object vehicle was initially defined as a vehicle entering the roundabout on the leg immediately to the subject vehicle’s left. An encounter was then defined as occurring when an object vehicle slowed down or took other action as a result of the subject vehicle. Under TCT, this would comprise an 'evasive manoeuvre' characterisation, albeit that unlike early TCT, there was no requirement for the manoeuvre to exhibit characteristics of active avoidance of a crash. However, as in TCT, the need for the manoeuvre to be visible to the researcher introduced subjectivity to the coding and raised the question of the validity of excluding encounters where no visible manoeuvre existed.

The definition of an encounter was therefore expanded to the case when the object vehicle should have slowed down, based on the behaviour of other vehicles; or when it caused the subject vehicle to take (visually observable) action. This definition enabled observations to be recorded where the vehicle being encountered failed to react.

- **Type**: bicycle or motor vehicle (car, motorbike, heavy vehicle). N = no vehicle provides a cross-check of validity for a record that would otherwise have no further data in it.
- **Entering direction**: mainly west or north. However in some cases, the action of a subject vehicle caused an already circulating vehicle to modify its behaviour in response e.g. if the subject vehicle cut in front of it. In these relatively few cases, the entering direction could be east, south or circulating. These entering directions were highlighted using formatting to ensure that this type of encounter was identifiable during analysis.

Vehicles entering from the north often responded to subject vehicles entering from the south, particularly if the subject vehicle was turning right. As previously noted, such traffic events were also recorded as encounters but create an asymmetry to the record (the north was the only leg where this was visible). Apart from removal through data cleansing, some elements of this behaviour could be captured for both south and west subject vehicles by capturing object vehicle yielding behaviour.

Object vehicle behaviour

- **Entering distance**: the object vehicle's location along its approach street when the subject vehicle was judged to have entered the roundabout. Entering is defined as crossing the yield line or, where the yield line is not visible, by first appearing in the camera frame (being a point very close to the yield line in all instances).
  Features against which observations could be judged had to be as similar as possible between the different legs of the roundabout and able to be identified despite the removal and replacement of the existing roundabout, including associated splitter islands and kerb build-outs, plus at differing angles of videoing.
  A non-linear numerical coding was adopted:

- 4 = local feature located a similar distance from the roundabout yield line (stobie pole in the west, wall edge in the north direction)
- 3 = edge of driveway (located similarly in both north and west directions)
- 2 = back of splitter island line-marking (while not exactly the same distance from the roundabout on every leg, this is at a similar distance)
- 1 = pedestrian kerb ramp location (this location was markedly different on the southern leg to other legs and an approximate equivalent location was used)
- 0 = yield line
- negative = forward of the yield line, measured relative to a car length.

These positions are not identical in each location but are similar enough within the accuracy of observing encounters and assigning coding. The further away a position was, the less critical its exact position given that the furthest positions were not visible in every camera angle. The features close to the roundabout were considered more important and present comparable points for judgements to be made about location.

Vehicles rarely stop at exact measurement points, so halves and quarters were used to indicate intermediate distances where relevant. However, as these were less rigorously applied and the data set suffered from small numbers problems, these tended to be rounded during the analysis.

As there were no similar features to judge distances into the roundabout, negative numbers relate to a nominal car length and are typically less than a single car length, on the basis that at one or more car lengths into the roundabout, the object vehicle has entered the roundabout well before the subject vehicle crossed its yield line and no real encounter results.

Parallax and judgement are factors in the accuracy of distance measurements, particularly from different viewpoints. The fact that the yield line is not quite straight in the before situation is a further complicating factor, as it the fact that vehicles do not travel straight into the intersection (hence the front of the car may be strongly skewed to the yield line, particularly for negative values). All distance measures are indicative only.

- **Stopped on entry**: whether the object vehicle was stopped as the subject vehicle crossed the yield line. Values:
  - Yes
  - No
  - ‘Virtually’ = arguably still moving, but stopped soon after or moving very slowly.

- **Clearance distance**: the object vehicle's location when the subject vehicle cleared the front of the object vehicle, i.e. the point where if the object vehicle moved forward, it would not collide with the subject vehicle.
  Distance codes are as for entering distance, plus 'n/a (P)' = not applicable as the subject vehicle did not pass in front of the object vehicle – for example, if an object vehicle stopped for a left turning subject vehicle. This 'cautious' behaviour was frequent enough that it was considered to warrant coding.
  For subject vehicles turning right, the subject vehicle doesn't clear the object vehicle per se; the point where the object vehicle and subject vehicle share the same travel line was used instead.
- **Clearance behaviour**: MO or blank. Used to indicate that the interacting vehicle is moving off (MO) as the subject vehicle passes in front of it.
- **Stop distance**: the object vehicle's location along its approach street at the point when it stopped to yield to the subject vehicle. Not all object vehicles stopped.
- **Stop behaviour**: added information about the behaviour of the object vehicle. The values used were:
  - 'Did not stop'
  - 'Virtually' = arguably still moving, but very slowly.
- **Conflict potential**: used to give insight into behaviours and situations, typically when the video would seem to indicate a degree of conflict potential. For example, a subject vehicle might enter the roundabout with the object vehicle at 2, no clearance distance and a behaviour of 'does not stop'. Depending on the relative speeds, the extremes that may have occurred are that object vehicle may have cut in front of the subject vehicle, forcing this to brake suddenly; or the subject vehicle may have been travelling slowly and the object vehicle passed easily in front of it, leaving plenty of headway. These events are differentiated between through the conflict potential coding.
  The values used were:
  - -3: Entirely clear – a traffic event with no encounter. This rating could reflect effects from relative speeds, but also the manual entry process: as an event unfolds, values for subject and object vehicles are entered, but the clearance is both a determining factor on whether the event is categorised as involving an encounter or not and one of the last elements of the event to be recorded. It was often quicker to assign a conflict potential than to amend the record to remove object vehicle data. This rating implies

that the record must be recategorised in the data as representing an event but not an encounter before analysis is undertaken.

- -2: Clear, but within a car length or so – if the subject vehicle abruptly came to a full stop, there might be the potential that the object vehicle would have to brake to avoid a conflict, but in any other circumstances there is no real encounter. Again, this assisted in the manual entry process but also in data cross-checks as the (potential) object vehicle was recorded. This was considered a null encounter value in the analysis.
- -1: This could indicate either that a subject vehicle entered while a circulating vehicle was in front of it, or entered close behind the circulating vehicle. Other codes or examination of video gave context to this. For example, this coding plus object vehicle entering direction enabled different types of impeded sightline events to be identified and examined.
- 0: Enters before the subject vehicle.
- 1: Both cross the yield line at the same time.
- 2: Enters after the subject vehicle; neither vehicle must change speed/ behaviour.
- 3: Enters after the subject vehicle (cuts in); one or other vehicle must slow down but can do so safely/ easily.
- 4: One or other vehicle must stop suddenly to avoid a collision within the roundabout.
- >4: Collision. No interactions of greater than a ‘4’ rating were observed.

As a data validity check, in addition to vehicle characteristics any record of an object vehicle recorded entering from the subject vehicle’s left must have at least one value of entering distance, positive stopped on entry, clearance distance, stopped distance, stopped behaviour or conflict behaviour in order to be valid.

Vehicle yielding behaviour

Under Australian law, a vehicle entering a roundabout must give way to a vehicle in the roundabout rather than to the right as at other intersections. (This is discussed in more detail in the analysis, examining give way behaviour). However, in the initial examination of video data, clear ‘yielding to the right’ behaviour was observed, as well as what might be termed cautious yielding – i.e. yielding when not required – and that a car which stops for one vehicle is more likely to remain stopped for the next vehicle, giving the first vehicle a greater clearance distance.

Given these patterns, and given that the failure mechanism of the entering-vehicle-versus-circulating-vehicle crash type is in legal terms a failure to yield, yielding behaviour was considered of interest and a method of recording and characterising yielding behaviour was developed.

The yielding field consisted of three linked observations:

- yielding to the immediately preceding vehicle (if one exists)
- yielding to the subject vehicle
- yielding to the next vehicle (if one exists).

Each observation recorded the vehicle type (bicycle, motor vehicle) and type of yielding, as far as this could be ascertained:

- mandatory under the law: the subject vehicle had crossed its yield line and had therefore entered the roundabout, or was at the yield line and a reasonable driver might consider that it would have entered the roundabout by the time the object vehicle entered the roundabout
- giving way to the right: the subject vehicle had not yet entered the roundabout but was at an entering distance of 0 to 1 from the yield line; the object vehicle slowed and yielded despite physically being able to enter the roundabout before the subject vehicle
- cautious yielding: this included several different situations including no requirement to yield (for example, the subject vehicle is turning left and indicating to turn left, or must itself yield to another vehicle, so would not conflict with the object vehicle) and yielding when the subject vehicle is at such a distance that a reasonable object driver could enter the roundabout before the subject vehicle (this depended on speed but typically included entering distances of 2+)
- following (previous field only): the object vehicle stopped because it was behind another vehicle.

From a data checking perspective, this field should have a value if an object vehicle has a positive entering distance value and a clearance distance value (or an indication of a cautious yield), does not have a conflict value indicating that no yield occurred, and is not a circulating vehicle.

Similarly to the assessment of evasive manoeuvres in Traffic Conflicts Technique, the intent in yield situations and even whether a situation was a yield or a deceleration on approach to the roundabout is difficult to conclusively identify, which is a proviso for this data.

Discussion

The coding system developed for this study enables a large amount of information to be captured fairly easily and consistently in an Excel spreadsheet. It is beyond reasonable limits to present the full database developed within this reporting but an indication of the coding is provided in Figure 6, below, and the Excel workbooks developed (PM peak before, PM peak after and All day) have been uploaded to Figshare (DOI: 10.6084/m9.figshare.14569446). Worksheets do not have identical fields in that certain behaviours such as tracking and tandem entry have been recorded in some cases only. Some datasets in the PM peak hour (before) situation have also been colour-coded to indicate lighting conditions.

Period stamp	Time stamp	Real time	Veh type	Entering (S, W)	Movement (L, R, T, U)	Type (C/B)	Entering dir	Entering dist	Stopped on	Clearance dist (@)	Clearance beh (MO)	Stop dist	Stop beh (v, DNS)	conflict with S	comment?	Previous M/P	Previous C/B	This (*) M/P	This (*) C/B	Next M/P	Next C/B
0554.011	6.32	16.00	C	W	T	N															
0554.011	6.51	16.01	C	S	T	N															
0554.011	7.06	16.01	C	S	L	N															
0554.011	7.11	16.01	C	S	T	N															
0554.011	7.29	16.01	C	W	T	N															
0554.011	7.31	16.01	C	W	L	N															
0554.011	7.34	16.01	C	W	T	N															
0554.011	7.35	16.01	C	S	T	C	W	1.50		0.00	MO	0.00					FOLL	M	C		
0554.011	7.42	16.01	C	W	L	N															
0554.011	7.44	16.01	C	S	T	N															
0554.011	7.50	16.02	C	W	T	N															
0554.011	7.56	16.02	C	W	L	N															
0554.011	8.05	16.02	C	S	T	N															
0554.011	8.13	16.02	C	S	T	N															
0554.011	8.40	16.02	C	W	T	C	N	1.50		0.25		0.50	V					M	C		
0554.011	9.07	16.03	C	S	T	N															
0554.011	9.13	16.03	C	S	T	N															
0554.011	9.28	16.03	C	W	R	N															
0554.011	9.39	16.03	C	S	L	N															
0554.011	9.47	16.03	C	S	T	C	W	1.25		0.25		0.25						M	C	M	C
0554.011	9.49	16.03	C	S	T	C	W	0.25	Y	0.25		0.25				M	C	M	C		
0554.011	9.53	16.04	C	W	L	N															
0554.011	10.01	16.04	C	S	T	C	W	1.25		0.00		0.00						M	C		
0554.011	10.04	16.04	C	W	T	C	N	0.50	Y	0.50		0.50						M	C	M	C
0554.011	10.07	16.04	C	W	R	C	N	0.50	Y	0.00	MO	0.50				M	C	M	C		
0554.011	10.31	16.04	C	W	T	N															
0554.011	10.56	16.05	C	W	T	N															

... 2015_05_06&07 C | 2015_05_12B | 2015_05_12C | 2015_05_15 B | 2015_05_15 C | 2015_05_18 B | 2015_05_18C | exposure | ...

Figure 6: Screenshot illustrating coded data, before PM peak, 12 May 2015 - motor vehicles.

The coding system is both flexible and robust, and applicable to any roundabout with a reasonable level of comparability. Indeed, measurement against features such as the yield line is transferable to other intersection layouts.

Compared to the coding used by Rodergerdts et al. (2007), this system is focused on capturing factors relatable to the entering-vehicle-versus-circulating-vehicle crash type that is the major crash type for all vehicles, but especially motor vehicle-bicycle crashes.

Compared to surrogate measures currently in use in Traffic Conflicts Technique such as Time-To-Collision, the use of physical features mirrors early TCT measures such as van der Horst's (1990) Time to Stop-line and Time To Intersection. It is hence conceptually compatible with Traffic Conflicts Technique, within the constraints of the outstanding question of what is being measured with current Traffic Conflicts Technique measures. However, this system can also be used to examine traffic events that lie outside Traffic Conflicts Technique's definition of conflict. That is, single-vehicle traffic events and events in which object vehicle behaviour responds to a subject vehicle without the vehicles having travel paths that intersect.

Practically, the system supports manual coding of data and is compatible with practical safety outcomes, notably Turner, Wood and Smith's (2009) use of visibility at 10m from the yield line as a key safety indicator for roundabouts.

The use of manual coding across a variety of viewpoints in this case would not provide sufficient precision to enable an Extreme Value theory approach to be tested. However, if the coding system were combined with consistent and calibrated video collection, and automated video analysis, statistical results could be generated that would enable observations to be compared using Extreme Value theory.

3. Results

The main results of the case study relevant to the thesis are presented in Chapter 5 of that document. In addition to these results, behaviour examined via coded traffic event data involved yield behaviour, stopping at the yield line, clearance distances and stopping distances. While some interesting indications were found, none of these could be disaggregated from speed effects, while small numbers and manual assessment gives limited confidence in these indications. Nonetheless, these are summarised for completeness in this Chapter.

Limitations of view angles in being able to see the yield line, and hence other vehicles' behaviour in relation to approaching vehicles, affected the ability to capture cautious yielding and give way behaviour in particular. These difficulties can be judged from the thumbnail photos provided (see Motor vehicle sampling section) and are summarised in Table 7.

	Date	View limitations	Effects/ implications
Before	7 May	West yield line not visible.	Augmented with 6 May data for yielding on western leg. Under/ poor estimation, yielding on northern leg to west vehicles.
	12 May	Good visibility to all yield lines.	
	15 May	South yield line not visible.	Under/ poor estimation, yielding on western leg.
	18 May	North yield line not visible, 7am-10am. South yield line not visible.	Augmented with 15 May data for northern yield line to overcome view limitations, 7am-10am. Under/ poor estimation, yielding on southern leg.
After	17 Sept	South yield line not visible. Glare in the late afternoon.	Under/ poor estimation, yielding to southern leg.
	20 Oct	South yield line not visible.	Under/ poor estimation, yielding to southern leg.
	22 Oct	South yield line not visible.	Under/ poor estimation, yielding to southern leg.

Table 7: Summary of the impact of view limitations on observations of yield behaviour.

In addition, the data capture used was reasonably conservative in the characterisation of cautious and give way to the right yields.

Comparative speeds

Speed is an important consideration for the case study conditions. Speed is difficult to measure from the video footage because of the different viewpoints and related parallax issues, and the deceleration/acceleration that occurs at roundabouts. However, some qualitative observations are made to provide some texture and context.

The overall range of travel speeds through the roundabout for bicycles seemed to be similar to the range exhibited by motor vehicles, with the slowest cyclists having a travel speed similar to heavy vehicles and the fastest cyclists having speeds comparable to general motor vehicle traffic – though not the fastest cars.

This impression was tested through a stop-watch comparison of a small sample of twenty through bicycle movements, which gave a time to negotiate the roundabout of under three seconds for the fastest cyclists and up to five or six seconds for more moderate cyclists. Cars also fell within this range. The slowest (right-turning) cyclist observed took twelve seconds to completely negotiate the roundabout – a little longer than the slowest motor vehicle, though this was probably related to the paucity of heavy vehicles undertaking right-turns.

The relatively similar speeds of cars and cyclists through the roundabout despite the higher speed of motor vehicles on straight street sections is related to roundabout design. Roundabouts slow vehicles by deflecting them from a straight-through path. But as bicycles are small and manoeuvrable, roundabout geometry does not cause appreciable deflection and if no other traffic is on the roundabout, a cyclist can traverse the roundabout at the same speed at which s/he approached it. This also results in speed profiles through the roundabout for cyclists being quite distinct from cars: drivers decelerate into and then accelerate out of a roundabout, while bicycles have a more constant speed through the roundabout. Also, while the speed ranges for cars and bicycles are more or less comparable, the mean speed of bicycles is reduced by unhurried cyclists, by faster cyclists having to slow for motor vehicles and by cyclists having to stop (e.g. to yield) and then start – or avoiding this by moderating their approach speed to suit.

Differences in acceleration between cyclists and cars are more obvious than differences in speed. For a cyclist, a stopped bicycle takes effort to accelerate back up to travel speed: it loses its dynamic balance and must be put back into balance before acceleration can occur (hence the use of track standing to enable a stopped cyclist to maintain dynamic balance). Since balance is part of stability, this is a safety as well as a speed/ convenience issue for cyclists. From one observation, stopping prior to entering the roundabout roughly doubled a fast cyclist’s travel time through the roundabout compared to a cyclist who didn’t have to stop. Many cyclists were observed minimising stopping behaviour by reducing speeds to allow forward movement to be maintained, and accelerating close after a vehicle had passed. (This appeared very attractive as a manoeuvre, probably because it also places the cyclist into an area free of motor vehicles).

While quantitative data could not be obtained, bicycles and cars appear to have lower speed/acceleration differentials in the after situation compared with the before situation. This was visible in the ‘imaginary elastic’ representing the hysteresis-like effect of a cyclist entering the roundabout and catching up to a preceding car, then falling behind as the car passes the apex of the curve and accelerates. This could be seen from the video via headway patterns between vehicles, where three patterns are possible (and were evident) for a cyclist following a car through the roundabout:

- Little or no change in headway
  Cyclist speed and acceleration match car speed and acceleration into, through and out of the roundabout.
  In the before situation, this pattern was observed only for the fastest cyclists and for the minority of cars that did not accelerate more strongly out of the roundabout than cyclists. This pattern became more common in the after situation, indicating car speeds and acceleration had moderated.
- Reducing headway
  A cyclist entering the roundabout after a car travels faster through or accelerates more strongly out of the roundabout.
  The pattern was uncommon in both the before or after situations, except with right-turning cars. This pattern was more commonly seen as part of a decreasing/ increasing headway pattern, where the fastest cyclists catch up to a preceding car but the latter pulls away as it accelerates out of the roundabout. The pattern seemed less common in the after situation, indicating that speeds of the fastest cyclists and/or car acceleration out of the roundabout had moderated.
- Increasing headway
  This was the most common pattern in the before situation, reflecting faster car acceleration out of the roundabout. It became less common in the after situation.

Where a car followed a bicycle through the roundabout, the car was able to match cyclist speed and acceleration in most cases. The only pattern of note is one of reducing headway/ starting to tailgate on the exit side of the roundabout, where cars accelerate more strongly out of the roundabout. This was less common in the after situation, again pointing to reductions in the speed and acceleration of cars.

Cautious yield behaviour

This describes object drivers slowing and/or stopping despite the vehicle approaching/ in the roundabout having a travel path that would not bring it in conflict with the object vehicle, as shown in Figure 7.

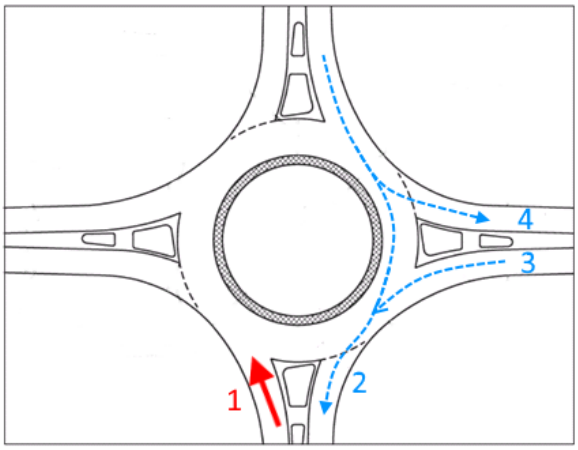


Figure 7: Cautious behaviour patterns - vehicles whose travel paths would not cross that of an object driver located (and yielding) at position 1.

Exposure data points to likely under-recording of cautious yielding events. The rate cautious yield behaviour is about 3-4% of encounters in the before situation, and 1% to bicycles. This appears to rise to 6% in the after situation. In the after situation, the cautious yield rate to bicycles was 1-2%, which cannot be interpreted as a noticeable change.

Prior yields

Cautious yields could be expected to occur more frequently once an object vehicle has already yielded, in line with Silvano et al.'s (2014) results regarding speed.

Fewer than half of all cautious yields to motor vehicles occurred after the object vehicle had previously yielded to another vehicle. (Rates regarding cyclists are too low to comment on.) Having stopped to previously yield may well be a driver of cautious yield behaviour, but does not appear to be the greatest determining factor.

Give way to the right

This describes object drivers slowing and stopping when they could arguably enter the roundabout before the subject vehicle (to their right) enters the roundabout. These object drivers are therefore yielding when not legally required and appear to be following a 'give way to the right' rule.

This behaviour was difficult to capture – or discriminate from other yielding behaviour – and data for bicycles was inconsequential. Nonetheless, there are indications of drivers applying this rule, at a rate of about 2% of all encounters in the before situation increasing to 4% in the after situation.

Previous yielding behaviour does not appear to be a major driver of give way to the right behaviour.

Neutral approach

In this behaviour, when a subject vehicle to the object driver's right is approaching, entering or in the roundabout, the object driver does not adjust speed or appear to react to the subject vehicle in any way.

For motor vehicles, rates of neutral yields appear to be similar in before and after situations – around 5-6% of all encounters ±0.5%. The coding for this pattern includes the situation where an object car enters the roundabout before a right-turning car completely clears the area in front of it.

Rates for bicycle subject vehicles were much higher than for cars, at 20-30% in the before situation and 30-40+% in the after situation (reflecting all day versus PM peak results). This mainly reflects the tendency of cyclists to enter closely after circulating vehicles, including as impeded sightline events examined in chapter 5 of the thesis; and right-turn vehicles as above.

Assertive approach

In this situation, the object driver approaches at a relatively high speed and/or actively accelerates in order to claim the circulating roadway before the subject vehicle. This approach is also captured through a rating in the conflict potential field, as:

- 3: The object vehicle enters after the subject vehicle (cuts in), one or other vehicle must slow down but can do so safely/easily.
- 4: One or other vehicle must stop suddenly to avoid a collision (within the roundabout).

As might be expected, rates of assertive approach encounters are very, very small and no meaningful statistical comparisons can be made. What is striking, however, is the relative consistency of rates for the four situations of all day and PM peak, in before and after situations. Here, the rate for bicycles is 1.5-1.8% and the rate for motor vehicles 0.0-0.2%. The higher rate for subject bicycles is true both for object vehicle encounters, where the subject vehicle is acted upon by the object vehicle, and circulating vehicle encounters, where the subject vehicle acts upon the circulating vehicle.

The individual events represented by these conflict potential ratings are described and illustrated via screenshots contained in the Appendix, for encounters involving bicycles.

Stopping at entry

Rates of stopping-at-entry are somewhere between twice and three times the rate of cautious yields (and without the same problems associated with the cautious yield data). The behaviour also displays less variance by subject vehicle type: rates are comparable for subject bicycles and subject motor vehicles, i.e. car drivers stop at similar rates for both bicycles and other cars: 5-6% in the all day before situation increasing to 10-11% in the after; and 10-12% in the PM peak before situation increasing to about 14% in the after situation.

This is reasonably intuitive in terms of lower approach speeds resulting from the geometric changes translating into a greater willingness on the part of object drivers to stop as part of yielding behaviour.

In all cases, the greatest contributor to stopped-at-entry events was yielding after mandatory yielding to cars. This contribution slightly decreased in the after situation as the proportion of yields in other cases increased, but this pattern was one of the two main yield types driving increases in stopped-at-entry events. The behaviour remained higher for subject motor vehicles than subject bicycles. This can be considered as a pointer to drivers being more willing to stop once they have already yielded, but it should also be noted that this could reflect platoon behaviour: upstream traffic signals on that local road network lead to vehicles arriving not only as a random flow of individual units but, in the PM peak in particular, as a series of convoys. An object vehicle that slows or stops to yield to a single car will frequently need to wait for several cars to pass before it can continue.

The contribution of no-prior-yield events increased quite markedly in the after situation, being the other (and second greatest) driver of increases in stopping-at-entry events. Given a lack of known network disturbance that would change platooning or convoy behaviour on the network, this can be considered to be a result of the geometric changes that occurred at the roundabout. The proportion of no-prior-yield events is higher when the subject vehicle is a motor vehicle compared to a bicycle, however the difference in behaviour between the two vehicle types reduced in the after situation, and most noticeably during the PM peak. In other words, the rate at which cars stopped for bicycles without first yielding to another vehicle increased more than the rate at which cars stopped for cars under the same conditions, and far more so in the pressure of PM peak hour traffic flows than all day.

When broken down into the location where object vehicles tended to stop, the numbers for bicycle data and the before motor vehicle data are too low to be statistically reliable – especially given the degree of accuracy involved in the manual assessment.

Clearance distance

The clearance distance is:

- the location of an object vehicle compared to its yield line
- at the point that the subject vehicle passes (clears) the object vehicle

such that no collision would occur if the latter moved forward.

In terms of data quantity, clearance rates are more similar to exposure data than the yield data examined above. From the before to the after situation, the number of events leading to numbers of clearance distances being recorded increasing in both all day and PM peak periods and for both motor vehicles and bicycles. This is summarised in Table 8.

	Bicycle subject	Motor vehicle subject
All day, before	21.9%	11.9%
All day, after	32.3%	18.6%
PM peak, before	31.6%	19.1%
PM peak, after	33.7%	24.8%

Table 8: Clearance records.

As with the exposure data, this points to more encounters occurring in the after situation compared to the before. The number of records for bicycles is relatively high compared to motor vehicles – about 10% higher in each case – reinforcing the exposure result of cyclists having more encounters in roundabouts than motor vehicles. Other than this, there are few other strong and consistent patterns revealed.

Stopping distance

In addition to object vehicles that had stopped when the subject vehicle entered the roundabout are object vehicles that were moving but later stopped. A stopping distance was recorded for these encounters and these stopping distances are examined in this section.

Rates for stopping distance events (which capture vehicles stopping as part of a yield where the object vehicle is located back from the yield line) are higher than rates for stopped-at-entry events (where object vehicles stop before the subject vehicle enters the roundabout). For bicycle subject vehicles and before data, PM period data makes up most of the daily data – some 80% in the case of the stopping distance record. Differences in daily and PM period data are therefore likely to reflect the limitations of the daily data representing only a single day rather than differences in traffic flows, at least for this data. Results are summarised in Table 9.

	Bicycle subject	Motor vehicle subject
All day, before	15%	10%
All day, after	17%	13%
PM peak, before	18%	13%
PM peak, after	17%	15%

Table 9: Stopping rates.

Stopping rates increased slightly for subject motor vehicles in the after situation, with some indications of a similar increase for subject bicycles in the daily data but not the PM peak data. Increases in most rates for total stopping clearances from before to after conditions indicates that this behaviour is complementary to stopped-at-entry behaviour rather than one behaviour replacing the other.

Object vehicles are more likely to stop as part of yielding for subject bicycles than for subject motor vehicles, though there is some indication of a slight reduction in this difference in the after situation.

Changes to roundabout geometry appear to have encouraged object drivers to stop further from the yield line when yielding to motor vehicles.

4. References

Chin H and Quek S (1997), Measurement of Traffic Conflicts. *Safety Science*, Volume 26, Number 3, pp169-185, 1997.

Cumming B (2012), A bicycle friendly roundabout: designing to direct cyclists to ride where drivers look. *4th Australian Cycling Conference*, Bonham J. and Lumb P. (eds.), pub. Australian Cycling Conference Inc., Adelaide.

Gårder P (1985), Theory for strong validation, application of Swedish results. *Proceedings from Evaluation 85: International Meeting on the Evaluation of Local Traffic Safety Measures*. Paris, France: Organisation National de Securite Routiere, 1985.

Hauer E (1978), Design Considerations of Conflict Survey. *Transportation Research Record*, Transportation Research Board, Issue 667, pp57-66, 1978.

Hitzemann M (2003), Reconstruction of low speed rear-end collisions – Technical means of assessing cervical spine injuries. Republished article, *Pain Research and Management*, Volume 8, Number 1, pp28-29.

Retting R, Ferguson S and McCartt A (2003), A Review of Evidence-Based Traffic Engineering Measures Designed to Reduce Pedestrian–Motor Vehicle Crashes. *American Journal of Public Health*, Volume 93, Issue 9, September 2003, pp1456-1463.

Rodergerdts L, Blogg M, Wemple E, Myers E, Kyte M, Dixon M, List G, Flannery A, Troutbeck R, Brilon W, Wu N, Persaud B, Lyon C, Harkey D and Carter D (2007), *Roundabouts in the United States.* NCHRP Report 572, National Cooperative Highway Research Program, Transportation Research Board, Washington DC, 2007.

Silvano A, Ma X and Koutsopoulos H (2014), A Hierarchical Modelling Framework for Vehicle-bicycle Interactions at Roundabouts. *Proceedings, International Cycling Safety Conference 2014,* 18-19 November 2014, Göteborg, Sweden.

Turner S, Roozenburg A and Smith A (2009), *Roundabout crash prediction models.* NZ Transport Agency Research Report 386, 102pp.

Turner S, Wood G and Roozenburg A (undated), *Accident Prediction Models for Roundabouts.* Beca Infrastructure Ltd technical paper, 14pp.

Van der Horst A (1990), *A Time-Based Analysis of Road User Behaviour in Normal and Critical Encounters.* TNO Institute for Perception, Delft, The Netherlands.

Zhang B and Ma Z (2015), Revolutionise Roundabout Design on Bicycle Routes. *AITPM National Conference*, Brisbane Australia 2015.

5. Appendix: Type 3 and 4 traffic encounters involving bicycles

Conflict rating 3

7 May, 5:08pm (before): A right-turning subject cyclist clearly indicates on entering the roundabout but is shielded from the object driver by a through car and needs to drop his arm to use the brakes. The object driver enters in front of the rider. Rather than pedal to accelerate out of the roundabout, as a cyclist commonly would, the rider coasts to give the car time to clear.




12 May, 9:55am (before): A subject cyclist is shielded by a circulating car and the object car enters across the cyclist's path of travel. The cyclist moderates speed to suit (again, in the form of not accelerating out of the roundabout).


12 May, 3:14pm (before): Having yielded to a circulating car, an object driver enters the roundabout slightly after a subject cyclist crosses the yield line. The driver appears to slow in case a car entering on the driver's left fails to yield, but in doing so obstructs the cyclist, who slows to avoid a (fairly low-speed) collision. The car following the cyclist also slows to suit.

12 May, 5:19pm (before): A left-turning driver judges that a subject cyclist will be held up by a circulating car and enters the roundabout; OR the driver's attention is directed at the circulating vehicle and suffers an impeded sightline to the cyclist; AND/OR the driver has a very poor sense of relative speeds. In any case, the vehicle enters after and in front of the cyclist, who is travelling much faster than the turning vehicle and must slow to avoid a collision.

15 May, 5:36pm (before): There is no obvious contributory factor to why the object vehicle fails to yield to a subject cyclist, except for low-light conditions. Although the cyclist has a front light, these tend to be very directional and may not have been visible to the object vehicle. The car following the subject bicycle was required to yield to a car entering on the south leg of the roundabout and that the object driver did not need to yield to this car.

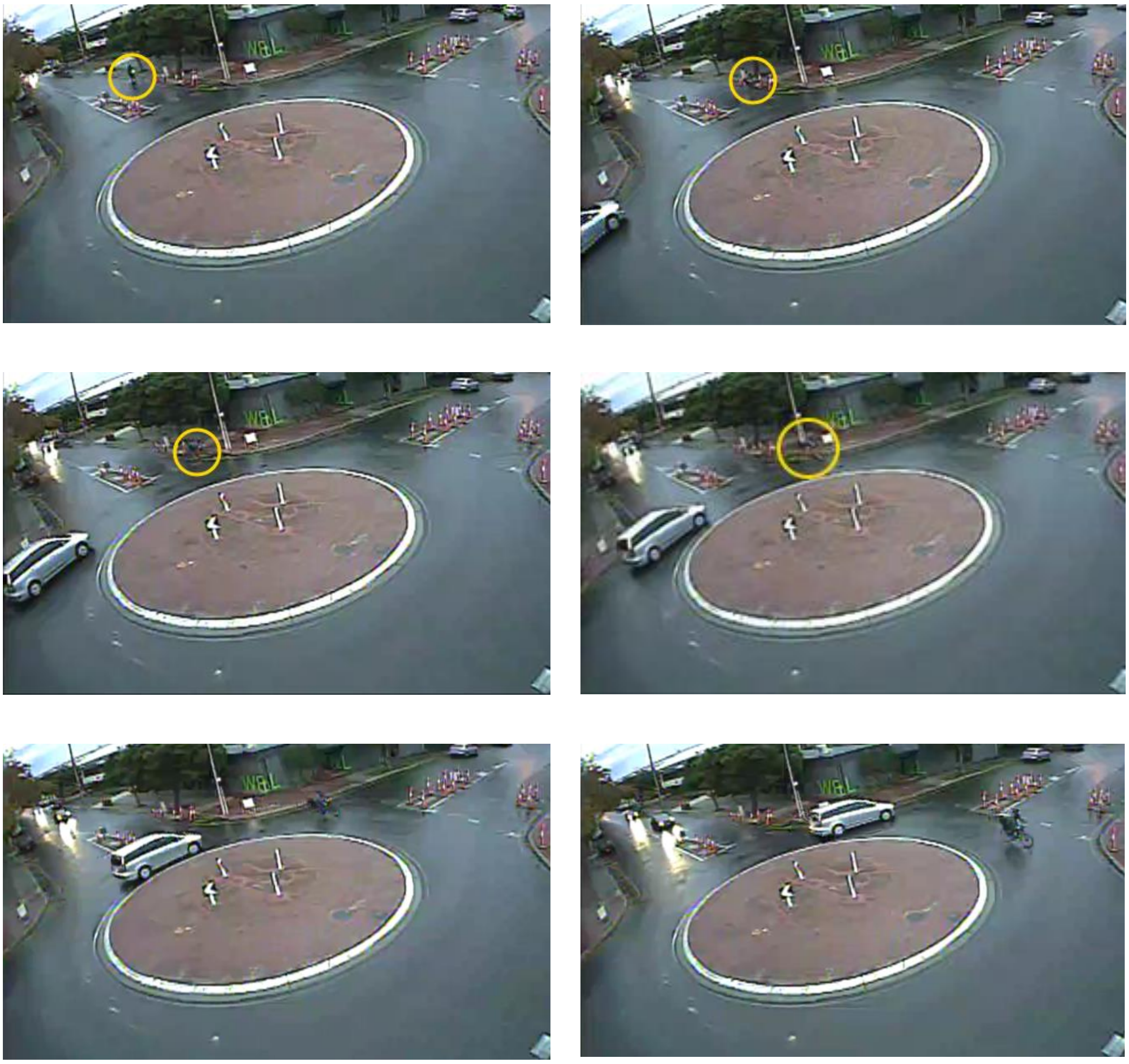
A particular feature of this encounter is that the driver does not appear to react to the bicycle at all. If so, had the cyclist – who was observing the object car – been more poorly positioned, the object car would have collided with the bicycle. Alternatively, the driver may have seen the bicycle but judged that it was safe to not change trajectory or speed, in which case the driver was putting significant faith in the ability of the rider to maintain through speed.

18 May, 5:15pm (before): There is no obvious contributory factor to why the subject cyclist fails to yield to a car that enters from the rider's right and is well into the roundabout before the cyclist. (In this case, the cyclist is both a subject vehicle on the west leg and an object vehicle for a subject car on the south leg; the encounter appears twice in the data.) The driver slowed for the cyclist in response.

A number of factors are not easily discerned from screen shots.

- The cyclist is leaning into the turn as s/he crosses the yield line, indicating that the cyclist has already committed to entering the roundabout. The rider may have judged that there was inadequate braking distance in wet conditions; 'steering out of trouble' is a strategy favoured by cyclists, although there is no indication that the rider is attempting to do so.
- It is unclear whether or not the car has lit headlights. No reflection from headlights would be visible at the given camera angle, unlike the two vehicles following the cyclist.

- It is possible that the car may be indicating a false left, for example because it had just turned out of a driveway.
- While the vehicle colouration appears bright on its upper surfaces, this is due to the reflection from a relatively bright sky and would be more obvious to a camera mounted above than to someone at ground level. In the absence of this, the car might have appeared to be a darker grey.
- The contrast conditions from the video cannot be considered to be equivalent to those experienced by a human on-site.
- Any back-lighting from the nearby Norwood Parade cannot be perceived from the video.



17 September, 8:30am (after): A vehicle entering on the east leg is indicating to turn right. However, the indicator light blinks off and is not seen to illuminate again after a point roughly aligned with the splitter island on the south leg. A subject cyclist entering on the west leg is unaware that the (now circulating) driver intends to turn right and enters the roundabout, inadvertently cutting in front of the circulating vehicle. The driver slows for the cyclist.

Indicator light on

Indicator light off, and stays off.

17 September, 3:10pm (after): A left-turning object driver initially misses or misjudges the speed of a subject cyclist, possibly exacerbated by the contrast conditions caused by dappled light. The driver enters the roundabout just after the bicycle, stops, the cyclist waves in acknowledgement and passes in front of the car, then the car completes its turn. Although the car intrudes some distance into the circulating roadway, the cyclist does not appear to need to adjust her/his line of travel.

Conflict rating 4

The only three recorded code 4 events recorded all occurred in the after situation and involved subject bicycles and object cars – the classic crash pattern that is the focus of this case study. An additional code 4 encounter was observed also in the after situation, involving a cyclist entering on the (unexamined) northern leg, initially as the object vehicle in a three-vehicle encounter.

19 September, 4:01pm (after): A car is following another car through the roundabout, both travelling at quite high speeds. There is no obvious reason why the second driver fails to notice the subject cyclist enter, however the driver does not markedly decelerate close to the roundabout entry, instead following a very similar travel pattern to the preceding car. It is possible that the driver is indeed following the preceding car since both vehicles turn right, but this is also a common movement at this location.

The cyclist is close to the splitter island when he realises that the object driver is not going to yield. This is roughly when the object driver notices the cyclist and brakes heavily. The cyclist swerves to avoid the collision at the same time that the car draws to a halt.






A particular feature of this encounter is its similarity to the code 3 encounter that occurred on 15 May at 5:36pm, except that in this case the object vehicle was on a closer collision course with the subject cyclist and the driver reacted to the cyclist's presence.

22 October, 5:03pm (after; external to the data record): A cyclist is approaching the roundabout at a rapid pace on the northern leg, as is a car to the cyclist's right (western leg). This makes the bicycle the object vehicle to the subject car. It is not observable whether the car is indicating, but the cyclist is acting as this is the expectation. However, the car doesn't slow markedly as it enters the throat of the western approach lane. The cyclist, who is then at the +1 point (pedestrian kerb ramp location), interprets the car's high approach speed as a signal that it may not turn left after all and brakes heavily, coming almost to a stop at the yield line. In fact, the car does turn left. The cyclist has retained dynamic balance and continues into the roundabout.

When the cyclist is at about the -1 point from the yield line (i.e. a car length into the roundabout), a car enters from the eastern leg. It brakes heavily and has intruded over the yield line by most of a car length when it draws to a halt, about a car length in front of the cyclist. The cyclist adjusts his travel line and passes in front of this second car.

While these two events are arguably unrelated, it is also possible that the driver entering on the eastern leg observed the cyclist's abrupt braking and expected the cyclist to stop completely. (From the video footage, this appears likely as the cyclist sits up, puts a foot out and loses his line). The driver therefore judges that s/he can safely negotiate the roundabout before the cyclist starts off again. When the cyclist instead continues, the driver takes time to react and must brake heavily in order to give way.

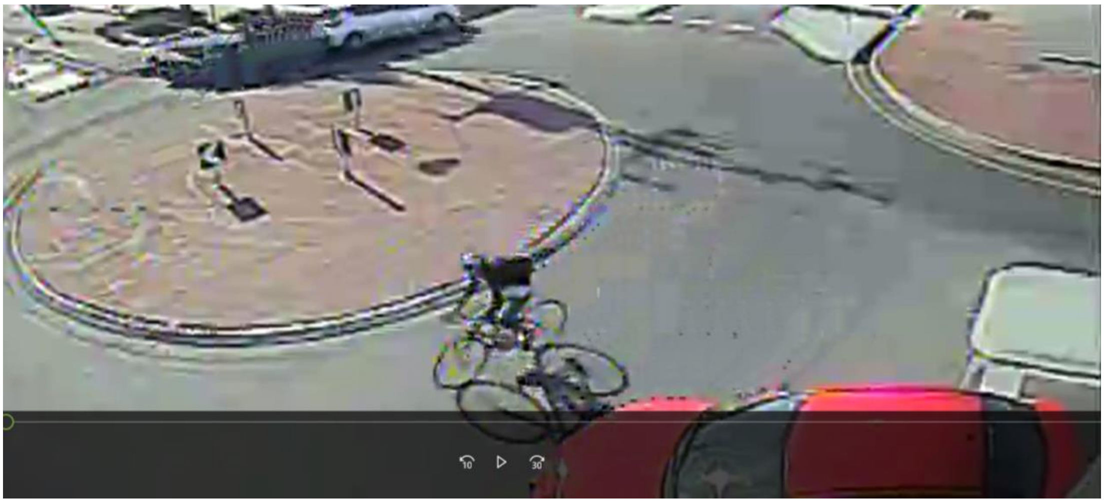
Subject car and object bicycle, both travelling quite rapidly.

Car does not slow markedly as it reaches the throat of the roundabout.

Car is still moving rapidly as it enters the roundabout; cyclist reacts by braking heavily.

Cyclist at a virtual stop, sitting up, pulling foot, losing line. Car turns left.

Cyclist has maintained dynamic balance, does not come to a complete halt before continuing into the roundabout.



22 October, 5:06pm (after): At first glance, this appears to be the case of a subject cyclist not noticing that a vehicle entering from the eastern leg has its indicator on and is turning right. The cyclist fails to yield and in response the circulating car stops suddenly on the roadway. This might be caused by the rider being focused on the stream of entering vehicles, for example.

However, it is notable that the rider stops pedalling on the approach to the roundabout – unusual for a cyclist intending to continue into the roundabout without yielding, although this could be related to a heavy flow of traffic at the time or the cyclist's intention to turn right – and brakes quite markedly as the circulating car approaches. It is possible that the cyclist had intended to yield or adopt a speed that would allow the circulating car to pass ahead, but the circulating driver's reaction to the cyclist apparently failing to yield changed the situation.

Cyclist coasting, car indicating.

Cyclist coasting, car indicating.

Coasting, and starting to lean into the turn.

Both cyclist and car brake.

Both car and bicycle stop

Driver waves cyclist through?

22 October, 5:11pm (after): A subject cyclist approaching the intersection observes a vehicle entering the roundabout to her/his right. The rider stops pedalling and attempts to retain dynamic balance while coasting as the vehicle passes but is unable to and must brake fairly heavily.

The cyclist checks to confirm whether an object motorcycle has stopped and will yield to the cyclist or take the opportunity to proceed through the roundabout. The motorcyclist has stopped. The cyclist rebalances and mounts as another vehicle enters the roundabout to the cyclist's right. As the cyclist starts to move off, he checks right, notices the circulating vehicle and stops. The circulating vehicle slows until it has passed the cyclist.

Cyclist fails to maintain momentum, forced to stop.

Preparing to re-start, looking at motorcyclist.

Cyclist still looking left.

Cyclist starts off, checks right, and stops.

Driver slows, proceeds with caution. The motorcyclist takes the opportunity to start off.

The cyclist again mounts as the car passes and all road users continue on their way.

Discussion

What is perhaps most noticeable is that in each of these code 4 cases the vehicle that initially failed to yield did subsequently yield, even if that yield occurred within the roundabout. Some cautious yields of the other vehicle also occurred. This contrasts to the before situation for the code 3 yields, where none of the vehicles that initially failed to yield later did so.

This is not necessarily surprising: in the code 3 situations, vehicles could and did pass safely through the roundabout without requiring heavy braking and/or changing travel paths, so the need for initially non-yielding vehicles to later yield was lower than in the code 4 situations.

It is notable, however, that the after code 3 involving a driver failing to yield mirrored two before code 3 situations, with the difference that in the after situation the driver subsequently yielded. (The situation is ambiguous for the other after code 3 in that when the cyclist became aware of the yield requirement, he was already in front of the car and not in a position to yield.)

Encounters above code 4 could have been recorded and would represent levels of actual collision if any had been observed. The lack of observed crash events is compatible with the character of crashes as rare, stochastic events.

The reducing frequency of encounters as conflict potential increases is also in keeping with concepts from Traffic Conflict Technique assuming connections between ‘severity’ and ‘proximity’ of non-crash events to representing crash risk. However, one implication of the difference between code 3 and 4 encounters is that the observable braking in the code 4 cases may in fact be indicative of a lower degree of collision potential than in the code 3 cases. This is in line with arguments outlined in Chin and Quek (1997) in their discussion about problems with conflict definition in Traffic Conflicts Technique: namely, that precautionary and evasive actions are difficult to differentiate between; and that the logical link of evasive action and conflicts with crashes is questionable, as many accidents and near misses occur because drivers have failed to take any action and the absence of evasive actions in critical situations maybe more problematic than their presence. Hence the conflicts seen and recorded as part of Traffic Conflicts Technique-based studies are not necessarily indicative of the underlying patterns related to the process model as it applies to crashes.

Unfortunately, the few cases captured in this study are insufficient to confirm that a difference in yielding behaviour is related to the before/ after geometry change. It can be conjectured that by directing an entering vehicle more tangentially, the before geometry could give the object driver the impression that rather than stopping, continuing along the set path of travel would be akin to manoeuvring out of the conflict zone – a ‘too far gone, better get out of the way’ decision base that does not reflect fact (continuing caused greater collision potential than stopping would have in the code 3 examples). In the radial case, continuing would more obviously risk a collision and would not be a viable option. Approach speeds are also likely to be relevant, and disaggregating this from other effects is very difficult.

Appendix E: Impeded sightlines – geometric analysis

The following scenarios are designed to indicate likely motorist sight distances for tangential and radial roundabouts in circumstances where a circulating car shields the view of a cyclist for a motorist approaching the roundabout.

Under the terminology adopted for the roundabout case study, the terms used would be ‘circulating vehicle’, ‘subject bicycle’ and ‘object vehicle’, however ‘circulating/shielding car’, ‘bicycle’ and ‘approaching car’ are considered more intuitive and will be used in this analysis.

The scenarios incorporate a number of assumptions regarding relative travel speeds/ distances and tracking, and are intended as a thought exercise rather than as a representation of real-life interactions. That is, these are intended to generate an appreciation for the effects of relative speeds and angles in the before versus under cases for different permutations and ranges of car and bicycle positions, rather than replicating actual conditions. Such an appreciation enables the implications of relative angles to be understood rather than assuming particular behaviour in terms of tracking, speed, etc.

The greatest proviso in these scenarios is that the travel speeds of vehicles in the before and after situations have been assumed to be the same, in order to produce conditions that can be compared on a geometric basis. However, the after geometry is designed to produce slower vehicle travel. The quantum of likely speed reduction in the after situation is unknown as design speeds do not necessarily translate to actual speeds – which are difficult to measure due to deceleration giving variable speeds and poor results for methods reliant on distance/ time. Zhang and Ma (2015a) put the 85th percentile speed for the tangential (before) design at 35km/h but the after speed is not known to have been recorded.

In practice, approaching drivers will tend to wait until a circulating car’s motion confirms it is not a hazard before they proceed (i.e. that the lack of a visible indicator signal isn’t a failure of the circulating driver to indicate a right turn). A slower circulating car in the after situation would give a cyclist more time to travel through and exit visual shielding than the before case i.e. improve safety more than the analysis indicates.

While the roundabout geometries are to scale, the cars shown are indicative only. View angles shown are the portion of the approaching driver’s field of vision that are potentially affected by shielding. Shading indicates full shielding and dot-dash lines indicate the extent of partial shielding. Narrower view angles indicate less likelihood of being affected.

Impeded sightlines

Four approaching vehicle positions are considered in this analysis:

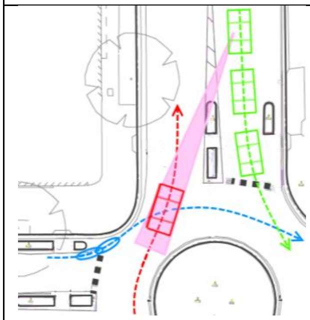
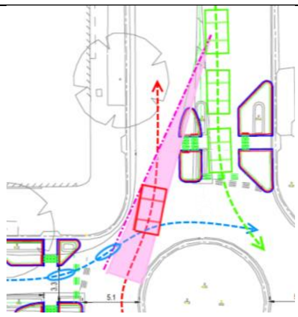
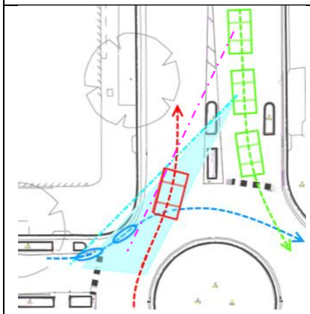
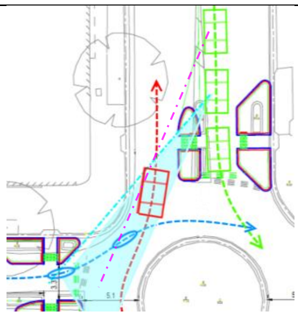
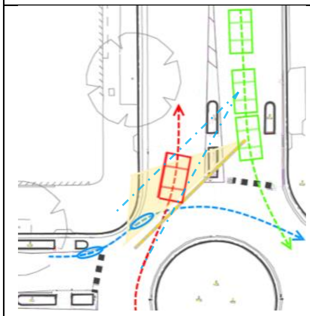
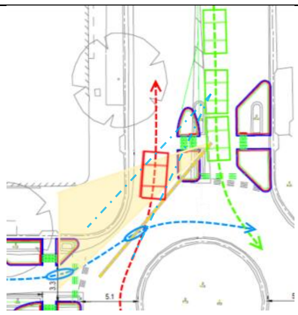
- Far – about 20m from the yield line – furthest north (top of page); view angle in pink
- Mid – about 10m from the yield line – half-way between the yield line and a far approach car; view angle in light blue
- Near – about half a car length (2-3m) from the yield line – view angle in yellow
- Yield line – view angle in yellow.

Approaching car positions are shown in green. A car roofed section has been shown to enable the driver's viewing position to be better defined.

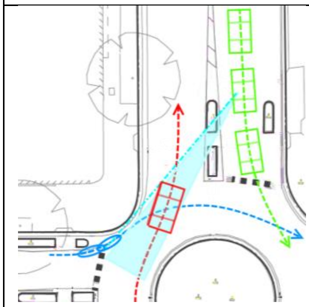
When the circulating vehicle potentially obstructing sightlines between a s bicycle and approaching car, it is referred to as a shielding vehicle and shown in red. A roofed section has been shown for these cars to illustrate the potential for sightlines to be entirely obscured compared to where sightlines over bonnet and boot sections could allow part of the cyclist to be visible. The presence of sightlines in these partial shielding situations depends on car design (front/ rear curvature, hatchback, 'whale tail', van, vehicle height, etc) and cyclist height and posture.

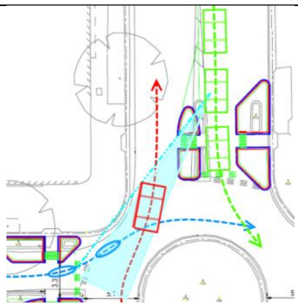
Subject cyclists are shown as a blue oval. The closest location to the shielding car is the minimum headway position; it is assumed a bicycle reaches this position having entered the roundabout at an earlier point based on judgement. In the before situation, cyclists entering closely after a potentially shielding vehicle were observed to track closely to the kerb at entry, and this is replicated in the tracking chosen.

Paths of travel are shown as dashed lines and view angles using shading (full shielding) and/or dot-dash lines (extent of partial shielding).

<table>
<tr><th>Before geometry</th><th>After geometry</th><th>Comments</th></tr>
<tr><td colspan="3"><u>Scenario 1</u>: a circulating car potentially shielding a bicycle; far approaching vehicle.
1.1: Initial situation.</td></tr>
<tr><td></td><td></td><td>Shielding potential is minor and quite similar between the before and after cases. Due to angles, the full and partial shielding situations are basically the same.
The minimum headway point for the before case is close to the yield line.
The radial geometry gives after cyclists more headway, encouraging earlier entry. An early-entering cyclist could start to enter an area of shielding.</td></tr>
<tr><td colspan="3">1.2: The shielding car travels half a car length further into the roundabout, the approach car is travelling faster and reaches the mid position in the same time. A car following the approach car would now be at the far position.</td></tr>
<tr><td></td><td></td><td>A before cyclist would still not be shielded from a far car, but an early-entering after cyclist could be almost fully shielded.
For the mid car, both before and after cyclists are shielded from the driver’s view, the before cyclist from a short distance into the roundabout and the after cyclist anywhere from the yield line to well into the roundabout.
View angles could be interpolated for slower approach car speeds.</td></tr>
<tr><td colspan="3">1.3: The shielding car travels another half a car length; the approaching car is assumed to still be travelling faster but decelerating. If the shielding car’s travel is faster compared to the approach vehicle than assumed, shielding effects would reduce at a faster rate.</td></tr>
<tr><td></td><td></td><td>For mid cars, the before bicycle would now be fully shielded. After bicycles would also be shielded, but an early-entering after cyclist would be emerging from full shielding.
For near cars, the before bicycle is at the edge of the full shielding, depending on the shape of the rear of the shielding car. The after bicycle is clear of full shielding from the yield line onwards.
If the shielding or approaching cars were half a car length further forward, no shielding would exist in either the before or after case.</td></tr>
</table>

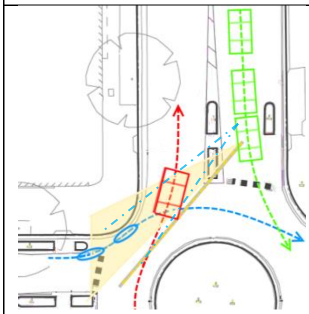
<u>Scenario 2</u>: the same circulating car shielding a bicycle to a mid approaching car.
2.1: Initial situation.

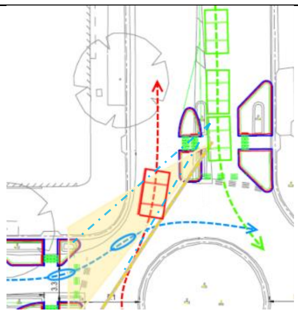




Again, actual shielding conditions are similar in the before and after cases but the straighter after geometry gives greater headway, allowing the after bicycle to be further into the roundabout at a similar shielding car position.
While the approaching driver might see the bicycle at the yield line, s/he would probably not be able to tell whether the bicycle enters the roundabout or stops at the yield line in either before or after cases.

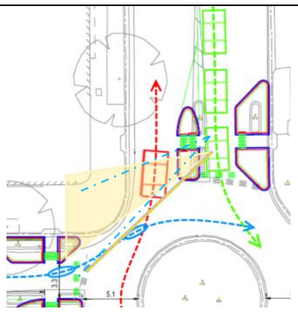
2.2 The shielding car travels half a car length; the approaching car is travelling faster but decelerating and travels a car length. View angles are also given for the situation if the approaching car only travelled half a car length (i.e. has the same speed as the shielding car).



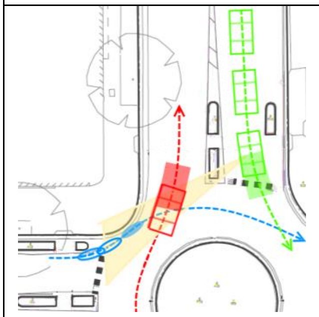
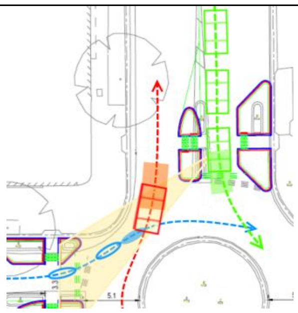
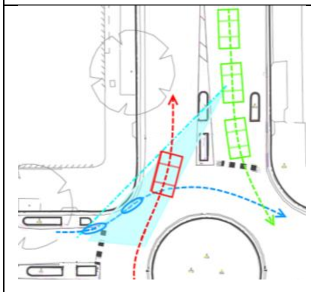
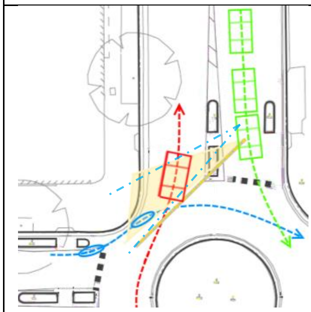
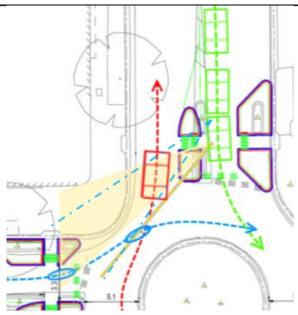
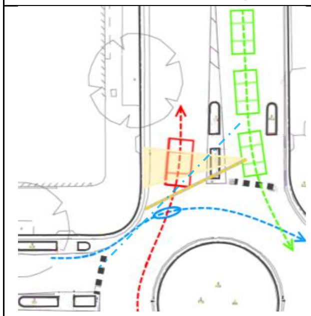
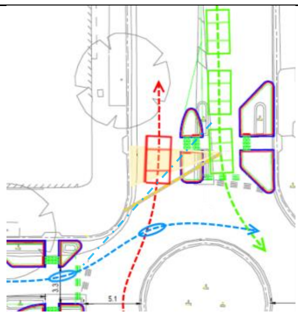


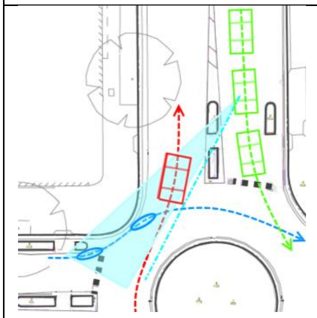
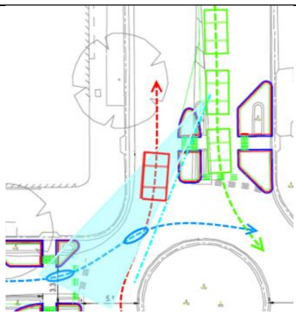
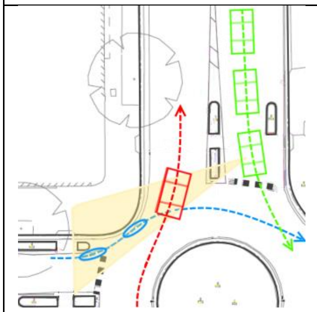
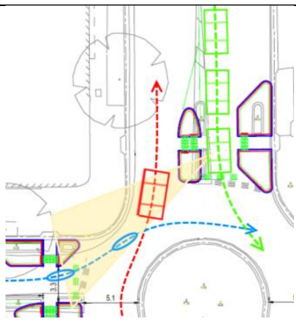
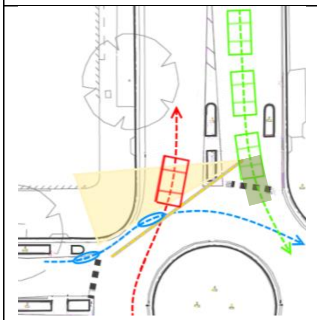
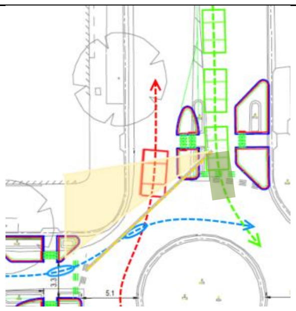
The before bicycle is still entering the roundabout, and fully shielded. The after bicycle is between the yield line and minimum headway point – and is close to emerging from full shielding.
Blue view lines indicate that if the approaching car were travelling at the same speed as the shielding car, bicycles would be fully shielded in both the before and after cases.

2.3 Both shielding and approaching cars travel half a car length further.



The before bicycle emerges from full shielding but partial shielding exists between the yield line and minimum headway location. The after bicycle is well clear of full shielding from the yield line onwards, with partial shielding between the yield line and half-way to the shielding car's travel path.
If the approach car started a half a car length further back (i.e. as per 2.2, blue view angles), before bicycles would be fully shielded but after bicycles only fully shielded near the yield line, being partially shielded thereafter.

<table>
<tr><td colspan="3">Scenario 3: the same circulating car potentially shields a bicycle to an approaching car at the yield line. Shading indicates the situation half a car length later, for shielding and entering cars; or a bicycle length later, assuming this is minimum headway situation is feasible.</td></tr>
<tr><td></td><td></td><td>Both before and after bicycles are fully shielded from an approaching car at the yield line. If either the shielding or approaching car were half a car length further forward, no shielding would occur. The approaching car should be able to enter and negotiate the roundabout before even an early-entering cyclist reaches a point of potential conflict, however a cyclist might need to adjust speed in the after situation. A pause before the car enters could also change the situation.</td></tr>
<tr><td colspan="3">Scenario 4: the circulating car is half a car length further along its path; potential shielding to a mid car.
4.1: Initial situation.</td></tr>
<tr><td></td><td></td><td>Both before and after cyclists are fully shielded from as far back as the yield line. Again, the after cyclist has greater headway and can enter earlier.</td></tr>
<tr><td colspan="3">4.2 The shielding car travels half a car length; the approaching car is travelling faster but decelerating and travels a car length.</td></tr>
<tr><td></td><td></td><td>The before bicycle is fully shielded, with additional partial shielding.
The after bicycle is clear of full shielding except at the yield line. Partial shielding could affect cyclists to a few bicycle lengths beyond the yield line.
Blue view lines show that if the approach car only travelled half a car length, the before bicycle would be fully shielded while the early-entering after bicycle would be emerging from partial shielding.</td></tr>
<tr><td colspan="3">4.3 Both shielding and approaching cars travel half a car length.</td></tr>
<tr><td></td><td></td><td>For a near car, full shielding would occur at the bicycle's yield line; in any other circumstance, both before and after bicycles would be fully clear of shielding – the after bicycle more so than the before bicycle.</td></tr>
</table>

<table>
<tr><td colspan="3">Scenario 5: shielding car is along its travel path when the cyclist enters the roundabout.
5.1: Initial situation, bicycle at the yield line. Shielding to a mid approach car.</td></tr>
<tr><td></td><td></td><td>Both before and after bicycles are fully shielded. With a greater headway, the after bicycle could have entered earlier and would be emerging from full shielding, with any other shielding relating to the shape of the shielding car.</td></tr>
<tr><td colspan="3">5.2: Same scenario, initial situation, bicycle at the yield line. Shielding to the approaching car at the yield line.</td></tr>
<tr><td></td><td></td><td>As in the above situation, both before and after bicycles would be shielded from an approach driver at the yield line.
In the after situation, an earlier-entering cyclist would be just emerging from full shielding, with any other shielding relating to the shape of the shielding car.</td></tr>
<tr><td colspan="3">5.3: Shielding car travels half a car length; approaching car travels about a car length.</td></tr>
<tr><td></td><td></td><td>As per 2.3, with both before and after bicycles clear of full shielding. (If the approaching car had only travelled half a car length, it would be as per 4.2.) If the shielding car had travelled further, even partial shielding would be eliminated in both and after cases.
If the yield line car in 5.2 is travelling at the same speed or more slowly than the shielding car (e.g. half a car length), there is no shielding to before or after cyclists.
The approaching car (shown as a shaded rectangle) is sufficiently far forward that it probably wouldn’t come into conflict with either of these cyclists, depending on relative speeds.</td></tr>
</table>