25 Years of road safety: The journey from thinking humans to systems-thinking

Rich C. McIlroy[1]*, Victoria A. Banks[1], Katie J. Parnell[1]

1. Transportation Research Group, Faculty of Engineering and the Environment, Boldrewood Campus, University of Southampton, Southampton, SO16 7QF, UK

* Corresponding author: r.mcilroy@soton.ac.uk

Abstract

Research into road safety has evolved from individual level component analysis to a much broader, systemic approach that acknowledges the fusion of 'socio' and 'technical' system elements. Over the past four decades, Professor Neville Stanton has contributed to over 179 journal articles, book chapters and conference papers in the field of road safety. The journey from 'thinking humans' to 'systems thinking' is demonstrated in this paper through the novel application of the Risk Management Framework (RMF) to the categorisation of research activities. A systematic review of Neville's contributions to the field of road safety demonstrates that over the years, his research activities have evolved from investigating single technological or human performance aspects in isolation (e.g., in-vehicle information design and workload) through to the holistic analysis of much broader systems (e.g., investigating road safety as a whole). Importantly, this evolution goes hand in hand with a change in the focus and emphasis of recommendations for improvements to safety. Going forward, Neville has helped pave the way for fundamental changes and improvements to be made to road safety systems around the world.

Keywords: Human factors methods, Sociotechnical systems, Risk management framework

Cite as: McIlroy, R. C., Banks, V. A., & Parnell, K. J. (2022). 25 Years of road safety: The journey from thinking humans to systems-thinking. *Applied Ergonomics*, *98*, https://doi.org/10.1016/j.apergo.2021.103592.

Introduction

Road traffic collisions kill an estimated 1.35 million people every year, with a further 20-50 million more being injured (World Health Organisation; WHO, 2020). Globally, road traffic collisions are one of the top 10 leading causes of deaths; for those aged 15 to 29 years, it is the primary cause of death. People of a lower socioeconomic status account for the largest proportion of road traffic deaths and the most vulnerable road users are pedestrians, cyclists, and motorcyclists, representing over half of all road traffic deaths (WHO, 2020). The rate of death on the world's roads has remained relative to the size of the world's population, suggesting things are not getting significantly worse; however, the commitment to reach the UN's Sustainable Development Goal (target 3.6) of a 50% reduction in road traffic deaths by 2020 has been far from achieved. There continues to be a strong association between the risk of road traffic death and the income level of a country, with fatality rates being more than three times higher in low-income countries (27.5 deaths / 100,000 population) compared to high income countries (8.3 deaths / 100,000 population) (WHO, 2018). This imbalance is further highlighted when it is considered that low- and middle-income countries (LMICs) are home to 60% of the world's registered vehicles and 85% of the global population yet see 93% of the world road traffic fatalities (WHO, 2018).

At the national level in the UK, fatality numbers have not decreased since around 2010; approximately five people die every day on the nation's roads, with the vulnerable road user groups (pedestrians, cyclists, and motorcyclists) over-represented in those statistics (Department for Transport, 2020). Although the COVID-19 pandemic has influenced the way we travel, road safety remains a priority for councils across the country, and organisations around the world. It is a societal challenge that we have faced since before the advent of the motor vehicle (e.g., Harper, 1903), and is an issue that will not solve itself. Just as the road safety challenge is sizeable, so is the road safety research domain. Even in Applied Ergonomics alone, it has represented a strong focus, with a cursory search of its back catalogue returning 246 articles, going back to 1988, continuing the term "road safety". New approaches are, however, required.

The wider human factors and ergonomics domain has moved towards whole systems perspectives. This is not a wholly new paradigm, with Applied Ergonomics having provided a forum for researchers interested in applying the systems perspective to system safety and performance going back to 1990 (with 197 articles containing the term "sociotechnical"). That said, the sociotechnical systems paradigm has gained traction as a lens through which to view road safety only since around 2010 (e.g., Larsson et al. 2010). To summarise, systems thinking is a conceptual orientation that is concerned with the interrelationships that exist between system components to create a functioning whole. In order to understand road safety, we must also understand the intrinsic relationships between the 'socio' and 'technical' elements of the system. It is this sociotechnical paradigm that is emerging as the leading candidate for the paradigm shift that many have argued necessary if we are to improve global road safety (e.g., Salmon et al. 2012; McIlroy et al., 2019). Moreover, it is a paradigm that has attracted increasing attention from Neville Stanton as his career has progressed, as will be seen below. Looking to the broader academic landscape (beyond Neville's contribution to it), academics are becoming increasingly active in applying system thinking to the road safety challenge (e.g., Adanu et al. 2019; Gamero et al. 2018; Morgan, 2017; Naumann et al. 2020a). That said, research in this field to which Neville has contributed (either directly or indirectly, through his mentorship legacy) is generally easier to find than research to which he has not contributed.

Leaving for a moment these relatively recent developments in research, it is worth drawing attention to the fact that road safety is a field in which Neville has been active and influential for over 25 years, a period that has seen significant change in terms of technology, legislation, and research practice. This paper aims to provide an overview of that work, bringing together Neville's activities in the road safety research domain over these past 25 years to review the breadth and value of his contribution to the field. To finish, we provide a brief discussion on some potential next steps for road safety research and practice.

Method

To identify articles to include in this review, the Scopus author profile database tool was used; no other databases were searched. At the time of review (November 2020), the author profile page for Neville Stanton listed 535 documents. One of the current authors went through the 535 titles selecting those concerning road safety (full texts were accessed where there was ambiguity in the title). Given the importance of safety to all on-road research and practice, all articles related to road transport were considered for inclusion, not only those explicitly mentioning 'safety'. The review included research on all modes of road transport, including motorised and non-motorised vehicles, as well as pedestrian safety and cycling. This resulted in the identification of 179 articles, conference papers, and book chapters. In a number of cases, conference papers corresponded to journal articles (i.e., the former being a simpler form of the latter), and journal papers to book chapters (where published research had been collated and released as collected works). As such, in order to minimise repetition in the review the decision was taken to exclude book chapters and conference papers. This resulted in the inclusion of 126 articles for review, spanning from 1996 to 2020. Each of the current authors then reviewed, in detail, one third of that sample.

The three current authors reviewed the collected works, inductively and collaboratively developing a set of themes that characterised the articles reviewed in terms of the methods used, the specific field of study considered, and the overall perspective taken by the article. These characteristics aimed to give a sense of research direction, methodology, recommendations made, and how this has changed over the years in which Neville has been active in the road safety domain.

A popular framework through which road safety and systems thinking have been combined is the Risk Management Framework (RMF; Rasmussen, 1997), a hierarchical description of a system that typically describes six levels of organisational abstraction: equipment and environment, end users, management, local government and industry, regulators and associations, and central government. Just as the framework can describe a system and its components, it can be used to categorise a process or activity in terms of the system level at which it is undertaken or directed. To this end, each article was considered in terms of two characteristics: 1) The level of the RMF to which the article as a whole was most relevant, or through which it could be considered (using the six original levels described by Rasmussen (1997)); and 2) the recommendations for road safety made in the article, in terms of the RMF level to which each of those recommendations applied.

To give examples for point one, an article was identified as corresponding to the upper-most level of the RMF if it explicitly took a whole-system perspective (e.g., '*The big picture on accident causation: A review, synthesis and meta-analysis of AcciMap studies',* Salmon et al. 2020), and to the lower-most level if it corresponded to a focus on equipment or the environment (e.g., *'Good vibrations: Using a haptic accelerator pedal to encourage eco-driving*', McIlroy et al. 2017). Regarding point two, recommendations first had to be identified. A 'recommendation' was considered as the explicit suggestion for an action or decision phrased in terms of its direct and practical impact on road safety (e.g., recommendations for future research were not included). At the lowest RMF level, equipment and environment, examples included *"visual HMIs can assist drivers in making a correct braking or lane change manoeuvre in a take-over scenario"* (p.20, Ericsson et al. 2018); at the central technical and operational management level *"future vehicle designers* *should employ their technology in driver support systems rather than in automation to replace the driver"* (p.365, Young & Stanton, 2002); and at the highest level, government policy and budgeting, *"There seems to be no simple solution to this problem, and new rules of the road may be required."* (p.423, Stanton et al. 2020). Recommendation identification was done individually by each author within their sub-sample of papers (by going through each article and picking out specific recommendations), then discussed collaboratively until full agreement was reached.

In addition to the RMF level, each article was also categorised in terms of the methods used and the field of road safety with which the article was concerned. Regarding an article's method, each of the current three authors independently and inductively developed categories as they went through their third of the selected articles. Categories pertaining to the field of road safety at which each article directed its focus were also developed this way. The authors then discussed the categories they had developed and collaboratively agreed upon a single classification scheme for each method and field. Articles were then revisited, and the updated classification schemes applied. The categories for the method and field of road safety research are detailed in Table 1.

Regarding methods, *surveys, focus groups, and interviews* are those studies that focus on the responses of individuals, or groups of individuals, to specific questions or topics; *systems analysis* include methods such as Accimaps and STAMP; *design methods* talk specifically of interface or system design using, for example, Design with Intent cards, or Ecological Interface Design; *on-road studies* use instrumented vehicles driving on test tracks or real roads; *simulator studies* represent all driving simulation research, whether desktop or through a high-fidelity system; *reviews and discussions* draw on previously published work; *combination approaches* include studies for which multiple methods have been used, for example where on-road and simulator trials have both been used in a single piece of research. The papers were also classified on the field of road safety research they related too. *General safety analysis and recommendations* covers those studies targeted at road safety as a whole, rather than focussing on any specific area (e.g., most systems-level research would come under this); *infrastructure* relates to the physical world, for example in rail crossing or junction design; *vehicle design* includes those studies focussed on in-vehicle information design that is not related to eco-driving or automation; *eco-driving safety* includes all studies focussed on energy use in the vehicle; *automation: general* covers studies related to automation that could not be included in the latter two categories; *automation: workload* includes work that explicitly investigates the effect of vehicle automation on driver workload and attention; *automation: driver interactions* covers those studies interested in interface design for vehicle automation, including handover of control considerations.

Table 1. Classification scheme for each article's chosen method and field of road safety

	Category	Example article
Method	Survey, interviews, and focus groups	*Should we pass on minimum passing distance laws for cyclists? Comparing a tactical enforcement option and minimum passing distance laws using signal detection theory* (Lamb et al. 2020)
	Systems analysis	*A sociotechnical approach to accident analysis in a low-income setting: Using Accimaps to guide road safety recommendations in Bangladesh* (Hamim et al. 2020)
	Design method	'*Ideation using the "Design with Intent" toolkit: A case study applying a design toolkit to support creativity in developing vehicle interfaces for fuel-efficient driving*' (Allison & Stanton, 2020)
	On-road study	*Breaking the cycle of frustration: Applying Neisser's Perceptual Cycle Model to drivers of semi-autonomous vehicles* (Revell et al. 2020)
	Simulator study	*Directability, eye-gaze, and the usage of visual displays during an automated vehicle handover task* (Clark et al. 2019)
	Review / discussion	*A human factors perspective on automated driving* (Kyriakidis et al. 2019)
	Combination approach	*Vehicle sensor data-based analysis on the driving style differences between operating indoor simulator and on-road instrumented vehicle* (Qi et al. 2019)
Field of road safety	General safety analysis and recommendations	*How do fatalistic beliefs affect the attitudes and pedestrian behaviours of road users in different countries? A cross-cultural study* (McIlroy et al. 2020)
	Infrastructure	*From interfaces to infrastructure: extending ecological interface design to re-design rail level crossings* (Read et al. 2019)
	Vehicle design	*In-vehicle information systems to meet the needs of drivers* (Harvey et al. 2011)
	Driver attention	*Exploring the mechanisms of distraction from in-vehicle technology: The development of the PARRC model* (Parnell et al. 2016)
	Eco-driving safety	*Cognitive Work Analysis for safe and efficient driving* (Birrell et al. 2012)
	Automation: General	*Who is in responsible for automated driving? A macro-level insight into automated driving in the United Kingdom using the Risk Management Framework and Social Network Analysis* (Banks et al. 2019)
	Automation: Workload specific	*Acclimatizing to automation: Driver workload and stress during partially automated car following in real traffic* (Heikoop et al. 2019)
	Automation: Driver interactions	*Is partially automated driving a bad idea? Observations from an on-road study* (Banks et al. 2018)

Inter-rater reliability

To assess inter rater reliability, five articles from each author's third of the 129 articles included in the review (i.e., 15 articles, 11.6% of the total) were randomly selected for reliability assessment by all three authors. The articles were assessed as a whole (i.e., its level on the RMF), the recommendations made in that article, the methods used, and the field of road safety it addressed. Where each article was assigned to a single category for RMF level, method, and road safety field, the 15 articles contained within them 34 distinct recommendations, with a range of one to six recommendations in each article (hence IRR calculations for recommendations was performed on 34 items, representing 8.2% of the 417 recommendations made across all 129 articles).

Fleiss' kappa and percentage agreement were calculated to determine the level of agreement between the three authors in their assigning of each article to a level of the RMF, a method, and a field of study (i.e., on 15 ratings in each category), and of each recommendation to a level of the RMF (i.e., on 34 ratings). Table 2 displays results. Fleiss' kappa indicated substantial (.61 – .80) or almost perfect (.81 - .99) agreement between raters on all aspects (Landis & Koch, 1977).

Table 2. Inter-rater reliability statistics for article RMF level, method, and field, and for the RMF level of each of the recommendations made, in 15 of the 129 articles included in the review

	Fleiss' kappa			Percentage agreement between raters		
	Kappa	95% CI	*p*	KP/RM	KP/VB	RM/VB
RMF Level	.614	.608 - .621	<.0005	66.7%	80.0%	80.0%
Method	.824	.819 - .828	<.0005	100%	86.7%	86.7%
Field	.784	.780 - .788	<.0005	100%	73.3%	73.3%
Recommendations	.756	.752 - .759	<.0005	76.5%	79.4%	91.2%

Results

As would be expected from an active academic, Neville has contributed to progressively more published articles as his career has advanced, with a lower proportion of works on which he is first author and an increasing number of works on which he is co-author. This illustrates a move towards the mentoring of the next generation of researchers. The total number of articles related to road safety he co-authored, and those on which he was first author, each year from 1996 to 2020, is presented in Figure 1. The figure also shows the number of distinct road safety recommendations made per published article; as can be seen, this has also increased as time has progressed. Note that this is not the raw number of recommendations made that year, but the average number of recommendations made per article published in a given year. This reveals the trend towards offering more practical road safety advice per research study as time has gone on.

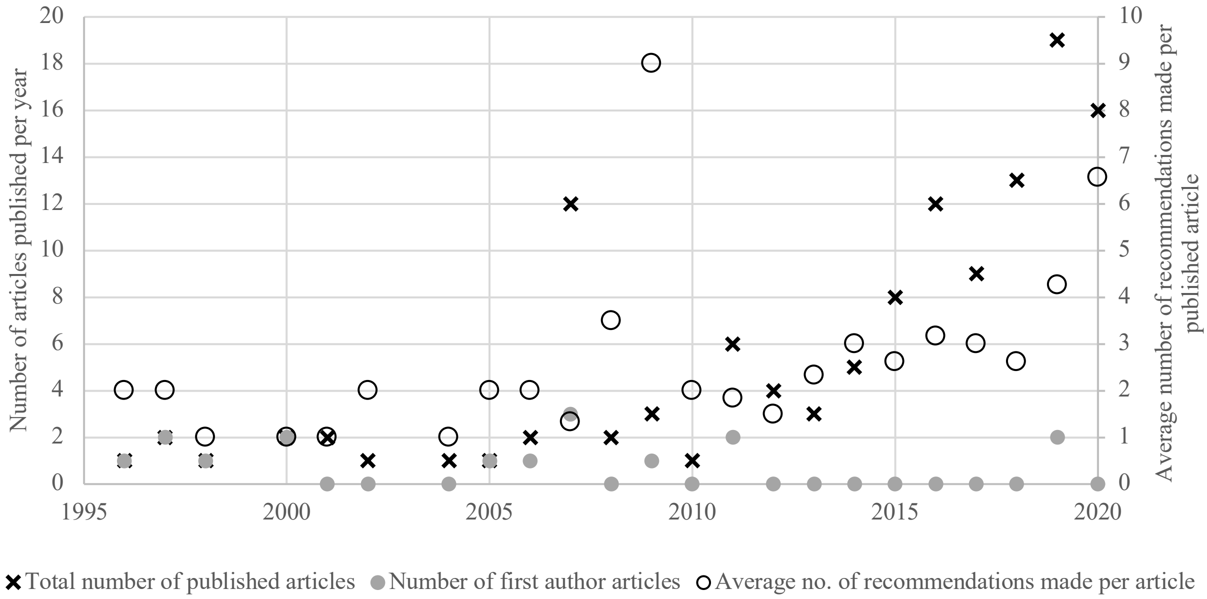

Figure 1. Total number of published articles per year (1996 to 2020) and number of those articles on which Neville is first author (on the left axis), and average (mean) number of road safety recommendations made per article (on the right axis).

In addition to a tendency to make more recommendations per paper as time has gone on, there has also been a tendency towards making recommendations that apply to higher levels of the road safety system. Table 3 shows the average number of recommendations made per paper that were categorised as being relevant to each level of the RMF. Recommendations made at the 'equipment and environment' and the 'end users' levels have been commonly made across all articles, regardless of the year of publication; however, it is in the past ten years (and the last three or four in particular), that recommendations at the higher levels of the RMF have been made.

Table 3. Average number of recommendations per paper assigned to each level of the RMF

Year of publication:	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Central government	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0	0.0	0.0	0.5	0.0	1.0	0.0	0.5	0.3	0.0	0.1	0.3	0.7	0.5	0.9	1.4
Regulators and associations	0.0	0.5	0.0		0.0	0.0	0.0		0.0	0.0	0.0	0.3	0.0	0.0	1.0	0.0	0.3	0.0	0.4	0.1	0.2	0.2	0.2	0.4	0.9
Local gov and industry	0.0	0.0	1.0		0.0	0.5	0.0		0.0	0.0	0.5	0.1	0.5	0.0	0.0	0.2	0.0	0.7	0.0	0.3	0.3	0.3	0.3	0.7	1.1
Management	0.0	0.5	0.0		0.5	0.0	1.0		0.0	0.0	0.0	0.5	0.5	0.3	0.0	0.2	0.8	0.0	0.6	0.9	0.3	0.8	0.8	0.9	1.6
End users	1.0	0.5	0.0		0.0	0.5	0.0		0.0	0.0	0.0	0.2	1.0	0.3	0.0	0.3	0.0	0.3	0.6	0.3	0.3	0.1	0.3	0.4	0.6
Equipment and environment	1.0	0.5	0.0		0.5	0.0	1.0		1.0	2.0	1.5	0.3	1.0	**8.3**	0.0	1.2	0.0	1.0	1.4	1.0	1.9	0.9	0.5	0.8	1.0

Note: In 2009, Stanton and Salmon (2009) proposed 24 potential technological solutions relevant to the equipment level to reduce driver errors, hence the outlier in bold (8.3) in that cell.

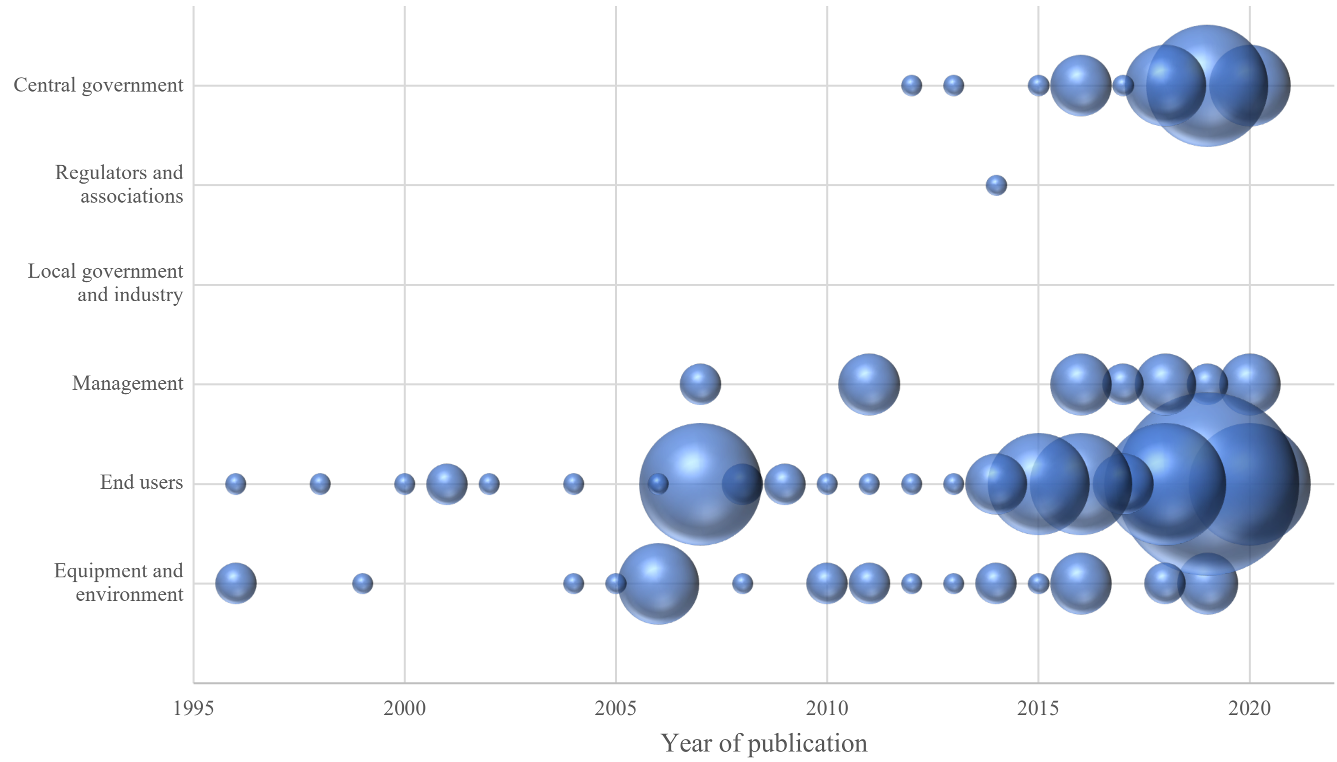

Figure 2. Chart displaying the level at which individual publications were categorised as being focussed. Bubble size represents the number of publications categorised as being at that level in a given year (e.g., one article was categorised at the 'end user' level in 2000; in 2020, four were categorised at the 'central government' level).

Further to the pattern of aiming individual road safety recommendations at a holistic, systems level (shown in Table 3), papers as a whole have been positioned more in terms of systems thinking and sociotechnical analysis as time has passed. Figure 2 displays the number of papers categorised as being positioned at each level of the RMF. The size of the bubble represents the raw number of papers published in a given year that were categorised by the current authors at a given RMF level. The increase in the volume of papers produced can be clearly seen, and just as with recommendations, research aimed at the lowest two levels is common across all years; however, research that takes a true systems viewpoint has only emerged in the past ten years or so.

This reflects a move towards systems thinking in human factors and ergonomics more widely. This is true in the road safety domain, and in Neville's contribution to it, with early work focusing on (for example) the individual driver in driving simulation studies, and later work analysing whole systems, using systems methodologies such as Accimap and STAMP (Figure 3). This trend is also reflected in the field of road safety to which the research directs its attention (Figure 4). The earliest articles included in our review looked primarily at automation and in-vehicle information design. As time went on, this focus expanded, with a greater focus on general system safety analysis and recommendation generation.

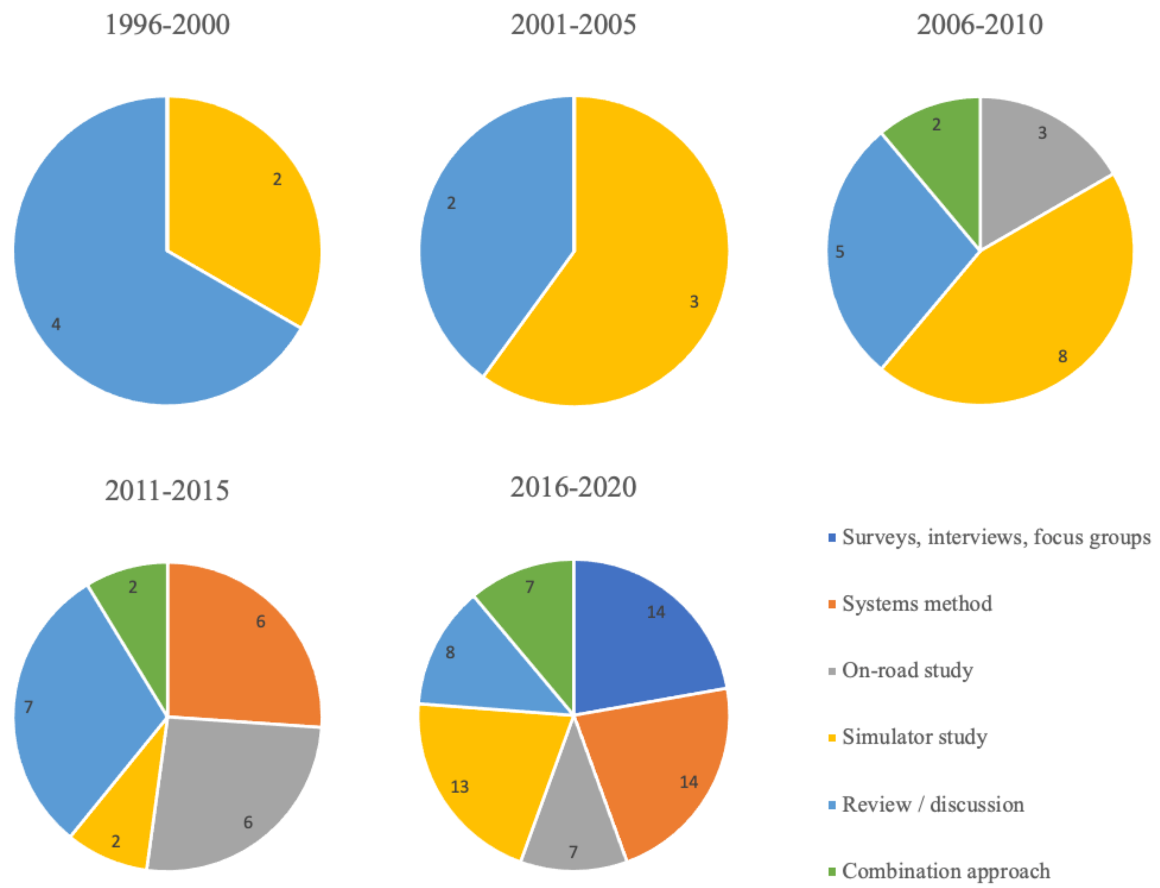

Figure 3. Break down of the number of papers utilising the different methods though the years

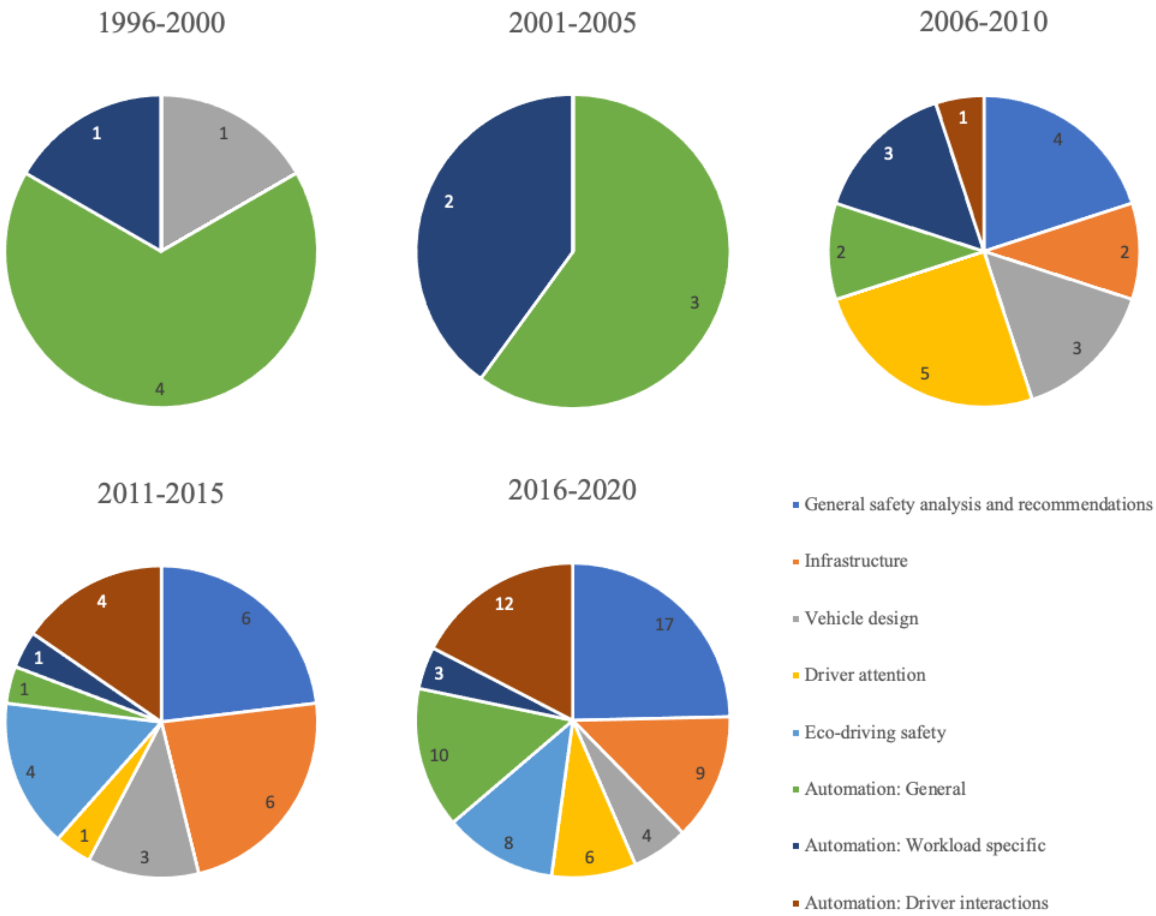

Figure 4. Break down of the number of papers studying the different fields of road safety through the years

Discussion

The review presented above gives an overview of work spanning 25 years, in a variety of sub-domains, using a multitude of method types, from desktop simulation with single human participants to sociotechnical methods analysing whole systems. Neville's career in road safety research has its beginnings in the very early stages of drive-by-wire systems and vehicle automation in the 1990's (Stanton & Marsden, 1996; 1997, Stanton et al, 1997). This work was important to the development of Adaptive Cruise Control (ACC) systems as they started to be integrated into road vehicles in the late 90's. Since then, his career has followed the development of increasingly more advanced and autonomous road vehicle technologies, developments which continue to the current day. As the above review's results demonstrate, he has also broadened his study of road safety as time has passed, from an initial focus on those technologies to an interest in multiple fields that impact upon road safety, including (but not limited to) driver training (Stanton et al, 2007), driver workload (Young & Stanton, 2007), automated vehicle system functionality (Stanton, 2019a), driver error (Stanton & Salmon, 2009) and collision analysis (Stanton et al, 2019).

In terms of methods, something that has featured throughout Neville's career is driving simulator research, where he has worked with progressively more advanced testing platforms. Figure 1 shows the different iterations of the Southampton University Driving Simulator through the years, equipment with which he has addressed a wide variety of research questions. Early driving simulator software was much more rudimentary than modern-day systems, and the first Southampton University Simulator was the front half of a Ford Orion, registered in 1993, with an Acorn Archimedes RISC PC. Data was recorded every 0.5 seconds. Partnerships with Jaguar Land Rover led to upgraded driving simulation with the full Jaguar XJ6 with a 140-degree field of view, before the latest update to the current Range Rover Evoque. This has a customisable HMI, a separate control room and two simulation software packages, allowing for a high degree of customisation. It can model all forms of road environment and specify the behaviour of AI cars, motorbikes, bicycles and pedestrians using scripting. It also generates a wide range of data on driving performance, such as vehicle speed, lane position and headway, doing so at up to 100Hz.

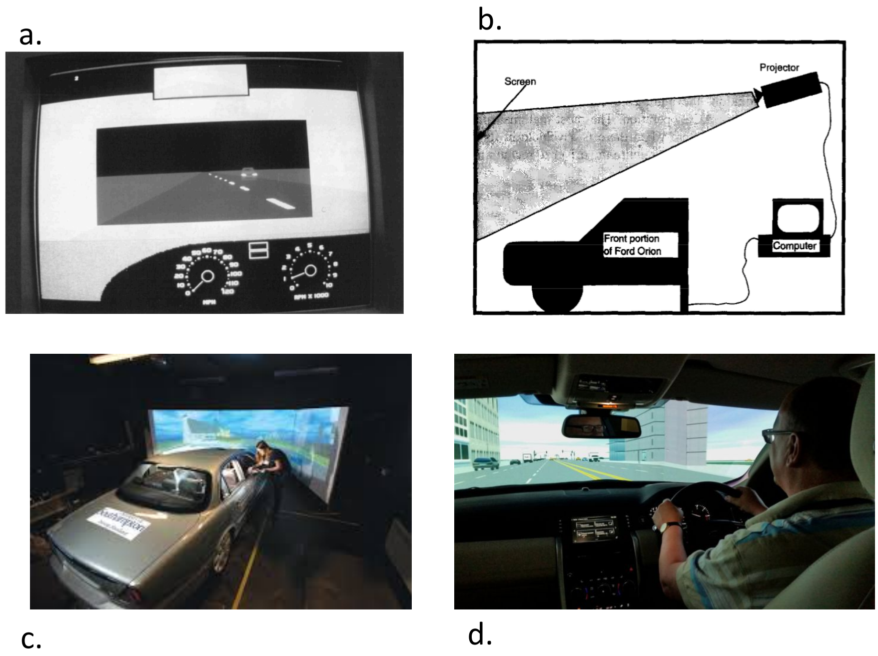

Figure 1. The Southampton University Driving simulator over the years. Taken from: a. Stanton & Pinto (2000); b. Stanton, Young & McCaulder (1997) c. https://www.southampton.ac.uk/news/2015/10/driverless-cars-epsrc-funding.page; d. https://www.southampton.ac.uk/engineering/news/2017/06/driverless-cars.page

In addition to simulation, Neville has highlighted the importance of ‘real-world’ research, especially in the form of on-road user trials. The first instance of such work came in a 2007 study exploring situation awareness in drivers and motorcyclists (Walker et al. 2007). In more recent years, this has included some of the earliest examples of on-road automated driving trials (Eriksson et al, 2017; Banks et al, 2018; Revell et al, 2020). The use of combinations of methods can also be seen from 2007 onwards, with Stanton et al.’s (2007) evaluation of an advanced driver coaching system, where the authors combined on-road investigations with driver interviews. It is important to point out that, in the above review, the *‘combination approach’* category has been applied where there are distinct method *types* being used together, with other examples including Parnell et al.’s (2018) study of interaction with technology both on the road and in the simulator or Read et al.’s (2018) use of document review combined with on-road observations to investigate pedestrian behaviour and safety.

Not included in our *‘combination approach’* category are uses of the systems methods that have emerged over the past decade. These methods require data as an input, data that itself can be gathered using a variety of methods (with document review and stakeholder engagement particularly common), so one could also consider them as combination approaches. Due to their prominence, however, they were assigned their own category in our review: ‘*systems analysis*’. Their growth in importance is highlighted not only by our categorising of articles by method, but by the positioning of the articles (and the safety recommendations presented within them) on the Risk Management Framework (RMF), Rasmussen’s (1997) hierarchical description of complex systems. Indeed, Neville’s work has championed the systemic approach and the application of sociotechnical systems theory and methods to road safety (e.g., Salmon et al, 2013; Parnell et al, 2017; Salmon et al, 2018; McIlroy et al, 2019), with the approach going far beyond the in-vehicle technology focus of early work.

This move towards systems thinking in road safety mirrors (or is mirrored by) the wider literature, beyond Neville’s contribution to it. As described in the introduction, Larsson et al.’s (2010) seminal work marked the beginning of this shift. Subsequent work by Salmon and colleagues (e.g., Read et al. 2013; Scott-Parker et al. 2015; Salmon et al 2016) provided developments in the field, with a variety of other researchers contributing to the literature by offering descriptions of the application of systems methods to road safety (e.g., Underwood & Waterson, 2014; Zhang et al. 2018) and discussions of how sociotechnical approaches and systems thinking are, or could be applied when thinking about land transport and safety (e.g., Hughes et al. 2015; Naumann et al. 2020b). This has evolved to the point that even some of the published work focussing on just one aspect of the system (e.g., its end users; Salmon et al. 2019) recognises the importance of the whole system and how system factors (e.g., structure, interactions, complexity, emergent properties, etc.) shape the behaviour and performance of those system components.

A good example of this is in Neville's work with Guy Walker and Paul Salmon in the on-road study of road user interactions (e.g., Walker et al. 2011; Salmon et al. 2014a; 2014b). According to our RMF categorisation system, above, these papers are positioned at the end user level; ostensibly they explore the experiences and cognition of the road transport system's end user (i.e., cyclists, drivers, and motorcyclists). That said, they are concerned with the interactions between those users, and the compatibilities (or lack thereof) in situation awareness therein. One could argue, therefore, that they take systems view of the matter. This is characteristic of Neville's work; although there may sometimes be a focus on a particular sub-system, it is in the dynamic interactions within that sub-system that Neville's research has directed its focus.

Although Neville has championed the use of multiple human factors methods (having written perhaps the most highly cited methods handbook; Stanton et al. 2017) his two strongest areas, at least in terms of road safety research, have been in systems approaches and in the use of driving simulation. Although the two approaches may not seem directly compatible, with one focussing ostensibly on the end user (i.e., a driver) the other taking a whole-system perspective, they can, in fact, be complementary. A good example of this is found in Beanland et al. (2018), work in which Neville was involved. Over an extended programme of work, researchers investigated rail level crossings using systems methods and developed three systems thinking-based new designs. In Beanland et al. (2018), those three physical environments were built in a simulated environment and tested with human drivers. This represents a potentially fruitful means to provide evidence for the efficacy of designs borne out of systems thinking. This is a challenge for sociotechnical systems thinkers and researchers within and beyond the road safety domain; to provide the necessary evidence for the benefit of systems thinking on which industry and policymakers can base decisions.

The work reviewed above is characterised by the increased use of systems methods (e.g., Accimaps, STAMP, CWA) as time has passed. This coincides with the increase in the number of road safety recommendations made, particularly those that target higher levels of the system. This is indicative of the desire to have a deeply impactful influence over road safety as a whole, not just over individual aspects of the system. In the early part of Neville's career, much of his research focussed on human performance with new automation technologies, commonly using driving simulation to explore the inherent challenges (e.g., Stanton et al. 1997). Many of the recommendations for safety that arose from that work focussed on the way the human interacts or communicates with the technology. For example, Stanton et al. (1997) pointed out that "ACC [Adaptive Cruise Control] systems need to effectively communicate the status of the ACC system to driver" (p.157).

Later examples of research on autonomous driving systems contain similar recommendation types, but also go further. For example, Banks et al. (2019) used the RMF, in combination with Social Network Analysis, to frame discussions around responsibility and automated driving. In addition to making recommendations aimed at users and their equipment (e.g., "Drivers must understand the limitations and capabilities of the automated system in use", p.7), they also proposed safety recommendations at higher levels of the system, going beyond the government level to include considerations of actors at the 'national committees' and 'international committees' levels, yet higher levels that Parnell et al. (2017) added on to the original six-level RMF (e.g., "Provide clearly worded legislation surrounding the design, use, testing of and implementation routes of automation to vehicle manufacturers", p.7, Banks et al. 2019). Key recommendations from other recent work suggest a need for new standards for the development and testing of vehicle systems (Stanton et al., 2019a) and, more broadly, the need for an integrated approach to road safety across all levels of the system to move the blame away from the driver (Hamim et al, 2020).

This work is now starting go beyond academia. In 2019, Neville was asked by the Royal Automobile Club (RAC) foundation to author a guide for policy makers and practitioners on the models and methods for collisions analysis. In that work he presented the need to utilise systemic approaches to address the complexity of road safety (Stanton, 2019b). In particular, he stated the value in applying the RMF and the associated Actor and Accimap methods (Svedung & Rasmussen, 2002). These are methods that Neville has applied, modified, and improved within the road safety domain with much success (e.g., Salmon et al, 2012; Parnell et al, 2017; McIlroy et al, 2019; Hamim et al, 2020; Salmon et al, 2020). Importantly, they are methods that lead the analyst to consider more than just the end users and environmental factors that dominate many discussions of road safety culpability and blame. It is in the opinion of the current authors, of an ever-growing body of researchers, policy makers, and practitioners (e.g., Peden & Puvanachandra, 2019), and ostensibly in Neville's, that this is the approach in which the future of road safety lies.

There are of course some challenges looking forward. Systems thinking and the sociotechnical paradigm are still relatively new to road safety discussions (despite the latter having a history going back to the 1950s; Trist & Bamforth, 1951) and their uptake beyond academia (and even within academia) is limited. The oft-cited gulf between research and practice (e.g., Underwood & Waterson, 2013) is, therefore, a very real and present challenge. Neville has had influence beyond academia on the design and uptake of some in-vehicle technologies (e.g., ACC, mentioned above; Stanton & Marsden, 1996; 1997, Stanton et al, 1997), and is beginning to have further impacts on collision investigation through the RAC-funded work described above; however, the widespread uptake of Human Factors and Ergonomics (HFE) approaches to safety in the road transport domain is yet to be seen. Although this is a challenge experienced across HFE, it is most acutely seen in the systems HFE field (Salmon et al. 2020). Despite the work of a researcher as prolific and influential as Neville, penetration into the practice and policy world is still lacking.

Although Neville's own work as an HFE consultant may be driven by his own (and others') research practices and findings (see Salmon et al. 2020), he represents more the exception rather than the norm. There are many reasons for this (several of which are summarised by Salmon et al. 2020), one being the lack of understanding and partnership between academia and industry (or, in the case of road safety, academia and policy and practice). A good example of where improved partnership has the potential for significant road safety benefits is in the interpretation, uptake, and implementation of the 'Safe System' approach. This is a way of thinking rooted in Sweden's Vision Zero strategy of the late 1990s (Ministry of Transport and Communications, 1997) that is characterised by an expanded view of road safety, one that understands responsibility for safety outcomes as shared across systems actors, not just placed on the shoulders of the end user. This is a welcome step in the right direction, and the fact that it is being taken up by a variety of governments and non-governmental organisations (e.g., UN, 2020; Gov. of Western Australia, 2020; Department for Transport, 2019; US Department of Transportation, 2020) is encouraging.

That said, 'Safe System' is not a true example of systems thinking (e.g., Larsson et al. 2010; Salmon et al. 2012). Unlike the sociotechnical approach, the 'Safe System' philosophy is not underpinned by complex systems theory or research evidence (for example, it does not place the same emphasis on emergent properties arising from component interconnections), nor is it associated with any established methods with which a practitioner or policy maker can address the challenges of the setting in which they are active (where the sociotechnical paradigm does have such methods). Indeed, some would argue that despite its acceptance of the influence of hierarchically abstract factors over system outcomes, ‘Safe System’ places excessive focus on the end user and the ‘errors’ they commit (noting that this is generally considered an outdated and unhelpful perspective; Salmon & Lenné, 2014). That said, ‘Safe System’ is still a somewhat nebulous idea, with significant variation in the ways it is expressed in policy and strategy documents; different actors in the road safety domain describe it in a variety of different ways, with some of those descriptions more (or less) end-user focussed than others. This is where the HFE and systems thinking community could have some meaningful influence, i.e., through influencing the way ‘Safe System’ develops as an approach (or philosophy), and how it is formalised and implemented.

Currently, ‘Safe System’ has only been discussed by large, international organisations (e.g., the WHO and the UN) and by charities and governments in high-income settings (e.g., Australia, the UK, the US). The uptake (or even discussion) of such approaches in low- and middle-income countries (LMICs; where the need for reform is greatest) is almost entirely lacking. This is where systems thinking can have even more profound effects, something that has started to happen with a UK aid-funded programme of research led by Neville (e.g., Hamim et al. 2020, 2021; Vu, 2019; Vu et al. 2020). This represents a promising opportunity; it may be easier for researchers to influence the interpretation and direction of ‘Safe System’ (i.e., to align more closely with contemporary systems thinking) and to encourage its uptake in lower-income settings, where it has not yet been adopted in any form, (i.e., is especially novel), than in high-income settings where strategies and policies already exist to some extent (ones that can vary in their alignment with contemporary systems thinking). Moreover, if the HFE and sociotechnical systems research community is to truly influence global road safety, it must direct its attention to these settings, where the burden is most keenly felt.

Conclusions

This review paper has given a summary of work that spans four decades (to clarify: the 1990s, 2000s, 2010s, and 2020s, should Neville read this and object to the implications of our phrasing). While fatalities from road traffic collisions have been on the rise in recent decades, historically, enhancements to the design of vehicles to protect the occupants, as well as the legislation and regulation targeting drivers, has dramatically improved road safety relative to population and motorisation rates. Nevertheless, in recent years there has been growing awareness of the need for collaborative effort between the multiple sectors responsible for the road transport system to reduce and eliminate road traffic fatalities (McIlroy et al, 2019; Parnell et al, 2018). This is further motivated by the increased presence of automation and the projections for automated vehicles (Banks et al, 2019). Neville has been highly influential across these areas, with his continued and impactful contribution to road safety persisting not only through his own continued work, but also through that of the many researchers he has supported along the way (the current authors included).

References

Adanu, E. K., Penmetsa, P., Wood, D., & Jones, S. L. (2019). Incorporating systems thinking approach in a multilevel framework for human-centered crash analysis. *Transportation research interdisciplinary perspectives*, *2*, 100031.

Allison, C. K., & Stanton, N. A. (2020). Ideation using the "Design with Intent" toolkit: A case study applying a design toolkit to support creativity in developing vehicle interfaces for fuel-efficient driving. *Applied Ergonomics*, *84*, 103026.

Banks, V. A., Eriksson, A., O'Donoghue, J., & Stanton, N. A. (2018). Is partially automated driving a bad idea? Observations from an on-road study. *Applied Ergonomics*, 68, 138-145.

Banks, V. A., Stanton, N. A., & Plant, K. L. (2019). Who is responsible for automated driving? A macro-level insight into automated driving in the United Kingdom using the Risk Management Framework and Social Network Analysis. *Applied Ergonomics*, 81, 102904.

Birrell, S. A., Young, M. S., Jenkins, D. P., & Stanton, N. A. (2012). Cognitive Work Analysis for safe and efficient driving. *Theoretical Issues in Ergonomics Science*, *13*(4), 430-449.

Clark, J. R., Stanton, N. A., & Revell, K. M. (2019). Directability, eye-gaze, and the usage of visual displays during an automated vehicle handover task. *Transportation research part F: traffic psychology and behaviour*, *67*, 29-42.

Department for Transport (2019). The Road Safety Statement 2019. Lifetime of Road Safety. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/817695/road-safety-statement-2019.pdf. Accessed 11/03/2021

Department for Transport (2020). Reported Road Casualties Great Britain: 2019 Annual report. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/922717/reported-road-casualties-annual-report-2019.pdf Accessed 01/03/2021.

Eriksson, A., Banks, V. A., & Stanton, N. A. (2017). Transition to manual: Comparing simulator with on-road control transitions. *Accident Analysis & Prevention*, 102, 227-234.

Eriksson, A., Petermeijer, S. M., Zimmermann, M., De Winter, J. C., Bengler, K. J., & Stanton, N. A. (2018). Rolling out the red (and green) carpet: supporting driver decision making in automation-to-manual transitions. *IEEE Transactions on Human-Machine Systems*, *49*(1), 20-31.

Gamero, N., Silla, I., Sainz-González, R., & Sora, B. (2018). The influence of organizational factors on road transport safety. *International journal of environmental research and public health*, *15*(9), 1938.

Government of Western Australia (2020). Road Safety Strategy Australia 2020-2030. https://www.rsc.wa.gov.au/RSC/media/Documents/Driving-Change-Road-Safety-Strategy-WA-2020_1.pdf. Accessed11/03/2021.

Hamim, O. F., Hoque, M. S., McIlroy, R. C., Plant, K. L., & Stanton, N. A. (2020). A sociotechnical approach to accident analysis in a low-income setting: using Accimaps to guide road safety recommendations in Bangladesh. *Safety science,* 124, 104589.

Hamim, O.F., Debnath, M., Hasanat-E-Rabbi, S., Hoque, M.S., McIlroy, R.C., Plant, K.L., & Stanton, N.A. (2021). Resolving the differences between system development and system operation using STAMP: A road safety case study in a low-income setting, *Ergonomics*, DOI: 10.1080/00140139.2021.1876928

Harper, C. G. (1903). *Stage-coach and Mail in Days of Yore: A Picturesque History of the Coaching Age*.. (Vol. 1). Chapman & Hall, limited.

Harvey, C., Stanton, N. A., Pickering, C. A., McDonald, M., & Zheng, P. (2011). In-vehicle information systems to meet the needs of drivers. *Intl. Journal of Human–Computer Interaction*, *27*(6), 505-522.

Heikoop, D. D., de Winter, J. C., van Arem, B., & Stanton, N. A. (2019). Acclimatizing to automation: Driver workload and stress during partially automated car following in real traffic. *Transportation research part F: traffic psychology and behaviour*, *65*, 503-517.

Hughes, B. P., Anund, A., & Falkmer, T. (2015). System theory and safety models in Swedish, UK, Dutch and Australian road safety strategies. *Accident Analysis & Prevention*, *74*, 271-278.

Kyriakidis, M., de Winter, J. C., Stanton, N., Bellet, T., van Arem, B., Brookhuis, K., ... & Happee, R. (2019). A human factors perspective on automated driving. *Theoretical Issues in Ergonomics Science*, *20*(3), 223-249.

Lamb, J. S., Walker, G. H., Fisher, V., Hulme, A., Salmon, P. M., & Stanton, N. A. (2020). Should we pass on minimum passing distance laws for cyclists? Comparing a tactical enforcement option and minimum passing distance laws using signal detection theory. *Transportation research part F: traffic psychology and behaviour*, *70*, 275-289.

Landis, J. R., & Koch, G. G. (1977). An application of hierarchical kappa-type statistics in the assessment of majority agreement among multiple observers. *Biometrics*, 363-374.

Larsson, P., Dekker, S. W., & Tingvall, C. (2010). The need for a systems theory approach to road safety. *Safety science*, *48*(9), 1167-1174.

McIlroy, R. C., Stanton, N. A., & Godwin, L. (2017). Good vibrations: Using a haptic accelerator pedal to encourage eco-driving. *Transportation research part F: traffic psychology and behaviour*, *46*, 34-46.

McIlroy, R. C., Plant, K. A., Hoque, M. S., Wu, J., Kokwaro, G. O., Nam, V. H., & Stanton, N. A. (2019). Who is responsible for global road safety? A cross-cultural comparison of Actor Maps. *Accident Analysis & Prevention,* 122, 8-18.

McIlroy, R. C., Kokwaro, G. O., Wu, J., Jikyong, U., Nam, V. H., Hoque, M. S., ... & Stanton, N. A. (2020). How do fatalistic beliefs affect the attitudes and pedestrian behaviours of road users in different countries? A cross-cultural study. *Accident Analysis & Prevention*, *139*, 105491.

Ministry of Transport and Communications, 1997. På väg mot det trafiksäkra samhället. Fritzes kundtjänst [On the way towards the traffic safe society]. Stockholm, Sweden.

Morgan, N. (2017). Cycling infrastructure and the development of a bicycle commuting socio-technical system: the case of Johannesburg. *Applied mobilities*.

Naumann, R. B., Sandt, L., Kumfer, W., LaJeunesse, S., Heiny, S., & Lich, K. H. (2020a). Systems thinking in the context of road safety: Can systems tools help us realize a true "Safe Systems" approach?. *Current epidemiology reports*, 1-9.

Naumann, R. B., Kuhlberg, J., Sandt, L., Heiny, S., Apostolopoulos, Y., Marshall, S. W., & Lich, K. H. (2020b). Integrating complex systems science into road safety research and practice, part 1: review of formative concepts. *Injury prevention*, *26*(2), 177-183.

Parnell, K. J., Stanton, N. A., & Plant, K. L. (2016). Exploring the mechanisms of distraction from in-vehicle technology: The development of the PARRC model. *Safety science*, *87*, 25-37.

Parnell, K. J., Stanton, N. A., & Plant, K. L. (2017). What's the law got to do with it? Legislation regarding in-vehicle technology use and its impact on driver distraction. *Accident Analysis & Prevention*, 100, 1-14.

Parnell, K. J., Stanton, N. A., & Plant, K. L. (2018). *Driver distraction: a sociotechnical systems approach*. CRC Press.

Peden, M. M., & Puvanachandra, P. (2019). Looking back on 10 years of global road safety. *International Health*, *11*(5), 327-330

Qi, G., Wu, J., Zhou, Y., Du, Y., Jia, Y., Hounsell, N., & Stanton, N. A. (2019). Recognizing driving styles based on topic models. *Transportation research part D: transport and environment*, *66*, 13-22.

Rasmussen, J. (1997). Risk management in a dynamic society: a modelling problem. *Safety Science*, *27*(2-3), 183-213.

Read, G. J., Salmon, P. M., & Lenné, M. G. (2013). Sounding the warning bells: The need for a systems approach to understanding behaviour at rail level crossings. *Applied Ergonomics*, 44(5), 764-774.

Read, G. J., Stevens, E. L., Lenné, M. G., Stanton, N. A., Walker, G. H., & Salmon, P. M. (2018). Walking the talk: comparing pedestrian 'activity as imagined'with 'activity as done'. *Accident Analysis & Prevention*, *113*, 74-84.

Read, G. J., Beanland, V., Stanton, N. A., Grant, E., Stevens, N., Lenné, M. G., ... & Salmon, P. M. (2019). From interfaces to infrastructure: Extending ecological interface design to re-design rail level crossings. *Cognition, Technology & Work*, 1-19.

Revell, K. M., Richardson, J., Langdon, P., Bradley, M., Politis, I., Thompson, S., ... & Stanton, N. A. (2020). Breaking the cycle of frustration: Applying Neisser's Perceptual Cycle Model to drivers of semi-autonomous vehicles. *Applied Ergonomics*, 85, 103037.

Salmon, P. M., Hulme, A., Walker, G. H., Waterson, P., Berber, E., & Stanton, N. A. (2020). The big picture on accident causation: A review, synthesis and meta-analysis of AcciMap studies. *Safety Science,* 126, 104650.

Salmon, P. M., McClure, R., & Stanton, N. A. (2012). Road transport in drift? Applying contemporary systems thinking to road safety. *Safety Science, 50*(9), 1829-1838.

Salmon, P. M., Read, G. J., Stanton, N. A., & Lenné, M. G. (2013). The crash at Kerang: Investigating systemic and psychological factors leading to unintentional non-compliance at rail level crossings. *Accident Analysis & Prevention*, 50, 1278-1288.

Salmon, P. M., Lenne, M. G., Walker, G. H., Stanton, N. A., & Filtness, A. (2014a). Exploring schema-driven differences in situation awareness between road users: an on-road study of driver, cyclist and motorcyclist situation awareness. *Ergonomics*, *57*(2), 191-209.

Salmon, P. M., Lenne, M. G., Walker, G. H., Stanton, N. A., & Filtness, A. (2014b). Using the Event Analysis of Systemic Teamwork (EAST) to explore conflicts between different road user groups when making right hand turns at urban intersections. *Ergonomics, 57*(11), 1628-1642.

Salmon, P. M., Lenné, M. G., Read, G. J., Mulvihill, C. M., Cornelissen, M., Walker, G. H., Young, K.L., Stevens, N., & Stanton, N. A. (2016). More than meets the eye: using cognitive work analysis to identify design requirements for future rail level crossing systems. *Applied Ergonomics*, *53*, 312-322.

Salmon, P. M., Read, G. J., Walker, G. H., Goode, N., Grant, E., Dallat, C., ... & Stanton, N. A. (2018). STAMP goes EAST: Integrating systems ergonomics methods for the analysis of railway level crossing safety management. *Safety Science*, 110, 31-46.

Salmon, P. M., Read, G. J., Beanland, V., Thompson, J., Filtness, A. J., Hulme, A., McClure, R. & Johnston, I. (2019). Bad behaviour or societal failure? Perceptions of the factors contributing to drivers' engagement in the fatal five driving behaviours. *Applied Ergonomics*, *74*, 162-171.

Salmon, P. M., Read, G. J., Walker, G. H., Stevens, N. J., Hulme, A., McLean, S., & Stanton, N. A. (2020). Methodological issues in systems Human Factors and Ergonomics: Perspectives on the research–practice gap, reliability and validity, and prediction. *Human Factors and Ergonomics in Manufacturing & Service Industries*. https://doi.org/10.1002/hfm.20873

Scott-Parker, B., Goode, N., & Salmon, P. (2015). The driver, the road, the rules… and the rest? A systems-based approach to young driver road safety. *Accident Analysis & Prevention*, *74*, 297-305.

Stanton, N. A., & Marsden, P. (1996). From fly-by-wire to drive-by-wire: Safety implications of automation in vehicles. *Safety Science, 24*(1), 35-49.

Stanton, N., & Marsden, P. (1997). Drive-by-wire systems: Some reflections on the trend to automate the driver role. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 211*(4), 267-276.

Stanton, N. A., Young, M., & McCaulder, B. (1997). Drive-by-wire: The case of driver workload and reclaiming control with adaptive cruise control. *Safety Science, 27*(2-3), 149-159.

Stanton, N. A., & Pinto, M. (2000). Behavioural compensation by drivers of a simulator when using a vision enhancement system. *Ergonomics*, *43*(9), 1359-1370.

Stanton, N. A., Walker, G. H., Young, M. S., Kazi, T., & Salmon, P. M. (2007). Changing drivers' minds: the evaluation of an advanced driver coaching system. *Ergonomics*, *50*(8), 1209-1234.

Stanton, N. A., & Salmon, P. M. (2009). Human error taxonomies applied to driving: A generic driver error taxonomy and its implications for intelligent transport systems. *Safety Science, 47*(2), 227-237.

Stanton, N. A., Salmon, P. M., Rafferty, L. A., Walker, G. H., Baber, C., & Jenkins, D. P. (2017). *Human factors methods: a practical guide for engineering and design*. CRC Press.

Stanton, N. A., Salmon, P. M., Walker, G. H., & Stanton, M. (2019). Models and methods for collision analysis: A comparison study based on the Uber collision with a pedestrian. *Safety Science,* 120, 117-128.

Stanton, N. A. (2019a). Thematic issue: Driving automation and autonomy. *Theoretical Issues in Ergonomics Science, 20*(3), 215-222.

Stanton, N. A. (2019b) Models and Methods for Collision Analysis : A guide for policymakers and practitioners. RAC Foundation. https://www.racfoundation.org/wp-content/uploads/Models_and_methods_for_collision_analysis_Stanton_March_2019.pdf. Accessed 11/03/2021.

Stanton, N. A., Eriksson, A., Banks, V. A., & Hancock, P. A. (2020). Turing in the driver's seat: Can people distinguish between automated and manually driven vehicles? *Human Factors and Ergonomics in Manufacturing & Service Industries*, *30*(6), 418-425.

Svedung, I., & Rasmussen, J. (2002). Graphic representation of accident scenarios: Mapping system structure and the causation of accidents. *Safety Science, 40(5), 397–417*.

Trist, E. L., & Bamforth, K. W. (1951). Some social and psychological consequences of the longwall method of coal-getting: An examination of the psychological situation and defences of a work group in relation to the social structure and technological content of the work system. *Human Relations*, *4*(1), 3-38.

UN (2020). Draft resolution of the General Assembly. Improving Road Safety. https://www.un.org/pga/74/wp-content/uploads/sites/99/2020/08/Draft-Resolution-Road-Safety.pdf. Accessed 11/03/2021.

Underwood, P., & Waterson, P. (2013). Systemic accident analysis: examining the gap between research and practice. *Accident Analysis & Prevention*, *55*, 154-164.

Underwood, P., & Waterson, P. (2014). Systems thinking, the Swiss Cheese Model and accident analysis: a comparative systemic analysis of the Grayrigg train derailment using the ATSB, AcciMap and STAMP models. *Accident Analysis & Prevention*, *68*, 75-94.

US Department of Transportation (2020). Integrating the Safe System approach with the Highway Safety Improvement Program. https://safety.fhwa.dot.gov/hsip/docs/fhwasa2018.pdf. Accessed 11/03/2021.

Vu, N.H. (2019). An application of system-based approach and Accimap technique on analyzing causes of road traffic accidents in Vietnam. *Journal of Transportation, Vietnam* (ISSN: 2354-0818, e-ISSN: 2615-9791)*, Special Issue, Vol. 12/2019, 46-53*. In Vietnamese.

Vu, N. H., McIlroy, R. C., Plant, K. L., & Stanton, N. A. (2020, July). Applying the Systems Theoretic Accident Model and Process to Analyze a Downgrade-Truck Collision Caused by a Brake Failure in Vietnam. In *International Conference on Applied Human Factors and Ergonomics* (pp. 322-329). Springer, Cham.

Walker, G. H., Stanton, N. A., & Young, M. S. (2007). Easy rider meets knight rider: an on-road exploratory study of situation awareness in car drivers and motorcyclist. *International journal of vehicle design*, *45*(3), 307-322.

Walker, G. H., Stanton, N. A., & Salmon, P. M. (2011). Cognitive compatibility of motorcyclists and car drivers. *Accident Analysis & Prevention*, *43*(3), 878-888.

World Health Organization. (2018). *Global status report on road safety 2018: Summary* (No. WHO/NMH/NVI/18.20). Geneva, Switzerland: World Health Organization.

World Health Organisation (2020) Road Traffic injuries. https://www.who.int/news-room/fact-sheets/detail/road-traffic-injuries. Accessed 11/03/2021.

Young, M. S., & Stanton, N. A. (2002). Malleable attentional resources theory: a new explanation for the effects of mental underload on performance. *Human Factors*, *44*(3), 365-375.

Young, M. S., & Stanton, N. A. (2007). What's skill got to do with it? Vehicle automation and driver mental workload. Ergonomics, 50(8), 1324-1339.

Zhang, Y., Liu, T., Bai, Q., Shao, W., & Wang, Q. (2018). New systems-based method to conduct analysis of road traffic accidents. *Transportation research part F: traffic psychology and behaviour*, *54*, 96-109.