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Mobility • Safety • Economy • Environment

Models and Methods for Collision Analysis

A guide for policymakers and practitioners

Professor Neville A Stanton

Human Factors Engineering, University of Southampton

March 2019

UNIVERSITY OF Southampton

The Royal Automobile Club Foundation for Motoring Ltd is a transport policy and research organisation which explores the economic, mobility, safety and environmental issues relating to roads and their users. The Foundation publishes independent and authoritative research with which it promotes informed debate and advocates policy in the interest of the responsible motorist.

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Registered Charity No. 1002705

ISBN: 978-1-9160527-1-0

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About the Author

Professor Neville Stanton, PhD, DSc, is a Chartered Psychologist, Chartered Ergonomist and Chartered Engineer. He holds the Chair in Human Factors Engineering in the Faculty of Engineering and the Environment at the University of Southampton in the UK. He has degrees in occupational psychology, applied psychology and human factors engineering and has worked at the Universities of Aston, Brunel, Cornell and MIT (Massachusetts Institute of Technology). His research interests include modelling, predicting, analysing and evaluating human performance in systems, as well as designing the interfaces and interaction between humans and technology.

Professor Stanton has worked on design of automobiles, aircraft, ships and control rooms over the past 30 years, on a variety of automation projects. He has published 40 books and over 300 journal papers on ergonomics and human factors. In 1998 he was presented with the Institution of Electrical Engineers Divisional Premium Award for research into system safety. The Chartered Institute of Ergonomics and Human Factors in the UK awarded him The Otto Edholm Medal in 2001, The President's Medal in 2008 and 2018, and The Sir Frederic Bartlett Medal in 2012 for his contributions to basic and applied ergonomics research. The Royal Aeronautical Society awarded him and his colleagues the Hodgson Prize in 2006 for research on design-induced, flight-deck error, published in The Aeronautical Journal. The University of Southampton has awarded him a Doctor of Science in 2014 for his sustained contribution to the development and validation of human factors methods.

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Disclaimer

Acknowledgements

Professor Neville Stanton would like to thank Professor Paul Salmon, Professor Guy Walker, Dr Maggie Stanton, Elizabeth Box and Dr Anneka Lawson for their assistance and support on this project.

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AEB	Autonomous Emergency Braking (Volvo)
EAST–BL	Event Analysis of Systemic Teamwork – Broken Links
EAST–BN	Event Analysis of Systemic Teamwork – Broken Nodes
FRAM	Functional Resonance Analysis Method
FTA	Fault Tree Analysis
HE	Hazardous event
HFACS	Human Factors Analysis and Classification Scheme
IE	intermediate event
RCIP	Road Collision Investigation Project
STAMP–CAST	Systems–Theoretic Accident Model and Processes – Causal Analysis using Systems Theory
STEP	Sequential Timed Event Plotting
STS	sociotechnical system(s)

About the report

In June 2018 the UK Government announced that £480,000 of funding was being provided to the RAC Foundation to lead a trial of innovative approaches to road collision investigation. The purpose of the Road Collision Investigation Project is to establish whether there is a business case for investing more resource into the investigation of road crashes to facilitate feedback and learning, in a manner akin to that already in place for the rail, air and maritime sectors within the UK. As part of this three-year project several police force areas in England are recruiting additional staff to collect and collate collision data which will be analysed to identify and understand common themes and patterns that result in death and serious injury on the public highway.

In order to test and trial a different approach to road collision investigation it is important, from the outset, to develop an understanding of the human factors and accident analysis models and methods used in other safety critical contexts. On that basis, following a competitive tendering process, we commissioned Professor Neville Stanton, from the University of Southampton, to advise on an appropriate framework to inform the direction and approach taken by the Road Collision Investigation Project.

The report describes how accident causation models have changed over time and details the rationale for taking a systems approach to collision investigation. A summary, explanation and comparison of key systemic human factors accident investigation models and human factors accident analysis methods is provided, illustrated by a case study from the US where an Uber vehicle was involved in a collision with a pedestrian in March 2018. Professor Stanton concludes with recommendations for the Road Collision Investigation Project taking account of this evidence base.

This report is being published today, as the first of a series of project technical notes and reports to support the development and delivery of the Road Collision Investigation Project. We hope that this report, and subsequent work, will be of interest to those responsible for identifying safety learning from incidents and look forward to continuing the dialogue with a broad range of stakeholders across the safety critical system landscape as we continue to develop this project.

For more information about the project please visit our website. You can also subscribe to our mailing list to receive project updates. The project team can also be contacted via email.

Elizabeth Box

Head of Research, RAC Foundation
Road Collision Investigation Project Manager, RAC Foundation

1. Introduction

1.1 Purpose

The purpose of this report is to make recommendations on how best human factors methods can be applied to the analysis of road traffic collisions, as part of the Road Collision Investigation Project (RCIP) to bring systems thinking to bear, to uncover the causes of road crashes and the contributory factors to their severity. This work follows a report by the director of the RAC Foundation, Steve Gooding (2017), on practical approaches to explore the value of establishing some form of collision investigation branch for roads. This report documents a scoping study comparing eight methods, which were used to analyse the much-publicised collision between an Uber vehicle and a pedestrian wheeling a bicycle that took place in the state of Arizona, USA, in March of 2018, and concludes with advocating an approach which, subject to refinement in use, could be applied through the RCIP to broaden and deepen the learning that could be gleaned from road crashes.

Specifically, this report aims to:

- describe how collision causation models and methods have changed over time;
- provide a summary and explanation of key systemic human factors models and methods;
- give case study examples of human factors collision analysis methods used in transport and other industries;
- apply different models to review how well they capture causal and contributory factors in road crashes, and
- furnish a view on the most appropriate collision analysis method with recommendations for the next steps in the project, including its application.

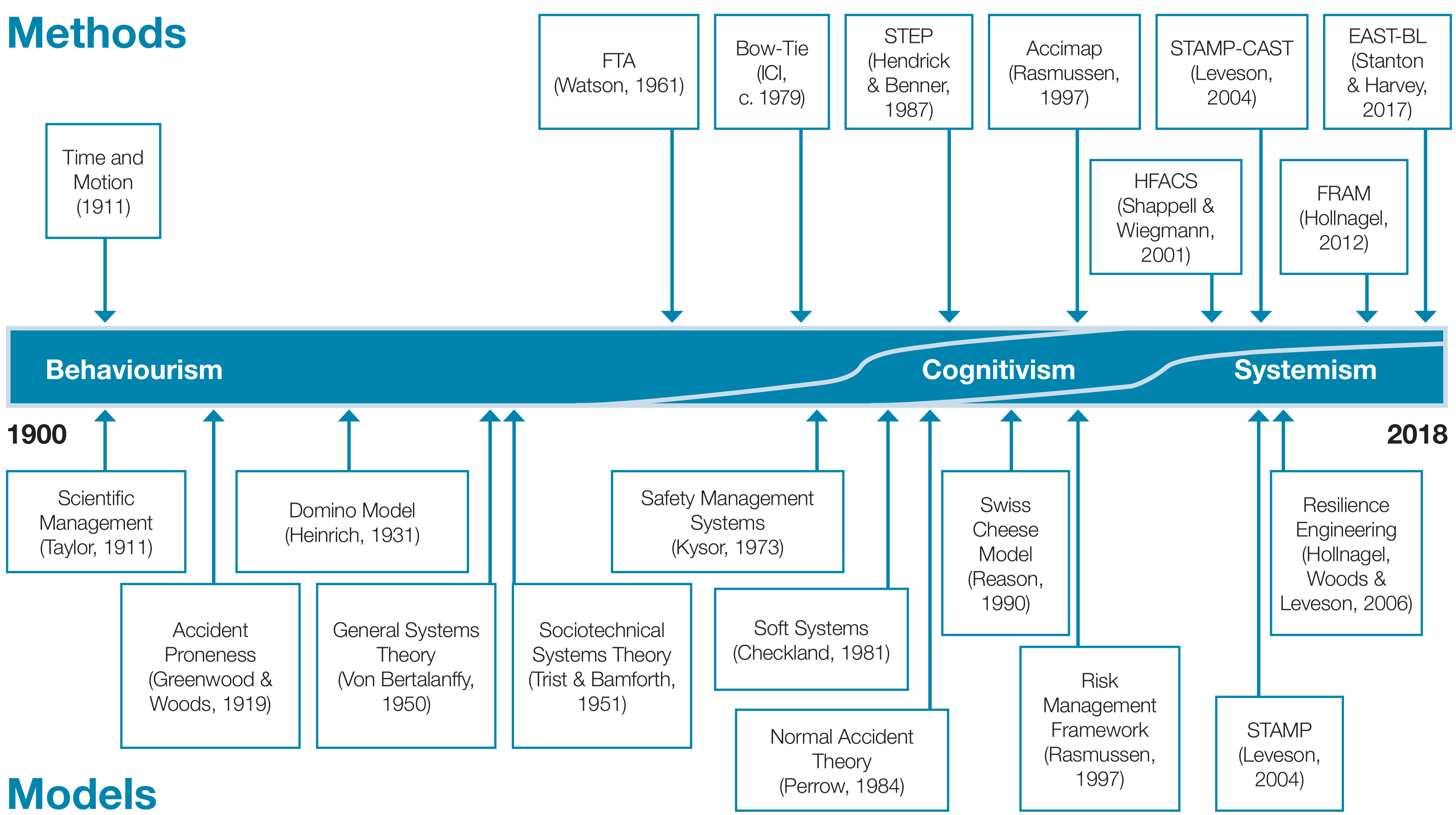
1.2 Background and context: UK road safety compared with other modes

Whilst it is acknowledged that the UK is one of the safest countries in the world in which to travel by road, there are still around 1,700 people killed annually (DfT, 2017; this figure appears to have plateaued over the past ten years), and a total casualty rate of ten times that figure. This compares unfavourably with 9 maritime fatalities in 2017 (MAIB, 2018); 85 aviation fatalities in the UK during the five-year period 2011 and 2016 (79 of these were in general aviation – Eurostat, 2018), in other words upwards of 15 per year; and 309 members of the general public fatalities in rail (of which 273 were suicide or suspected suicide, leaving 36 from other causes) in 2017 (ORR, 2017). Additionally there was 1 rail workforce fatality and 15 passenger fatalities. Air, maritime and rail modes all have accident investigation branches that investigate incidents with the aim of making their transport system safer, and these have had some success – as attested by the very low fatality figures. The comparatively higher figures in road transport have led to the question of whether a collision investigation branch for roads could help to identify interventions that would reduce fatalities and serious injuries (Gooding, 2017). Approaches to collision analysis have changed over the past century, as shown in the following chapter.

2. Timeline of Models and Methods Development

As Figure 2.1 shows, the dominant theories have changed over the timeline between 1900 and 2018. In the early 1900s the focus of attention in incident investigation was the work environment, with legislation being introduced to enhance worker safety. Measures such as systematically recording incidents, providing workers with protection from equipment, breaking work into its component parts (Scientific Management: Taylor, 1911) and investigating incident-proneness (Greenwood & Woods, 1919) led to measures that began to improve the work environment. The cause-and-effect model (classically, the Domino Model as proposed by Heinrich (1931)) epitomises the prevalent view of that time, wherein the aim of incident investigation was to prevent all incidents, with defences and barriers being put in place to prevent incidents from occurring. This focus continued until the 1950s, when modern risk management began. The new approach recognised that zero risk is not achievable, but rather that system safety techniques benefited organisations by *reducing* the frequency of incidents, with the result that interest was stimulated in understanding how and why incidents occurred. Until the 1960s the focus was largely on individual behaviour, with behaviourism as the dominant research paradigm. Dominant models at this point were Scientific Management, Accident-Proneness and the Domino Model. These models have focused on attributing blame to individuals and searching for a root cause of incidents. The associated methods based on these models (i.e. Fault Tree Analysis, Bow-Tie and STEP (Sequential Timed Event Plotting)) are linear and decompositional in nature (presenting events in a sequential manner and breaking them down into their component parts). As such they tend to search for faulty components and place an emphasis on human error.

Figure 2.1: Timeline of selected models (below line) and methods (above line)



Note: (a) Watson's work on FTA for Bell Laboratories in 1961 is referenced by ScienceDirect, undated;
(b) EAST–BL: Event Analysis of Systemic Teamwork – Broken Links;
FTA: Fault Tree Analysis;
FRAM: Functional Resonance Analysis Method;
HFACS: Human Factors Analysis and Classification Scheme;
STAMP–CAST: Systems–Theoretic Accident Model and Processes – Causal Analysis using Systems Theory;
STEP: Sequential Timed Event Plotting

During the 1960s, systems became increasingly diverse, requiring safety systems to become correspondingly more complex, necessitating structures in place to implement, maintain and improve them. In addition, General Systems Theory (Von Bertalanffy, 1950) proposed the idea that all things are composed of systems. In recognition of this, Kysor (1973) introduced the concept of a Safety Management System. A Safety Management System is a system that is used to manage or control safety, or a management system aimed at promoting safety. Whilst there was still a search for a root cause of any given incident, the emphasis on organisational and management features meant that incidents began to be conceptualised as having their genuine root cause in these factors. Alongside this development there were changes that broadened the focus still further to government and international levels, with the Health and Safety Executive being set up in the UK in 1975, increased legislation in Europe, and the World Safety Organization with its international standards being established also in 1975. At the same time a number of major disasters occurred, leading to investigations and the publication of official reports, which in turn increased awareness of the multiple influences that operate when an incident happens. This led to further safety legislation and a shift from individual initiatives to a systemic approach, with large companies integrating safety management into their management framework. There has been an increasing recognition from that period onwards that safety management is a process rather than an outcome.

The rise of cognitivism in the 1970s led to the linking of behaviour to underlying cognitive functions and interaction with the world. This saw an increase in emphasis on psychological factors, with a focus on decision-making, particularly in relation to 'errors'. Reason (1990) made a distinction between 'errors' (unintended acts) and 'mistakes' (deliberate acts, though not malicious in intent). He classifies 'slips' as failures of attention, and 'lapses' as failures of memory. Both slips and lapses are examples of where the action was *unintended*, whereas mistakes are associated with *intended* action, but nevertheless having a poor outcome. A mistake occurs when an actor intentionally performs an action that turns out to be wrong. Therefore mistakes originate at the planning level, rather than the task-execution level, and can thus also be termed planning failures. This thinking has influenced the development of methods that have decisions and actions embedded within them, such as HFACS (the Human Factors Analysis and Classification Scheme) and AcciMap. The STEP method focuses on decisions and actions across time (sequentially), whilst methods such as AcciMap, HFACS and STAMP (Systems–Theoretic Accident Model and Processes) consider decisions and actions across levels of the system.

Although Sociotechnical Systems Theory was originally developed in the 1950s, it took decades to reach mainstream risk management, and has attracted increasing interest in more recent years. It was during the 1980s that the term 'sociotechnical system' was first mentioned in relation to safety management and organisational design (Robinson, 1982). This broadened the scope of investigation to the work system (consisting of the social and technical subsystems in a given environment) as the unit of analysis. Sociotechnical Systems Theory rose in popularity from the mid-1980s with Soft Systems Methodology, Normal Accident Theory and then the Swiss Cheese Model. The Swiss Cheese Model underpins the HFACS method, viewing collisions as happening when factors align in such a way as to produce negative consequences.

Rasmussen (1997) proposed the Risk Management Framework – this highlighted the role of actors at all levels of the system as responsible for safety. This changed the focus of incident investigation from deconstructing what had happened in terms of events, acts and errors, to designing improved systems. The approach shows that there can be many reasons why a collision occurs, and that all of them need to be mitigated if the collision is not to reoccur in the future. The Risk Management Framework provided the theoretical basis for the AcciMaps and STAMP methods.

Resilience engineering was developed in the mid-2000s and has led to the development of FRAM (the Functional Resonance Analysis Method). Finally, the EAST–BL (Event Analysis of Systemic Teamwork – Broken Links) method is based on a general model of Sociotechnical Systems Theory and assesses resilience in the networks. Both approaches recognise that system behaviour cannot be predicted purely by predicting the behaviour of the component parts. Each subsystem will have its own goals and functions. The models need to account for interactions between these subsystems, which may be non-linear. Alongside this there has been a shift from 'human error' to 'human performance variability'. Thus the understanding has moved from the dichotomous conceptualisation of correct and incorrect behaviour to recognising that there is a range of human performance for which systems need to accommodate and offer resilience. Methods such as FRAM and EAST–BL take a holistic approach that is not domain-specific.

It has been argued that systemic approaches are needed to address the complexity of road safety (Salmon and Lenné, 2015). By adopting the Rasmussen (1997) Risk Management Framework, it is possible to view road traffic collisions resulting from:

1. multiple contributory factors rather than a single poor decision/action;
2. multiple system actors, rather than just road users alone;
3. interactions between multiple contributory factors and their emergent properties (i.e. properties beyond the individual person or system component that emerge through their interaction);
4. vertical integration across actors and events at all levels of the system;
5. poor quality of (or absence of) communication and feedback across levels of the system, not just deficiencies at one level alone;
6. migration of system performance over time (at multiple levels of the road transport system), from safe to unsafe, under the influence of various pressures, such as economic and physical resources and constraints; and
7. a combination of triggering events (at multiple levels of the road transport system), each of which is unlikely in isolation to cause significant problems, but all of which occurring together can be catastrophic.

Resilience engineering offers a way of thinking about the dynamics of a system. More resilient systems have a greater ability to return to a stable state after some disturbance. In road transport terms, this means the ability of the road system to either prevent collisions or to return quickly to normal running after a collision has occurred.

The selected methods are reviewed in the following chapter.

3. Methods Selected for Review

Eight methods were selected for the review on the basis of the initial call for proposals (AcciMap, Fault Tree Analysis (FTA), HFACS and STAMP–CAST), reading of the contemporary literature on sociotechnical systems methods (EAST–BL and FRAM) and speaking with collision analysts (Bow-Tie and STEP), as shown in Table 3.1. The literature is vague on the source of the Bow-Tie model, suggesting that Imperial Chemistry Industries (ICI) developed it sometime in the late 1970s.The literature is similarly vague on the source of FTA, suggesting that it was developed in Bell Laboratories in 1962. Sources of all the other methods are provided in the references.

Table 3.1: List of methods and corresponding models

Method	Model type	Pioneer(s)	Date	Source
AcciMap*	Heterarchy	Rasmussen	1997	*Safety Science*
Bow-Tie	Tree structure	ICI	c. 1979	ICI
EAST–BL	Networks	Stanton and Harvey	2017	*Ergonomics*
FTA*	Tree structure	Watson	1961	Bell Laboratories
FRAM	Network	Hollnagel	2012	Book (Ashgate)
HFACS*	Taxonomic	Shappell and Wiegmann	2001	*Human Factors and Aerospace Safety*
STAMP–CAST*	Control structure	Leveson	2004	*Safety Science*
STEP	Multilinear	Hendrick and Benner	1987	Book (Marcel Dekker)

Source: Author's own

Notes: (a) * methods specified in RCIP call for proposals;
(b) Watson's work on FTA for Bell Laboratories in 1961 is referenced by ScienceDirect, undated.;
(c) EAST–BL: Event Analysis of Systemic Teamwork – Broken Links;
FTA: Fault Tree Analysis;
FRAM: Functional Resonance Analysis Method;
HFACS: Human Factors Analysis and Classification Scheme;
STAMP–CAST: Systems–Theoretic Accident Model and Processes – Causal Analysis using Systems Theory;
STEP: Sequential Timed Event Plotting

As Table 3.1 shows, each of the methods is associated with an underlying model type, the pioneer(s) of the method, the date it was developed/published, and its source.

A short description of each of the methods is contained within Appendix A. The application of the AcciMap method to a case study is presented in the next section, and applications of the other methods may be found in Appendix B.

4. Case Studies Based on the Uber Vehicle Collision with a Pedestrian

To make a direct comparison of the methods, a case study was selected to which all of the methods could be applied. This case study was based on the Uber vehicle collision with a pedestrian wheeling a bicycle, which occurred at approximately 21.58 on 18 March 2018 in Arizona, USA. Although the full report by NHTSA (the US National Highway Traffic Safety Administration) was not available at the time of this study, there was sufficient information available to undertake analysis with the methods selected for review (a short preliminary report was available: NTSB, 2018). This analysis is based upon information that was available at the time of writing the report. As the investigation progresses, these details may change and/or further details may come to light. However this is unlikely to change the nature of the comparison of methods, which was the purpose of this exercise. The timeline of the immediate events leading up to the collision, as far as they are known, are presented in Table 4.1.

The background to this collision is that Uber decided to test its automated vehicles in Arizona after being denied testing in California (owing to the requirement for testing permits, a ruling which Uber disputed). The Arizona State governor made it known that he would allow testing without special vehicle permits. Prior to the vehicle testing, Uber recruited and trained drivers to work eight-hour shifts in its vehicles. The role of the drivers was to observe the vehicle and to note events of interest on a central tablet. They were also supposed to regain control of the vehicle in the event of an emergency. In order for the testing to proceed, Uber disabled the Autonomous Emergency Braking (AEB) and the Volvo City Safety system. These systems were removed in order to avoid an erratic ride in the vehicle, such as vehicle braking in the event that objects in the vehicles path were falsely detected. Following the collision of the Uber vehicle with the pedestrian, the testing programme was suspended. There is an ongoing investigation into the collision (NTSB, 2018). Analysis of the collision was undertaken in this paper using all eight methods in order to highlight the differences between the approaches. The AcciMap analysis is presented in this chapter, with the other seven analyses presented in Appendix B. The AcciMap analysis has been chosen here as it offers the most comprehensive description of the collision and was found to be superior in the comparison of methods.

Table 4.1: Timeline of events leading to Uber vehicle collision with pedestrian

Time	Event
18.30	44-year-old Rafaela Vasquez arrives for work at the Uber facilities in Tempe, Arizona.
21.14	Vasquez leaves the Tempe facilities in a self-driving 2017 Volvo XC90 operated by Uber to run an established test route through downtown Tempe.
21.39	The vehicle is switched to autonomous mode.
Unknown	A report from Tempe police alleges that Vasquez began streaming *The Voice* on the *Hulu* app on a smartphone (disputed by Vasquez). During this time the Tempe police allege that Vasquez can be seen frequently looking down at the lower centre console area near her knee and frequently smirking and laughing. Her hands were not visible in the frame of the surveillance footage. Police determine she looks down 204 times over the course of 11.8 miles. Her eyes were off of the road for 6 min 47 sec during this period [i.e. over 25% of time].
21.58 (approx.)	Vasquez looks up while driving northbound on Mill Avenue toward Curry Road, approximately 0.5 seconds before the crash. She attempts to swerve left before striking 49-year-old Elaine Herzberg at 39 mph [speed zone posted at 45 mph] as she crosses the street mid-block. *Hulu's* records also show the streaming of the show ended at this time.
21.59 (approx.)	Vasquez calls 911 and is released later that night after speaking to police. She stated she was monitoring the self-driving system interface and neither her business nor personal phones were in use.

Source: https://eu.azcentral.com/story/news/local/tempe/2018/06/22/fatal-uber-crash-timeline-crash-and-investigation/725921002/; https://www.theguardian.com/technology/2018/mar/28/uber-arizona-secret-self-driving-program-governor-doug-ducey; https://www.bbc.com/news/technology-44243118; https://www.citylab.com/transportation/2018/03/former-uber-backup-driver-we-saw-this-coming/556427/ and https://www.ntsb.gov/investigations/AccidentReports/Reports/HWY18MH010-prelim.pdf

The AcciMap process begins with an Actor Map to identify the main parties that are potentially involved in influencing the collision, as shown in Figure 4.1. The Actor Map in Figure 4.1 shows eight levels of the system, from 'equipment and environment' at the lowest level up to 'international influences', the highest level. The next step is to identify the contribution (or lack of contribution) of each actor that influenced the events leading up to the collision, as shown in the AcciMap in Figure 4.2.

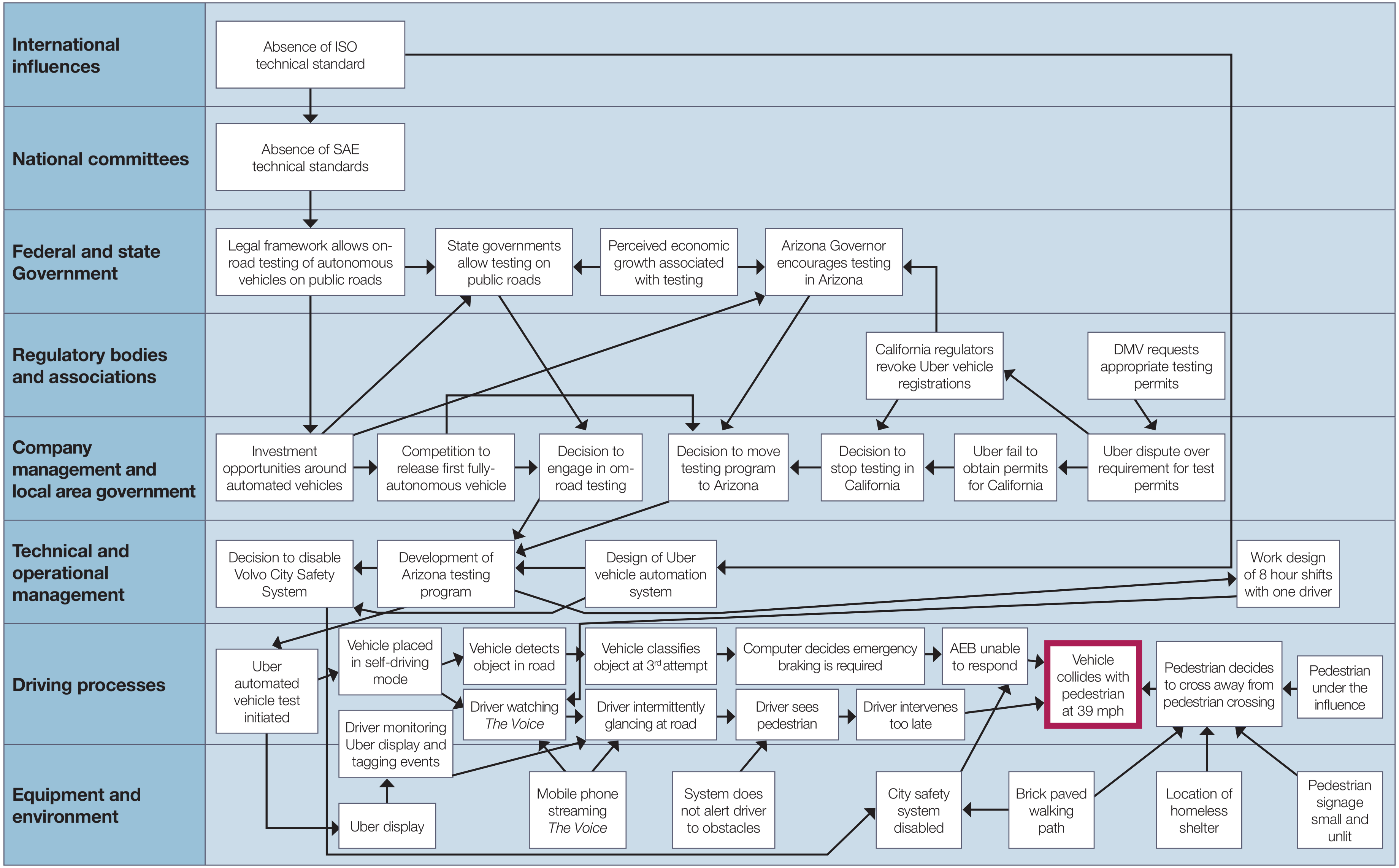
Figure 4.1: Actor Map of the Uber collision with a pedestrian

International influences	International Organization for Standardization					
National committees	Society of Automotive Engineers					
Federal and state Government	Federal Government	California State Government	Arizona State Government			
Regulatory bodies and associations	California regulators	Arizona regulators				
Company management and local area government	Uber	Volvo	Urban planners			
Technical and operational management	Uber engineers					
Driving processes	Driver	Pedestrian				
Equipment and environment	Automated vehicle	Road	Median	Junction	Bicycle	Signage

Source: Author's own

The events, failures, decisions and actions are shown in the boxes with relationships between them indicated by the arrows in Figure 4.2. At the top of the AcciMap, the lack of international and national standards for automation design and testing meant that Uber had no technical guidance for appropriate interfaces, safety standards or testing regimes. Uber was originally planning to undertake its testing in California but there was a dispute over the need for permits to operate an automated vehicle. Uber argued that as a driver was present, no permit was necessary, but the California regulators disagreed and revoked the Uber vehicle registrations. On hearing this, the governor of Arizona encouraged Uber to continue its testing in his state. This decision may have been based on the perceived economic growth expected to follow investment in the development of autonomous vehicles. Uber set up its testing programme in Arizona with plans to conduct on-road studies (there is considerable competition between companies to have the first on-road fully autonomous vehicle). A decision was taken by the Uber engineers to disable the Volvo City Safety system (including the AEB system) as it can induce an erratic ride experience, if false obstructions are detected. Uber recruited drivers who were trained over three weeks to operate the vehicle. They were to work eight-hour shifts, driving around a preset route, monitoring the automated vehicle's functioning and noting any abnormalities or points of interest on a tablet mounted in the centre console. In summary, the task required them to look at the road scene, evaluate the performance of the vehicle and make notes as required on a tablet. As already noted in Table 4.1, the driver looked up about half a second before the collision and, on spotting the pedestrian wheeling a bicycle across the road (taking a direct route to a homeless shelter), she grabbed the steering to attempt a swerve. Although the vehicle automation had identified the pedestrian (on its third attempt) and activated the AEB, it did not respond because the Uber engineers had disabled it. The pedestrian was struck at a speed of 39 mph and died in a local hospital (Titcomb & Sabur, 2018). It was also noted that the pedestrian was not crossing the road at the pedestrian crossing. Although the crossing point had the appearance of a pedestrian crossing, there were small unlit signs stating that the actual pedestrian crossing was further up the road. It is possible that the pedestrian may not have seen the signs (as there was no roadway lighting). The autopsy revealed that the pedestrian was intoxicated with methamphetamine and marijuana.

Figure 4.2: AcciMap of the Uber collision with a pedestrian



Source: Author's own

The AcciMap in Figure 4.2 shows the analysis of the collision together with the many underlying influences that led up to the fatal event. From the collision analysis, it is possible to develop recommendations with the aim of preventing this type of event from reoccurring. Examples of the type of recommendations that could be developed are illustrated in Table 4.2. At the top two levels (international influences and national committees), new standards for vehicle automation and on-road testing are required. Governments and regulatory bodies (the next two levels down) need to develop and enforce new laws for vehicle automation and their on-road testing. At the next level down, the company needs to undertake a comprehensive analysis of human and technical risks, accompanied by task and workload analysis. At the same level, local planners should improve lighting and fence off central reservations where there is a natural crossing point. Technical and operational management need to better understand the demands made on drivers of automated vehicles and share tasks accordingly. The vehicles should be fitted with dual control and two drivers present. The inbuilt vehicle safety systems should be left intact. Finally, at the bottom level, drivers should place all nomadic devices in the glovebox before the vehicle is put in motion. The point here is that collisions do not result from any single point of failure; rather they are systemic and multicausal in nature. To reduce collisions, issues need to be addressed at *all* of the system levels.

The seven other case studies applying the methods to the Uber collision are contained with Appendix B.

Table 4.2: List of potential recommendations

System levels	Potential recommendations
International influences	Develop new standards for vehicle automation (e.g. head-up interface) Develop new standards for on-road testing of vehicle automation (e.g. two testers in vehicle)
National committees	Develop new standards for vehicle automation Develop new standards for on-road testing of vehicle automation
Federal and state government	Develop new laws on vehicle automation Develop new laws for on-road testing of vehicle automation Require permits for on-road testing of vehicle automation
Regulatory bodies and associations	Enforce new laws on vehicle automation Enforce new laws for on-road testing of vehicle automation Enforce permits for on-road testing of vehicle automation
Company management and local area government	Uber: Undertake comprehensive driver task analysis Undertake comprehensive analysis of human and technical risks Analyse the workload of human driver with automation City Planners: Fence off central reservations that are not part of pedestrian crossings Improve highway lighting
Technical and operational management	Conduct pilot studies with human drivers to discover potential problems Share tasks between two drivers to ensure sufficient rests (eyes-out versus eyes-in tasks) and swap tasks regularly Leave safety systems intact (including the AEB) Fit dual controls to vehicle so that both drivers can drive the vehicle manually if required
Driving processes	Ensure that one driver is eyes-out at all times and swap tasks between drivers regularly
Equipment and environment	Place all nomadic devices (such as phones) in glovebox before the vehicle is driven

Source: Author's own

5. Comparison of Methods

A comparison of the methods was undertaken by three human factors experts (see Appendix C) across a range of theoretical, methodological and practical criteria as shown in Table 5.1 to Table 5.4.

As Table 5.1 shows, the systems levels are represented on the vertical axis and the eight methods in alphabetical order on the horizontal axis. It is important that the collision analysis methods are able to address all of the levels in the system, as systemic approaches are most likely to identify underlying, multiple, interacting causes of collisions. Whilst any analyst could subjectively include any level in their analysis, the comparison was based on what is typically analysed and what the methods explicitly guide. The AcciMap and STAMP–CAST methods (highlighted in red) address all of the levels in the system, from equipment and environment at the lowest level all the way up to government policy and budgeting at the highest level. This means that these two methods are recommended from a system coverage standpoint.

Table 5.1: Evaluation of methods against the system levels

Systems levels	AcciMap	Bow-Tie	EAST-BL	FTA	FRAM	HFACS	STAMP-CAST	STEP
Government policy and budgeting								
Regulators and associations								
Local area government, company management								
Technical and operational management & supervision								
Physical processes and actor activities								
Equipment and environment								

Source: Author's own

Table 5.2 shows an evaluation of the methods against the seven tenets of collisions. These tenets are the main principles of collision causation identified in the scientific literature (Rasmussen, 1997). It is important that a collision analysis method is able to account for each of these tenets in its representation. No method covered all seven tenets, and only the AcciMap method (highlighted in red) covered six of the tenets (missing the migration of performance from safe to unsafe). To undertake the latter would require the method to have a dynamic aspect that could animate performance migration. Perhaps it is no surprise that AcciMaps perform well against these criteria as they are based on the original work from Rasmussen (1997). Nevertheless, AcciMap is recommended from a collision tenets standpoint.

Table 5.2: Evaluation of methods against the seven tenets of collisions

Seven tenets of accidents	AcciMap	Bow-Tie	EAST-BL	FTA	FRAM	HFACS	STAMP-CAST	STEP
Multiple contributory factors								
Multiple actors								
Interactions between (contributory) factors								
Vertical integration								
Communications and feedback								
Migration of performance from safe to unsafe								
Triggering event(s)								

Source: Author's own

An evaluation of the eight methods against seven methodological criteria (as shown in the vertical axis of Table 5.3) was also undertaken. The AcciMap and FTA (highlighted in red) were rated as having more methodological integrity than the other six methods by the experts. The lack of an inbuilt classification scheme is judged to be a weakness in both of these methods. Nevertheless, the AcciMap and FTA are recommended from a methodological standpoint.

Table 5.3: Evaluation of methods against the methodological criteria

Methodological criteria	AcciMap	Bow-Tie	EAST-BL	FTA	FRAM	HFACS	STAMP-CAST	STEP
Evidence of reliability	Medium	N/A	N/A	High	N/A	Medium	N/A	N/A
Evidence of validity	Medium	N/A	N/A	High	N/A	Medium	N/A	N/A
Complexity of approach	Low	Medium	Medium	Medium	High	Low	High	Low
Reliance on subject matter experts	Medium	Medium	High	High	Medium	Medium	High	Medium
Auditability and traceability of system influences	High	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Applicability to analysis of road traffic accidents	High	Medium	Low	Medium	Low	Medium	High	High
Inbuilt classification scheme of contributory factors	No	No	No	No	No	Yes	Yes	No

Source: Author's own
Note: N/A = not applicable

Finally, an evaluation of the eight methods against six practical criteria (see the vertical axis of Table 5.4) was undertaken. These include usability criteria and evidence of practical impact. The AcciMap method (highlighted in red) was rated as more practical than the other seven methods by the experts.

Table 5.4: Evaluation of methods against the practical criteria

Practical criteria	AcciMap	Bow-Tie	EAST-BL	FTA	FRAM	HFACS	STAMP-CAST	STEP
Ease of use (high = easy)	High	Medium	Medium	Medium	Low	High	Low	High
Application time (low = quick)	Low	Medium	Medium	Medium	High	Medium	High	Medium
Training demand (low = little training demand)	Low	Medium	High	Medium	High	Low	Medium	Low
Simplicity of interpretation (high = simple)	High	High	Medium	High	Low	High	Medium	High
Tools required (low = no tools above pen and paper)	Low	Low	Low	Low	Medium	Medium	Medium	Low
Evidence of practical impact (high = good)	Medium	High	Low	High	Medium	Medium	Medium	Medium

Source: Author's own

In summary, the AcciMap method was evaluated as performing best across all of the theoretical, methodological and practical criteria. As such, it is the recommended approach for the RCIP studies.

6. Recommendations

This report has sought to present a view on collision analysis methods and their applicability to road collisions. Expert judgment has been used to compare the eight methods selected for review, and these have been applied to a case study, with this application presented so that their analysis and representation can be better understood. From this analysis, the Actor Map and AcciMap methods are recommended and next steps for the Road Collision Investigation Project (RCIP) have been developed.

- **Develop classification scheme for Actor Maps and AcciMaps**

To help with the consistency of reporting and aggregation of data, classification schemes need to be developed for the Actor Maps and AcciMaps. A recent study has already presented an Actor Map scheme for the UK (McIlroy et al., 2018), which would provide a good starting point.

- **Matrix for linking of events in AcciMaps**

To improve the usability of the AcciMap method, a matrix for associating events at the same and different levels in the system hierarchy should be developed. This should make it easier for analysts to construct AcciMaps.

- **Development of training materials for Actor Maps and AcciMaps**

A training package needs to be developed for training analysts in the construction of Actor Maps and AcciMaps.

- **Pilot study of training in Actor Maps and AcciMaps**

A pilot study should be conducted with the training package so that the materials can be evaluated and refined before delivery. This will also offer the opportunity to conduct early studies of reliability and validity of the Actor Map and AcciMap methods.

- **Revision of training materials**

The training materials will need to be revised in light of the pilot study before final delivery.

- **Rollout of training for RCIP study**

The training needs to be delivered to those analysts participating in the RCIP. Studies of the reliability and validity of the Actor Map and AcciMap methods also need to be conducted alongside the training. Studies of adherence to the Actor Map and AcciMap methods should be conducted at intervals across the lifetime of the RCIP.

Appendix A: Description of the Methods

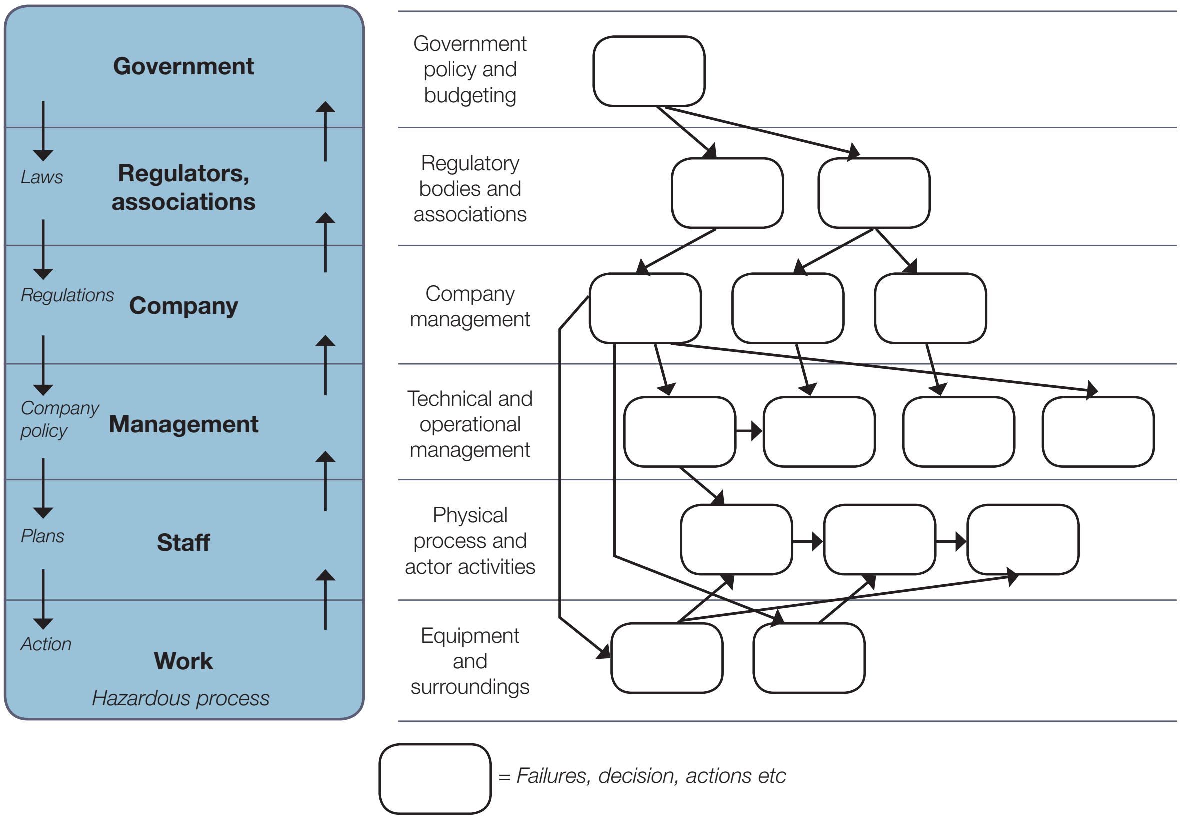
A description of each of the eight methods being considered in the evaluation is presented in alphabetical order with a brief description and the accompanying model.

ACCIMAP is based on Rasmussen's (1997) Risk Management Framework. He used a road traffic collision to demonstrate the AcciMap analysis, giving the example of an oil truck which crashed, disgorging oil into a reservoir. Accimap is a generic approach which has been widely used in many different domains. Normal variations in behaviour (rather than exceptions) are seen to result in collisions within the system. The method identifies and links contributory failures (both top-down and bottom-up) across six levels of the sociotechnical system (government, regulators/associations, company, management, staff, work) so that countermeasures can be put in place (see Figure A.1).

The **strength** of this approach is that it is holistic, describing failures across the system and allowing measures to be identified to ameliorate for this. The lack of taxonomies makes it flexible to fit different domains.

There are **limitations**, however. It does not specifically identify cognitive factors, and it highlights decisions rather than the factors influencing those decisions. The lack of taxonomies means that it is dependent on the subjective judgment of the analyst, which may impact on its reliability. Moreover, without taxonomies, aggregate analysis of multiple collision cases becomes more difficult. The output in diagrammatic form is quite complex.

Figure A.1: The AcciMap model



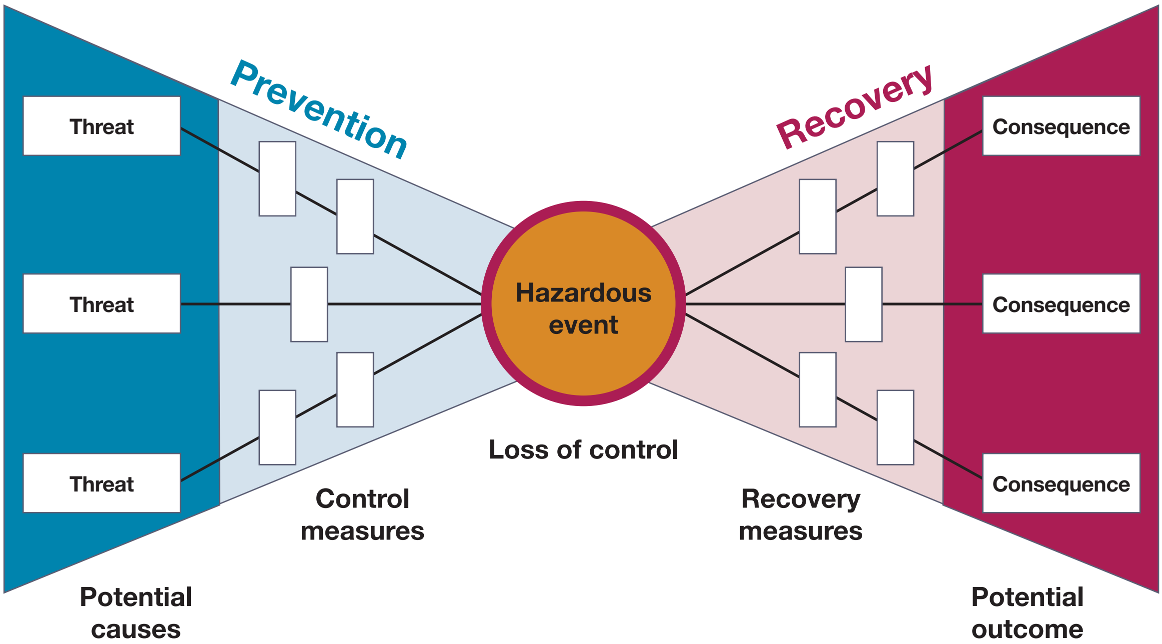
Source: Svedung & Rasmussen (2002)

BOW-TIE has its origins in process engineering. It shows the relationship between the causes and consequences of an event in a Bow-Tie diagram (see Figure A.2) – so called owing to its shape, which obviously resembles a bow tie. In the centre of the Bow-Tie diagram is the hazardous event (HE). The left wing of the bow uses Fault Tree Analysis to show the relationship between the possible causes (and possible mitigating control and recovery safety measures, current or planned) of an event. The right wing of the bow uses event tree analysis to show the relationship to the consequences (and possible recovery measures, current or planned) that may follow the event. Thus the Bow-Tie method generates a diagram that identifies: the HE, the causes that may lead to the HE, the consequences that may result from the HE, and the safety measures that may change the likelihood of the causes (proactive safety measures) or the consequences (reactive safety measure) of the HE.

The **strength** of the model is that it gives a clear causes/consequences diagram of the incident and it can be used to model likely scenarios.

The **limitations** are that it is a sequential model, and as such does not show interactions between the risk factors; moreover, it does not take into account the higher levels, such as policy and regulation.

Figure A.2: The Bow-Tie model



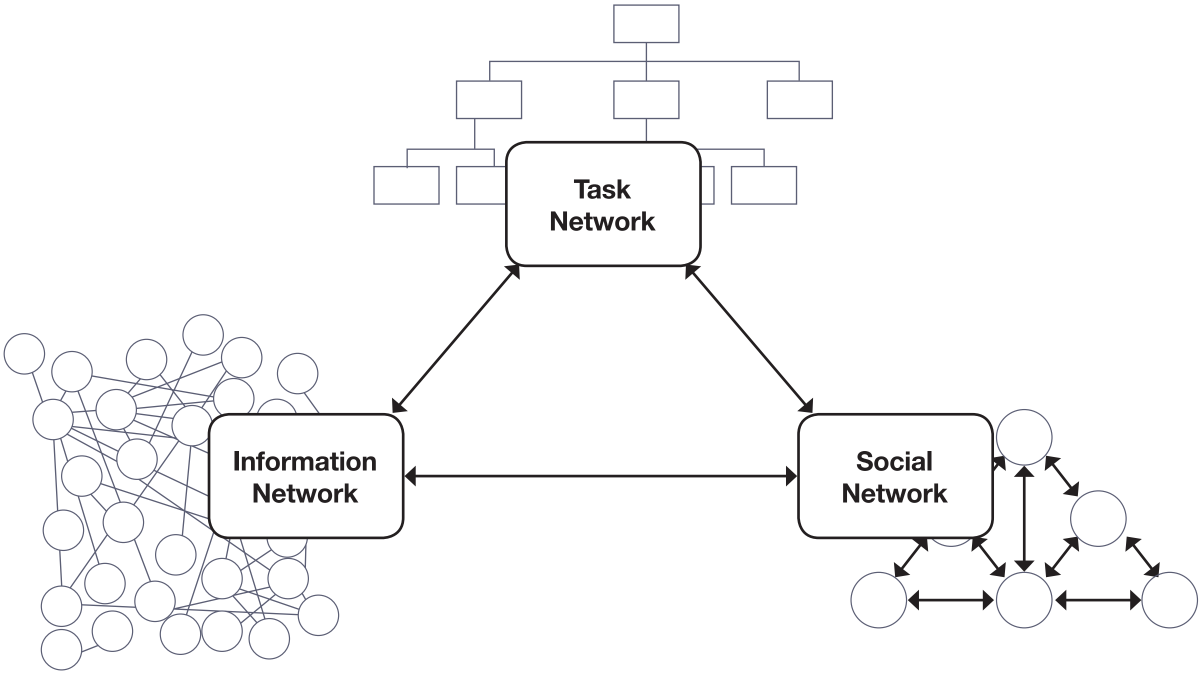
Source: https://slideplayer.com/slide/12655534 (slide 8)

EAST–BL (Event Analysis of Systemic Teamwork – Broken Links) views collisions as a consequence of variability in human performance, leading to a failure to communicate information via social and task networks (see Figure A.3). EAST analyses the communication of information in the system, providing a clear visual representation of the system, the key agents in decision-making, and the relationship between individual components. When applying EAST analysis, the social, task and information systems are developed separately and then combined into a network diagram. The first step is to conduct an AcciMap analysis, placing subsystems within the sociotechnical systems (STS) at different levels, showing the links for decision-making and communications between related nodes. In this way, network diagrams are constructed showing the main agents and their relationships. These allow quantitative SNA (social network analysis) metrics to be calculated. For each EAST network, key nodes (i.e. those with the largest number of connections) and key agents are identified. EAST analysis can be used to analyse events prospectively (Broken Links) or retrospectively (Broken Nodes). The analysis in this document is undertaken using broken-node analysis (as it is an event that has already taken place). Broken nodes are failures of the nodes in the social, task and information networks. Broken nodes are identified and the consequences are analysed.

The **strength** of EAST–BN (Event Analysis of Systemic Teamwork – Broken Nodes) is that it provides an integrated and holistic approach to interrogating the social, task and information aspects of the STS. It provides a comprehensive model of nodes and links with information flow that can be applied in any domain.

The **limitation** is that diagrams can be complex.

Figure A.3: The EAST model



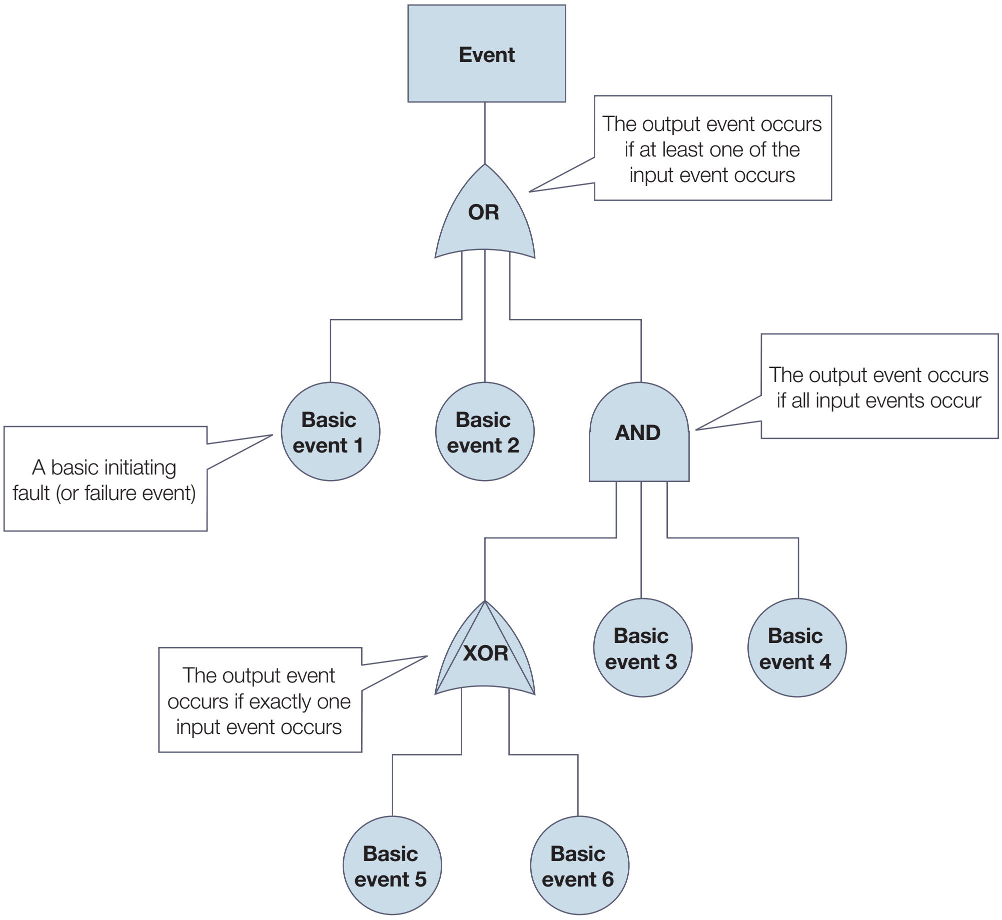
Source: Stanton et al. (2018)

FTA (Fault Tree Analysis) provides a visual representation that identifies and analyses the risk factors involved in a particular incident or event. FTA can be used pre-event to look at possible causes and mitigating measures, and post-event to analyse collisions that have happened. The first step in FTA is to establish a top event (see Figure A.4). All the possible ways that this event could have occurred are then listed. Each option is investigated, using ‘AND’/‘OR’ gates to link the events into a tree. The gates represent ways in which human/ machine interactions can produce events. ‘AND’ gates mean that both events need to occur for the output event to occur, while ‘OR’ gates mean that only one is necessary. Then a Boolean expression is used to determine ‘cut sets’. These are the components in a system which, when they fail, result in system failure.

The **strength** of an FTA is that it is a sequential model describing and analysing the events leading up to an incident and highlighting countermeasures that could be put in place to ameliorate this.

The **limitations** are that continuous and concurrent events are hard to represent in the model, and the interactions between components are not adequately shown. Further, FTA does not take a systems approach and could be said to be reductionist in understanding risk and safety management, if one accepts the premise that a complex system cannot be understood simply by looking at the system’s component parts.

Figure A.4: The fault tree model



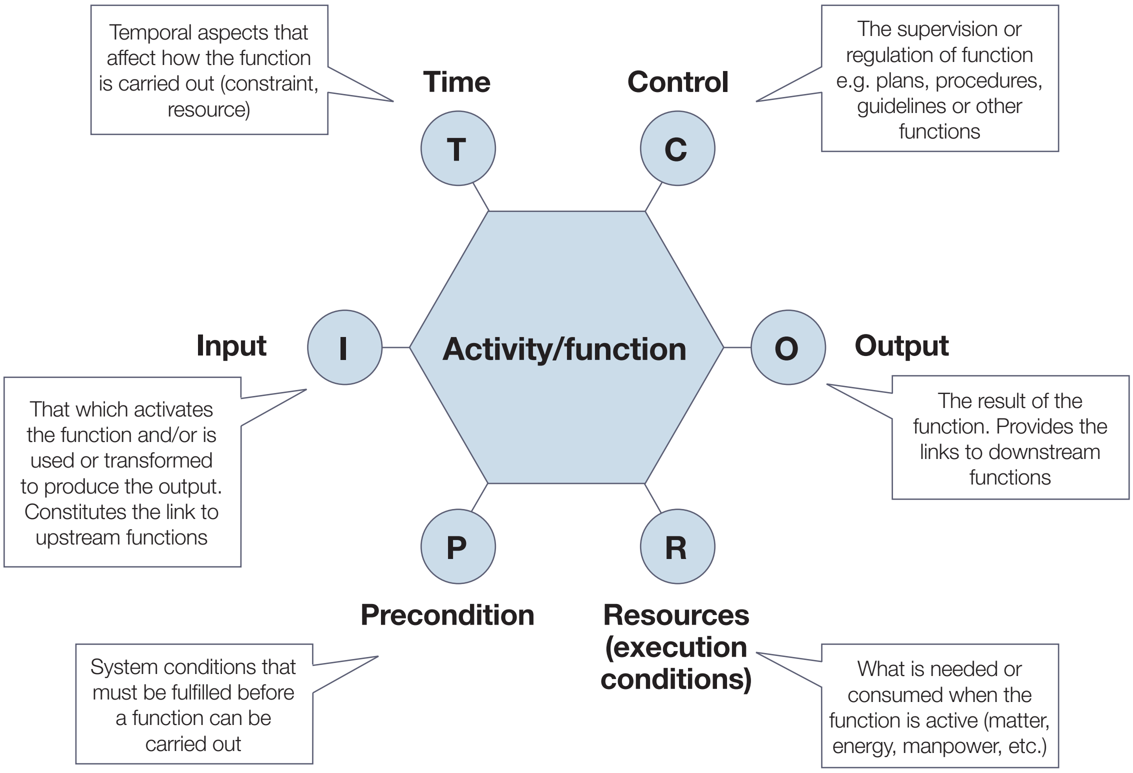
Source: https://conceptdraw.com/a362c3/p1/preview/256

FRAM (Functional Resonance Analysis Method) is based on the principle that variability in performance is both normal and necessary, also that the combination of normal variability can lead to unexpected consequences that can exceed normal limits and result in a critical incident. The FRAM method develops a diagrammatic model of the system and system behaviour illustrating the dynamic nature of interactions. Where functions interact they are described as 'couplings' (see Figure A.5). Couplings may occur only under certain circumstances. It could be that normal variability on its own may not create a problem, but when it occurs alongside other variability it can lead to excessive variability and an incident occurs. The FRAM method entails first identifying and describing the system functions, then specifying the variability and links between functions. Finally measurers/barriers that monitor or reduce unwanted variability are highlighted.

The **strengths** of FRAM are that it looks at normal performance and its variability. It also considers interactions between functions and their cumulative affect. In this way it takes a systems approach to provide the what, when, how and why of the incident. It can be used to identify potential risks and countermeasures to put in place, as well as after an event to identify causes.

One **limitations** of FRAM is that it does not consider the higher levels of functioning such as government and regulatory bodies.

Figure A.5: The couplings model



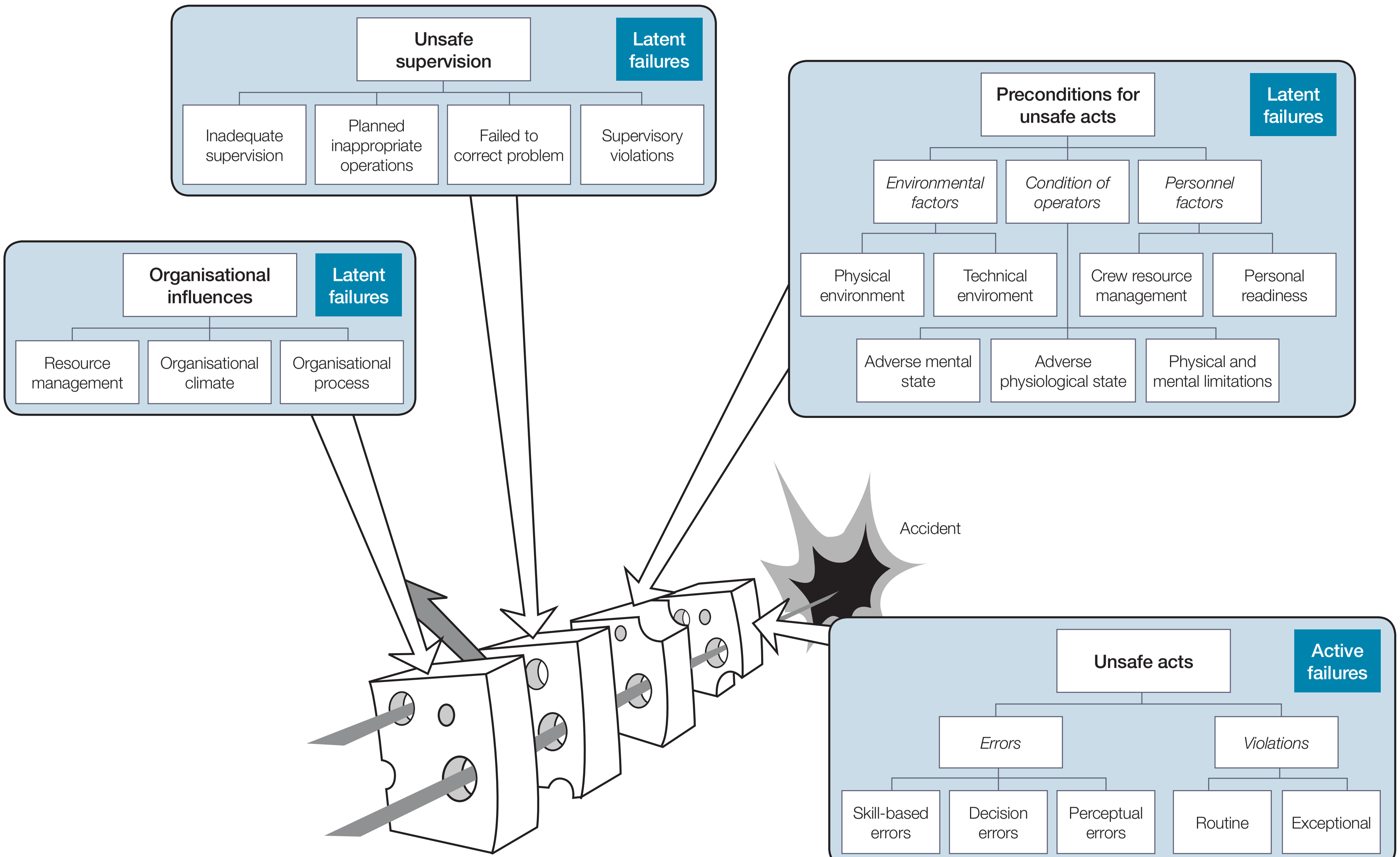
Source: https://www.slideshare.net/stargate1280/overview-of-systemic-modeling-approaches (slide 12)

HFACS (Human Factors Analysis and Classification Scheme) is a taxonomy-based collision analysis method, initially developed for the aviation industry. It is based on Reason's Swiss Cheese Model. It classifies and links failures across four levels (see Figure A.6). It identifies human and system contributions so that countermeasures can be deployed to prevent or reduce further collisions. HFACS protocol begins with the analysis of primary reports. Data is categorised according to the taxonomy.

The **strength** of taxonomy-based methods is that they make themes in causal factors easy to identify, and also enhance reliability. They lend themselves to multiple-case analyses. A visual representation is produced which is clear and easy to read.

The **limitation** is that taxonomies can constrain the classification to certain types of failures, and they need to be developed to be domain-specific. Having only four levels means that higher levels, such as government and regulators, are not considered; however, more recent analyses have extended HFACS to include 'government' and 'other' categories.

Figure A.6: The HFACS model



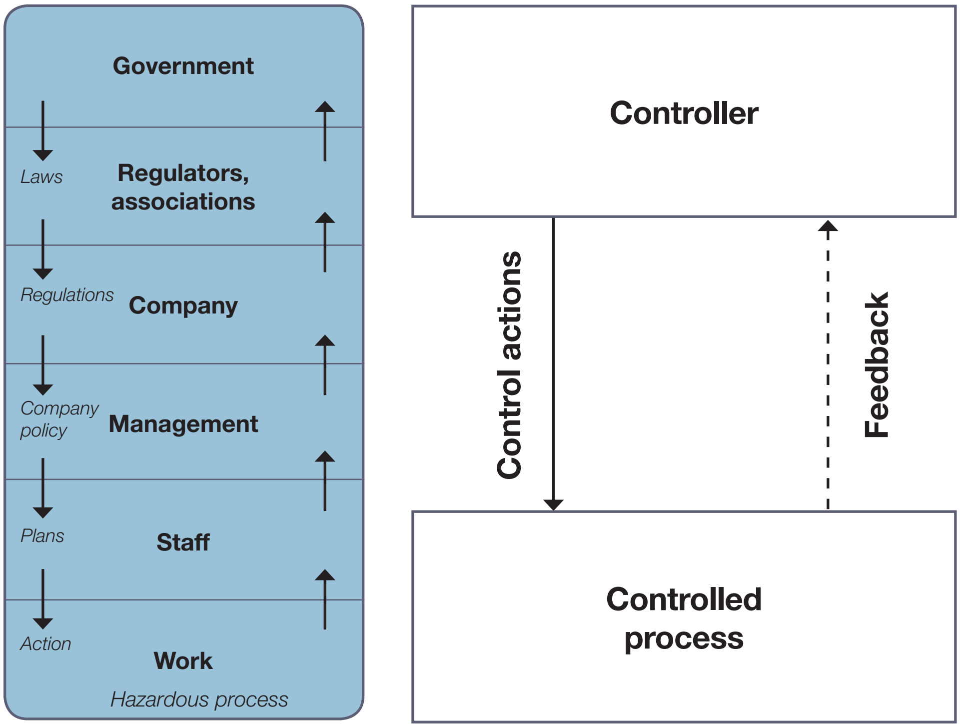
Source: Salmon et al. (2012)

STAMP (Systems–Theoretic Accident Model and Processes) is based on Sociotechnical Systems (STS) Theory, which is generic rather than domain-specific. It can be used for collision analysis post-event and/or risk analysis pre-event, and provides an overview whereby systems are seen as having hierarchical levels, each with a control structure. Controls enforce constraints, resulting in safe behaviour. Controls and constraints operate bottom-up and top-down between levels. Rather than incidents being viewed as the consequence of events, they are seen as resulting from control failures (i.e. inadequate enforcement of constraints or lacking/inaccurate constraints). The system must have an adaptive feedback mechanism of control and information. Systems–Theoretic Accident Model and Processes – Causal Analysis using Systems Theory (STAMP–CAST) proposes a taxonomy of control failures using observations and scenarios as data collection methods. It accounts for cognitive factors by considering the context for decisions and including a ‘mental model flaws’ category. The first step in carrying out a STAMP–CAST analysis is to model levels of the STS (see Figure A.7). Next, the potential or actual collisions to be considered, and the control flaws and hazards are identified (see Table A.1). Then a model of the functional control structure is created, specifying potential unsafe control actions and how they could occur. Lastly, remedies are suggested. The output consists of two stages: the control structure and then a more detailed analysis of key personnel selected from the control structure.

The **strength** of constructing a control structure diagram is that a deeper representation of the system is developed, which provides a more comprehensive understanding than linear models and allows modelling of future scenarios to aid collision prevention. The whole system, including social and organisational factors, is considered, with the interactions that lead to collisions being identified. Thus appropriate countermeasures can be specified and put in place.

The **limitations** of this approach are the time taken and knowledge required to construct the control structure diagram. Moreover, it can be more suited to technical and control failures, with environmental factors being more challenging to fully consider, and complex human and organisational factors being harder to place. It also assumes a hierarchical model but relationships between the agencies and agents are not necessarily hierarchical.

Figure A.7: The STAMP model



Source: Rasmussen (1997); Leveson (2011)

Table A.1: Classification of key hazards in STAMP–CAST

Control flaw	Hazard
Inadequate enforcement of constraints (control actions)	• Unidentified hazards • Design of control algorithm (process) does not enforce constraints • Inadequate co-ordination among controllers and decision-makers
Inadequate execution of control action	• Communication flaw • Inadequate actuator operation • Time lag
Inadequate or missing feedback	• Not provided in system design • Communication flaw • Time lag • Inadequate sensor operation (incorrect or no information provided) • Inadequate co-ordination among controllers and decision-makers

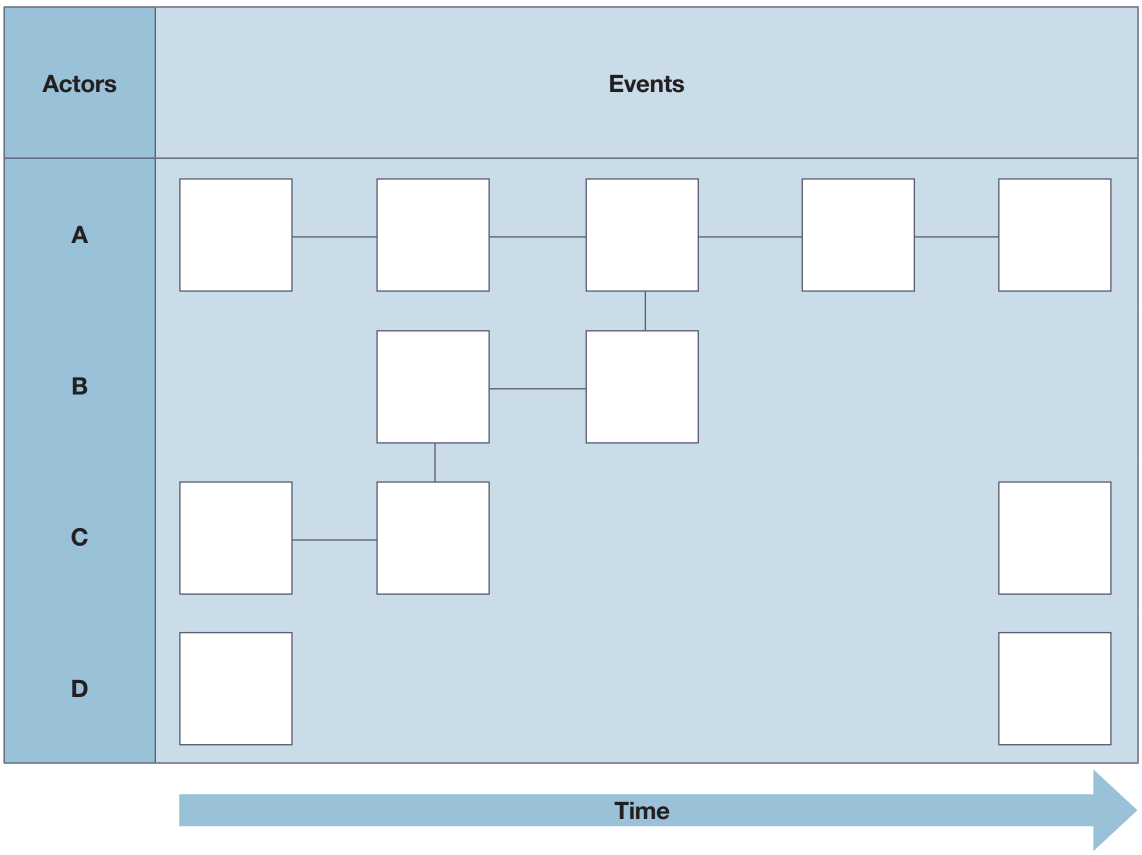
Source: Author's own, based on Leveson (2012)

STEP (Sequential Timed Event Plotting) is a sequence model that plots a timeline of events from the start to finish of a critical incident. Each actor is specified on the left-hand axis of a STEP worksheet with time running along the y-axis (see Figure A.8). Each event/action performed by an actor is represented by a 'building block', which has information on the time, duration, agent, event/action and source. Directional arrows show the relationships between events. In this way, STEP provides a visual representation of the events in a logical order, showing events happening in sequence or in parallel and the nature of any interaction between them. Once the worksheet has been completed, the backSTEP technique is used to work from end to start of the incident and ensure that all events are listed and the building blocks are placed accurately. The worksheet is then analysed to identify safety problems (represented by a triangle) and specify countermeasures.

The **strengths** of STEP are that it is relatively simple to use and offers a clear description and analysis of the 'what happened when' so that countermeasures can be identified and put in place. By highlighting the interactions in the incident it demonstrates the impact of one agent/event on another.

However, the **limitations** are that its scope in that it does not represent workplace, management, regulatory or government factors, and it does not offer a systems analysis of the critical incident.

Figure A.8: The STEP model



Source: www.hhs.iup.edu/CJANICAK/SAFE541CJ/Module3Right.htm

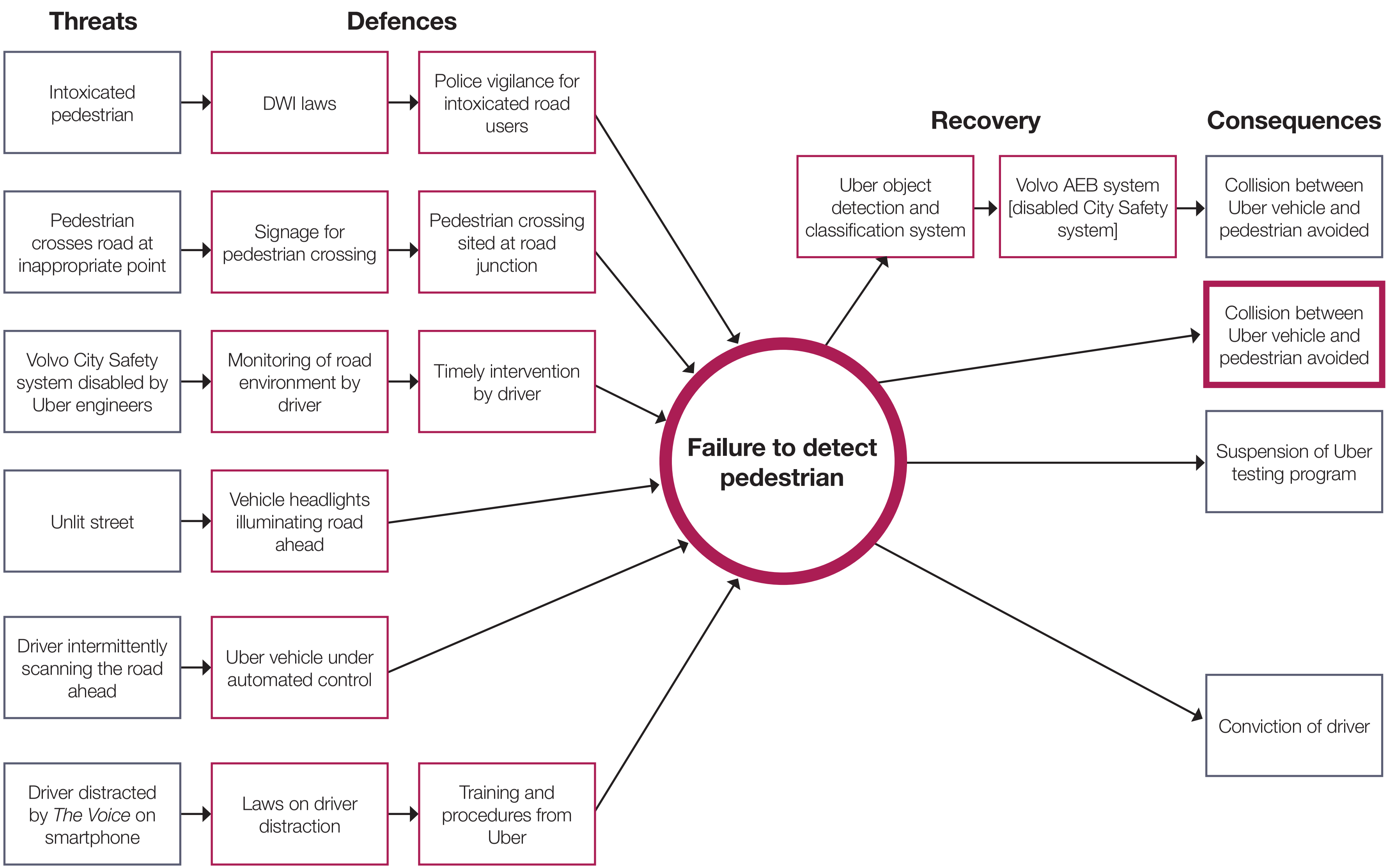
Appendix B: Case Studies Applying the Methods to the Uber Collision

The further seven case studies are presented in alphabetical order of the method name (the AcciMap analysis, recall, was presented in Chapter 4). Each is accompanied by a brief description of the way in which the method represents the Uber collision with the pedestrian. This analysis is based upon information that was available at the time of writing the report. As the investigation progresses, these details may change and/or further details may come to light. However this is unlikely to change the nature of the comparison of methods, which was the purpose of this exercise.

BOW-TIE represents the threats on the left-hand side of Figure B.1 (i.e. the pedestrian intoxicated with methamphetamine and marijuana, the pedestrian crossing the road at an inappropriate point, the disablement of the Volvo City Safety system by the Uber engineers, the unlit street, the driver scanning the road ahead only intermittently, and the driver allegedly watching *The Voice* on a smartphone). The corresponding system defences are highlighted in red after each of the threats. These defences, if activated, are supposed to prevent each of the threats from leading to a hazard (which is represented in the circle in the centre of the figure, i.e. failure to detect pedestrian).

None of the defences worked in this case. Potential recovery mechanisms are presented before the consequences as they could, if activated, mitigate the outcome. In this case, although the Uber system did eventually detect and classify the pedestrian, it was unable to activate the AEB system because it had already been disabled by the Uber engineers. This led to the consequences: the collision between the Uber vehicle and the pedestrian, the suspension of the Uber testing programme, and the police considering whether the driver should be prosecuted.

Figure B.1: Bow-Tie analysis of the Uber collision with a pedestrian



Source: Author's own

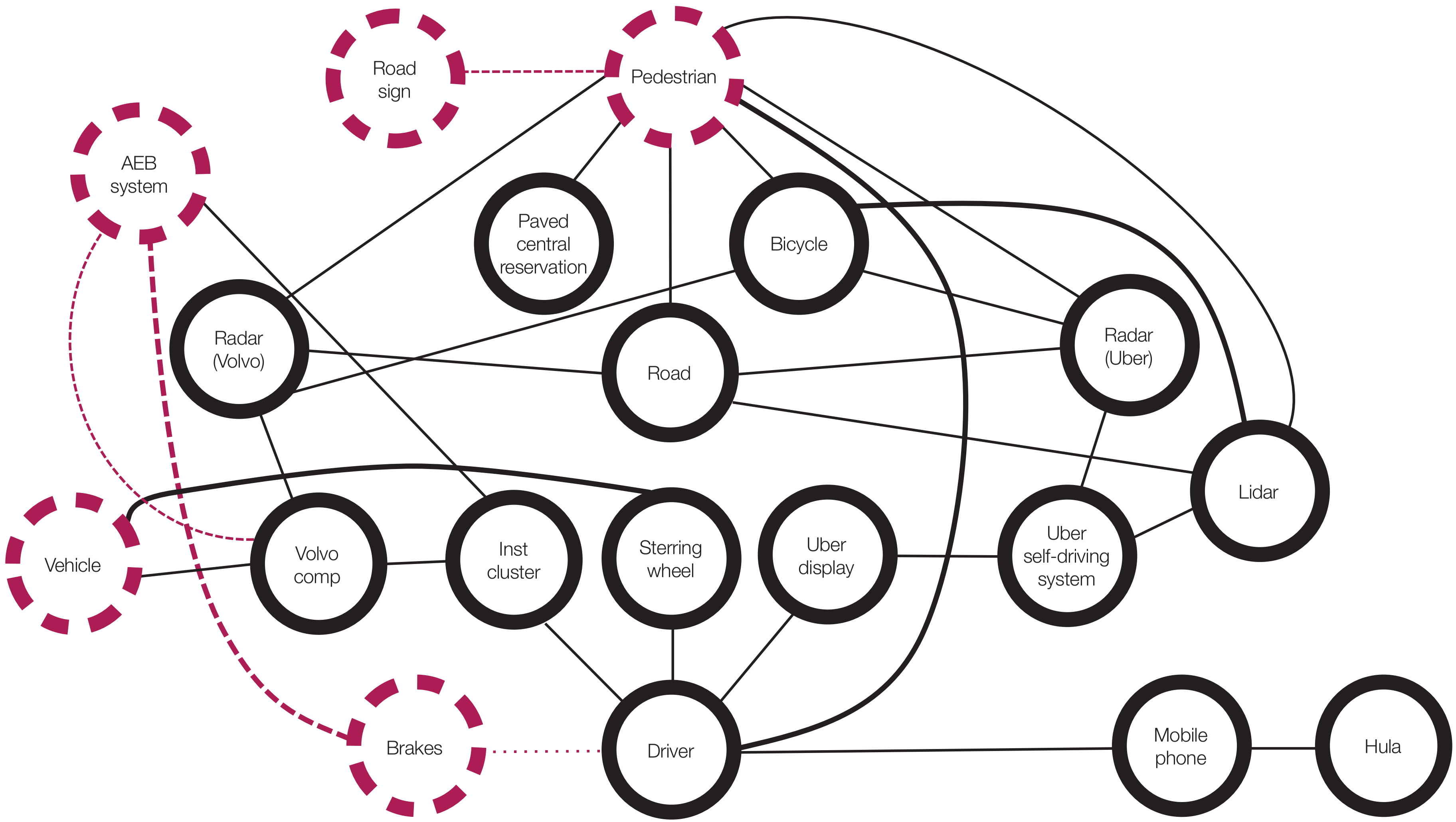
EAST–BN (Event Analysis of Systemic Teamwork – Broken Nodes) represents the task (bottom left), information (top right) and social (bottom right) networks for the Uber collision analysis in Figure B.2. (Recall that the BN – 'Broken Nodes' – version of this method is used to analyse retrospectively.) The broken nodes are represented by the red dashes in the three networks. A broken node is one that is performing suboptimally. There were 9/16 broken nodes in the task network, 8/26 broken nodes in the information network and 5/19 broken nodes in the social network.

For example, in the social network Figure B.2a, the pedestrian did not obey the no-crossing sign, but the no-crossing sign was small and unlit. Similarly, the vehicle did not brake for the pedestrian, but the AEB system had been disabled.

In the task network Figure B.2b, the pedestrian did not read the sign and find a safe place to cross, nor check the road for traffic. The vehicle did not monitor the driver's alertness, nor provide them with warnings when the need to take manual control arose. Similarly, the driver did not monitor the driving environment or behaviour of the vehicle adequately, nor did they take over manual control before the collision was unavoidable.

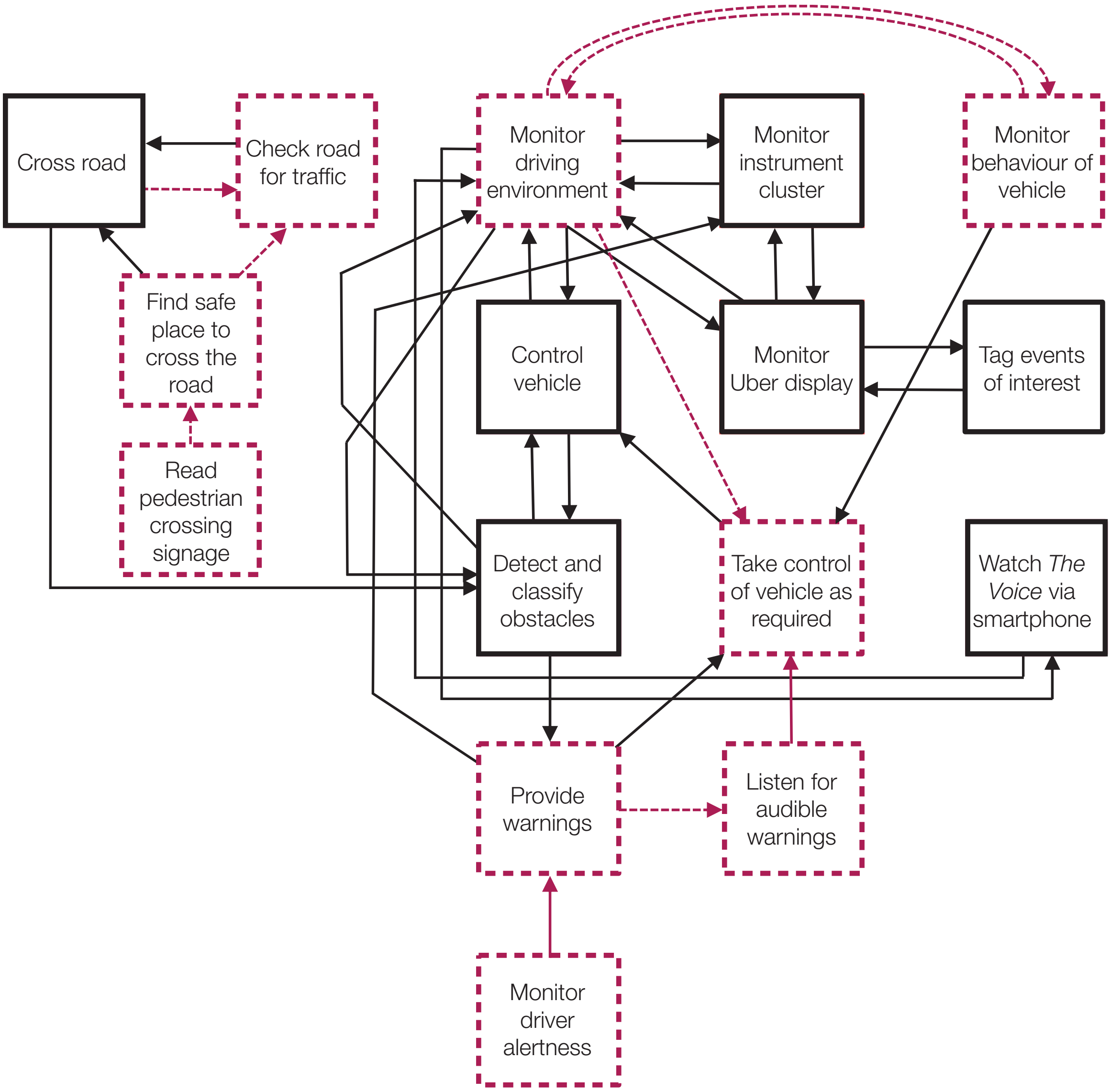
In the information network Figure B.2c, the pedestrian did not use the information from the signage to cross further up the road. The Uber vehicle automation system had problems in classifying the pedestrian, first classifying it as unknown, then as a car and finally as a bicycle. With the obstacle detected, it could not evoke the AEB as it had been disabled. Finally, it has been alleged that the driver was attending to *The Voice* rather than the road environment, which led to a very late detection of the pedestrian.

Figure B.2b: EAST–BN analysis of the Uber collision with a – the social network



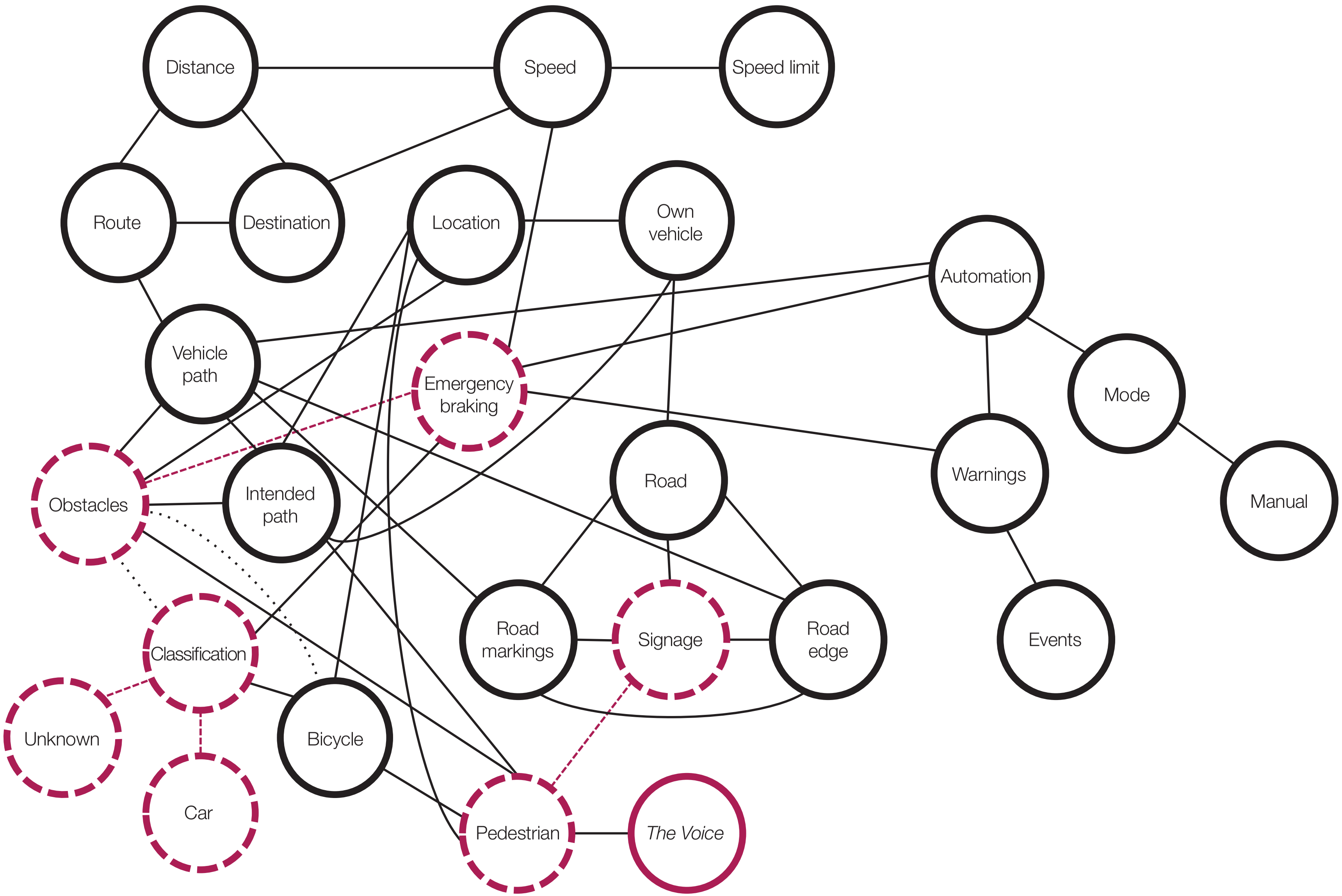
Source: Author's own

Figure B.2a: EAST–BN analysis of the Uber collision with a – the task network



Source: Author's own

Figure B.2c: EAST–BN analysis of the Uber collision with a – the information network

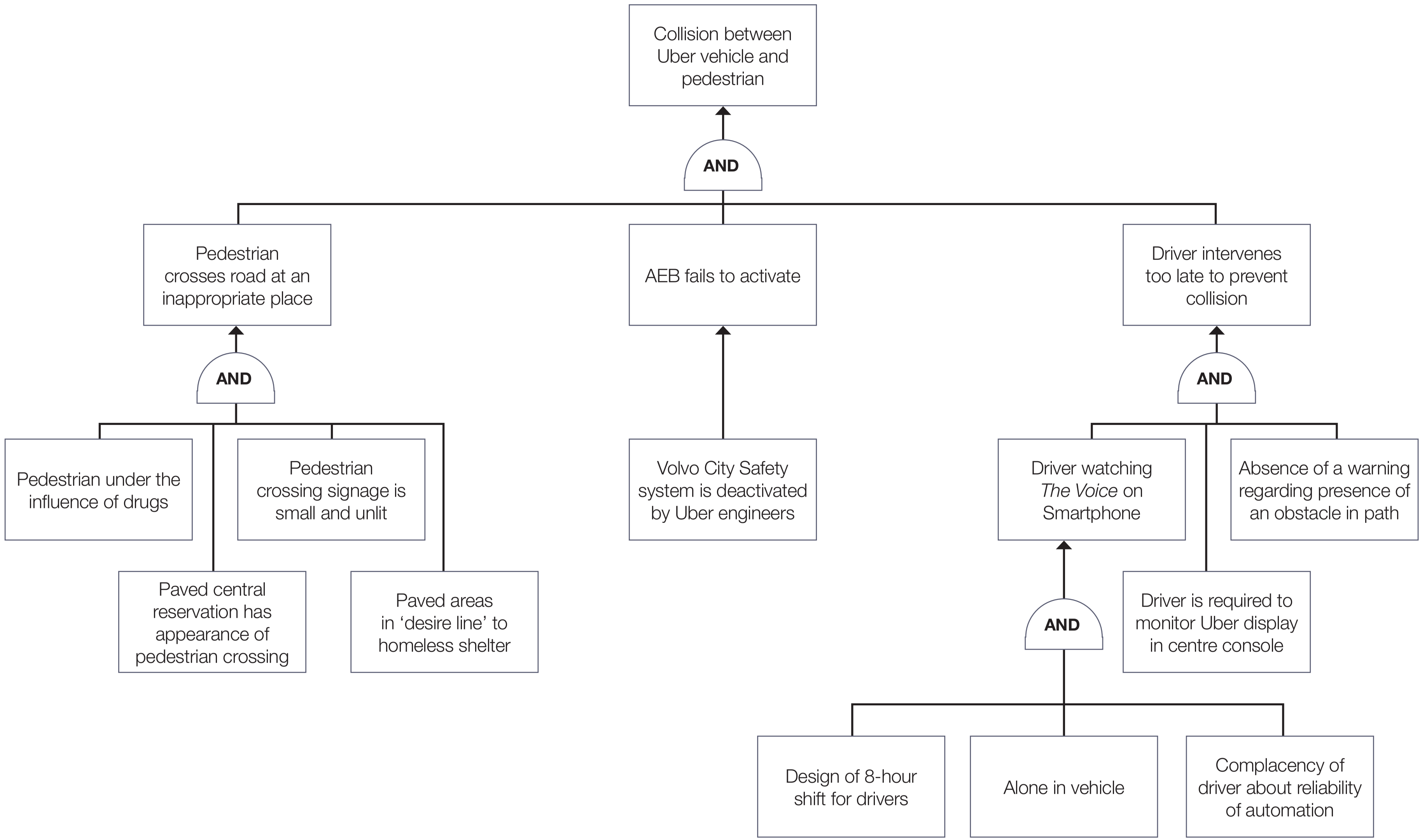


Source: Author's own

FTA (Fault Tree Analysis) presents all of the immediate factors that led to the collision between the Uber vehicle and the pedestrian (which is the top event in Figure B.3). As this analysis is representing a real event, there are no ‘OR’ gates, just ‘AND’ gates.

In this case, the pedestrian chose to cross the road at an inappropriate point, which was probably due to a combination of being under the influence of drugs, the paved central reservation having the appearance of a pedestrian crossing, the pedestrian crossing signage being small and unlit, and the paved area being in the desire line to the homeless shelter (the path the pedestrian was taking). The AEB failed to activate because it had been disabled by the Uber engineers (because they thought the Volvo City Safety system would trigger at false obstacles and cause erratic driving of the autonomous vehicle). Finally, the driver intervened too late to prevent the collision, which was probably due to a combination of allegedly watching *The Voice* on a smartphone, being required to monitor the Uber display on the centre console, and the absence of a warning to alert the driver to the presence of an obstacle in the path of the vehicle. The reasons why the driver was allegedly watching *The Voice* on a smartphone could be related to the design of eight-hour shifts in an automated vehicle with repetitive work, being alone in the vehicle, and a sense of complacency about the reliability of the automation. All of these factors combined to produce the collision.

Figure B.3: Fault Tree Analysis of the Uber collision with a pedestrian



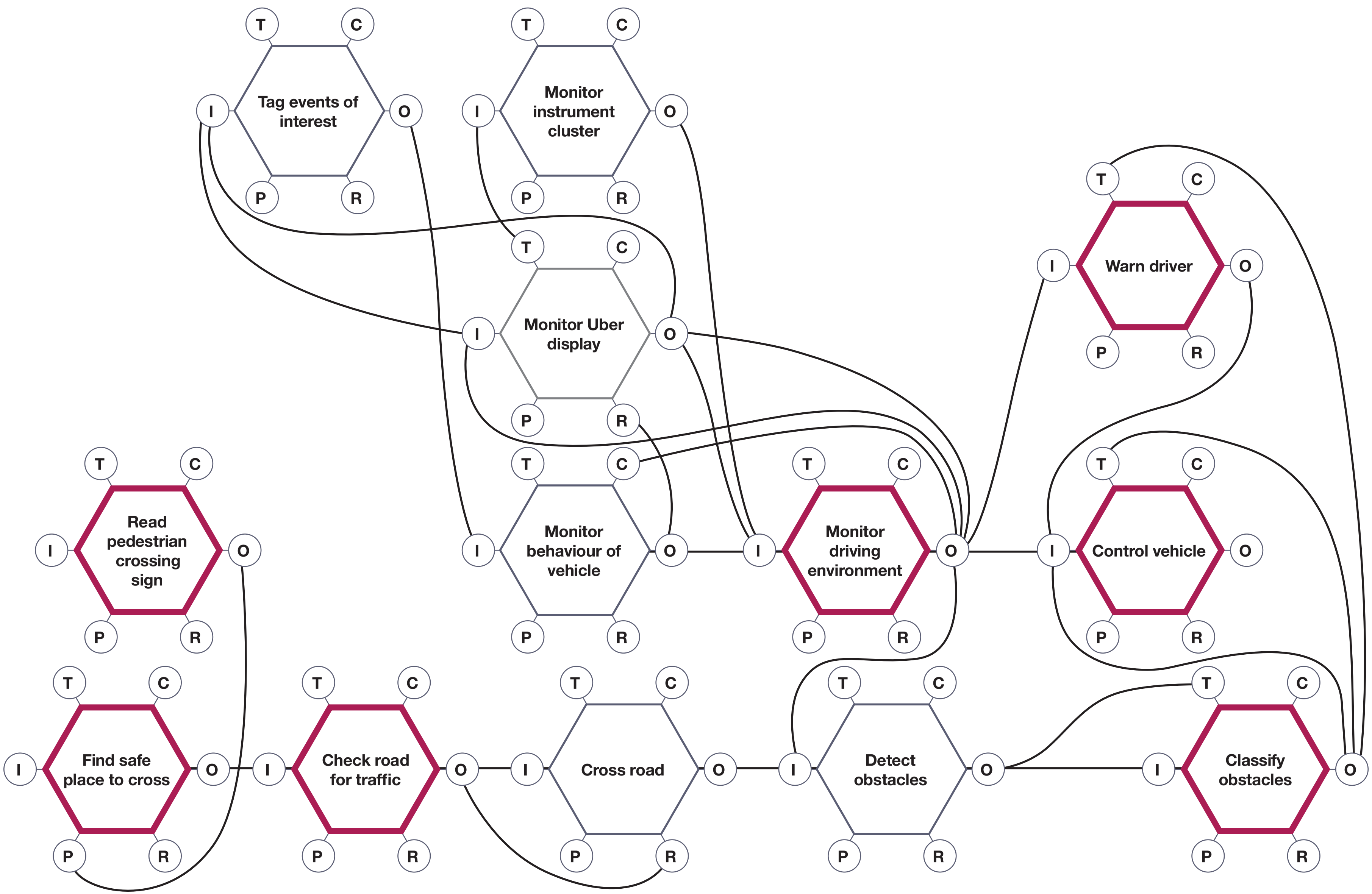
Source: Author's own

FRAM (Functional Resonance Analysis Method) represents the function involved in the collision between the Uber vehicle and the pedestrian. Those functions associated with performance variability (i.e. functions can become off-nominal and abnormal) are represented with a red outline in Figure B.4. All other functions performed normally.

The functions in the bottom left of Figure B.4 relate to the pedestrian who, apparently, did not read the pedestrian crossing sign, find a safe place to cross or check the road for traffic. The functions on the right-hand side of Figure B.4 relate to the Uber automation and the driver. The Uber automation had some initial difficulty in classifying the pedestrian, but did not warn the driver. The Uber automation was also unable to control the vehicle in an emergency because the Uber engineers had disengaged the AEB. Finally, the driver did not monitor the driving environment adequately nor control the vehicle before the collision.

So, as can be seen in Figure B.4, 7/13 functions did not behave in the manner expected for safe operation of the system. In terms of FRAM, the performance variability of these functions by the pedestrian, the Uber vehicle and the driver led to the collision.

Figure B.4: FRAM analysis of the Uber collision with a pedestrian



Source: Author's own

HFACS (Human Factors Analysis and Classification Scheme) is used to classify the system failure for the Uber collision with a pedestrian in Table B.1. The four system categories are in the left-hand column, subcategories in the middle column, and failures in the right-hand column.

As shown in Table B.1, under 'organisational influences', the Uber organisation had failed to identify risky behaviours (by the engineers and drivers) in the testing programme (such as disabling safety systems and allegedly attending to smartphones instead of the road). A comprehensive human and technical risk assessment is required to identify these factors.

Under 'supervisory factors', the prescribed tasks could be too much for one driver: monitor the road environment for hazards, monitor the instrument cluster, monitor the Uber vehicle for problems, monitor the Uber console for anomalies, note any issues on the Uber tablet, and be prepared to take manual control of the vehicle in case of problems. Despite this overtasking, there was also a failure to identify risky behaviours of drivers in the plans for the testing programme. This analysis could have alerted Uber to the issue of the driver not attending to the road environment.

Four 'preconditions for unsafe acts' were noted. For the physical environment, the paved area in the central reservation looked like a crossing, which is probably why the no-crossing signage was posted. Additionally, the signage was small and unlit and would be difficult to see at night. As for the technical environment preconditions, the Uber engineers had disabled the Volvo City Safety system and with it the AEB. The Uber automation also had problems classifying the pedestrian. Regarding the adverse psychological state, the pedestrian was intoxicated with methamphetamine and marijuana; and for physical/mental limitations, the driver had many competing tasks.

Finally, the 'unsafe acts' comprised decision errors (the pedestrian not using the proper pedestrian crossing), perceptual errors (driver not having appropriate awareness of the road environment) and routine violations (driver allegedly watching *The Voice* on a smartphone).

Table B.1: HFACS analysis of the Uber collision with a pedestrian

Category	Subcategory	Failure
Organisational influences	Organisational process	Failure to identify risky behaviours in testing programme
Supervisory factors	Inadequate supervision	Overtasking of driver
	Failure to correct a problem	Failure to identify risky behaviours of drivers in plans for testing programme
Preconditions for unsafe acts	Physical environment	Design of paved area (looks like crossing) Failure to light signage
	Technological environment	Disabling of Volvo City Safety Misclassification of obstacle
	Adverse physiological state	Pedestrian intoxication
	Physical/mental limitations	Conflicting driver tasks
Unsafe acts	Decision errors	Failure of pedestrian to use pedestrian crossing
	Perceptual errors	Driver losing situation awareness of road environment
	Routine violations	Driver allegedly watching *The Voice* on smartphone

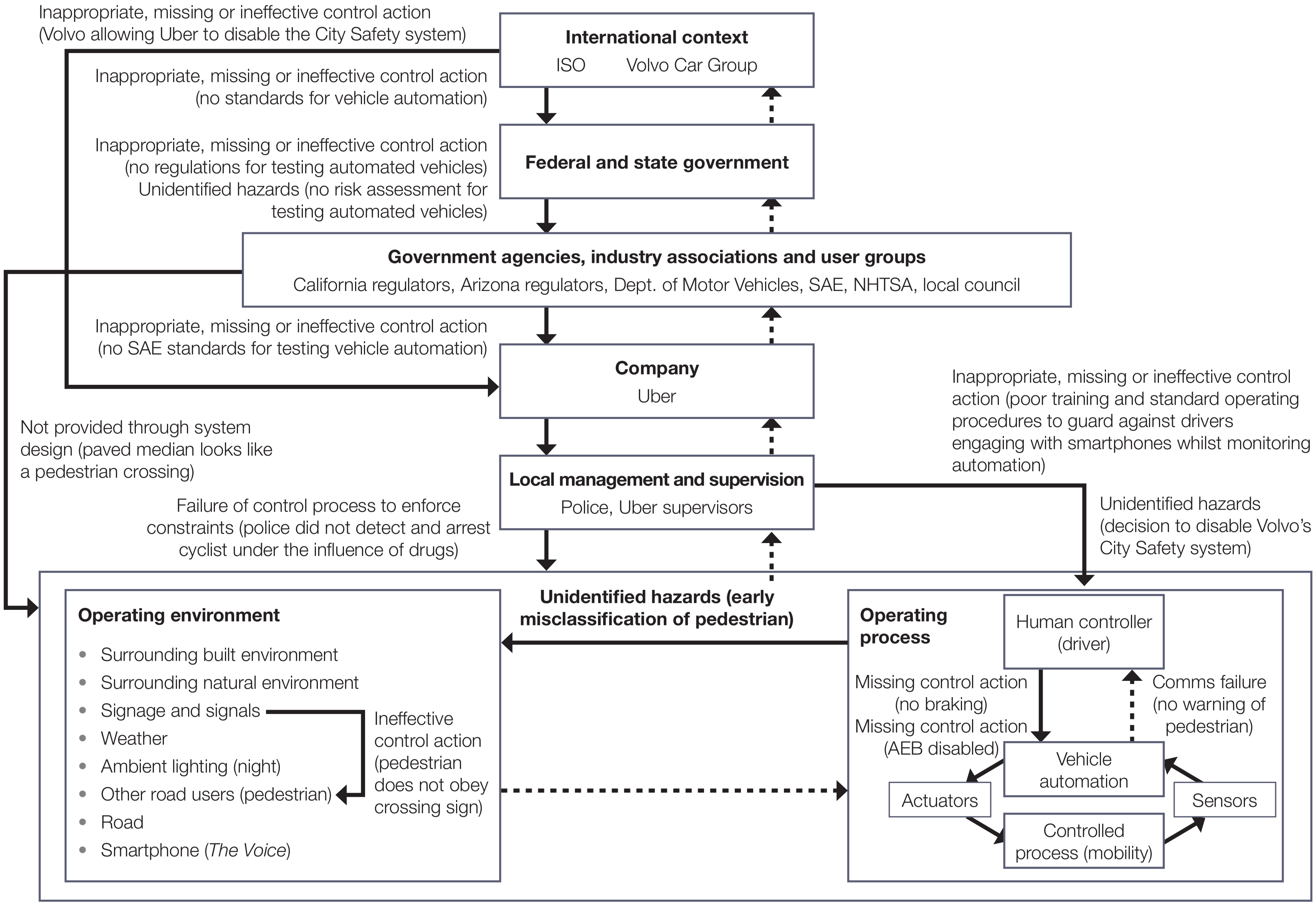
Source: Author's own

STAMP-CAST (Systems–Theoretic Accident Model and Processes–Causal Analysis using Systems Theory) shows the hierarchy of organisations in Figure B.5, from the international context at the highest level to the operating environment and operating process at the lowest level. At each level, the key hazards were identified in terms of control flaws, such as inadequate enforcement of constraints, inadequate execution of control actions and inadequate or missing feedback.

At the level of international context, Volvo did not prevent the City Safety system from being disabled and there were no international standards for safe vehicle automation. The federal and state government did not have regulations for risk assessment and safe testing of automated vehicles. At the level of industry associations, there are no SAE (Society of Automotive Engineers) standards for testing vehicle automation on the road. Local government had developed a paved central reservation that looked like a pedestrian crossing, and installed a small unlit sign to say that it was not a pedestrian crossing. Uber's training did not guard against drivers engaging with smartphones while driving, nor against its engineers disabling the Volvo City Safety system (thereby removing the safety net of the AEB). In the operating environment, the pedestrian did not obey the pedestrian crossing sign (probably as a consequence of the combination of the walkway being on the preferred path, the low visibility at night and the small signage). In the operating process, there was no warning to the driver about the presence of a pedestrian, and the AEB did not activate (because it had been disabled). There was initial misclassification of the pedestrian by the Uber systems, showing an interaction between the operating process and environment.

What the STAMP-CAST analysis shows is failures at all levels in the systems, to do mainly with control rather than feedback.

Figure B.5: STAMP–CAST analysis of the Uber collision with a pedestrian



Source: Author's own

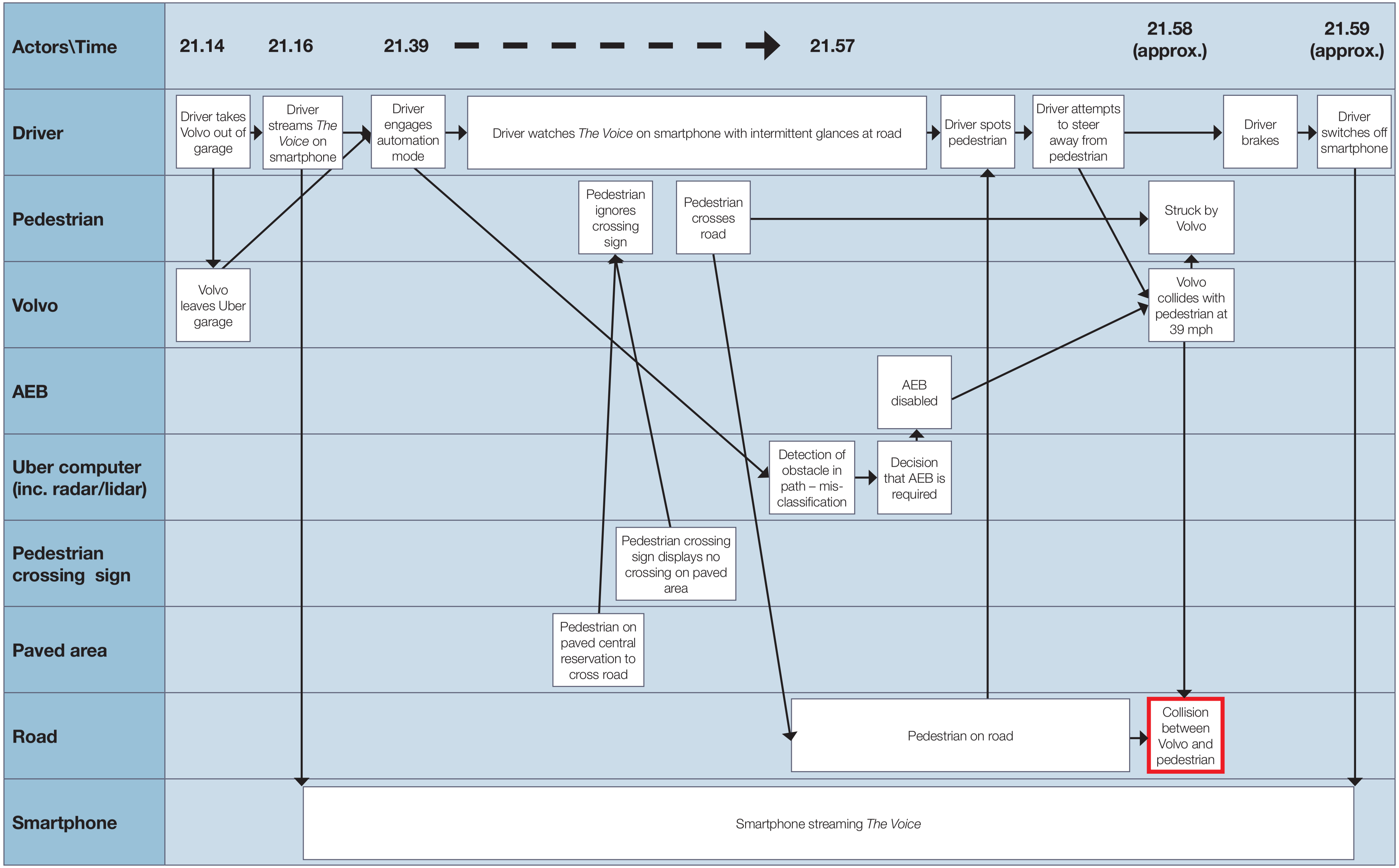
STEP (Sequential Timed Event Plotting) shows the timed sequence of events leading up to the collision between the Uber vehicle and the pedestrian in Figure B.6 (red box highlights collision).

The sequence begins with the driver taking the Volvo out of the garage at 21.14. Then it is alleged that *The Voice* is streamed on the driver's phone. The driver engaged automation mode at 21.39 and the vehicle proceeds around a preset route. A police report states that the driver looks down 204 times over the course of 11.8 miles. It is calculated that the driver's eyes were off of the road for 6 min 47 sec in the period immediately prior to the collision.

At some point during this time, a pedestrian wheeling a bicycle decides to cross the road. The road is dark and unlit at the central reservation when the pedestrian crosses. There is a small unlit sign stating that the pedestrian crossing is further up the road. The Uber system detects an obstacle in its path and initially misclassifies it (originally as unclassified, then as a car, then as a bicycle). Then the system called for the AEB to be activated, but it was already disabled by the Uber engineers.

About half a second before the collision, the driver looks up and spots the pedestrian. The driver attempts to steer the vehicle away from the pedestrian but they are struck at 39 mph. Approximately one second after the collision, the driver applied the brakes. When the vehicle stops the driver calls 911 to report the collision, and then switches off the phone.

Figure B.6: STEP analysis of the Uber collision with a pedestrian



Source: Author's own

Appendix C: Expertise of Human Factors Analysts

Metrics	Prof N Stanton	Prof P Salmon	Prof G Walker
Affiliation	Southampton, UK	USC, Australia	Heriot-Watt, UK
Years in HFE (Human Factors Engineering)	32	17	19
H index (Scopus)	50 (cites = 9,047)	37 (cites = 4,674)	33 (cites = 3,460)
H index (ResearchGate)	57 (cites = 12,598)	38 (cites = 4,892)	38 (cites = 4,560)
H index (Google Scholar)	73 (cites = 20,543)	50 (cites = 9,151)	44 (cites = 7,070)
Books (edited/authored)	20/28	4/19	2/17
Journal papers	326	190	115
Research awards	8	12	4
Journal editorship	1	1	2
Journal SAB (Scientific Advisory Board)	3	2	0

References

Checkland, P. (1981). *Systems Thinking, Systems Practice.* Chichester: Wiley.

DfT (Department for Transport) (2017). *Reported Road Casualties in Great Britain: 2017 summary.* Accessed 28 January 2019 from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/744078/infographic-2017-annual-report.pdf

Eurostat (2018). *Air Safety Statistics in the EU.* Accessed 28 January 2019 from https://ec.europa.eu/eurostat/statistics-explained/index.php/Air_safety_statistics_in_the_EU

Gooding, S. (2017). *Towards an Accident Investigation Branch for Roads?* RAC Foundation. Accessed 28 January 2019 from https://www.racfoundation.org/wp-content/uploads/2017/12/Towards_an_Accident_Investigation_Branch_for_Roads_Steve_Gooding_December_2017.pdf

Greenwood, M. & Woods, H. M. (1919). *The Incidence of Industrial Accidents upon Individuals: With special reference to multiple accidents (Report No. 4).* London: HMSO.

Heinrich, H. W. (1931). *Industrial Accident Prevention: A scientific approach.* New York: McGraw-Hill.

Hendrick, K. & Benner, L. Jr. (1987). *Investigating Accidents with STEP.* New York: Marcel Dekker.

Hollnagel, E. (2012). *FRAM: The Functional Resonance Analysis Method: Modelling complex socio-technical systems.* Farnham: Ashgate.

Hollnagel, E., Woods, D. D. & Leveson, N. (eds.) (2006). *Resilience Engineering: Concepts and Precepts.* Aldershot: Ashgate.

ICI (c. 1979). *Bowties: history.* Accessed 5 February 2019 from https://web.archive.org/web/20160414013947/http://bowtiepro.com/bowtie_history.asp

Kysor, H. D. (1973). Safety management system. Part I: the design of a system. *National Safety News*, 108: 98–102.

Leveson, N.G. (2004). A new accident model for engineering safer systems. *Safety Science*, 42(4): 237–270.

Leveson, N.G. (2011). *Engineering a Safer World: Systems thinking applied to safety*. Boston: MIT Press.

McIlroy, R. C., Plant, K. L., Hoque, M. S., Wu, J., Kokwaro, G. O., Vũ, N. H. & Stanton, N. A. (2018). Who is responsible for global road safety? A cross-cultural comparison of Actor Maps. *Accident Analysis and Prevention*, 122: 8–18.

MAIB (Marine Accident Investigation Branch) (2018). *Annual Report 2017*. Accessed 28 January 2019 from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/720443/MAIB_Annual_Report_2017.pdf

NTSB (National Transportation Safety Board) (2018). *Preliminary Report Highway: HWY18MH010*. Accessed 28 January 2019 from https://www.ntsb.gov/investigations/AccidentReports/Pages/HWY18MH010-prelim.aspx

ORR (Office of Rail and Road) (2017). *Rail Safety Statistics: 2016–17 Annual statistical release*. Accessed 30 January 2019 from http://orr.gov.uk/__data/assets/pdf_file/0017/25622/rail-safety-statistics-2016-17.pdf

Perrow, C. (1984). *Normal Accidents: Living with high-risk technologies*. New York: Basic Books.

Rasmussen, J. (1997). Risk management in a dynamic society: a modelling problem. *Safety Science*, 27(2–3): 183–213. Accessed 30 January 2019 from http://orbit.dtu.dk/ws/files/158016663/SAFESCI.PDF

Reason, J. (1990). *Human Error*. Cambridge: Cambridge University Press.

Robinson, G.H. (1982). Accidents and sociotechnical systems: principles for design. *Accident Analysis and Prevention*, 14(2): 121–130.

Salmon, P. M., Cornelissen, M. & Trotter, M. J. (2012). Systems-based accident analysis methods: a comparison of Accimap, HFACS, and STAMP. *Safety Science,* 50(4): 1158–1170.

Salmon, P. M & Lenné, M. G. (2015). Miles away or just around the corner? Systems thinking in road safety research and practice. *Accident Analysis and Prevention*, 74: 243–249.

Shappell, S. A. & Wiegmann, D. A. (2001). Applying reason: the human factors analysis and classification system (HFACS). *Human Factors and Aerospace Safety*, 1(1): 59–86.

Stanton, N. A. & Harvey, C. (2017). Beyond human error taxonomies in assessment of risk in sociotechnical systems: a new paradigm with the EAST 'broken-links' approach. *Ergonomics*, 60(2): 221–233.

Stanton N. A., Salmon P. M. & Walker G. H. (2018). *Systems Thinking in Practice: Applications of the event analysis of systemic teamwork method*. CRC Press: Boca Raton, USA.

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

Taylor, F. W. (1911). *The Principles of Scientific Management.* New York: Harper & Brothers.

Titcomb, J. & Sabur, R. (2018). *Driverless Uber car kills female pedestrian in first deadly crash.* Telegraph, 19 March. Accessed 31 January 2019 from https://www.telegraph.co.uk/technology/2018/03/19/driverless-uber-car-kills-female-pedestrian-first-deadly-autonomous

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.

Von Bertalanffy, L. (1950). An outline of general system theory. *British Journal for the Philosophy of Science*, 1(2): 134–165.

ScienceDirect (undated). *Fault-Tree Analysis.* Elsevier. Accessed 14 February 2019 from https://www.sciencedirect.com/topics/engineering/fault-tree-analysis

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RAC Foundation
89–91 Pall Mall
London
SW1Y 5HS

Tel no: 020 7747 3445
www.racfoundation.org

Registered Charity No. 1002705

Designed and printed by
The Javelin Partnership Ltd
Tel: 0118 907 3494

Produced on paper from a managed
sustainable source which is FSC certified
as containing 50% recycled waste.

Main proofreader:
Beneficial Proofreading Services
Tel: 07979 763116

ISBN: 978-1-9160527-1-0