Human Factors: A New Approach for Designing the Truck-Driver System

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ABSTRACT

The logistics sector is an often forgotten force behind modern life in the UK, and it is increasingly under pressure to become more efficient, more safety-conscious, and more environmentally sustainable. This triple bottom line necessitates deep changes to the traditional way of working. As evidenced by an expert-led technology forecast, many technological and organisational interventions are on the horizon for the next 15-30 years. This rapid pace of advancement, together with the frequent assumption that workers are ‘hyper-rational’, echoes a worrying pattern from other sectors that have since benefited from human factors & ergonomics (HF/E) expertise. This thesis aims to apply HF/E principles and methods to both current and projected future truck-driver scenarios, in order to leverage the most agile and intelligent agent in the logistics system: the human.

Despite a lack of past work at this intersection, logistics and HF/E can be drawn together by their mutual use of systems complexity concepts. This thesis proposes that logistics is a large, complex adaptive socio-technical system (CASTS), and reviews HF/E methods to determine their fit to different system scales and dynamics. From this it is determined that initial work requires a bottom-up focus on the truck-driver system. A range of methods are employed to understand the existing truck driving task and what it requires of the modern driver; identify and prioritise potentially critical system ‘parts’; design new supportive technologies from scratch in a way that allows for emergent behaviour; and analytically prototype how truck-driver systems are likely to change in projected future scenarios.

This work provides new practical insights for current truck-driver systems, and a map of how this may change – shedding light on potential future problems and how we might adapt to them before they occur. Not only does this thesis provide a solid empirical foundation and a ‘direction of travel’, it also contributes the methodological guidance necessary to strategise next steps beyond this thesis, into deeper logistics complexity. Taken together this demonstrates the power of human factors methods for logistics, and their potential for other unexplored ‘complex adaptive sociotechnical systems’ (CASTS).

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DECLARATION STATEMENT

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GLOSSARY

ACRONYM	FULL TERM
ACAS	Active Collision Avoidance System(s)
ADEF	Average Distance Emissions Factor
ADS	Abstraction-Decomposition Space
AH	Abstraction Hierarchy
AoF	Allocation of Function Analysis
BOS	Behavioural Observation Scale
CAS	Complex Adaptive System(s)
CASTS	Complex Adaptive Socio-technical System(s)
CAT	Contextual Activity Template
CDA	Coordination Demands Analysis
CO_2	Carbon Dioxide (Emissions)
CO_2e	Carbon Dioxide Equivalent (Emissions)
ConTA	Control Task Analysis
CPC	Certificate of Professional Competence
CREAM	Cognitive Reliability and Error Analysis Method
CWA	Cognitive Work Analysis
DoA	Degree of Automation
DML	Decision-Making Ladder
DSA	Distributed Situation Awareness
DSI	Driver Skill Inventory
DSRC	Dedicated Short-Range Communications
EAST	Event Analysis of Systemic Teamwork
GPS	Global Positioning System
GTA	Groupware Task Analysis
HERA	Human Error and Recovery Assessment Framework
HF/E	Human Factors & Ergonomics
HGV	Heavy Goods Vehicle
HTA	Hierarchical Task Analysis
HTAoCD	Hierarchical Task Analysis of Commercial Driving
HTA-T	Hierarchical Task Analysis for Teams
MARS	Mission Awareness Rating Scale
MSD	Musculoskeletal Disorders
PRQ	Primary Research Question
RQ	Research Question
SABARS	Situation Awareness Behavioural Rating Scale
SAD	Strategies Analysis Diagram
SAGAT	Situation Awareness Global Assessment Technique
SBD	Scenario-Based Design
SME	Subject Matter Expert
SNA	Social Network Analysis
SOCA	Social & Organisational Cooperation Analysis
SRQ	Sub- Research Question
StrAn	Strategies Analysis
STS	Socio-Technical System(s)
SUS	System Usability Scale
TBL	Triple Bottom Line
TCD	Task-Centred Design
TNA	Training Needs Analysis
TNAoCD	Training Needs Analysis of Commercial Driving
TRL	Technology Readiness Level
TTA	Team Task Analysis
V2X	Vehicle-to-X (Infrastructure, Vehicle, etc.)
WBV	Whole-Body Vibration
WCA	Worker Competencies Analysis
WDA	Work Domain Analysis

LIST OF PUBLICATIONS BY THE CANDIDATE

In the course of this research the following papers were published by the candidate:

Walker, G. H., Salmon, P. M., Bedinger, M., & Stanton, N. A. (2017). *Quantum ergonomics: shifting the paradigm of the systems agenda.* Ergonomics, 60(2), pp. 157-166. http://dx.doi.org/10.1080/00140139.2016.1231840

Bedinger, M., Walker, G. H., Piecyk, M., & Greening, P (2016). *21st century trucking: a trajectory for ergonomics and road freight*. Applied Ergonomics, 53(B), pp. 343-356. http://dx.doi.org/10.1016/j.apergo.2015.06.022

Bedinger, M. (2016). Book review – Driving with music: cognitive-behavioural implications. Ergonomics, 59(10), pp. 1403-1404. https://doi.org/10.1080/00140139.2016.1143678

Walker, G., Bedinger, M., Salmon, P., & Stanton, N. (2016). *Fortune favours the bold.* Theoretical Issues in Ergonomics Science, 17(4), pp. 452-458. http://dx.doi.org/10.1080/1463922X.2015.1109732

Walker, G., Salmon, P., Bedinger, M., & Stanton, N. (2016). *What the Death Star can tell us about ergonomics methods*. Theoretical Issues in Ergonomics Science, 17(4), pp. 402-422. http://dx.doi.org/10.1080/1463922X.2015.1130879

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Bedinger, M., Walker, G. H., Piecyk, M., Greening, P. (2014). *Human factors in the supply chain: a trajectory for technology and behaviour in the UK logistics industry*. In 19th Annual Logistics Research Network (LRN) Conference, 3rd-5th September 2014, Huddersfield.

Chapter 1:
Introduction

1.1. Road freight, the triple bottom line, & human factors

The triple bottom line (TBL) is a business management concept which aims to measure the financial, social, and environmental performance of a business over time in order to truly account for the full cost of doing business (Elkington, 1997; The Economist, 2009). The TBL looms large in the windscreen of the freight sector, a sector upon which daily life in the UK critically depends. Over the past decade there has been significant pressure to minimise emissions and safety risks related to commercial driving, while at the same time having to support growing operational demands. These tensions have exposed the need for radical new approaches, one of which is applied human factors/ergonomics (HF/E). In this domain HF/E is significantly under-represented yet has scope for significant impact. This thesis, therefore, attempts to establish the role of HF/E in the design of current and future logistics systems.

1.1.1. Road freight & sustainability pressures

HGV (heavy goods vehicle) freight accounts for approximately 1,674 billion tonnes-km of goods moved, or 89% of domestic logistics activity (Department for Transport, 2016). Unfortunately HGV freight has a disproportionally high impact on emissions. It contributes 16% of transport-related emissions despite making up only 5% of overall vehicle miles (Department for Transport, 2017). Department for Transport figures from 2009 reported that freight vehicles above 3.5 tonnes contributed to approximately 20% of all domestic transport carbon emissions and 4.2% of total national carbon emissions (Department for Transport, 2009a). Due to this disproportionate impact (as contextualised in Figure 1.1), there is a significant amount of political and societal pressure on the logistics industry to reduce its carbon footprint, with reductions for UK commercial vehicle operators set at 80% by 2050 compared to 1990 levels (Department for Transport, 2017).

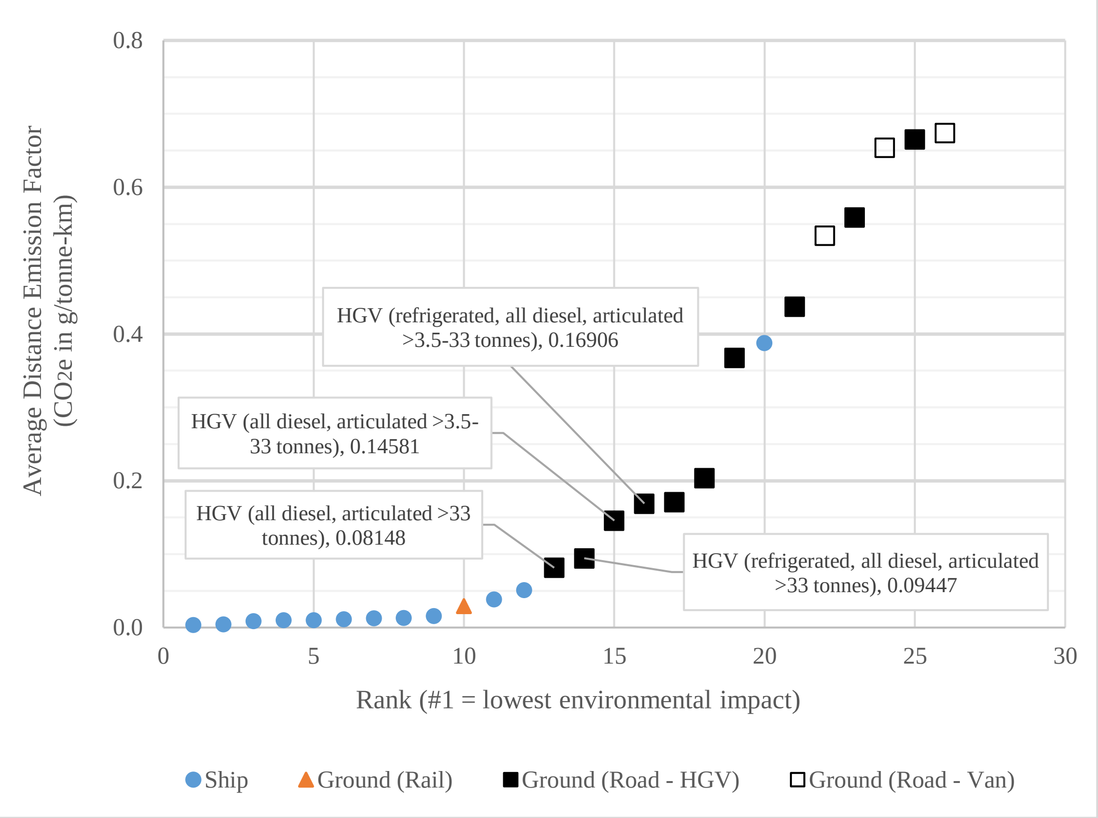

Figure 1.1: Freight transport modes ranked by average distance emission factor (ADEF), discounting air freight (statistics from DEFRA, 2016)

The tension between operational and environmental performance presents new challenges and new opportunities for developing engineering interventions targeting emissions. Many changes to traditional working practices have been proposed to achieve the necessary reductions. Unfortunately most high-level, top-down logistics interventions have yet to be realised. The organisation of large-scale collaborative consolidation centres, for example, would support more efficient distribution, but are unlikely to become the status quo of logistics operations for some time (Janjevic & Ndiaye, 2017). Shifts to alternative manufacturing methods such as 3D printing have not yet reached a level of maturity suitable for mass adoption (McKinnon, et al., 2015). As a result we have the current situation which is currently dominated by HGV-based road freight.

In the absence of top-down interventions political and operational stakeholders are turning to more ‘bottom-up’ interventions to assuage the environmental concerns of their regulators and customers, often at the excited recommendation of environmental researchers (Chapman, 2007). The future truck – and the driver charged with operating it – are often the focus for near-term solutions. Vehicle design, including automated technology, claims to provide some attractive solutions – some of which are beginning to be trialled on public roads (e.g. Wong, 2016; Burgess, 2017). At the other end of the spectrum driver training is seen as a relatively low-cost, low-barrier intervention as shown in Figure 1.2 below. Taken as a whole, the potential savings available from optimising the future truck and its driver are thought to be significant. Indeed, they rival or even exceed such 'headline' interventions as dual fuels, electrification and even completely new forms of higher capacity vehicle. But can these interventions deliver on what is promised?

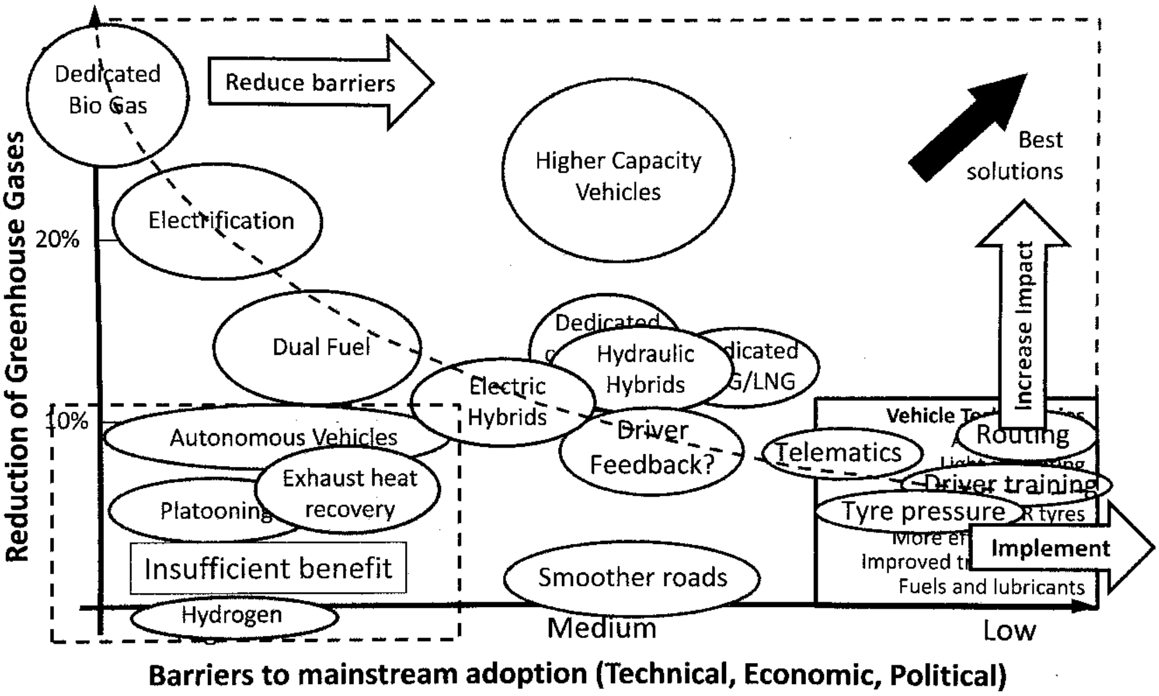

Figure 1.2: Logistics interventions plotted by the Centre for Sustainable Road Freight, by their potential for CO_2 emission reductions and barriers to mainstream adoption (Cebon, 2017)

1.1.2. The potential of human factors for logistics

The logistics system is a socio-technical system; it is a combination of human and technical elements. Yet where is the human in logistics research? New logistics research themes are attempting to incorporate behavioural elements at various levels (e.g. exploration of trust in business relationships as in Hou, et al., 2013, etc.) but this work is far from complete. It merely signals that behavioural issues are increasingly recognised among logistics researchers and that significant potential exists in this area. Examinations of human-technology interaction are rare, often passing over commercial drivers completely (Dekker, et al., 2012), and leading to negative impacts on the cognitive and behavioural aspects of tasks (e.g. Allen & Brown, 2008). Potentially substantial issues include the ability of people to reclaim control from automatic systems (e.g. Norman, 1990); the new and sometimes arbitrary tasks created (e.g. Bainbridge, 1983); behavioural and risk adaptation (Wilde, 1982); and the panoply of effects arising simply from all the unplanned adaptions people perform in order to make a new technology suit their own needs and preferences (Clegg, 2000). The current picture is inconsistent. Even real-world driver training measures that must, by their nature, directly address the 'human' driver have no consistent design rules. Due at least in part to this lack of understanding and guidance, the outcomes of driver training courses (e.g. for eco-driving) continue to vary widely, as exemplified in Figure 1.3.

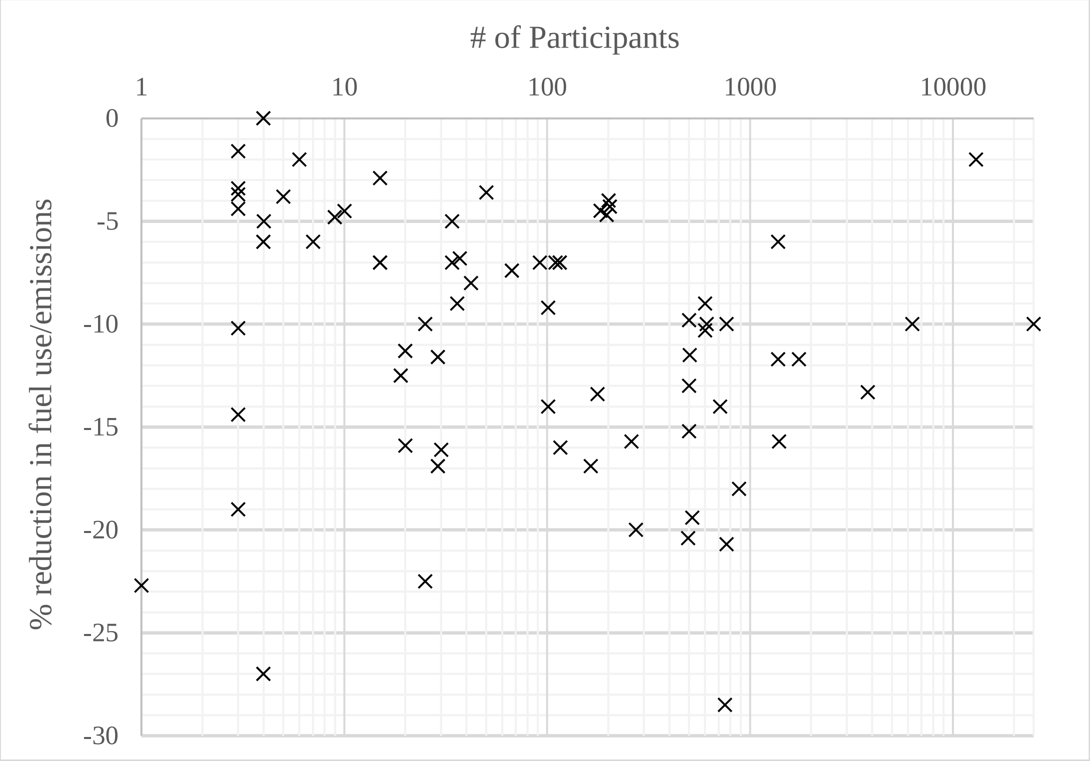

Figure 1.3: Improvements gained by eco-drive training (from a literature review which returned 16 eco-driving projects, that included 64 different test groups)[1]

This lack of comprehensive evaluation means that interventions may in reality have minimal – or potentially detrimental – environmental and safety-related effects, sometimes at considerable economic cost (e.g. Harris, et al., 2007; Beekun, 1989). Furthermore when evaluative measures are taken, they seem to reside in a tacit theory of

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[1] Jeffreys, et al., 2016; Ho, et al., 2015; Husnjak, et al., 2015; IEE, 2015a; IEE, 2015b; Sullman, et al., 2015; Wu, et al., 2015; Andrieu & Saint Pierre, 2014; Backhaus, 2014a; Backhaus, 2014b; IEE, 2014; Rionda, et al., 2014; Rolim, et al., 2014; Stromberg & Karlsson, 2014; Degraeuwe & Beusen, 2013; Gudmundsen, 2013; IEE, 2013a; IEE, 2013b; IEE, 2013c; IEE, 2013d; IEE, 2013e; Rutty, et al., 2013; Saynor, 2013; Stromberg & Karlsson, 2013; Andrieu & Saint Pierre, 2012a; Andrieu & Saint Pierre, 2012b; IEE, 2012; Schulte, 2012a; Schulte, 2012b; Cebrat, 2011; IEE, 2011; Saynor, 2011; AEA Group, 2010a; AEA Group, 2010b; Cebrat, 2010; Department for Transport, 2010a; Beusen, et al., 2009; Department for Transport, 2009b; Symmons, et al., 2009; Symmons & Rose, 2009; IEE, 2008; Zarkadoula, et al., 2007; Department for Transport, 2006; Department for Transport, 2003; Boocock, 2001

human behaviour: that within the logistics system humans are ‘hyper-rational’ (Croson, 2013).

In an increasingly automated and data-centric transport system, it is often forgotten that logistics is a sociotechnical system, one comprised of humans and technology, and that success relies on these two aspects being jointly optimised. The importance of acknowledging the human, and the dynamic and highly variable nature of such sociotechnical systems, is explained by Woods (2006, p. 21):

> *…[Resilience] depends on a distinction between understanding how a system is competent at designed-for-uncertainties, which defines a ‘textbook’ performance envelope and how a system recognizes when situations challenge or fall outside that envelope – unanticipated variability or perturbations…Resilience is concerned with monitoring the boundary conditions of the current model for competence (how strategies are matched to demands) and…monitoring resilience should lead to interventions to manage and adjust the adaptive capacity as the system faces new forms of variation and challenges*.

Woods (2006, p. 22) further explains that:

> *Unanticipated perturbations arise (a) because the model implicit and explicit in the competence envelope is incomplete, limited or wrong and (b) because the environment changes so that new demands, pressures, and vulnerabilities arise that undermine the effectiveness of the competence measures in play.*

In this characterisation it is clear that as a system acts and evolves more rapidly, it is increasingly important to form a full understanding of the so-called ‘competence envelope’. To address Woods’ first condition of unanticipated disruptions, the understanding of logistics competencies must be formalised and expanded. To address the second condition, foresight into future logistics systems must be gained. This thesis addresses both.

To do this, a behaviour-sensitive approach to the evaluation and design of socio-technical logistics systems is first required. The human factors knowledge base and methodological toolkit fit the bill precisely. With roots in the military, aviation, nuclear power, and other safety-critical domains, human factors has a long history of holistically evaluating socio-technical systems (STS) where an issue has been found with the existing design (van Schalkwyk & Steenkamp, 2017). More recently human factors analysis has been developed to detect system weaknesses before an inefficient error or hazardous event occurs (Le Coze, 2008; Moray, 2008; Salmon, et al., 2011; Salmon, et al., 2017). In general, HF/E aims to “maintain a technology watch on future and anticipated development” and “ensure involvement at the beginning of research and development” in a way that has promise to keep up with the rapid pace of change in modern logistics systems (Bartlett, 1962 as cited in Stanton & Stammers, 2008, p. 7). These capabilities make human factors ideally-suited to achieving the triple bottom line, as research increasingly calls attention to the potential risks of ‘business-as-usual’ and the need for resilient logistics (Levalle & Nof, 2017).

Despite this clear potential, and specific calls from the HF/E community for the study of sustainability, complexity, and emergence in human activity (Dekker, et al, 2013; Garcia-Acosta, et al., 2014), we return again to a central point: HF/E has been largely unused in logistics. This thesis represents an opportunity to address this shortcoming.

1.1.3. The Centre for Sustainable Road Freight

The Centre for Sustainable Road Freight was established in 2012 to research engineering and organizational solutions to make road freight economically, socially and environmentally sustainable (Centre for Sustainable Road Freight, 2019). It aims to:

1. research the sustainability of road freight transport: from tactical to strategic, fundamental to applied, micro and macro-level perspectives
2. develop innovative technical and operational solutions to road freight transport challenges
3. develop tactics and strategies to meet Government emissions reduction targets for the road freight sector, mapping out ways to provide an 80% reduction in CO_2 emissions due to road freight transport by 2050.

A vital feature of the Centre is its close links with the freight industry, with £4.4m in funding from the Engineering and Physical Sciences Research Council and £1.4m from the industrial consortium. The consortium includes key freight operators such as DHL and Wincanton, along with vehicle industry partners such as Volvo and Goodyear, and regulatory bodies such as the Freight Transport Association. These partners help set the research agenda and spearhead the adoption of the results by the road freight industry.

Because of its linkage to the Centre for Sustainable Road Freight – and crucially, its key stakeholders – this thesis has a rare opportunity to leverage the strategic advantages of HF/E (stronger relationships with dependent system actors who are less able to influence system design but have a strong interest in its outcome) while nullifying the strategic disadvantages of HF/E (weaker relationships with dominant system actors who have considerable power to influence system design) (Dul, et al., 2012). This would undoubtedly fulfil an important research need to perform truly cross-disciplinary work with multi-disciplinary industrial cooperation (Rasmussen, 1997), and begin work on a high-potential research intersection: logistics and HF/E.

1.2. Overall aim of the thesis

1.2.1. Purpose

The potential for HF/E to answer a range of prescient issues in logistics is high. This research intersection drives the thesis aims. Throughout the initial chapters of this thesis Partington's framework will be used to guide the research process and thus the approach to empirical studies. Partington's four aligned elements of the research process include the aim or purpose; the research question; the theoretical perspective; and finally, the research design (Partington, 2002). As shown below in Figure 1.4, the overall purpose of this thesis is to support the logistics sector in a more holistic approach to truck-driver system design, with the ultimate aim being to achieve the triple bottom line in current and future scenarios.

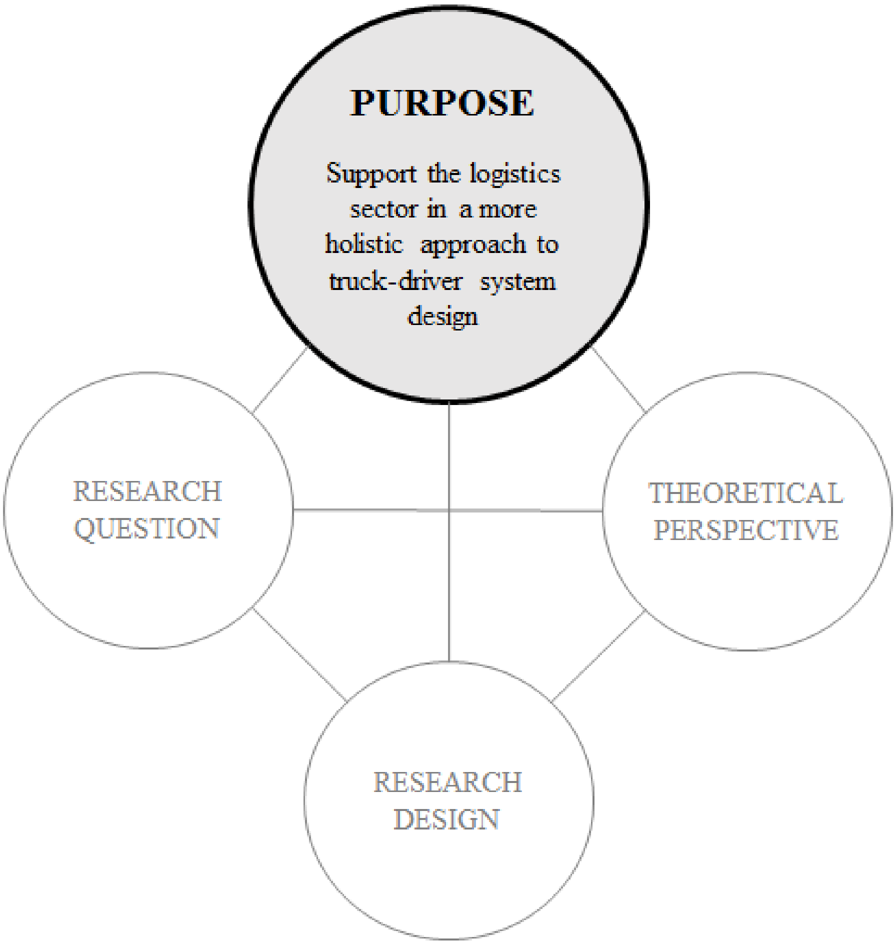


Figure 1.4: Purpose of the thesis, as in Partington's four aligned elements of the research process (2002, p. 139)

1.2.2. Research question

The second step of Partington's framework is to define the research question. As shown in Figure 1.5, the primary research question is: *How can current & future truck-driver systems be better designed to meet the triple bottom line (TBL) of safety, efficiency, and environment?*

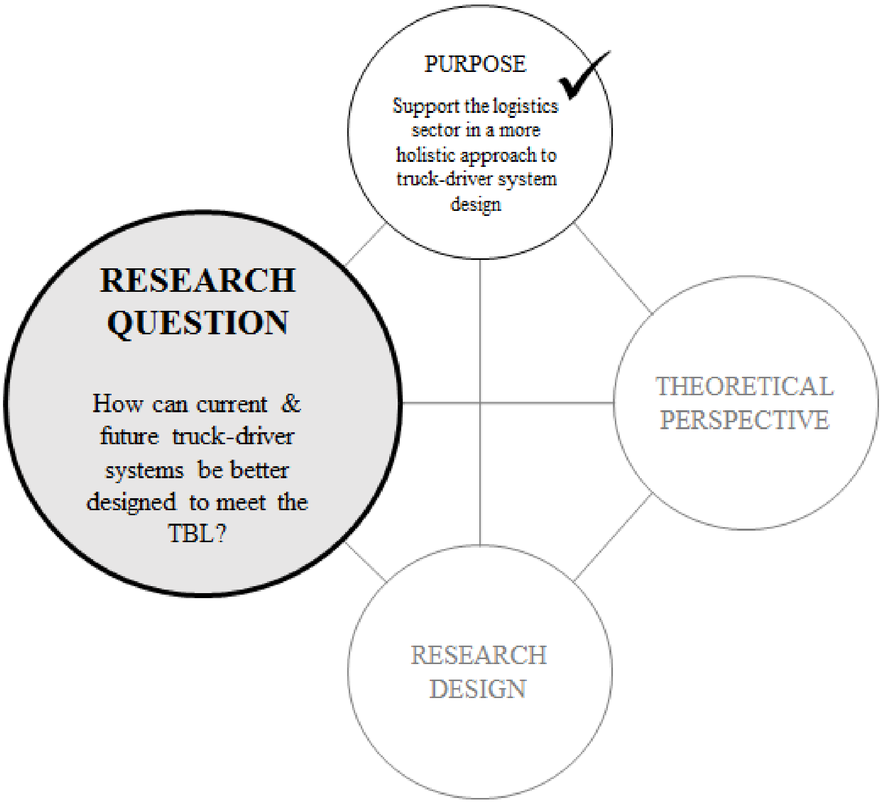


Figure 1.5: Primary research question, as in Partington's four aligned elements of the research process (2002, p. 139)

The last two elements of the research process (the theoretical perspective and the research design) require further elaboration for HF/E-logistics research, particularly as this is a relatively new research intersection without much existing guidance. As such, the thesis has three main objectives. Objective 1 is to overview the potential fit of HF/E principles and methods to solving problems within road freight systems. Objective 2 is to apply specific HF/E methods to formalise and expand our understanding of the truck-driver system, ensuring that it is not "incomplete, limited, or wrong" (Woods, 2006, p. 22), and addressing the first condition of unanticipated system disruption. Objective 3 is to gain foresight into future system conditions, and incorporate these into adapted versions of present-day analyses, for future scenarios. These adapted analyses for future scenarios respond to "new demands, pressures, and vulnerabilities that undermine the effectiveness of competence measures in play", thus addressing the second condition of unanticipated system disruption (Woods, 2006, p. 22).

A collection of research sub-questions will be asked which elaborate on these elements. This allows such inter-disciplinary guidance to be developed, and for the primary research question to be approached in a more specific way. These sub-questions correspond to various chapters throughout the thesis, as outlined in Figure 1.6 below.

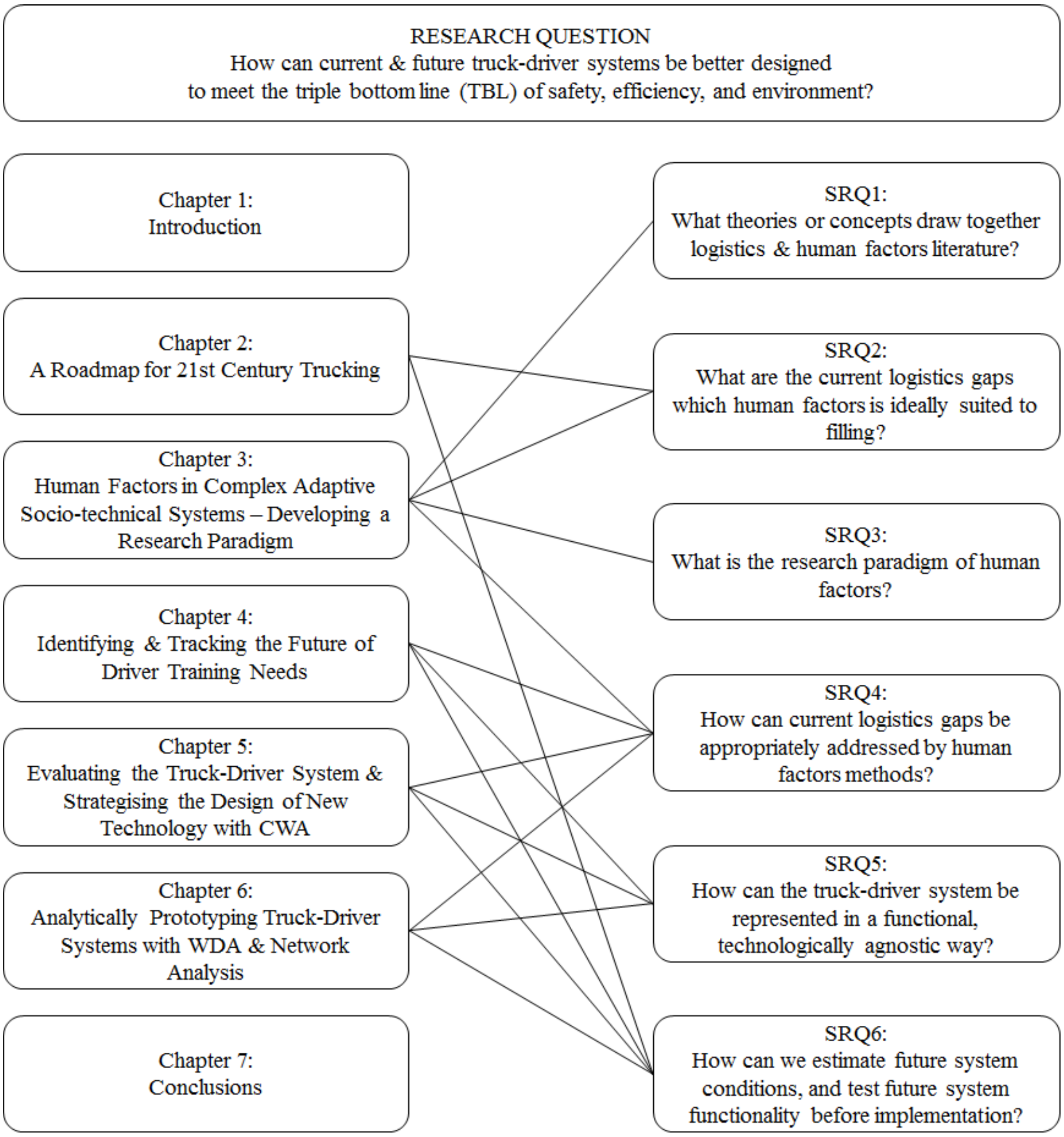


Figure 1.6: Sub-research questions & connection to each thesis chapter

1.3. Structure of the thesis

This thesis follows a novel structure that is not typical of a traditional logistics management PhD. This is because logistics is undergoing a transformation. Road freight is experiencing rapid and unprecedented technological and organisational change. In this sense the sector now resembles other domains (such as nuclear power and air traffic control), which have required and benefitted from HF/E insights. To acknowledge and address this, the thesis first scans the horizon to explore what future road freight might be like without intervention, making a robust case for HF/E at the outset.

As such *Chapter 2* looks into the long-term future of road freight operations to scope the gaps and opportunities in next-generation logistics system design. Subject matter experts (SMEs) from across a spectrum of manufacturers, customers, and policy-makers contributed to a technology trajectory which built a picture of future road logistics scenarios in 2020, 2025, 2030, and 2050. This forecast of technology, policy, and associated human factors illustrates what is on the horizon, and strengthens later efforts to 'future-proof' new system designs. This shows that technology alone is not enough to meet sustainability targets, and human-centred logistics research is now imperative. Overall the technology forecast sets the scene for a vast expanse of possible research directions.

Another reason for the thesis' novel structure is that the work that follows resides at an intersection of disciplines, where little existing HF/E work has been performed within logistics. Thus additional work is required beyond the traditional considerations of a management thesis to ensure the intersections of HF/E and logistics are sufficiently drawn together, building a literature review and methodology section together in Chapter 3.

Chapter 3 prioritises next research steps in this area, narrowing from the wider logistics system, to the truck-driver system. This involves a review of the literature in, surrounding, and connecting three bodies of research – human factors, road freight, and complex systems. The latter comes into the equation because of the intersection of the former. As a sociotechnical system logistics exhibits complex behaviour and needs to be studied as such. Research gaps and compatibilities are detailed to show that the intersection of these fields is a fertile ground for novel and impactful research. This provides a sound basis for the characterisation of logistics as a complex adaptive, socio-technical system (CASTS). Chapter 3 also situates the reader within the typical HF/E research paradigm. This is often implicit in human factors work when, in fact, it needs to be explicit. This description clarifies the ontology, epistemology, and methodology commonly adopted by the field in general. A human factors methods review is performed to determine the extent to which they cover different levels (and interactions between levels) of CASTS, and can be truly used as methods of 'systems analysis'. Methods are selected from this review which first build a robust knowledge base of the sector, upon which more novel approaches can be taken beyond this thesis. Overall, this chapter provides a necessary characterisation of logistics as a CASTS, but points first to completing research at the level of the truck-driver system, before wider logistics issues can be explored.

Chapter 4 begins building the knowledge base in this area with structured reference documents. These describe commercial driving tasks (the Hierarchical Task Analysis of Commercial Driving, or HTAoCD) and associated training needs in the form of Knowledge, Skills, and Attitudes (KSAs) required of the human operator (the Training Needs Analysis of Commercial Driving, or TNAoCD). Using the trajectory developed in Chapter 2, these reference documents were revised to reflect changes and track training needs in the truck-driver system in 2020, 2025, and 2030. In other words, this Chapter provides insights into how the truck driving task is going to change in future; how truck driving will need to be changed; and who the future truck driver will be.

Chapter 5 presents the first three stages of Cognitive Work Analysis (CWA) framework – Work Domain Analysis (WDA), Control Task Analysis (ConTA), and Strategies Analysis (StrAn) – as applied to trucking operations. These methods were used to design a new real-world truck technology in collaboration with Scania AB, a leading European truck manufacturer. A prioritisation method was also developed to navigate the application of ConTA to large-scale CASTS. Chapter 5 serves as a strong example of HF/E potential, as it flexibly describes the socio-technical system, informs next-generation design, and analytically prototypes future systems. In particular, this demonstrates the capability to identify critical work activities through a new prioritisation method developed in line with CASTS theory – thus channelling design efforts toward the minimisation of likely future risks.

Chapter 6 uses the 2015 WDA developed in Chapter 5 as a basis, and adapts the analysis for future truck-driver systems projected by the technology trajectory in Chapter 2. This 'Abstraction Hierarchy forecast' from 2015–2030 characterises system functionality at each time step. Network metrics are applied to each abstraction hierarchy to identify potentially critical system components at each time step, and track overall changes to how the truck-driver system is projected to function. This novel approach showed that without regular observation and the capability to introduce timely and skilfully-designed interventions, system functionality may centralise to a few critical nodes over time. In other words, this approach shows not just *that* the current trajectory of truck-driver automation is high-risk, but *how* this is the case, and thus where to prioritise design efforts to minimise those risks.

Chapter 7 concludes the thesis by describing its theoretical, methodological, and empirical contributions, its limitations, and newly-enabled possibilities for future work. Indeed, it emerges that considerable potential exists to not just apply HF/E to the truck-driver system in order to help it achieve the triple bottom line, but for this novel domain to drive equally novel enhancements in theory and method.

The following Chapters reveal in detail exactly how this potential has been identified and addressed. Table 1.1 shows the significant original contributions to theoretical, methodological, and empirical knowledge this body of work makes.

Table 1.1: Theoretical, methodological & practical contributions of the thesis

CHAPTER	NOVEL CONTRIBUTION		
	THEORETICAL	METHODOLOGICAL	PRACTICAL / EMPIRICAL
Chapter 1: Introduction			
Chapter 2: A Trajectory for 21st Century Trucking			• Technology forecast for road logistics (2015–2050) • Associated trajectory of human factors issues • Associated trajectory of CO_2 emissions
Chapter 3: Human Factors in Complex Adaptive Socio-technical Systems – Developing a Research Paradigm	• Identification of logistics as a Complex Adaptive Socio-technical System (CASTS) • Definition of the Human Factors research paradigm (ontology, epistemology, & methodology)	• Review of Human Factors methods (extent of systems coverage)	
Chapter 4: Tracking the Future of Driver Training Needs		• Analytically prototyping future systems with Hierarchical Task Analysis • Analytically prototyping future systems with Training Needs Analysis	• Detailed description of present-day truck driving tasks • Detailed description of present-day training needs for truck drivers • Forecast of how truck driving tasks will change (2020-2050) • Forecast of how truck driver training needs will change (2020-2050)
Chapter 5: Evaluating the Truck-Driver System & Strategising the Design of New Technology with CWA		• Prioritisation approach for Control Task Analysis as applied to large CASTS	• Formative characterisation & evaluation of current truck-driver system functionality • Novel design for a real-world truck technology
Chapter 6: Analytically Prototyping Truck-Driver Systems with WDA		• Analytically prototyping future systems with Work Domain Analysis • Network analysis of abstraction hierarchies • Identification of ‘stable’ and ‘flexible’ abstraction hierarchy nodes, & implications for adaptive behaviour	• Forecast of truck-driver system functionality (2015–2050) • Identification of most interdependent components in truck-driver systems (2015–2050)
Chapter 10: Conclusions			

Chapter 2:
A Trajectory for 21st Century Trucking

2.1. Introduction

2.1.1. The importance of forecasting

In Chapter 1 the overall aim of the thesis was identified. This was to support the holistic design of a truck-driver system. Chapter 2 makes progress toward this aim by illustrating what is currently on course for the truck-driver system of the future, and scoping the gaps and opportunities for next-generation design. This activity is generally referred to as forecasting.

Forecasting is a strategic planning technique. It takes many forms and is undertaken for many purposes. It is common for forecasts, road-maps, and scenario analyses to be developed in response to practical needs. These include coping with and recovering from unexpected disruptions or system failures (Ponomarov & Holcomb, 2009; Gilly, et al., 2014; Limnios, et al., 2014) through to maintaining a competitive advantage (Vishnevskiy, 2015; 2016). They are increasingly popular approaches for coping with and adapting to future work contexts (Wilkinson & Eidinow, 2008), in particular how sustainability requirements will affect logistics systems (e.g. von der Gracht & Darkow, 2016). Whilst forecasts of various sorts are increasingly ubiquitous in logistics research, a standardised approach for forecasting the potentially associated human factors does not yet exist. Such an approach will be developed and presented in this Chapter.

2.1.2. Human factors foresight

If we are to adapt with future logistics systems in a fast-paced and dynamic environment, and address the human elements of the system therein, attempts at any level of foresight will be critical. According to Woods (2006, p. 22):

> *Unanticipated perturbations arise (a) because the model implicit and explicit in the competence envelope is incomplete, limited or wrong and (b) because the environment changes so that new demands, pressures, and vulnerabilities arise that undermine the effectiveness of the competence measures in play.*

Forecasting future technologies, and therefore future logistics scenarios, will be an essential component for addressing new demands, pressures, and vulnerabilities, or

Woods' second cause of unanticipated perturbations. The direct research question which flows from this is:

- *How can we estimate future system conditions, and test future system functionality before implementation? (SRQ6)*

In order to adequately tackle SRQ6 progress is required on the following more indirect research question:

- *What are the current logistics gaps which human factors is ideally suited to filling? (SRQ2)*

2.2. Design

To provide the necessary insights into new demands, pressures, and vulnerabilities within the logistics system, particularly those which bear on the commercial driver, a survey of leading logistics practitioners was performed. Industry-led insights were also reflected off a systematic review of the knowledge base. The focus of the review was on commercial vehicle technologies intended to reduce greenhouse gas emissions. This enabled a technology trajectory to be developed featuring those elements relevant to the commercial driving task. Consistent with a systems approach, the trajectory did not only address technologies related to operational driving tasks but also technologies related to distribution and delivery tasks. Logistics technologies intended to reduce fuel costs and carbon emissions all hold the potential for unexpected and previously unstudied human-technology interactions. This Chapter sets out to highlight where and of what types these interactions may be.

2.2.1. Validity of forecasting efforts

Any process of forecasting necessarily involves predicting phenomenon that are both deterministic and complex before they occur. It is important to note that inherent in all forecasting and road-mapping methods is the unique challenge of construct and predictive forms of validity. By its nature, forecasting means it is not yet possible to know for certain if long-term predictions have been proven correct, or even how well the method has measured the target construct. This means that construct validity (the extent that a method measures the trait it is intended to measure) and predictive criterion validity (the effectiveness of a method in the prediction of future performance). This does not mean all hope has to be abandoned. Forecasting has been used frequently and successfully in many domains (e.g. Carvalho, et al., 2013; Vishnevskiy, et al., 2015; Vishnevskiy, et al., 2016), but is important not just in the eventual outputs but also the formative process of performing the activity. A 2001 study forecasting private vehicle technology (Walker, et al., 2001) employed a similar approach and has since yielded a fairly accurate forecast.

At present concurrent criterion validity – the relationship of a newly-applied test to an existing test for the same construct – cannot be addressed as there is no alternative method. By default this make forecasting the most powerful approach available.

Several forms of validity can be addressed. Content validity – the representativeness of the assessment instrument and having an adequate sample – is addressed by eliciting expert insights from a range of stakeholders at the forefront of UK logistics manufacturing, policy, and operations. This ensured a wide range of situational factors were considered in the forecasting of uptake beyond technology readiness, to also include market forces, new legislation, customer preferences, etc. Researchers working on solely academic rather than commercial activities were assumed not to hold adequate expertise in these wider situational factors, and thus were not approached. Face validity – whether the method and results appear to be valid to experts – is addressed by the inclusion of SMEs and the process of iteratively revisiting the forecast 'model'.

Although a somewhat loose fit with traditional validity measures, forecasting is an iterative, collaborative process which fits with constructivist grounded theory measures of validity, particularly modifiability (Holton, 2008; see Table 3.5).

2.3. Procedure

2.3.1. Technology forecast

Academic journal search engines were used in initial searches for logistics technology information, followed by a targeted search of logistics, transportation, environmental interest, and human factors publications (e.g. Transportation Research; Annual Reviews in Control; Safety Science). This was supplemented by publicly-accessible web engine searches for technical documentation and statistical information from industry and relevant government bodies (e.g. Amsterdam Group; Department for Transport). Iterations of this process were carried out to ascertain the technical details, maturity, and affected user of each technology or trend. First-stage search terms were developed to detect technologies across logistics contexts, for example: heavy goods vehicle technology, intelligent transport systems, warehouse management systems technology, green logistics technology, logistics ICT, etc. This was expanded upon iteratively as necessary to cover specific trends, technologies, vehicle types, and user characteristics as they occurred. Attention was also given to alternative terms, spelling variations, and acronyms, to ensure inclusion of specialised nomenclature from each of the targeted subject areas.

Relevant organisations were also identified. Experienced sector specialists in managerial roles were contacted, including areas as diverse as: logistics policy, infrastructure technology development and implementation, and key commercial activities with in-house distribution and/or third-party logistics. In the e-mail of initial contact, a brief overview was provided to the potential participant to describe the research project, the planned use of any data collected, the planned questions to be asked, the option to conduct the data collection via phone interview or in-person interview, and an assurance that all responses will be anonymised and aggregated. This allowed participants to be provided information about the intended research, reflect fully on this under no time pressure from the researcher, and agree or disagree to the terms on their own time, before participating. No incentives were offered for participation in the study. Written consent was obtained for all participants via e-mail.

The researcher's contact details were provided and reference to the overall research consortium was made such that participants were enabled to contact the researcher or project supervisors for further information or regarding any concerns. Participants were notified of their right to decline to answer any specific questions (though all participants answered all questions), and notified of their right to withdraw at any time by contacting the researcher. At the start of in-person interviews, requests were made to record the session, and where consent was granted, recordings were made. In the majority of cases, notes of responses were handwritten in the researcher's personal notebook, and in other cases typed and stored as Word documents saved to the researcher's personal laptop or a cloud storage system (Dropbox). Participant names were not taken on any associated recordings and only company name, official title, experience, age, and gender were taken down in the researcher's notes. All files stored on Dropbox were password protected. Recordings (where consent was given) were made either by use of a smartphone app or a laptop program, and saved to the researcher's personal laptop. Full ethics approval was received from the Ethics Officer within the School of Management and Languages at Heriot-Watt University prior to beginning interviews.

Key stakeholders from the UK logistics industry participated in the study. These included several major third-party logistics operators, international vehicle manufacturers, and UK government bodies (see Table 2.1). Semi-structured interviews were conducted with the specialists in person or by telephone and there were 23 respondents in total (see Table 2.1). Open-ended interview questions were based around the following structure: *What vehicle/warehouse/logistics transport technologies do you envision being implemented in the next 5 years; 10 years; 15 years; and beyond 15 years?* Elaboration was encouraged to maximise the specificity of general technologies or timelines. Salient trends were followed up with a question of the form: *Could you elaborate on this trend/technology, and clarify when it is likely to be implemented in the logistics environment?*

Table 2.1: Participant details for technology trajectory interviews

Area of Logistics	*Participant Category*	*Job Title*	*Experience (Years)*	*Age (Years)*	*Gender*
Logistics Fleet (Internal to Company)	Customer	Group Transport Manager	24	46	M
	Customer	Transport, Logistics & Warehouse Fleet Manager	13	35	M
	Customer	Senior Fleet Manager	Unknown	Unknown	M
Warehouse Management	Intermediary	Consultancy Director	31	56	M
Third-Party Logistics	Customer	Innovation & Efficiency Manager	10	31	M
	Customer	Technical Services Director	27	49	M
Policy (in Logistics/ Vehicle Specification)	Intermediary	Commercial Vehicle Development Manager	26	48	M
	Intermediary	Director of Policy	33	51	M
	Intermediary	Managing Director for Membership & Policy	31	56	M
	Customer	Road Strategy & Technology Lead	3	31	M
Technology Research & Development	Intermediary	ITS Regional Director	22	45	F
	Supplier	Head of ITS Development	25	48	M
	Supplier	Principal Engineer	11	35	M
	Supplier	Development Engineer	6	28	M
	Supplier	Strategy & Business Development	16	34	M
	Supplier	Advanced Engineering Program Manager	4	28	M
	Supplier	Transport Solution Specialist	27	53	M
	Supplier	Project Manager	15	40	M
	Supplier	Chief Engineer - Chassis Strategies & Vehicle Analysis	6	28	M
	Supplier	Vehicle Control & Analysis	12	34	M
	Supplier	HMI Technology Project Manager	13	36	F
	Supplier	Cognitive Engineer	9	35	M
	Supplier	Specialist in HMI for Intelligent Vehicles	6	28	F
TOTAL			370	875	
AVERAGE			16	40	M

Technologies and timescales identified in the interviews were documented as individual entries from each participant, along with applicable context (e.g. vehicle, infrastructure, etc.). Most technologies were identified consistently by multiple participants. Where discrepancies in the implementation timeline were present, a mean was taken and a standard deviation calculated to provide a range. Individual entries were synthesised into categories based on technical knowledge gained in the literature review. For example, both in-vehicle and portable telematics devices were categorised as ‘Telematic Data Collection’.

2.3.2. Examination of associated HF/E

From the literature review three central classes of technology were found, described by Walker et al. (2001) as: transparent, opaque, and enabling. Technologies described as ‘transparent’ often relate to ubiquitous computing tasks which may be less directly apparent to the user, but which aim to optimise the fundamental links between vehicle and driver controls. The use of ‘opaque’ technologies may be more apparent to the end user, as these have a more readily discernable interface between vehicle and driver. Both transparent and opaque technologies have the potential to carry feedback which is minimally or highly obvious to the end user, feedback which they interact with during performance of the task. ‘Enabling’ technologies create a framework for components to improve overall mechanical and electrical efficiency. In this work, enabling technologies may include basic design interventions such as aerodynamic fairings, or supporting systems technology such as natural gas infrastructure. Technologies like these ‘enable’ other technologies and ways of operating. The technologies identified by interview participants are described in terms of these three categories.

To examine more specific HF/E issues, several constructs were selected from the literature. Reference was made to existing NASA/FAA guidance on TRLs in order to map broad classes of HF/E issues to each stage of technology development contained in the forecast. The HF/E issues which aligned to these broad criteria were feedback, attention, and locus of control (Krois, et al., 2003). This follows some previous HF/E forecasting activity in the passenger vehicle domain (Walker, et al., 2001; 2015). Clearly there are many more HF/E constructs than can these (see Heikoop, et al., 2016), and these broad issues are not intended to be exhaustive. They are however intended to be good general indicators of HF/E issues, because they are:

- relevant to an immediate timescale
- relevant to operational behaviour (in preference to broad issues)
- focussed on the end-user (in this case those involved directly in the truck/driver system)
- relevant to the first and last stages of information processing (information acquisition, and action implementation) at their most basic level
- measurable (at least to some extent)

For the above reasons the three selected HF/E issues can be easily identified as being applicable (or not) to individual technologies, without more detailed knowledge of specific context and wider work systems. For example, constructs such as mental workload require consideration of a wider set of situational factors, beyond the understanding of an individual technology design. This is why for mental workload, along with other systems-level HF/E constructs, "a generally accepted definition does not exist" (Heikoop, et al., 2016, p. 290). These types of construct require a deeper, situational examination which is outside the scope of a high-level technology forecast. To include up to twelve other constructs (see Heikoop, et al., 2016) would simply show a consistently rising trend where all issues are applicable to all technologies. The selected HF/E issues are more readily discernible in their impacts, and thus are simpler to discriminate where they will be applicable, at a non-situational scope of analysis. These three broad HF/E issues are as follows:

HF/E Issue 1: Feedback – This attribute describes the extent to which the work system provides 'cues' to the end user enabling them to effectively perform their task in context (in this case the task of delivery driving of a commercial vehicle). This feedback consists of three types of physiological signals received from the environment, including auditory signals such as engine noise or alarms; haptic signals such as vehicle handling 'feel' or vibrations; or visual signals such as speedometer readings or observation of other vehicles in the road environment. Not only is feedback essential to task performance for the direct user, but it is also essential for the surrounding agents within the environment to ascertain information about behaviour which may impact their own tasks. For example, pedestrians at a crossing may use visual cues or auditory feedback from approaching vehicles to gauge whether it is safe to cross. Technologies described as 'transparent' or 'opaque' carry feedback which is moderately or highly obvious to the end user, with which they interact throughout performance of the task.

HF/E Issue 2: Attention – For present purposes this describes a broad class of cognitive activity linked to where perception is directed, its links to user's expectations and workload, and also speaks towards situation awareness and decision-making. Clearly technologies have a significant future role in directing where cognitive resources will fall and for what purposes.

HF/E Issue 3: Locus of control – Recent research has characterised locus of control as a malleable contextual attribute affected by situational factors rather than a fixed personality trait. This suggests a powerful connection to human-system interactions (Huang & Ford, 2012). From a systems perspective, any socio-technical work system has an allocation of function or a division of task responsibilities between human and technological actors. A human user's understanding of this distribution of task responsibilities, and its impact on behaviour, describes the individual's locus of control (Rotter, 1954). This perception of responsibility has influence on where and how the user's cognitive attention is directed and, once again, technologies have a significant future role in which system agent has responsibility and a willingness to act.

These three HF/E issues were placed in context with current and future commercial driving technology and the results analysed.

In order to link individual technologies to an examination of system design, the degree of automation (DoA) was considered in relation to the commercial driving task. DoA characterises the task's allocation of function, by defining the contribution of technologies in terms of their levels of automation, as well as across four stages of information processing. The levels automation are: not applicable to the task, low (interpreted as fully manual or human-led), moderate (interpreted as partially-automated), or high (interpreted as fully-automated). The four stages of information processing are: information acquisition, information analysis, decision & action selection, and action implementation (Onnasch, et al., 2014). Due to fact that DoA covers these four stages of information processing, there is an emphasis on the full cycle of decision-making, rather than a mere performance of physical actions. Thus by applying this specific framework published by Onnasch et al. (2014), some technologies which may appear to be automated in a general sense may actually receive a 'No' or 'Low' DoA score.

2.3.3. Projection of CO_2 reductions

Projections of future CO_2 emissions were calculated for each technological development contained in the forecast. This was undertaken using an approximated range of carbon reduction estimates for each identified technology based on the available literature. These carbon estimates were then multiplied by the number of affected vehicles in the UK's goods vehicle fleet based on their annual mileages and indicative drive cycles. Table 2.2 makes explicit these assumptions and is based on current national statistics (Department of Energy & Climate Change, 2014; Department for Transport, 2012a; Department for Transport, 2012b; Department for Transport, 2010b; Department for Transport, 2010c; Department for Transport, 2009c; Department for Transport, 2009d; Allen & Brown, 2008). Of course, technologies may not occur strictly in isolation and may instead occur in conjunction with other technologies (AEA, 2012, p. 45). The possibility (or indeed impossibility) of technologies being co-implemented was explored, and the carbon impacts then re-assessed. Alternative propulsion methods have, at present, been excluded from the HF/E forecast not because HF/E issues are absent, but because of current uncertainty in uptake, niche applications, and a separate area of work clearly being required. The forecast is open and flexible and can be added to as new knowledge and insight becomes available.

Table 2.2: Vehicle category assumptions for CO_2 reduction projections (seen in Figure 2.7)

VEHICLE CATEGORY	WEIGHT RANGE	DISTANCE TRAVELLED*	PROPORTION OF DISTANCE TRAVELLED BY VEHICLE CATEGORY
	(tonnes)	*(km/year)*	%
Heavy duty / heavy goods	25 – 44	11,067,000,000	20.41%
Medium duty inter-city distribution	7.5 – 25	2,557,400,000	4.72%
Medium duty urban distribution	7.5 – 25	807,600,000	1.49%
Medium goods	3.5 – 7.5	3,149,000,000	5.81%
Light goods	0 – 3.5	36,630,000,000	67.57%

**approximated from Department for Transport (2010b; 2010c)*

2.4. Results & discussion

2.4.1. Technology forecast

Each interview participant identified a technology and its likely time of implementation, and responses were logged in a master list to track the number of times each technology was identified, as well as the variability in perceived timescale to implementation. The trajectory for commercial vehicle technology use in the UK was constructed from these results, and was further classified by those technologies suggested to be in widespread or niche use. The review of industry and academic literature mapped well on to the list of technologies constructed from participant responses, and helped to provide a range of carbon reduction estimates as cited in Table 2.3.

Table 2.3: Individual technologies with timeline, description, purpose, class, Degree of Automation, HF/E issues, and CO_2 reduction impact

TIME-LINE	TECHNOLOGY	DESCRIPTION	PURPOSE	CLASS	DEGREE OF AUTOMATION	HF/E ISSUES	CO_2 REDUCTION PER HGV
2020	Aerodynamic Fittings	Small aerodynamic adjustments to the cab or trailer reduce drag and fuel use	Reduces CO_2	Enabling	No	Feedback to User (Auditory); Feedback to User (Haptic)	2.0% - 4.0% (Atkins, 2010)
	Heat Management	Heat management recovers and recycles engine heat to power a supporting turbine and generate energy	Reduces CO_2	Enabling	No	Feedback to User (Auditory); Feedback to User (Haptic)	3.0% - 6.0% (Baker, et al., 2009)
	Electrification of Hotel Loads	Electrification or alternative fuel use to support hotel loads (e.g. chilled trailers) in place of traditional fuel use	Supports alternative propulsion methods	Enabling	Low	None	
	Haptic Interfaces	Haptic interfaces include touchscreen displays, vibratory seats or seatbelts, haptic pedals, haptic steering etc.	Variable	Opaque	Low	Attention; Feedback to User (Auditory); Feedback to User (Haptic)	
	Next-Generation Digital Tachograph	Next-generation digital tachographs transmit vehicle dynamics and legally-required working hours data wirelessly to cloud storage, as opposed to the current method of data storage on integrated circuit cards carried by drivers	Safety-related	Opaque	Low	Attention; Feedback to User (Auditory); Feedback to User (Haptic); Feedback to User (Visual); Locus of Control	
	On-Board Safety Cameras	Safety cameras and in-cab displays make blind spots (thus surrounding road users) more visible to the driver, and are increasingly coupled with collision warning systems and/or ADAS feedback	Safety-related	Opaque	Low	Feedback to User (Auditory); Feedback to User (Visual)	
	Real-time Traffic Data	Provision of open-access real-time traffic data enables commercial software and application development for integration with in-vehicle information systems such as sophisticated satellite navigation systems	Supports advanced routing	Enabling	Low	None	
	Simulator Training	Driving simulators provide commercial vehicle driver training in a safe and controlled virtual environment	Supports eco-driving training	Enabling	Low	Attention; Feedback to User (Auditory); Feedback to User (Haptic); Feedback to User (Visual); Locus of Control	
	Collision Avoidance Warning Systems	Collision warning systems use surround sensor systems to detect nearby road objects to warn the driver of a projected collision	Safety-related	Opaque	Moderate to High	Attention; Feedback to User (Auditory); Feedback to User (Haptic); Feedback to User (Visual); Locus of Control	
	Mild Hybrid Propulsion & Stop/Start Systems	This vehicle type is designed to be partially supported by electric propulsion, often with capability to automatically turn off the vehicle's engine after a short period of time at a stop in order to conserve fuel use	Applicable for medium duty urban vehicles and light duty vehicles only	Transparent	Moderate to High	Attention; Feedback to User (Auditory); Feedback to User (Haptic); Feedback to Others (Auditory); Locus of Control	
	Advanced Driver Assistance System (ADAS) Feedback	ADASs utilise vehicle dynamics data to provide warnings to the driver in safety-critical situations, and increasingly as feedback to improve eco-driving practice	Variable	Opaque	High	Attention; Feedback to User (Auditory); Feedback to User (Haptic); Feedback to User (Visual); Locus of Control	
	Automated Emergency Braking (AEB)	Automated emergency braking (AEB) detects nearby vehicles or objects and autonomously takes over control of the vehicle to slow or stop in the event of an imminent crash	Safety-related	Transparent	High	Attention; Feedback to User (Auditory); Feedback to User (Haptic); Feedback to User (Visual); Feedback to Others (Visual); Locus of Control	
	Topographical Adaptive Cruise Control (TACC)	Topographical adaptive cruise control autonomously adjusts vehicle speed based on the movement of surrounding vehicles, a set target speed, or a projection of upcoming gradient using GPS triangulation, or any combination	Reduces CO_2	Opaque	High	Feedback to User (Auditory); Feedback to User (Haptic); Feedback to User (Visual); Feedback to Others (Visual); Locus of Control	2.0% - 6.0% (Baker, et al., 2009)
2021	Low Rolling Resistance Tyres	Low rolling resistance tyres minimise frictional losses between tyre and roadway, and thus reduce fuel use	Reduces CO_2	Enabling	No	Feedback to User (Auditory); Feedback to User (Haptic); Feedback to Others (Auditory)	4.0% - 8.0% (Baker, et al., 2009)
	Telematic Data Collection	Telematic data collection supported by personal devices (e.g. smartphones) use accelerometers, GPS, and wireless connection to vehicle electronic control units to collect and analyse data related to driver behaviour	Supports eco-driving reviews	Enabling	Moderate	Attention; Feedback to User (Auditory); Feedback to User (Haptic); Feedback to User (Visual); Locus of Control	
2022	Advanced Satellite Navigation & Routing Systems	Sophisticated satellite navigation systems will be customised to specific vehicle types for weight and dimensional data in order to avoid restricted routes (e.g. low bridges), and increasingly incorporate real-time traffic data	Variable	Opaque	Moderate	Attention; Feedback to User (Auditory); Feedback to User (Haptic); Feedback to User (Visual)	
	Integrated Aerodynamic Design	Aerodynamic design of the total vehicle system (cab and trailer) reduces drag and fuel use	Reduces CO_2	Enabling	No	Feedback to User (Auditory); Feedback to User (Haptic)	10.0% - 12.0% (Baker, et al., 2009)
	Lightweighting	Use of novel lightweight materials reduces vehicle system weight and reduces overall fuel use	Reduces CO_2	Enabling	No	Feedback to User (Auditory); Feedback to User (Haptic)	1.5% - 3.0% (Atkins, et al., 2013)
	Active Dolly Steering	Active dolly steering relies on advanced electronic control unit algorithms to enable large articulated vehicles to manoeuvre in roundabouts or otherwise tight spaces	Supports longer, heavier vehicles	Transparent	Moderate	Attention; Feedback to User (Haptic); Locus of Control	
	Active Steering	Active steering adjusts the degree to which steering wheels contributes to wheel movement dependent on vehicle speed, such that manoeuvring in	Supports longer, heavier vehicles	Transparent	Moderate	Attention; Feedback to User (Haptic); Locus of Control	

		urban areas or small spaces at low speed is ergonomically optimised for the driver					
	Infrastructure-to-Vehicle (I2V) Communications	Wireless communications (e.g. dedicated short-range communications) transmit local traffic condition information to each vehicle	Supports advanced routing	Opaque	Moderate	Attention; Locus of Control	
2023	Active Collision Avoidance Systems (ACAS)	Active collision avoidance systems (ACAS) employ automated emergency braking as well as trajectory control in the event that the surround sensor system detects an imminent crash with an oncoming or leading vehicle	Safety-related	Transparent	High	Attention; Feedback to User (Auditory); Feedback to User (Haptic); Feedback to User (Visual); Feedback to Others (Visual); Locus of Control	
2025	Reduction of Rearward Amplification	The advanced development of control engineering to reduce rearward amplification is intended to increase stability, decrease the risk of rollover, and adjust vehicle dynamics for optimal fuel use for longer heavier vehicles	Supports longer, heavier vehicles	Transparent	No	Feedback to User (Haptic)	
	Contactless Inductance Charging	Contactless inductance loops allow vehicles with electric propulsion to charge while in motion, thus extending the range of the vehicle	Supports alternative propulsion methods	Enabling	Low	Locus of Control	
	Head-Up Displays	Head-up displays present information on the windscreen in order to optimise attentional resources	Variable	Opaque	Low	Attention; Feedback to User (Visual); Locus of Control	
	Optimised Mirror Design	Tailored cab and mirror design improves the driver's visibility of nearby road users	Safety-related	Enabling	Low to Moderate	Attention; Feedback to User (Visual)	
	Integrated Tachograph & Telematic Data Collection	Advanced telematic data collection and tachograph systems may be integrated for streamlined collection of data for legal requirements, driver monitoring, and real-time feedback	Supports eco-driving reviews	Enabling	Moderate	Attention; Feedback to User (Auditory); Feedback to User (Haptic); Feedback to User (Visual); Locus of Control	
	Electric Hybrid Propulsiom	New propulsion method are supported by alternative fuel, which necessitate advanced control engineering, drive-by-wire systems, and regulation of the vehicle via the electronic control unit	Reduces CO_2; variable applicability	Transparent	Moderate to High	Feedback to User (Auditory); Feedback to User (Haptic); Feedback to Others (Auditory)	Variable – not detailed due to uncertainty of uptake
2026	Expansion of Truck or Trailer Dimensions	Larger hauls contribute result in fewer heavier vehicles on the roadways, thus the expansion of truck or trailer dimensions systemically reduces fuel use	Reduces CO_2	Enabling	No	Feedback to User (Auditory); Feedback to User (Haptic); Feedback to Others (Visual)	10.0% - 30.0% (Morrison, et al., 2014)
2027	Battery Electric Propulsion	New propulsion method are supported by alternative fuel, which necessitate advanced control engineering, drive-by-wire systems, and regulation of the vehicle via the electronic control unit	Reduces CO_2; variable applicability	Transparent	Moderate to High	Feedback to User (Auditory); Feedback to User (Haptic); Feedback to Others (Auditory)	Variable – not detailed due to uncertainty of uptake
	Diesel-Mix Fuel Use	Additives which help to maintain the engine and advanced engine control strategies which support precise injection of diesel-petrol mix fuels improve efficiency	Reduces CO_2	Enabling	Moderate to High	None	Unknown for logistics vehicle use
	Fatigue Detection Technology	Fatigue detection technology monitors the driver to recognise physiological signs of fatigue, and provides warnings to alert the driver, or triggers autonomous vehicle control to reduce the likelihood or severity of an incident	Safety-related	Opaque	Moderate to High	Attention; Feedback to User (Auditory); Feedback to User (Haptic); Feedback to User (Visual); Locus of Control	
	Automated Low Speed Manoeuvring	Automated low speed manoeuvring utilises the surround sensor system to take autonomous control of the vehicle in order to make complicated reversals into loading bays or perform other low speed manoeuvres.	Supports longer, heavier vehicles	Opaque	High	Attention; Feedback to User (Auditory); Feedback to User (Haptic); Feedback to User (Visual); Feedback to Others (Visual); Locus of Control	
2033	Heavy Goods Vehicle (HGV) Platooning	Platooning utilises surround sensor systems to facilitate vehicle-to-vehicle communication, appointing a lead vehicle in a 'road train' and enabling autonomous control of following vehicles at an optimal distance, minimising aerodynamic drag	Reduces CO_2	Opaque	High	Attention; Feedback to User (Auditory); Feedback to User (Haptic); Feedback to User (Visual); Feedback to Others (Auditory); Feedback to Others (Visual); Locus of Control	2.1% (Bergenheim, et al., 2012) - 20.0% (Ricardo AEA, 2009)
2034	Dedicated Gas Propulsion	New propulsion method are supported by alternative fuel, which necessitate advanced control engineering, drive-by-wire systems, and regulation of the vehicle via the electronic control unit	Reduces CO_2; variable applicability	Transparent	Moderate to High	Feedback to User (Auditory); Feedback to User (Haptic); Feedback to Others (Auditory)	Variable – not detailed due to uncertainty of uptake
2036	Dual Fuel Gas Propulsion	New propulsion method are supported by alternative fuel, which necessitate advanced control engineering, drive-by-wire systems, and regulation of the vehicle via the electronic control unit	Reduces CO_2; variable applicability	Transparent	Moderate to High	Feedback to User (Auditory); Feedback to User (Haptic); Feedback to Others (Auditory)	Variable – not detailed due to uncertainty of uptake
2037	Natural Gas Infrastructure	Natural gas infrastructure supports long-haul journeys in vehicles using natural gas as alternative fuel	Supports alternative propulsion methods	Enabling	No	None	
	Hydrogen Fuel Cell Propulsion	New propulsion method are supported by alternative fuel, which necessitate advanced control engineering, drive-by-wire systems, and regulation of the vehicle via the electronic control unit	Reduces CO_2; variable applicability	Transparent	Moderate to High	Feedback to User (Auditory); Feedback to User (Haptic); Feedback to Others (Auditory)	Variable – not detailed due to uncertainty of uptake

Figure 2.1 shows projected future technology to 2020 as identified by industry experts.. These include technologies with a wide range of driving task implications. The highest degree of automation (DoA) is found for automated emergency braking systems, for example. Items in Figures 2.1 through 2.3 denoted by an asterisk were identified for niche use only; in the short term this includes mild hybrid and stop/start systems.

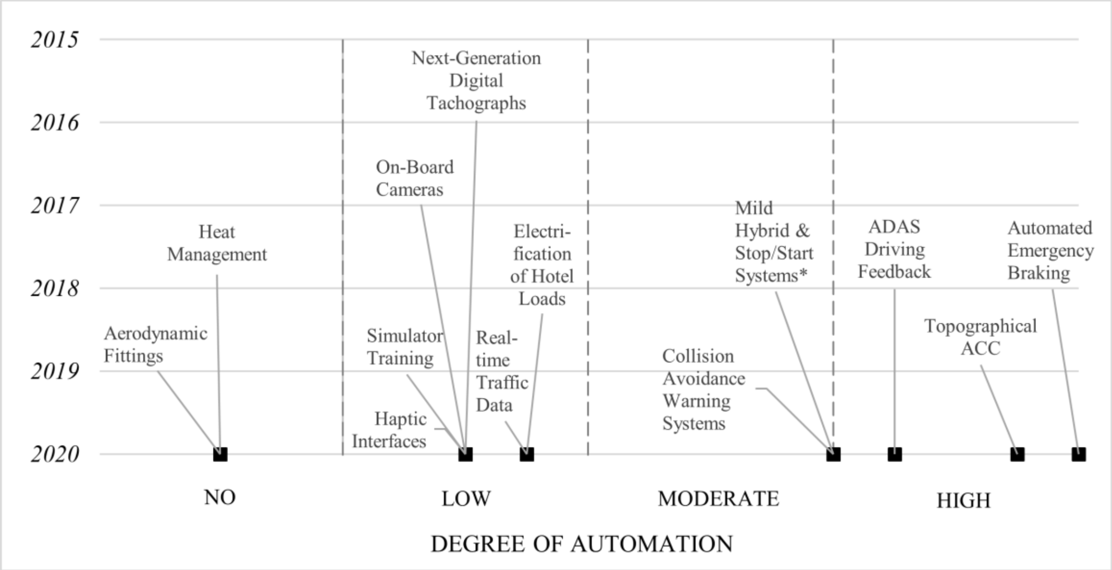


Figure 2.1: Commercial vehicle technologies in UK identified for short term 2015-2020

In the medium term (Figure 2.2), technologies with more profound task implications are expected to be implemented. These include sophisticated infrastructure-to-vehicle communications, vehicle-to-vehicle communications, and other applications relying on sensor systems. At the highest DoA, Active Collision Avoidance Systems are designed to brake autonomously, as well as adjust the trajectory of the vehicle in the event of a collision with an oncoming vehicle. Electric hybrid vehicle use was identified for niche industries or applications by 2025.

In the long term (Figure 2.3), many of the technologies identified fall in the range of moderate to high degrees of automation. The items identified included the expansion of truck or trailer dimensions by 2026, as well as the availability of natural gas infrastructure in 2037. Four of the ten technologies for implementation in the long term were identified for niche applications or industries only, including battery electric vehicles, dual fuel vehicles, dedicated gas vehicles, and hydrogen fuel cell vehicles. Technologies with the highest DoA included automated low-speed manoeuvring by 2027, and commercial vehicle platooning by 2033.

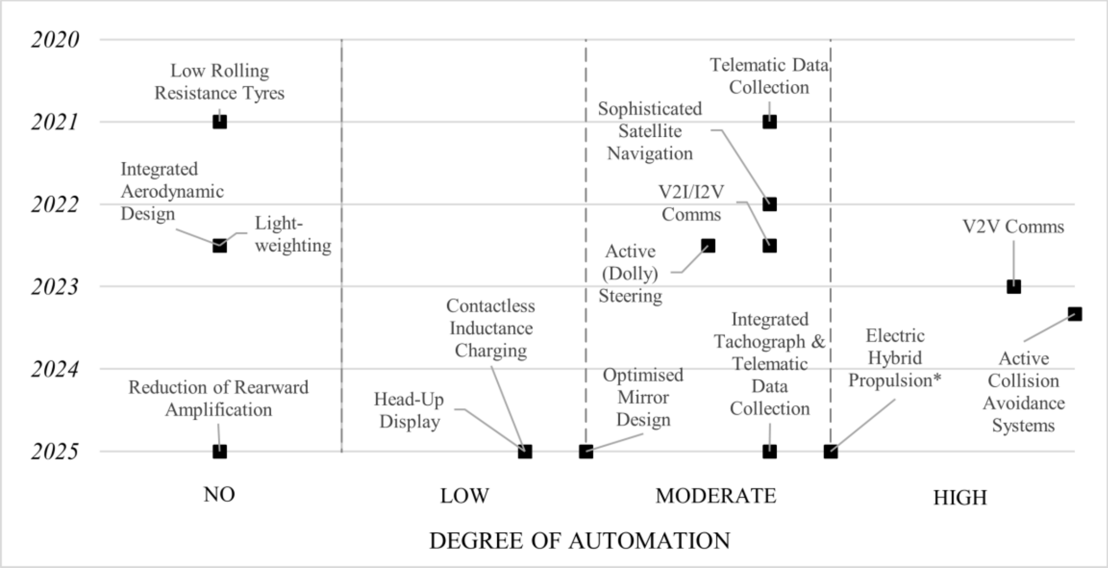


Figure 2.2: Commercial vehicle technologies in UK identified for medium term 2020-2025

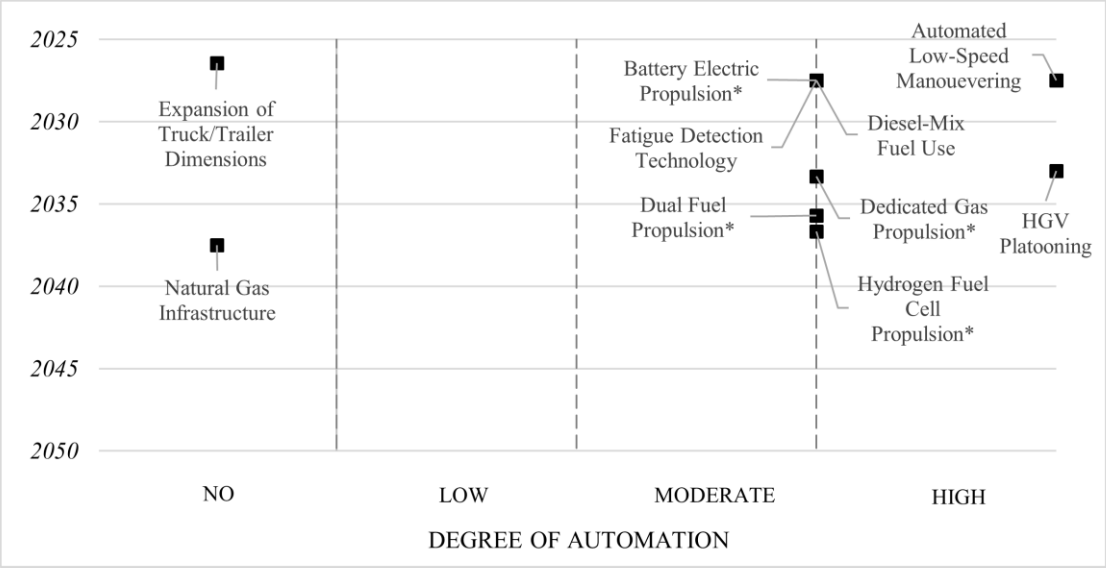


Figure 2.3: Commercial vehicle technologies in UK identified for long term 2025-2030

Many participants expressed caution about identifying novel technologies and applications beyond 2030, due to the 10- to 15-year life cycle of commercial vehicle development and uncertainty regarding future operating conditions. Although the majority of identified technologies were identified consistently by participants within a given time step, alternative propulsion methods (and supporting infrastructure) identified in Figures 2.1 through 2.3 carried the widest variability in time to implementation. This may be a reflection of each participant group's localised perspective of the system, or due to concerns surrounding a solid business case for such technologies, including the geographical availability of future infrastructure to reliably support operations-as-usual in terms of journey range (Ricardo AEA, 2012). While technology 'suppliers' may understand that interventions are technologically ready, the fleet operators who represent the majority of technology 'customers' may be more risk-averse. One additional explanation for this difference may be that while drivers report more support for the implementation of environmentally-friendly technologies, operators' decision-making processes rely primarily on cost (Schweitzer, et al., 2008).

Despite some understandable reluctance and caution in making long-range predictions some trends and movements are still well evident. Figure 2.4 zooms out to present a high-level overview of general logistics trends offered by the expert participants. Short-term trends include the development of driver training legislation, and further customisation of vehicle technology to drive cycles and applications. In the medium term, we expect to see communications integration with intelligent transport systems, and the development of increasingly autonomous vehicles. In the longer term, specific legislation and regulation of autonomous vehicle applications are expected.

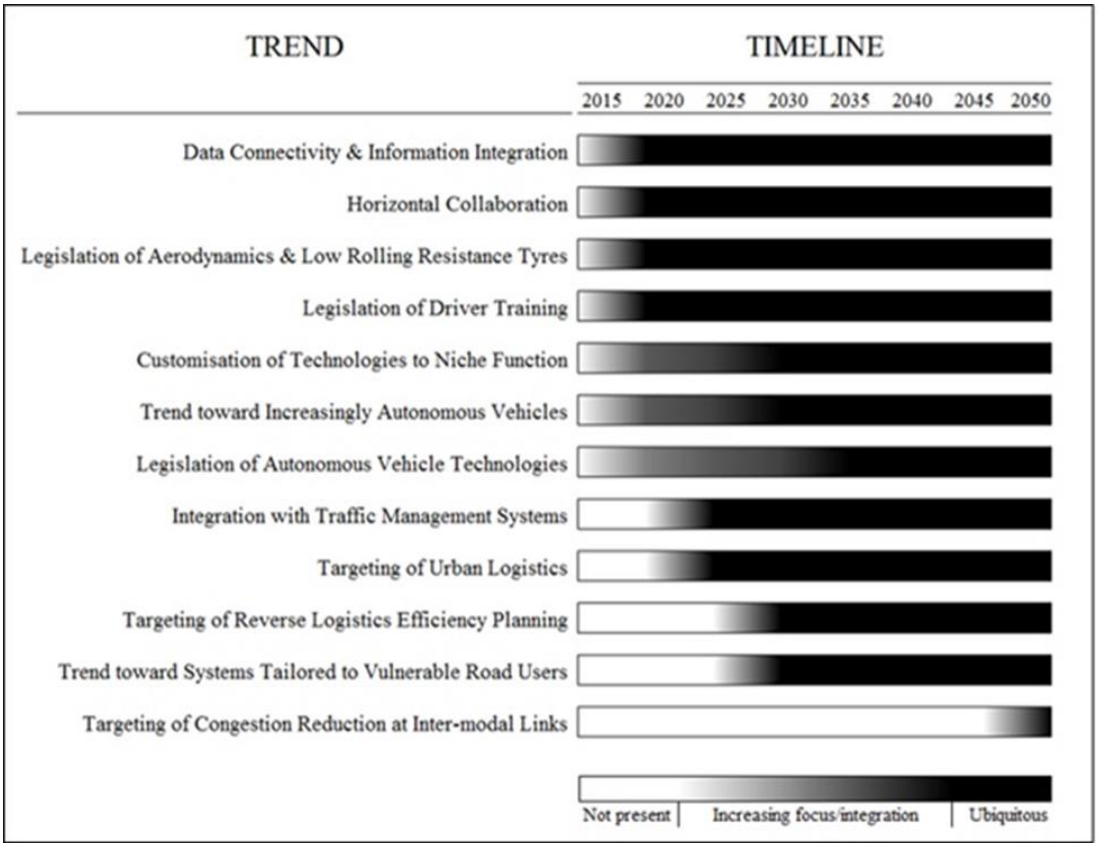


Figure 2.4: Commercial road freight trends volunteered by expert participants

Throughout the technology trajectory, the changing nature of the driver role is acknowledged in driver training and legislation. Training is often the intervention of first choice when dealing with behavioural issues, but experience in applied ergonomics suggests a range of other potentially useful interventions. These include error-tolerant systems (Johnson, 1996), adaptive automation (Byrne & Parasuraman, 1996), and designs which cleverly constrain behaviour so that the desired behaviour is the same as the easiest, most natural one for people to perform in real-life (Dekker, 2017). A greater focus on human factors within the logistics domain could help to shift the current dialogue.

2.4.2. HF/E trajectory

The previous section presents forecasts of road freight technology and trends. This section proceeds to map the technology to its associated HF/E issues. It is important to note that the human factors evaluation being currently applied serves only to highlight generic human factors issues. The purpose is to provide a foundation for more in-depth contextual analysis of each technology later in the thesis and beyond. Figure 2.5 begins by showing the potential human factors associated with each road mapped technology, and their aggregated significance over time.

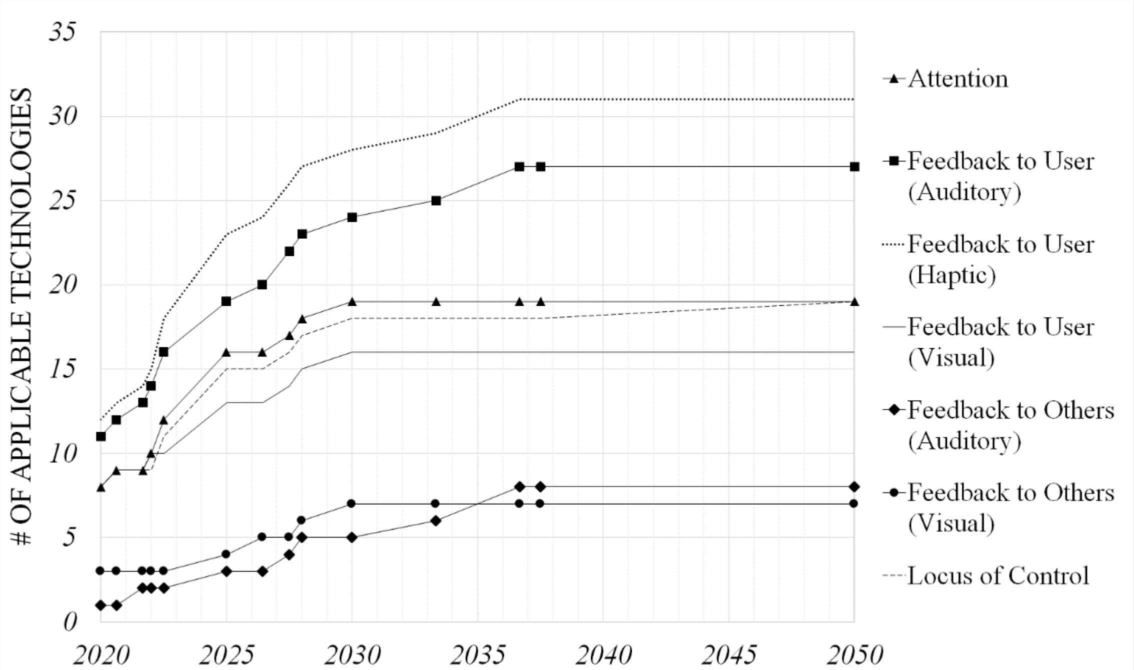


Figure 2.5: Associated human factors of logistics technologies in UK & their aggregated significant over time

Some significant impacts for the driver/vehicle system centre around for the removal and/or augmentation of haptic feedback, followed by the similar removal/augmentation of auditory feedback. The significance of ‘locus of control’ at each time step of the trajectory suggests that an approach for system evaluation will also need to include more consideration of issues like allocation of function. Studies indicate that drivers may adjust their locus of control in a natural process of adaption to new technology over long-term use (e.g. Hoedemaeker & Brookhuis, 1998; Rudin-Brown & Parker, 2004; Maltz &

Shinar, 2004; Skottke, et al., 2014). This carries potential risks to safety or, at the very least, technological effectiveness in the case of system failure.

The DoA analysis was documented for each identified technology, and then aggregated for each time step (as depicted in Figures 2.1 through 2.3). While high degrees of automation support routine operations, they also carry negative effects when the system malfunctions or fails. In layperson's terms this is referred to as the 'lumberjack effect', indicating that 'the higher they are, the harder they fall' in terms of recovery from system failure. The meta-analysis carried out by Onnasch et al. (2014) found this effect to be exacerbated in certain system designs. A performance step-change occurs when the design of automation shifts from allocation of information analysis, to decision and action selection. From the analysis of identified technologies, 'information analysis' was found to be the stage of information processing with the largest increase in allocation to technology between 2020 and 2050, followed closely by 'action selection'. This trend suggests that future technologies are at high risk of the 'lumberjack effect' whereby system performance under expected conditions is adequate, but in the event of a failure, disruptions are difficult to recover from. In the specific context of commercial driving and logistics operations, the DoA remains more or less constant over time, however the characteristics of such automation become generally more complex and more demanding of technological agents.

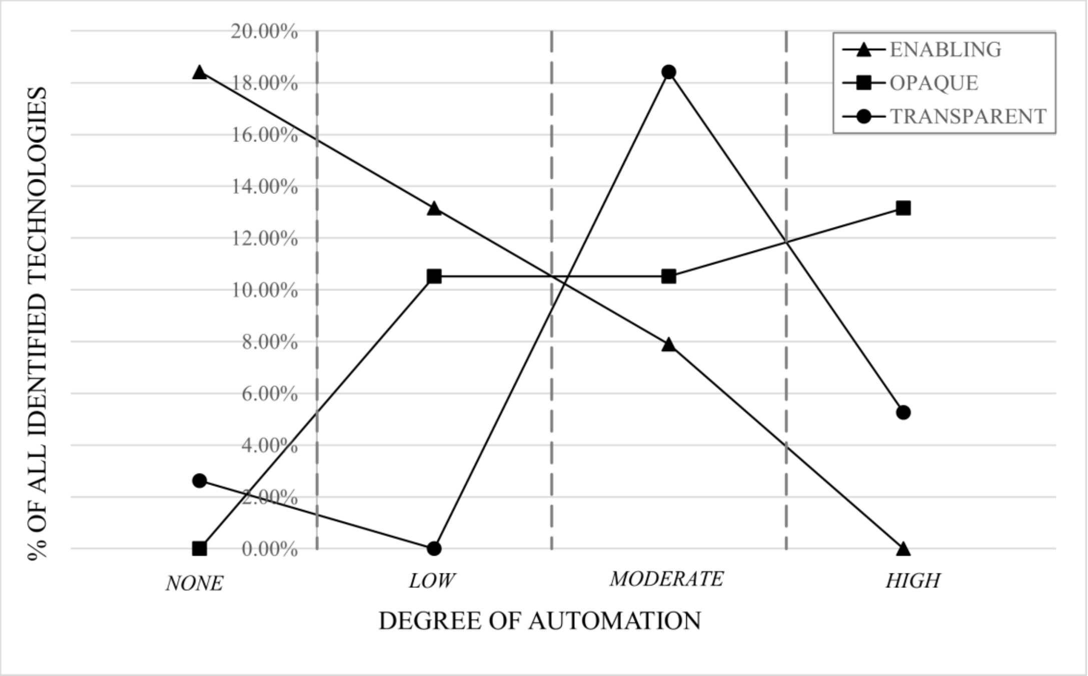


Figure 2.6: Proportion of transparent, opaque, and enabling technologies identified mapped against degree of automation (DoA) categories

Figure 2.6 also shows a broad relationship between technology classification into enabling, opaque and transparent categories, and the DoA. It shows that of the technologies identified by participants, enabling technologies occur most frequently at no or low degrees of automation. In contrast, opaque technologies were found most frequently at high DoAs. Interestingly, the proportion of transparent technologies varies with DoA. In other words, technologies designed to mediate and optimise interactions between vehicle and driver may not be apparent to the end user, but are nonetheless projected to carry out a range of tasks with widely varying complexity.

2.4.3. Projected CO_2 reductions

The intended goal for many of the identified new technologies is to reduce carbon emissions. Figure 2.7 has been based on industry estimates for engineering technologies and shows progress in carbon reductions against future targets. A working assumption is that increasing road freight activities due to economic growth will largely cancel out projected engine efficiency improvements (AEA, 2012).

With these caveats in place what is immediately striking is that engineering technologies identified within the timeline fall short of achieving the required carbon reduction targets of 80% by 2050. The projections shown below acknowledge two scenarios (a minimum and maximum impact) for two types of estimations (per HGV, and across the entire national logistics fleet regardless of vehicle classification). None of these conditions succeed in meeting the reduction requirement. Not only this, but Figure 2.7 also relies on the assumption that each engineering technology is adopted by 100% of applicable vehicle types.

The fact that engineering alone is not sufficient to reach carbon reduction targets is based on the most optimistic case possible. As can be seen in the high occurrence of ‘niche only’ technologies in Figure 2.3 (and the estimates in Figure 2.7) there may be diminishing returns over time from the implementation of engineering interventions in isolation. In fact, by 2030, many engineering technologies will be in widespread use, placing increasing emphasis on behavioural and systems solutions as time progresses.

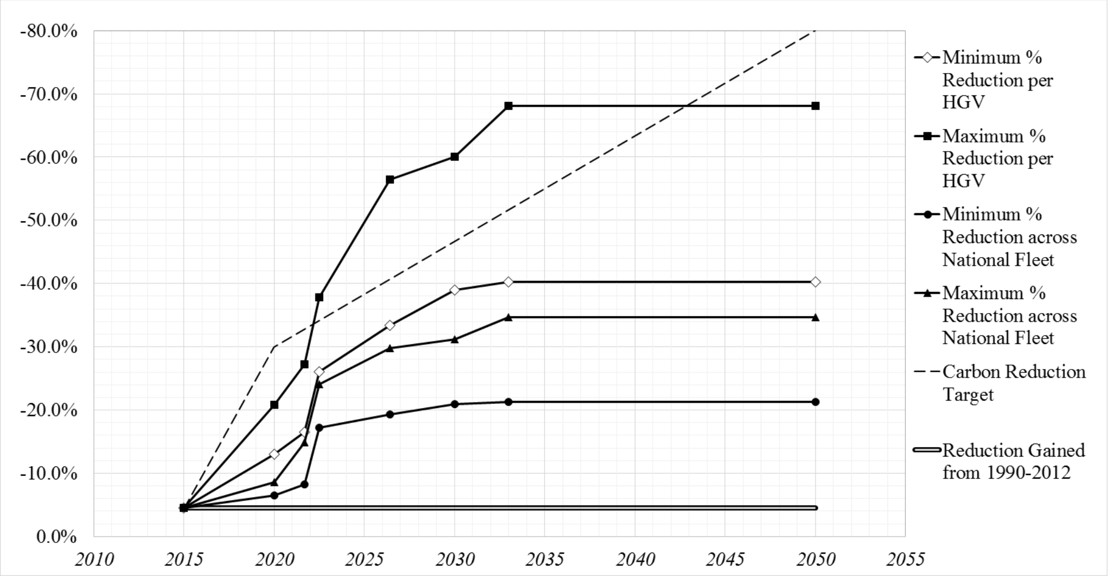


Figure 2.7: Estimated carbon reduction gained by identified engineering technologies (not including alternative propulsion methods, due to uncertainty in proportion of uptake)

The wide 27.85% gap between the maximum and minimum estimates for CO_2 reductions per HGV points to the complexities of technology trials in real-world logistics systems, and the need for contextual analysis to maximise practical impact. Interview responses also suggest short time frames of predictability and the sensitivity of the logistics system to time, which may delay the uptake of more radical technologies in risk-averse environments, further emphasising the need for deconstruction and analysis of one currently elusive influence: the human factor. From the above analysis the call to action could not be clearer.

2.5. Is technology alone enough?

Is technology alone enough? The results of this study suggest that it is not. This work reveals the key to achieving mandated carbon emissions will increasingly rely on behavioural interventions and systems design. From the above results it is clear that future commercial vehicles will incorporate a great number and wide range of transparent, opaque, and enabling and systems technologies. But what will this future actually look like? In place of a lengthy ordering of facts an alternative method has been chosen. The findings have been synthesised into two test drives in order to speculatively demonstrate the wide range of potential issues or benefits. An optimistic and pessimistic commercial vehicle test drive are described below.

2.5.1. Scenario 1 – An optimistic 2030 test drive

Before leaving for work, the driver checks their assigned tablet or phone and signs in to their profile on their organisation's app, which displays their truck and delivery assignment. When reaching the assigned truck, the driver notices some minor fender damage, and takes a picture with their tablet or phone which is sent with a time stamp to the vehicle depot garage, where the damage can be roughly assessed and parts can be manufactured from their 3D printer and replaced at the end of the driver's shift. The driver then switches to a tachograph app, and switches in to 'driving' mode through the touchscreen interface, which activates Bluetooth communication to connect with the CANbus and continuously collect vehicle dynamics data. This legally-required tachograph data is sent to a cloud storage point associated with the driver and their base office, along with the driver's 'shift profile' driving behaviour which is calculated in relation to a targeted delivery timeline, fuel efficiency, or eco-driving behaviour. The driver's fleet manager can track or review this information at any time, and the driver can opt to have this information sent to their profile or personal e-mail address in a weekly report, should they wish to examine their performance between meetings with fleet managers. To heighten the competition in order to sustain engagement with the program, weekly tables are posted (in an anonymised format) in the base office, where drivers can see the progress they have been making and their rank amongst the other company drivers.

The driver then starts up the vehicle, activating the advanced driver assistance system and the head-up display which provides the information for navigation, weather and road conditions, and rest stop areas. Route directions are displayed on the windscreen and are dynamically updated throughout the journey, based on real-time congestion data, roadworks information provided by infrastructure-to-vehicle communication, and the set dimensions and weight as calculated by the vehicle's CANbus. Moving through an outer urban area, the driver accelerates a bit too harshly, and the ADAS provides visual feedback on the windscreen, advising the driver to slow and 'smooth' this driving behaviour in order to optimise fuel usage. The driver continues on and attempts a left-hand turn, during which a cyclist in the driver's blind spot triggers the sophisticated active collision avoidance system which is continually feeding surrounding sensor data to the vehicle's computerised control unit. The sensors detect a possible (but not imminent) collision, and the ADAS collision warning uses a vibratory alert in the steering wheel. This haptic warning and the auditory warning coming from the dashboard draws the driver's attention immediately to the on-board safety camera visual, which has appeared in the head-up display. Paired with traditional mirrors which have been optimised based on interface guidance (built from information on blind spots and visual search behaviour) this enables the driver to manoeuvre cooperatively with the cyclist, avoiding an accident.

On arriving at the pick-up point, the lot is packed with vehicles. To minimise the waiting time for vehicles further down the queue, and the chances of getting into a tough spot or causing a safety incident in the lot, the driver pulls in and switches on the automated low-speed manoeuvring function which seamlessly and autonomously reverses the 40-tonne vehicle into the loading bay while using the sensor system to detect for nearing obstacles. The driver again uses the telematics tachograph application on their assigned personal device to switch to ‘other work’ mode, before switching off the vehicle and opening an app containing delivery information. After using the personal device to complete any administrative work and loading the vehicle with goods, the driver switches the tachograph app back on to ‘driving’ mode, and uses the dynamic force steering to manoeuvre easily around tight corners and spaces at the pick-up point.

Accelerating on approach to the highway, the driver works effortlessly with the vehicle, as despite the larger vehicle dimensions, greater payload, and intensive lightweighting, the truck-trailer combination has undergone an integrated aerodynamic design. Similarly, while the trailer unit is propelled partially by isolated electromobility and many other parts of the vehicle are controlled electronically, the computerised control unit continually optimises vehicle dynamics and stability. Entering the highway, the driver switches on the topographical adaptive cruise control (TACC), which communicates with GPS to project the gradient of upcoming terrain, and takes control of vehicle dynamics to optimise medium-term fuel usage. The ACAS corrects the truck’s trajectory where necessary, ensuring that it remains between the lane boundaries. This same data is simultaneously used in determining the trajectory of oncoming vehicles so that in the event of a possible head-on collision, the truck can autonomously adjust its own steering and dynamics to create an aversive trajectory. Suddenly, a passenger vehicle traveling in the adjacent lane cuts in front of our vehicle, triggering the automated emergency braking which stops the truck just in time to avoid an incident. The driver regains control of the vehicle, and switches the TACC back on as traffic resumes normally.

Several other trucks on the highway join up with our driver, using vehicle-to-vehicle sensor communication to create an aerodynamically optimised vehicle platoon. The following drivers in the platoon take a supervisory role over their vehicles, and are able to finish some administrative ‘paperwork’ (completed via a tablet application) for their next destinations.

A few miles before reaching the off-ramp for the delivery point, the truck’s CANbus wirelessly sends notifications to the ADAS of surrounding road train vehicles that our driver will soon be exiting the platoon and the preceding truck in the queue will be required to take over. A roadside wireless infrastructure-to-vehicle communications point links the local area’s traffic management system in with the vehicle’s ADAS, and a warning appears on the head-up display regarding a point of congestion on the route which was projected by the satellite navigation system at the outset of the shift. The satellite navigation system suggests a route change to the next off-ramp, which under normal conditions would take a few minutes longer, but in this instance will save a substantial amount of time by avoiding the incident causing congestion ahead. The driver accepts this suggestion, and then switches off the TACC to make a lane change, and continues ahead to the next off-ramp in order to make it to the first delivery destination in a safe and timely manner.

After a long and tiring day behind the wheel, the driver is on the way back to the base of operations. It is dark and overcast, and the toll of the day causes the drowsy driver to close his eyes. The fatigue detection system, using an optical tracking camera, is immediately triggered by this behaviour and prepares to take temporary control to stop the vehicle. However, the simultaneous haptic vibration in the seat as well as an auditory alarm alerts the driver before this is necessary, and the ADAS projects the remaining miles on the journey onto the head-up display, and suggests a nearby rest stop location for a short break. After a temporary switch to ‘break’ mode in the tachograph app and having a strong cup of coffee, the driver returns smoothly to the base office and signs off, feeling satisfied with their driving style and performance in the face of today’s hard work and the next fleet manager meeting.

2.5.2. Scenario 2 – A pessimistic 2030 test drive

Before leaving for work, the driver checks their assigned tablet or phone and signs in to their profile on their organisation’s app, which displays their truck and delivery assignment. When reaching the assigned truck, the driver notices some minor fender damage, and takes a picture with their tablet or phone which is sent with a time stamp to the vehicle depot garage, where the damage can be roughly assessed and parts can be manufactured from their 3D printer and replaced at the end of the driver's shift. The driver then switches to a tachograph app, which requests an update before opening. After waiting several minutes for this to complete while in the depot, the driver switches in to 'driving' mode through the touchscreen interface, which activates short-range Bluetooth communication to connect with the CANbus and continuously collect vehicle dynamics data. This legally-required tachograph data is sent to a cloud storage point associated with the driver and their base office, along with the driver's 'shift profile' driving behaviour which is calculated in relation to a targeted delivery timeline, fuel efficiency, or eco-driving behaviour. The driver's fleet manager tracks company drivers in order to ensure they arrive at their destinations on time in the most fuel-efficient way possible, and if necessary in the case of delays or poor driving behaviour, can phone or contact the driver immediately. At meetings with fleet managers, most drivers don't mind the new technology however different drivers have a wide range of different driving styles, and different managers have varying levels of understanding regarding how the new technology functions. Some drivers receive weekly progress reports on their driving style and enjoy participating in the weekly tables – as all of the drivers know each other, it doesn't take long to determine which scores belong to which driver in the anonymised format. However, the majority see these eco-driving reviews as a 'check-the-box' exercise and view it as conflicting with the primary goal under real-world conditions – quick and incident-free delivery – thus are not as invested in the program when independently at work on the road. Some drivers have even learned to cheat the system by using unconventional manoeuvres such as avoiding the brake pedal and only applying the handbrake when deceleration is needed at low speeds. Not only do manoeuvres such as these cause considerable wear to the vehicle, but these also may increase overall emissions from abrupt deceleration and acceleration manoeuvres.

The driver starts up the vehicle, activating the advanced driver assistance system and the head-up display which provides the information for navigation, weather and road conditions, and rest stop areas. Although the ADAS contains valuable information, it's all a bit too much for the driver before even leaving the base depot, and the driver spends a few minutes minimising and adjusting the majority of the default visuals. Whilst personalising their own display, they are distracted from the immediate road environment, causing jerky, abrupt manoeuvres which increase emissions for the first several minutes of the drive. Using the sophisticated satellite navigation system, the driver begins moving through an outer urban area and on pulling forward through an intersection the driver perceives that a vehicle travelling in a perpendicular lane is not slowing down enough to come to a full stop. Our driver ignores the ADAS' visual feedback and accelerates harshly through the last of the intersection, in order to avoid an incident which might have been caused by the other driver's misperception of how quickly a heavy vehicle can accelerate from a full stop. The vehicle in front of the truck comes to a sudden stop, and the truck's sensors activate the automated emergency braking to bring the truck to an abrupt stop just before impact – and by sheer luck, our driver has already cleared the intersection at the rear, as the lights have again changed priority and traffic has resumed. Once the ADAS notifications have disappeared and traffic ahead has continued on, the driver moves forward and attempts a left-hand turn, during which a cyclist in the driver's blind spot triggers the sophisticated active collision avoidance system. The sensors detect a possible (but not imminent) collision, and the ADAS collision warning uses a vibratory alert in the steering wheel. This haptic warning and the auditory warning coming from the dashboard alert the driver, but of the many forms and locations of feedback, the driver is having a difficult time determining which type of hazard is being picked up on by the system. This is especially because the cyclist has now moved out of the scope of the on-board safety camera, and while the driver is checking the visual on the head-up display, the cyclist has changed lanes away from the scope of the sensors and mirrors. From the perspective of the driver, the ADAS collision warning could have been activated by any number of cyclists zipping between lanes and through traffic, or simply a technological glitch. Amidst the continuously changing stream of information the driver is processing about the surrounding traffic at this intersection, the collision warning is quickly and unconsciously shrugged off, and the driver continues toward the pick-up point.

On arriving at the pick-up point, the lot is packed with vehicles. To minimise the waiting time for vehicles further down the queue, and the chances of getting into a tough spot or causing a safety incident in the lot, the driver pulls in and switches on the automated low-speed manoeuvring function. All is going well until the surrounding activity in the lot repeatedly triggers the automated emergency braking, at which point the driver deactivates both the automated emergency braking and the low-speed manoeuvring function to perform the activity without interruption. The driver again uses the telematics tachograph application on their assigned personal device to switch to 'other work' mode, before switching off the vehicle and opening an app containing delivery information. However, the data connection is limited in this area and the wireless internet connection available at the pick-up point is strained from the number of users attempting to log on for their own delivery information. Our driver enters the pick-up point office, which is busy with drivers trying to sort out the details of their work in order to make it to their delivery point in time, and eventually receives the relevant information. After using the (slow, albeit functional) data connection to complete any administrative work on their personal device and loading the vehicle with goods, the driver switches the tachograph app back on to 'driving' mode and prepares to depart. The dynamic force steering is designed to navigate easily around tight corners and spaces but the driver, prepared to depart for the highway, is not expecting the sensitivity of the steering wheel, and thus harshly corrects manoeuvers in order to adjust their driving style and avoid collisions and scrapes in the lot.

Accelerating on approach to the highway, the driver feels disjointed from the vehicle, having to constantly adjust to unexpected handling characteristics produced by the combination of aerodynamic design and computer-optimised dynamics. Entering the highway, the driver switches on the topographical adaptive cruise control (TACC), which communicates with GPS to project the gradient of upcoming terrain, but at the start of the first incline the driver is unsettled by the lack of forward momentum and the feeling that they will roll back into traffic, causing them to switch the function off. The driver continues on, aware that the ACAS corrects the truck's trajectory where necessary to ensure that it remains between the lane boundaries and providing an automated aversive trajectory in the case of an oncoming vehicle. The driver assumes that the ACAS will take over in an emergency and deems the likelihood of an emergency low given the current traffic conditions, and so takes a few moments to readjust settings within the vehicle, change music playing from his personal device, and get comfortable. As the driver is refocusing his attention back to the traffic environment, a passenger vehicle traveling in the adjacent lane accelerates and cuts in front of our vehicle. While the driver begins to instinctively manoeuvre by slowing down and slightly swerving, the expected auditory and visual collision warning are activated, but the automated emergency braking is not – in his rush to reach the delivery point on time, the driver has forgotten to turn the function back on after leaving the pick-up point. Although the driver's expectation is that the vehicle will take control and automatically stop, the driver manages to swerve into the next lane before regaining control of the near-incident.

After rejoining with the normal flow of traffic, several other trucks on the highway join up with our driver, using vehicle-to-vehicle sensor communication to create an aerodynamically optimised vehicle platoon. However, one truck in the middle of the platoon is alerted to one or two faulty sensors, which disables it from receiving the information necessary to integrate with the other trucks and forces the driver to exit the platoon. In order to retain some degree of fuel saving, this driver manoeuvers to the back of the platoon but remains disconnected. Although aware of the disconnection with vehicles in front, the driver's experience with platoons causes them to unconsciously maintain a slightly closer following distance than is safe without automated support. The lead driver in the platoon does not rely on semi-autonomous technology, but the following connected drivers take a supervisory role over their vehicles, allowing them to focus on other work tasks or have a quick bite to eat on the road. While several following connected drivers are simultaneously eating lunch, reading about safe rest stop location, and reviewing a driver performance profile from the previous week, the car traveling in front of the lead truck in the platoon decelerates harshly in reaction to an animal on the roadway.

The lead vehicle's automated emergency braking is activated in time to avoid a rear-end collision, and while the following connected drivers are distracted from the driving task, the vehicle-to-vehicle communication allows them to remain unscathed. However, the driver of the final disconnected vehicle in the platoon has no field of vision to be alerted to the incident and a faulty sensor system which has disabled both collision warnings and the automated emergency braking. Due to the normalcy of a close following distance in a platoon setting, the final disconnected driver's close following distance and locus of control cause a delay in response, and a harsh rear-end collision results with the vehicle in front which is still connected to the platoon. The remainder of the platoon receives notifications of an incident on their head-up displays, however this provides few details. This allows the drivers who are still connected within the platoon to slow, and verbally communicate via the Bluetooth-enabled ADAS. There is considerable confusion about the events of the incident due to the fact that the final connected driver has now stopped and sensors are out of range resulting in a disconnection from the information circulating amongst the platoon. Once it has been assessed that only the last driver in the platoon has been affected, the unaffected section of the platoon is keen to move forward with their deliveries and to leave the involved drivers deal with the incident. Luckily, neither driver is injured, but both must call in the incident as each vehicle requires roadside assistance. Both have received automated incident report questionnaires which have been sent to their personal device after being activated by the vehicle dynamics data in the CANbus of their vehicle, which serve the dual purpose of incident reporting to the authorities and detailing insurance claims. While each driver is struggling to complete the section “Who do you believe is at fault for the incident and why?” assistance turns up on the scene and brings their attention to getting their vehicles evaluated and back on the road.

A few miles before reaching the off-ramp for the delivery point, the truck’s CANbus wirelessly sends notifications to the ADAS of surrounding road train vehicles that our driver will soon be exiting the platoon and the preceding truck in the queue will be required to take over as lead vehicle. A roadside wireless infrastructure-to-vehicle communications point links the local area’s traffic management system in with the vehicle’s ADAS, and a warning appears on the head-up display regarding a point of congestion on the route which was projected by the satellite navigation system at the outset of the shift. The satellite navigation system suggests a route change to the next off-ramp, which under normal conditions would take a few minutes longer, but in the case of an incident will save a substantial amount of time by avoiding congestion. The driver accepts this suggestion, and waits for confirmation from the preceding vehicle that it is suitable to disconnect from the platoon. The driver eventually receives confirmation, but due to the distraction of following drivers this occurs only after passing the suggested off-ramp, and the satellite navigation system struggles to keep pace with the dynamic changes of the task. Preparing to double back, the driver continues ahead to the next off ramp and makes an exit while the satellite navigation system is processing new information from the roadside traffic management system points. Meanwhile, the head-up display is rapidly filling with rest stop suggestions and other local information. Eventually an optimal route is provided and displayed on the ADAS, but by the time it is provided the driver is forced to awkwardly manoeuver into another lane at the first junction in order to adhere to this route guidance. This is especially difficult given that the traffic management system is rerouting the majority of vehicles along this new route away from the originally reported incident, and as a result the local network is quickly becoming more congested. The driver has delivered to this location before, and being familiar with the area decides to switch off the ADAS and take roads they believe are likely to circumvent the major congestion areas in order to complete a safe and timely delivery.

After a long and tiring day behind the wheel, the driver is on the way back to the base of operations with all automated support enabled. It is dark and overcast, and the toll of the day causes the driver to rub his eyes. The fatigue detection system, using an optical tracking camera, is immediately triggered by this behaviour and releases a haptic and auditory alert, which startles the driver and causes them to swerve slightly while another vehicle is preparing to pass. Although the lane-keeping system is not activated due to the inability to detect faded markings at the roadside, the driver quickly adjusts and regains control, meanwhile becoming increasingly frustrated with the multiple "nagging" vehicle warnings and producing the temptation to deactivate any automated support. The ADAS projects the remaining miles on the journey onto the head-up display and suggests a nearby rest stop location for a short break, which is ignored by the driver in their determination to finish their day and return home, despite the driver allowing the notifications to remain on the display (potentially causing further distractions) due to fatigue. As night falls and the cab darkens, it begins raining heavily and the driver opts not to turn on in-cab lighting in order to avoid impairing his vision of the surrounding traffic. The driver allows their eyes to close again just briefly, with the subconscious expectation that an alert will trigger the fatigue detection warning. However, the poor lighting conditions in the cab disrupt the system's ability to perform, and it is not activated; instead, the driver is awoken by an abrupt stop caused by the automated emergency braking system. As they regain awareness of the situation, the driver pulls to the edge of the road to assess the situation, and begins to dread the next review meeting with management due to the high rate of harsh driving behaviours which occurred throughout the shift.

The truck ends its day at the garage, however the maintenance check requested in the photo taken by the driver was bumped significantly in the queue due to a glitch in data connectivity at the start of the driver's shift. As a result, the truck will be out of service for the following shift and a driver has to be assigned to drive a temporary replacement truck from another depot some miles away.

2.6. Conclusions

In this Chapter a first of its kind Human Factors road map for the logistics system was created. From this, the 'call to action' which underlies the thesis is clear. Within the commercial driving sector there is a significant potential role for HF/E research. Indeed, it will be indispensable in meeting increasingly aggressive carbon reduction targets. Progress, therefore, has been made on the following research sub-questions, with particular emphasis on SRQ6 and the ability to 'predict the future':

- *What are the current logistics gaps which human factors is ideally suited to filling? (SRQ2)*

- *How can we estimate future system conditions, and test future system functionality before implementation? (SRQ6)*

Progress on the proximal research question about 'predicting the future' (SRQ6) is manifest in three technology trajectories which focussed on the technology itself, associated human factors, and potential reductions in CO_2 emissions. Results indicate that future commercial vehicles and logistics distribution systems will be designed with increasingly complex automation, and that the nature of this increasing reliance on technology may also increase negative effects on system performance in instances of malfunction or failure. The stand-out finding is that technology alone will not be sufficient to achieve ambitious CO_2 reduction targets, and that the 'human factor' holds the key to unlocking considerable future potential.

The first-of-its-kind nature of this analysis helps advance a powerful agenda for 'human-in-the-loop' design. The results indicate that a mix of technologies, practices and approaches will be necessary to achieve emissions reduction targets. From this it would seem that low-cost, low-risk human factors research in the road freight sector has a sound business-case and is well worth exploring. With the need for Human Factors research in the logistics sector made clear the motivation for the work presented in the following Chapters is also transparent.

It is instructive to return once more to the pessimistic thought experiment. This 'test drive' showed the possibilities which support (or necessitate) behaviour which may be contradictory to eco-driving guidance and have practical implications for fuel efficiency. These considerations have a very real commercial and environmental impact for the road freight industry. It is also worth noting that for the purposes of illustrating as many of the identified technologies as possible, the pessimistic test drive involves several instances of the driver quickly adjusting and regaining control of the vehicle in time to avoid an incident. And what of the driver? It cannot be assumed they will be young and male. Important changes in the driver demographic may see greater challenges with the acceptance of new technology, meaning systems require holistic design with consideration of new and different user types. This further stresses the importance of human factors in this domain.

Rather than end on a downbeat note, the first optimistic test drive can instead be revisited. It provides a glimpse of the potential of future technology and system design to achieve the triple bottom line of environmental, economic and social sustainability. In order to ensure this potential is fulfilled and to maximise the impact of these results on wider system behaviour, future practice will need to incorporate a greater degree of human factors input throughout the design process. In the following chapters this journey is begun, firstly with a more in depth consideration of what the precise research paradigm is, and the methods needed, followed by a number of innovative practical applications and extensions of those methods. This begins to respond to the very real and present 'call to action' identified in this Chapter.

Chapter 3:
Human Factors in Complex Adaptive Socio-technical Systems – Developing a Research Paradigm

3.1. Introduction

In Chapter 2 the ‘call to action’ was identified by developing a first-of-a-kind human factors forecast for the logistics sector. It was found that the existing techno-centric approach to truck-driver systems will not be enough to meet CO_2 reduction targets for the industry. Furthermore, technologies targeting a single purpose (e.g. CO_2 reduction) continue to be designed without reference to the whole truck-driver system or wider operational contexts. The current approach to design has unknown consequences for safety and efficiency, and high potential for unintended effects on environmental performance. Clearly, then, there is a strong need for human factors research in this domain. Before proceeding to address this gap it is important to establish a solid research paradigm resting on sound ontological and epistemological foundations. This Chapter, therefore, synthesises past research in human factors and logistics and determines how this new combined problem space can be investigated more systematically. Linked to this are a number of important research questions around which progress needs to be made, namely:

- *What theories or concepts draw together logistics & human factors literature? (SRQ1)*
- *What are the current logistics gaps which human factors is ideally suited to filling? (SRQ2)*
- *What is the research paradigm of human factors? (SRQ3)*
- *How can current logistics gaps be appropriately addressed by human factors methods? (SRQ4)*

This chapter picks up on an emerging theme identified in Chapter 2. Here the need for a more complete, holistic view of the human/logistics system was clearly evidenced. This theme needs to be developed much further. In doing so SRQ2 can be addressed in detail.

A gap in knowledge and practice, one which human factors is ideally suited to filling, is the notion of a systems approach. This provides a rigorous means of making previously neglected elements of system behaviour, namely the human elements, more ideologically and scientifically explicit. To enable this the philosophical position of the human factors discipline needs to be explored. This will lend theoretical and methodological structure to a strategy for future research. There are four main parts:

Part 1 of this Chapter reviews the relevant literature across logistics, HF/E, and the systems theories which serve as their foundation. The term ‘system’ is used frequently and this section links past literature to propose logistics as a large-scale Complex Adaptive Socio-Technical System (CASTS). In doing so it asks a bold question: in logistics, and indeed HF/E, are we truly engaging in ‘systems thinking’ in the pursuit of knowledge at these research intersections?

Part 2 of this Chapter makes explicit the assumptions of the author’s research paradigm. Although this is a common stage of academic work in every discipline, human factors studies rarely if ever make their research paradigm explicit. For the past decade, the primary concern of human factors has been ensuring methods “produce something of quality and value”, or ‘utility’ (Dekker, et al., 2010, p. 36). Only recently has this paradigmatic ambiguity come to the forefront. As the field matures broader reflections about its place are increasingly being published (Dekker & Nyce, 2015; Le Coze, 2017). The second section of this chapter, therefore, provides a welcome overview of ontologies, epistemologies, and methodologies common to human factors and logistics.

Part 3 develops a strategy – because one does not currently exist – for translating the chosen ontological, epistemological, and methodological position into a practical implementation of research. In other words, HF/E methods are reviewed to better understand those which can be used to drive out findings of value, in the context of large-scale CASTS. This methodological map is used to select appropriate methods for further chapters of this thesis.

3.2. Part 1: Are we really engaging in systems thinking?

Systems thinking is a way of conceptualising and viewing the world in more holistic and connected ways. Within this broad heading exist a myriad of different approaches ranging from biologically inspired ‘open systems’ ideas, theoretical challenges to Newtonian physics and determinism, right through to emerging fields of complex adaptive systems (CAS). Systems thinking is a hot topic and comparable systems agendas currently exist in both logistics and human factors research. Despite sharing a positive disposition towards systems ideas, literature which incorporates logistics, human factors, and systems ideas is scattered. This is despite an evident need for a more widespread, ‘by-default’ systems-oriented approach. This is where the need to determine whether our understanding of the word ‘system’ in any one discipline enables us to adequately capture actual system behaviour.

The definition of ‘systems’ varies with each academic field in a number of ways. In the present context systems can be understood broadly as “a regularly interacting or interdependent group of items forming a unified whole” (Merriam-Webster, 2017). It is however important to acknowledge that systems may be of different levels of scale (e.g. a single person vs. an entire organisation), different levels of interconnectivity to other systems (e.g. closed vs. open), different capabilities of system actors (e.g. deterministic vs. learning agents), and different or even multiple forms (e.g. cognitive vs. physical).

3.2.1. How logistics defines and deals with ‘systems’

In an attempt to improve predictability, capture complexity, and better manage other concepts often associated with the ‘human factor’, systems theory has been increasingly applied to the logistics industry (Mingers & White, 2010; Kunsch, et al., 2007). It is worth noting that systems in logistics literature are typically defined at the scale of an entire supply chain ‘system’. This is a relatively ‘macro’ view targeted at high-level decision-makers. In logistics terms this type of system conceptualisation is aimed at influencing the supply chain from the strategic or tactical level. That is, focusing on decisions related to supplier-customer contracts, the acquisition of new assets, etc., rather than the operational level of individual workers and their allocated tasks.

From this systems view entire sub-fields of logistics have emerged. These include systemic concepts such as supply chain 'stabilisation’ (Hill, et al., 2012), 'integration' (Frohlich & Westbrook, 2001; Mitra & Singhal, 2008; Flynn, et al., 2010), 'collaborative management' (Barnes & Liao, 2012), ‘resilience’ (Ponomarov & Holcomb, 2009) and 'visibility' (Caridi, et al., 2010; Musa, et al., 2014). It also includes life cycle carbon accounting and integrated assessments, (e.g. Gimenez, et al., 2012; Hacking & Guthrie, 2008; Sanchez Rodrigues, et al., 2015; Schaltegger & Csutora, 2012). Of course, recent focus has also been placed on the Internet of Things (IoT) and the techno-centric study of large information networks (Glassman, 2012; Gubbi, et al., 2013; Miorandi, et al., 2012) and from this there is an emerging consensus that supply chains are not just systems, but a particular ‘type’ of system; a complex adaptive system (CAS) (Larsen, et al., 1999;

Choi, et al., 2001; Surana, et al., 2005; Pathak, et al., 2007; Hwarng & Xie, 2008; Wycisk, et al., 2008; Li, et al., 2009; Behdani, 2012; Lorentz, et al., 2013; Hwarng & Yuan, 2014; Levalle & Nof, 2017). Even here, no clear-cut definition for a complex adaptive system exists.

CAS theory has produced numerous general principles and characteristics which have been synthesised in Table 3.1. Overarching these properties is the central idea that CAS are characterised by emergent behaviour – i.e., "the arising of novel and coherent structures, patterns and properties during self-organization [of individual agents]" (Goldstein, 1999, p. 49).

Table 3.1.: General principles & characteristics of complex adaptive systems
(synthesised from Holland, 1995; Cilliers, 1998; Pohl, 1999; Levin, 2002; Holland, 2006; Gros, 2011)

#	*Principle*
1	System agents are heterogeneous, i.e. do not have the same capabilities and constraints
2	Interactions are rich, i.e. any agent or sub-system is affected by and affects several other agents or sub-systems
3	Interactions are first with immediate 'neighbours' who modulate influence of interactions throughout the rest of the system
4	Interactions can be physical or informational (or both) in 'flow type'
5	Many concurrent feedback loops exist throughout the system, but not in any structured, centralised, or comprehensive way
6	Agents in the system are likely to be ignorant of the behaviour of the system as a whole, due their localised access to information/stimuli
7	The system is 'open' in such a way that its boundaries are difficult or impossible to define (before the boundaries change)
8	Interactions are non-linear, i.e. small changes can cause very large, disruptive 'cascade' effects or tipping points; as a result the behaviour of individual agents cannot predict the behaviour of the overall system
9	The system has a stored history, which as the system evolves is co-responsible for present behaviour, i.e. past context/situations matter, and the system evolves progressively in stages
10	Interactions/attachments to other agents are determined by preferential (not random) attachment, i.e. agents use functional rules called schema, 'success criteria', or 'measures of fitness' which influence their choices
11	System structure is non-linear, i.e. often systems follow a scale-free Pareto principle, fostering a "rich-get-richer" process of connectivity
12	The size of the system is sufficiently large that conventional descriptions (e.g. a system of differential equations) cease to assist in understanding the system

In supply chain research methods exist to study CAS behaviour. At present this primarily takes the form of agent-based modelling, which is a resource-intensive, computer-based simulation approach. Despite the promise and value of agent-based modelling approaches, it is fair to say that conceptual and mathematical models in this domain have struggled to maintain validity in the long-term due to the typically large scale, strategic level of analysis, and the rate of change in real-world logistics operations. Some logistics studies have ventured into the consideration of complex behavioural factors at the strategic or tactical level (e.g. trust) (Hou, et al., 2013). This targeting of high-level decision-makers is interesting. It tacitly assumes high-level decision-makers are the exclusive (or at least primary) engineers of the system. This is an odd paradox. CAS emphasises bottom-up processes driving complex macro-scale effects rather than the other way around. One explanation for this analytical focus are the thin profit margins of the logistics sector. These pressures encourage viewing the system through a lens of engineered operational efficiency (e.g. Baker & Canessa, 2009). This paradoxical thinking influences how micro-scale systems, such as truck-driver systems (e.g. Pillac, et al., 2013), are also viewed. These too have a tendency to be regarded as behaving in a deterministic and entirely controllable manner. The implicit assumption, despite the presence of systems thinking, is an often high degree of operational-level standardisation, predictability, and rationality. This assumption, in extreme cases, can deceptively cast agents as calculable, rational machines engineered for productivity. A 'hyper-rational' characterisation which is far removed from what the term 'system' might actually imply.

According to Croson et al. (2013) hyper-rational actors are characterised by the following:

1. they are motivated by self-interest in ultimately monetary terms;
2. they always operate in a conscious, deliberate manner; and
3. they behave optimally for a specified objective function.

Of course, this level of stability and standardisation is not realistic in a human world, and far from the philosophical ideals of HF/E. They have also been thoroughly discredited in critiques of Taylorism and other 'hard' forms of organisational psychology. Despite this, a form of 'tacit-Taylorism' appears alive and well in logistics studies. For example, micro-scale systems such as individual warehouse operations have received limited attention, but where they have they often adopt this deterministic and hyper-rational paradigm of organisational 'top-down' control. It seems clear that logistics studies have been steered in the direction of CAS and socio-technical systems theory (STS) (e.g. Behdani, 2012), but these concepts have not achieved full or consistent integration. The systems debate in logistics, therefore, faces a fundamental paradox. By approaching humans as hyper-rational agents (at best tacitly, at worst overtly), the very 'bottom-up' emergent behaviour that characterises logistics 'systems' cannot arise. Worse, it becomes neglected in logistics research. Where Human Factors connects to this debate is that it is couched in a systems ontology. This brings the possibility of different, yet complimentary systems-based tools and methods, ones which foreground the role of human-centred bottom up processes.

3.2.2. Human factors & complex systems

HF/E has a history of influencers thinking beyond the illusion of the hyper-rational worker, adopting Rasmussen's perspective that "bad outcomes are not the result of human immoral choice, but the product of normal interactions between people and systems" (Dekker, 2017, p. 554). The counterpoint, of course, is that so-called socio-technical systems can be designed so these components are 'jointly optimised' for human well-being and overall system performance. Eschewing the notion of hyper-rationality opens the door for complexity.

There is an abundance of HF/E research on complexity and systems generally (e.g. Vicente, 1992; Wilson, 2000; Carayon, 2006; Salmon, et al., 2009; Walker, et al., 2010; Leveson, 2011; Karwowski, 2012; Wilson, 2014), and considerable crossover in more specific studies. Intentionally or not HF/E has borrowed specific terminology from CAS theory, and created models of interaction similar to the feedback loops found in CAS. Table 3.2 is not an exhaustive list but it shows the presence of CAS concepts in common HF/E concepts like the Perceptual Cycle Model (PCM), the Skill-Rule-Knowledge (SRK) framework, and distributed situation awareness (DSA).

Table 3.2: CAS themes within common HF/E concepts

HF/E theory/model/concept	HF/E definition/principles	Relation to CAS
Sociotechnical systems theory (Trist & Bamforth, 1951; Appelbaum, 1997; Walker, et al., 2009; Read, et al., 2015b; Walker, et al., 2010)	"Design choices are contingent and do not necessarily have universal application. What works in one situation and context may not work in another" "Users of systems interpret it, amend it, massage it and make such adjustments as they see fit and/or are able to undertake. Therefore, design should incorporate adaptability and change" "From the moment users start to use the system they are on the road to co-evolution. The perceptive designer will see that the design of future capabilities is already underway" (Read, et al., 2015b adapted from Walker, et al., 2009, p. 825-6)	Stored history derived from past experience informs present behaviour; Many concurrent feedback loops exist throughout the system; Interactions are non-linear
Schema theory (Mandler, 1984 & Brewer, 1987 as cited in Stanton & Young, 2000; Plant & Stanton, 2012; Plant & Stanton, 2015)	"[Schema are] an organised mental pattern of thoughts or behaviours to help organise world knowledge" (Neisser, 1976 as cited in Plant & Stanton, 2012)	An agent's strategy for organising knowledge and continuously developing their own rules/understanding of the system
Skill-Rule-Knowledge framework (Rasmussen, 1983; Vicente, 1992; Kilgore & St-Cyr, 2006)	"Skill-Based Behavior represents sensory-motor interactions consisting of smooth, automated, and integrated patterns that take place without conscious control. Rule-Based Behavior represents the invoking of stored rules derived from procedures, past experiences, or operating instructions. Knowledge-Based Behavior represents functional reasoning about the goals to be achieved, where operators rely upon internal knowledge of the system…to solve problems" (Kilgore & St-Cyr, 2006, p. 507)	'Signs', 'signals', and 'symbols' guide different types of agent behaviour; Stored history derived from past experience informs present behaviour; Different interactions are 'activated' by certain signals
Perceptual cycle model (Neisser, 1967; Neisser, 1976; Plant & Stanton, 2012; Plant & Stanton, 2015)	"The environmental experience results in the modification and updating of cognitive Schemata and this in turn influences further interaction with the environment" (Plant & Stanton, 2012, p. 302)	Interactions can be physical or informational; Different interactions are 'activated' by certain signals; Schema are updated based on signals from the environment
Mental models (Rasmussen, 1979; Johnson-Laird, 1983; Rouse & Morris, 1986; Wilson & Rutherford, 1989; Stanton & Young, 2000; Sinreich, et al., 2005;	"Mental models are inferred representations of a specific state of affairs" (Brewer, 1987 as cited in Stanton & Young, 2000, p. 325) "A dynamic representation or simulation of the world" (Johnson-Laird, (1983; 1989) as cited in Stanton & Young, 2000, p. 324)	An agent's internal map of the world and how it functions

Richardson & Ball, 2009; Revell & Stanton, 2012)		
Swiss Cheese model of accident causation (Reason, 1990; Sheridan, 2008)	“Small errors and failures combine and grow into large failures and accidents” (Sheridan, 2008, p. 421)	‘Proximal’ and ‘remote’ actors reflect the notion of agents’ localised access and ‘neighbourhoods’; Interactions in the system produce non-linear results, i.e. change can occur suddenly from cascade effects or tipping points
Task-artefact cycle (Carroll & Rosson, 1992)	“A given task sets requirements for the design of an artifact to help an individual perform the task. The resulting artefact…creates new or unexpected possibilities or pose new constraints on the performance of the task. These…suggest a revision of the original task for which the artefact was made. The new task sets new requirements for the redesign of the artifact and so on and so on” *(Interaction Design Foundation, n.d.)*	In CAS theory, schematics are a collection of functions (tasks) and physical objects (artefacts); Agents use their schemata (measures of fitness) and receive signals from their environment, and consequently use and adapt their schematics; Interactions can be physical or informational
Disaster incubation (Dekker & Pruchnicki, 2014)	“Incubation is about incremental, or small, seemingly insignificant steps eventually contributing to extraordinary unforeseen events” (Dekker & Pruchnicki, 2014, p. 541)	Interactions in the system produce non-linear results, i.e. change can occur suddenly from cascade effects or tipping points
Distributed situation awareness (Stanton, et al., 2006; Salmon, et al., 2008; Stanton, et al., 2009; Sorensen & Stanton, 2011; Stanton, Salmon & Walker, 2015)	“DSA is considered to be activated knowledge for a specific task within a system at a specific time by specific agents, that is, the human and nonhuman actors in a system” (Stanton, Salmon & Walker, 2015, p. 47) “Situation awareness resides in neither the individual nor the world”, and as such “awareness is distributed across human and technological agents involved in collaborative activity” (Plant & Stanton, 2013, p. 8)	Agents have (and only require) localised access to the system; Interactions can be physical or informational; Interactions occur out of proximity *and* ‘activation’; Interactions cause non-linear results

The HF/E discipline has considerable potential to navigate the dynamic environment of a CAS. Going further still, it would not be out of the question to term logistics as a ‘complex adaptive socio-technical system’ (CASTS). The promise of a CASTS approach is that patterns of human behaviour at the lower levels of the logistics system – e.g. the truck-driver system – can be identified and evaluated, and the effect these micro-level changes have on macro-level shifts explored. Once critical areas of the system are located, human factors techniques may be used to develop useful and effective solutions.

3.2.3. A short synthesis of HF/E-logistics research

These theoretical intersections have powerful potential, but to what extent have they been applied? Despite the growing acknowledgment of contextual human behaviour which defies the ‘hyper-rational’ (e.g. Bendoly, et al., 2010) penetration of human factors research in supply chain studies is limited. Only a handful of human factors studies have been performed in the specific area of logistics (e.g. Goode, et al., 2014), with little reference to the micro-scale study of heavy goods vehicle design and commercial drivers (i.e. the ‘truck-driver’ system). Only 139 articles in mainstream HF/E journals (Applied Ergonomics; Ergonomics; Human Factors; International Journal of Industrial Ergonomics) make reference to the terms ‘freight’, ‘logistics’, ‘truck’, ‘lorry’, ‘commercial vehicle’, ‘heavy vehicle’, ‘HGV’, or ‘professional driver’. Of these 139 articles:

- *less than half* (61 articles) included these terms in their title or keywords, and one of them was a publication arising from this thesis;
- 38% (53 articles) focused *exclusively* on physical ergonomics (e.g. whole-body vibration (WBV), musculoskeletal disorders (MSDs), etc.);
- 33% (46 articles) were published before the year 2000, when working practices and technology in the logistics industry were considerably different; and
- 20% (28 articles) were published between 2013–2018 (the time period in which the author developed this thesis, somewhat limiting their influence on the design of this work).

Given the incomplete spread of logistics-specific research in HF/E, and the surge of more recent publications, it is clear that significant research gaps and opportunities exist in this area. The potentially powerful compatibilities covered in this section are, unfortunately, still largely ignored by fields of research which claim to be pragmatic and interdisciplinary. Table 3.3 overviews the extent of these intersections for research problems in general; Table 3.4 overviews the extent of these intersections for research problems specifically focused on environmental sustainability.

Table 3.3: Extent of general logistics, ergonomics, & ergonomics/logistics research at various scales

Field	*Macro- or Meso-Scale*	*Micro-Scale*
Logistics	Yes; cognitive & physical	**Limited; almost exclusively physical**
Ergonomics	Yes; cognitive & physical	Yes; cognitive & physical
Ergonomics in Logistics	**None**	**Limited; almost exclusively physical**

Table 3.4: Extent of sustainable logistics, ergonomics, & ergonomics/logistics research at various scales

Field	*Macro- or Meso-Scale*	*Micro-Scale*
Logistics	Yes; mainly cultural	**Limited; almost exclusively physical**
Ergonomics	**Limited; mainly cultural**	Some; cognitive & physical
Ergonomics in Logistics	**None**	**None**

These gaps present a challenge which informs the overall research design of this thesis. This first challenge is an empirical one. While logistics behaviour has thus far largely been studied on a macro-scale, human factors research methods have often been applied at a micro-scale. Where in the previous section it was found that existing logistics research trends toward being top-down, macro-view, and deterministic, human factors research is generally bottom-up, micro- or meso-view, and non-deterministic. Logistics is a relatively new domain for human factors study with few existing foundational documents readily available. Even the most established HF/E methods (e.g. Hierarchical Task Analysis or HTA) have not been regularly or recently applied to truck-driver systems at a micro-scale. This suggests our focus should be on truck-driver system first, and later – perhaps beyond this thesis – expand to wider CASTS issues in the logistics system.

The second challenge is the sound selection of methods to effectively study truck-driver systems. In order to begin a combined HF/E-logistics research strategy it is necessary to adopt, and make explicit, a research paradigm. The remainder of this chapter explains different research paradigms, and makes explicit this thesis' selected research design from ontology, epistemology, methodology, and through to the selection of specific methods.

3.3. Part 2: What is the HF/E research paradigm?

In Chapter 1, Partington's framework introduced the four aligned elements of the research process. Having now identified a research purpose and a primary research question, two of the four elements have already been outlined, as shown in Figure 3.1 below.

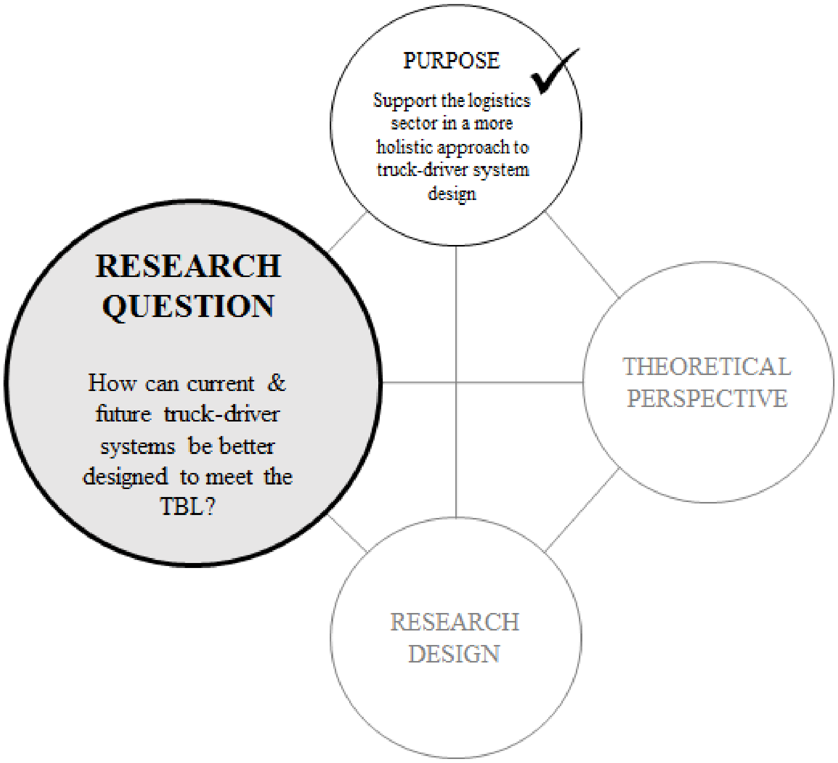


Figure 3.1: Primary research question & purpose, as in Partington's four aligned elements of the research process (2002, p. 139)

The next steps in Partington's framework are to identify the theoretical perspective and research design of the work. The purpose of this section is to explore typical ontologies, epistemologies, and methodologies, and make explicit the research paradigm of HF/E to be adopted within this thesis.

3.3.1. Ontology

Ontology can be defined as a world view, which identifies at a foundational level what constitutes reality and how inquirers might understand existence. Social research thinkers categorise these worldviews and their overlaps in many different ways. For example, Creswell (2014) describe these as postpositivist, constructivist, transformative, and pragmatic; Bryman and Bell (2011) simplify these to objectivism and constructionism; Crotty (1998) uses positivism (and postpositivism), interpretivism (including symbolic interactionism, phenomenology, and hermeneutics), critical inquiry, feminism, and postmodernism. It is clear there is a diverse range of ontologies, and it is common for different social researchers to perceive and employ these differently, even attaching them firmly to (or naming them interchangeably with) descriptions of paradigms, worldviews, or epistemologies. In the words of Hughes & Sharrock (1997, p. 95), "the whole history of Western philosophy could perhaps be written as describing a contest between the various ways of formulating just what, philosophically speaking, this distinction is [between mind and matter]". In light of this overwhelming question, and its many different answers, this section will make clear the assumptions of the author around not only which ontology is being adopted but also what exactly ontology is taken to mean. Here Figure 3.2 portrays the ontological space in which research in general can operate, using three main axes. The y-axis is about the existence of universal properties in the 'thing' being researched. The x-axis is the nature of the reality being observed. The z-axis is about the existence of a reality behind perception. When these axes are crossed several common ontologies can be plotted within them. For example, the nominalist ontology is at the extremes of all three axes. It takes the position that properties are always unique to specific sets of objects and physical contexts, and thus no universal laws can be derived for application to different sets of objects or physical contexts. The positivist ontology takes a position much more common to the 'hard' sciences. An objective reality and universal properties both exist which can be derived empirically. Several other ontological positions are portrayed in Figure 3.2. The subtle realist ontology is of note as this adopts the viewpoint that an objective reality exists, but the researcher's knowledge of reality is limited by individual perspective. This view attempts to make experiential assumptions transparent to resolve this limitation, and is an approach commonly found in the social sciences.

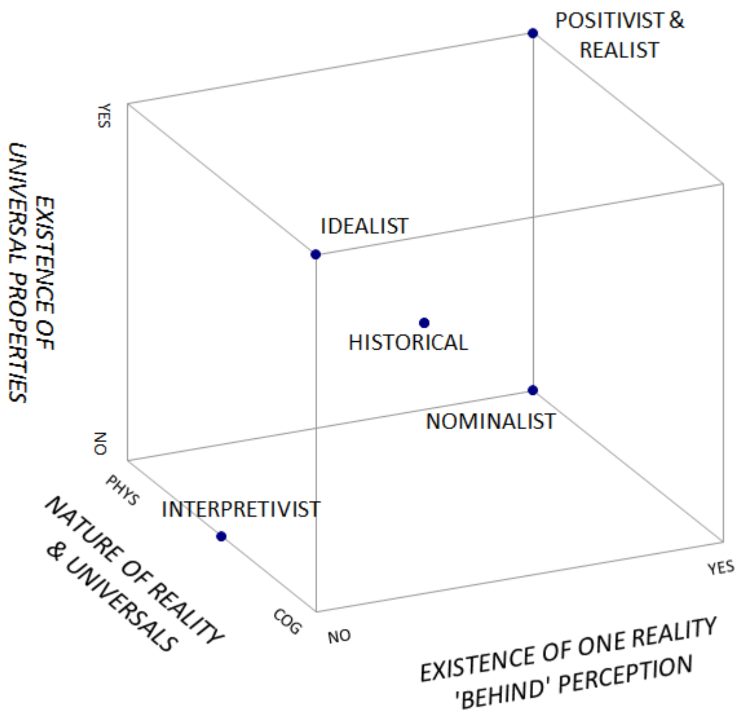


Figure 3.2: Ontological positions in research (Walker, et al., 2016)

3.3.2. Epistemology

If ontology is all about what constitutes reality, then epistemology is about what knowledge is, what constitutes valid knowledge, and how knowledge is best acquired. Again there are different perspectives which can be adopted. Subjectivist epistemology takes the position that it is impossible to separate the researcher from their experience, and that the best strategy for obtaining knowledge is not only to acknowledge but also embrace individual biases and assumptions. Empirical epistemology relies on observation and information gained primarily through the physical senses. This perspective serves as the foundation for the scientific method, but fundamentally acknowledges that all objective knowledge is probabilistic and open to revision. Generally, subjectivist epistemologies are held by researchers in the humanities, often associated with the constructionist, constructivist, transformative, interpretivist, critical inquiry, postmodern, or historical worldviews (Bryman & Bell, 2011; Creswell, 2014; Crotty, 1998). On the other hand empirical epistemology is held by researchers in the "hard" sciences, and is often associated with the positivist, objectivist, or postpositivist worldviews (Bryman & Bell, 2011; Creswell, 2014; Crotty, 1998). Here there are widely-accepted mechanics (e.g. biological and physical laws) and a high rate of repeated, standardised application of methods which can adequately describe the majority of findings. It is noteworthy that in the sciences described, the level of granularity considered is often extremely fine (e.g. a cellular or even atomic level), while in the humanities, the levels of system granularity are far coarser (e.g. interactions between an agent and culture).

3.3.3. Methodology

Making explicit what is being regarded as reality (ontology) and the nature of knowledge (epistemology) informs the methods by which knowledge of a given reality can be derived. Both logistics management and HF/E domains employ different methodologies at different levels of granularity, but as both are practically-driven research areas, concentrate generally on action research and grounded theory. In the development of methodology, several considerations are necessary to ensure robust results. Traditionally, validity – which can be assessed in at least five ways – is of principal concern for the construction of a robust methodology. As shown in Table 3.5, considerations of validity are also supplemented by a range of other factors, in particular the desire to make academic work accessible to real-world stakeholders and applicable to real-world problems.

In constructivist grounded theory methodology (commonly employed in logistics), validity is characterised differently to the traditional definitions above. While Classic and Straussian grounded theories rely on objectivism (Kenny & Fourie, 2014; 2015), constructivist grounded theory allows for novelty of approach, parsimony, and ecological validity – all of which increase relevance to non-academics in real-world situations. Table 3.5 provides a more complete explanation by summarising the typical criteria considered.

Table 3.5: Factors & criteria affecting method selection

Constructivist Grounded Theory measures (Holton, 2008)		
Fit		the emergence of conceptual codes and categories from the data rather than the use of preconceived codes or categories from extant theory
Workability		the ability to explain and interpret behaviour in a substantive area and to predict future behaviour
Relevance		the focus on a core concern or process that emerges in a substantive area; its conceptual grounding in the data indicates the significance and relevance of this core concern or process thereby ensuring its relevance
Modifiability		the ability to be continually modified as new data emerge to produce new categories, properties or dimensions of the theory; this living quality of grounded theory ensures its continuing relevance and value to the social world from which it has emerged
HF/E measures (Stanton, et al., 2005; Wilson, 2005)		
Validity	Construct	the extent that a method measures the trait or theoretical construct that it is intended to measure
	Content	the "representativeness and relevance of the assessment instrument of the construct being measured"
	Face	estimates the validity of a method by using researcher expertise to survey whether or not the method appears to measure the target variable, sometimes by way of a process referred to as *interpellation* (Dekker, et al., 2010)
	Criterion (concurrent)	characterises the relationship of a newly-applied test to an existing test which is intended to measure the same construct
	Criterion (predictive)	measures the effectiveness of a method in the prediction of future performance
Reliability		the ability to be applied with the same result by the same or different analyst(s)
Generalizability		reproducibility across domains, etc.
Non-reactivity		the ability to unobtrusively collect sufficient and representative data
Acceptability		the readiness of stakeholders requesting analysis to accept the method
Ease/feasibility of use		the level of skill/training required to adequately apply the method
Resource requirement/Time of administration/Ethics & resources/Cost-effectiveness		the investment required in both time (indirect cost) and direct financial costs to adequately apply the method

3.3.4. Methods & their approaches to reasoning across the system

A comprehensive human factors and management sciences methods review is not within the scope of this work. Despite this, general themes regarding logic and reasoning approaches can be derived. Table 3.6 lays out the reasoning approach underlying research design and method selection across a spectrum of deductivism, inductivism, and abductivism.

Table 3.6: Overview of reasoning approaches (example & formal description from Timmermans & Tavory (2012, p. 170-1)

Reasoning approach	*Example*	*Formal description*	*Layman's description*
Deductivism	1. All A are B. 2. C is A. 3. Thus, C is B.	"…begins with a rule and proceeds through a case to arrive at an observed result, which either demonstrates the rule or falsifies it…"	We know all the rules and can interrogate the data, to get a result
Inductivism	1. All observed A are C. 2. Thus, all A are C.	"…starts with a collection of given cases and proceeds by examining their implied results to develop an inference that some universal rule is operative…"	We make an educated guess at the rules guided by a nearly complete set of data, to get a result
Abductivism	1. The surprising fact C is observed. 2. But if A were true, C would be a matter of course. 3. Hence, there is reason to suspect that A is true. (as in Peirce, 1934, p. 117)	"…starts with consequences and then constructs reasons…"	We make an intuitive guess at the rules based on an incomplete set of data, to get a working theory of the rules

Deductivism (sometimes called "top-down logic") takes a closed set of wholly knowable, general rules, and makes specific conclusions reductively. In other words, a deductive conclusion is completely certain based on a set of premises that are in and of themselves completely certain. Inductivism ("bottom-up logic") does the opposite, by drawing broad rule generalisations from a very large collection of specific instances. Inductive conclusions are likely, but not guaranteed with complete certainty. Abductivism makes conclusions based on the available group of observations (i.e. context), favouring the most likely situational explanation. These reasoning approaches weave together specific epistemologies, methodological levels of granularity, and methodological approaches.

1. Firstly, the deductive approach is tied to objectivism, while inductive and abductive approaches may be adopted within subjectivist epistemology.

2. Secondly, these epistemologies reflect the level of certainty possible within the analyst's conceptual model of the system, at the appropriate level of granularity for their focus of research (i.e. the "hard" sciences are often studied at a finer level of granularity with relatively well-understood and widely-accepted mechanics). The level of granularity is therefore critical to the matching of methods to problems. The deductive, inductive, and/or abductive approaches may be more suitable in the examination of a specific level of granularity or specific type of interaction between levels.
3. Thirdly, the three reasoning approaches can be linked to three categories of method approaches commonly used in HF/E research. Deductivism (where we know all of the rules) complements prescriptive methods where we prescribe what *should* happen within a system. Inductivism (where we take an educated guess at the rules based on a large set of observations) complements descriptive methods where we describe our current understanding of what *does* happen. Abductivism (which allows for a wide and ever-flexible range of system rules) complements formative methods which allow the analyst to see what *could*, rather than what should or what does happen.

All three reasoning approaches – deductive, inductive, and abductive – could be employed in the study of CAS, provided these are matched suitably to different types of problems. Abductivism and formative method approaches are particularly well-suited to CAS where causes and effects are hidden from view. In the words of Peirce himself (1934, p 171, as cited in Timmermans & Tavoy, 2012): "[Abduction] is the only logical operation which introduces any new ideas; for induction does nothing but determine a value, and deduction merely involves the necessary consequences of a pure hypothesis." Despite this, analysts often feel more comfortable using normative (that is, prescriptive or descriptive) approaches, and this is certainly the case in some of the logistics research identified earlier. For example, the 'hyper rational' characterisation of human actors in a logistics system places the problem on a similar footing to a 'pure hypothesis' when, in fact, it is anything but.

It is now time to bring these multiple strands together and make these ontological, epistemological and methodological assumptions clear and transparent. Figure 3.3 attempts to do this by representing the general suitability of a range of broad reasoning and method approaches to each level of granularity within CASTS.

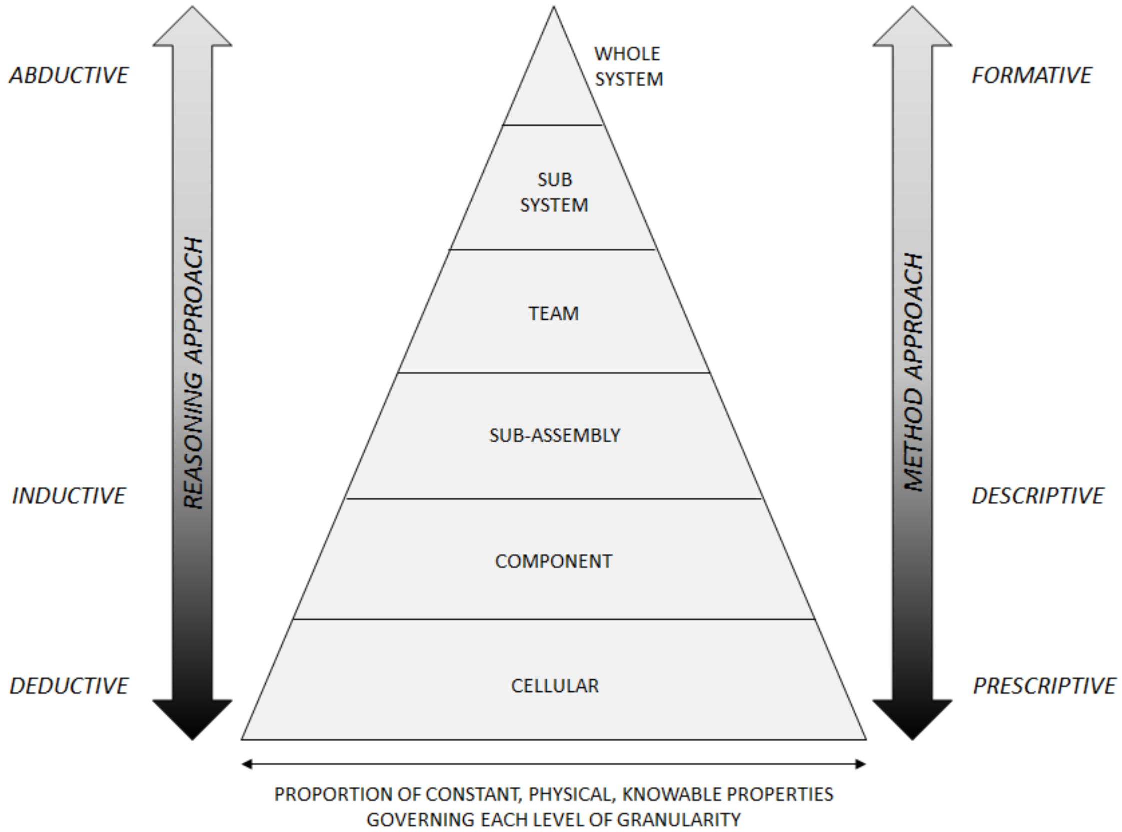


Figure 3.3: Broad representation of reasoning approaches & method approaches at levels of granularity and corresponding levels of uncertainty within a complex adaptive socio-technical system (e.g. logistics)

On the practical question of selecting methods for problems which reside at the intersection of HF/E and logistics, it is likely that a mixture of reasoning and method approaches will be required. Just as in Walker et al.'s (2009) 'Approach vs. Problem' matrix, different approaches target different solutions. This is further illustrated by Annett's (2002) categorisation of 'analytic' vs. 'evaluative' ergonomics methods. Analytic methods depend upon the critical thinking skills of the analyst to determine what area and scope of research is most relevant to develop a model. Evaluative methods relate to measurement of specific parameters and give the illusion of empirical epistemology. In practice both types of methods implicitly adopt a subjectivist or transactionalist epistemology. Annett (2002) points out that validity and reliability for each type of method rely heavily on the assumptions, conceptual model, and skills of the analyst. In other words, human factors methods usually rely on a reasoning approach which falls somewhere between inductive and abductive in nature. Logistics research is similar. It has commonly employed constructivist grounded theory, which also blends a combination of deductive and inductive reasoning approaches. Given this we can understand the following: what is of utmost importance are not the 'neat distinctions' of a research design, but instead the researcher's full understanding of where each available method fits within ontological, epistemological, methodological, and reasoning classifications. This process of developing the research design does not secure a static and infallible step-by-step plan, but instead maximises awareness of potential advantages and disadvantages of any given research strategy. In line with Charmaz's (2008) principles of 21st century constructivist grounded theory, the (1) treatment of the research process *itself* as a construction and (2) improvisation of methodological and analytic strategies throughout the research process enables a robust yet flexible path forward. This is the spirit of the research design process currently being described, and leads to the following stated research paradigm.

3.3.5. The HF/E research paradigm

The greatest insight currently available will be gained by acknowledging the importance of experience, perspective, and personal interpretation – in both gaining knowledge in and from the 'real world', and in relating and sharing this knowledge amongst the research community. Thus, the thesis takes the following positions (see published work explicating these positions in Walker et al., 2016; 2017).

3.3.5.1. Adopted research paradigm

In general a paradigm or underlying philosophical system of *pragmatism* will be adopted. Pragmatism "replaces the older philosophy of knowledge approach (e.g., Guba, 1990; Guba & Lincoln, 2005; Lincoln, 2010), which understands social research in terms of ontology, epistemology, and methodology" (Morgan 2014b, p. 1045). This means various ontological, epistemological, and (particularly) methodological stances can be tailored to suit the context of the research focus. In other words, "there is no deterministic link that forces the use of a particular paradigm with a particular set of methods" (Morgan 2014b, p. 1045).

This moves away from 'clean' mutually exclusive lines of epistemological and methodological options, advocating for a more pluralistic and integrated approach. In doing so there is "an emphasis on abduction, intersubjectivity, and transferability" (Morgan 2007 p. 72) in a push away from traditional positivist thinking. Based on Dewey's model of experience, pragmatism moves away from a highly abstract philosophy about the nature of reality or truth (i.e. the 'metaphysical'), and toward a philosophy that is highly contextual and utility-based – both in terms of rooting research in real-world practice, and in terms of acknowledging the role (emotional, social, and otherwise) of the researcher with the field (Morgan 2014b).

3.3.5.2. Adopted ontology

An ontology of *subtle realism* will be adopted. This stance adopts the view that it is possible to approximate the extent of objectivity attained, and it advocates that the optimal strategy to mitigate these perspective-based limitations is to make the experiential perspective of the researcher as transparent as possible. A physical reality and its universal properties are assumed to exist objectively 'behind' human perception, but the researcher's ability to know this reality is limited by perspective. This acknowledgment – that the researcher and 'objective' reality are inextricably entangled – complements the pragmatist effort to move away from portraying research as a 'spectator sport' (Dewey 1998), where the researcher and subject are cleanly separated.

To clarify this within the context of pragmatism, "ontological arguments about either the nature of the outside world or the world of our conceptions are just discussions about two sides of the same coin" (Morgan 2014b, p. 1048). In other words, pragmatism does not rely on metaphysical assumptions about ontology and epistemology as essential criteria for differentiating approaches to research – nor does explicating an ontological or epistemological position undermine pragmatism. The role of pragmatism is expanded upon in the next section on epistemology.

3.3.5.3. Adopted epistemology

It is important to first clarify the role of epistemological positions within the context of pragmatism. In traditional research philosophy, various epistemological positions are situated cleanly in an abstract, mutually exclusive framework, determined by the assumptions a researcher makes about the nature of reality (ontology) and the procedures which should be applied (methodology). A researcher might use these traditional 'camps' of research philosophy almost as a flow chart, where certain beliefs about the nature of reality and knowledge would determine a methodology which should be strictly adhered to. Instead, pragmatism "replaces arguments about the nature of reality as the essential criterion for differentiating approaches to research" (Morgan 2014b, p. 1049). In pragmatism, greater importance is placed on the researcher's approach to inquiry, which is explicitly recognised as an iterative process of interaction between the researcher's beliefs and actions. Here, different traditional 'camps' each provide different contexts and standards for inquiry, each offering their own value in a way that is not necessarily mutually exclusive. This is why Morgan (2014b) acknowledges the importance of considering differences between the various 'procedures' used to acquire knowledge, and likewise for considering the various 'purposes' to which that knowledge is put: to understand their individual contributions to and limitations within a collective toolkit..

With the above in mind, this work will adopt an epistemology rooted in *transactionalism/constructivism.* Subjective epistemology acknowledges the influence of individual perspective on the attainment of knowledge, and that the researcher and the object of research are inseparable. The transactional (or constructivist) epistemology further disentangles this concept, by proposing that actors generate conceptual models of reality which are reinforced or deselected, and that these interactive cognitive-physical processes create the structure for sense-making within a given social context. In other words, this is in line with Morgan's description of the interaction of beliefs and actions. This type of sense-making is held to be what constitutes valid knowledge, and thus the nature of inquiry is along these lines. This echoes pragmatist concepts such as Dewey's 'experimental nature of truth', Rorty's 'correspondence theory of truth', and the general view that knowledge is a set of tools that is time- and context-dependent, rather than an ultimate and everlasting hierarchy of truths (Bryant 2009).

The adopted paradigm, ontology and epistemology fit into Partington's 'theoretical perspective' in the way shown in Figure 3.4 below.

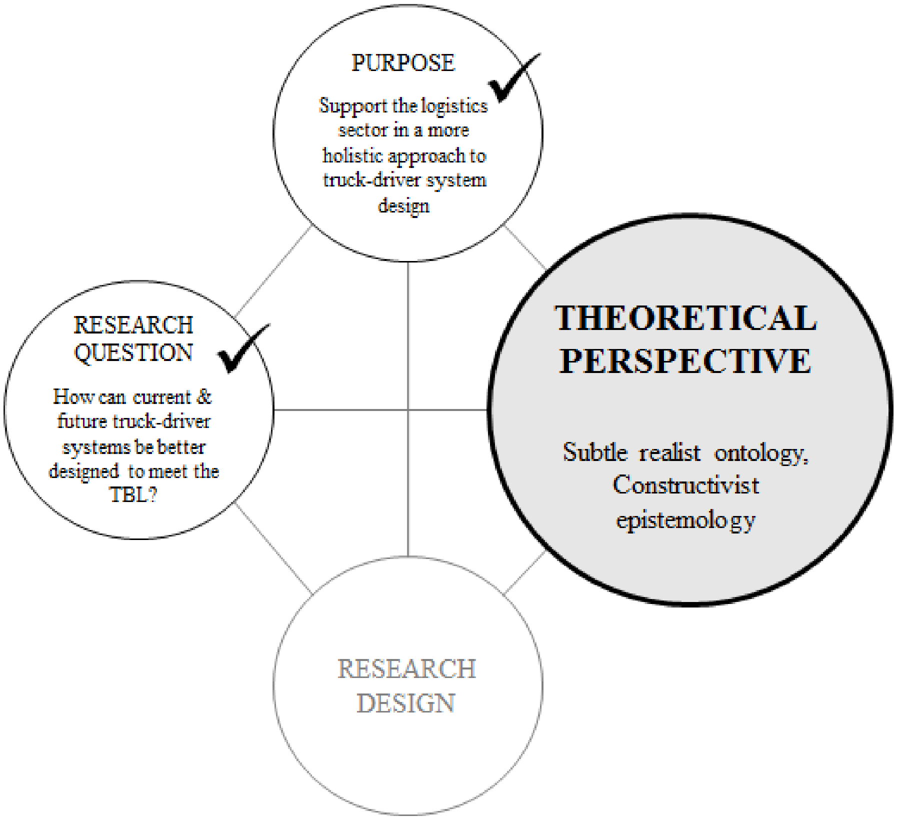


Figure 3.4: Theoretical perspective, as in Partington's four aligned elements of the research process (2002, p. 139)

3.3.5.4. Adopted methodology

An exploratory methodology rooted in *pragmatism* and inspired by *contextual constructivist grounded theory* will be used via a *mixed methods approach* (Bryant & Charmaz, 2007; Charmaz, 2008; Ong, 2012; Matavire & Brown, 2013; Loonam, 2014; Ward, et al., 2015; Charmaz, 2017).

From a methodological standpoint, the pragmatic paradigm "concentrates on beliefs that are more directly connected to actions…shift[ing] the study of social research to questions such as: How do researchers make choices about the way they do research? Why do they make the choices they do? And, what is the impact of making one set of choices rather than another?" (Morgan 2014b, p. 1051).

Grounded theory generally expands behavioural analysis beyond the unit of an individual to an event or system (Glaser & Strauss, 1967), laying the foundation for the study of interactions and aiming to build ‘a combinative inventory of possible situations’ (Baszanger & Dodier, 1997 in Bryant, 2003, p. 4). These are common themes in existing human factors systems research. Today, grounded theory is an umbrella term including a “constellation of methods” rather than a single approach (Charmaz 2006), particularly as the controversy between Glaser and Strauss has led to multiple variants. Bruscaglioni (2010) interprets this controversy as being centred on the difference in logical arguments used to theorize in each variant. This highlights the importance of defining reasoning approaches and which of these is best matched to different HF/E problems, as has been done in Section 3.3.4. Where the original grounded theory founded by Glaser and Strauss was inductive (or abductive to a small extent), the later work of Strauss is abductive (Reichertz 2007).

The variants of grounded theory which lend flexibility to abductivism (e.g. Strauss & Corbin, 1990; Bryant & Charmaz, 2007) are the inspiration for this methodological approach, as these explicitly acknowledge that the researcher’s experience of the phenomenon prior to beginning the research will inextricably affect codes and interpretation of data. In other words, this thesis does not undertake studies which explicitly code and develop theory according to classic grounded theory procedures. In such Glaser variants, the mind is treated as a ‘tabula rasa’ and the researcher is cautioned against performing any literature review prior to beginning a study. This is despite a repeated claim by Glaser that “all is data” (Glaser 2002). If “all is data”, data could certainly also include pre-existing literature, and furthermore the mind is not a blank slate at the start of each study (Bryant 2009).

Instead it is taken that “theoretical preconceived knowledge has an important role in coding [and interpretation of data], according to the idea that the elements that constitute the hypotheses are already in our mind” (Strubing 2007 as interpreted in Bruscaglioni 2016, p. 2021). In reinterpreting GTM in a constructivist sense, Bryant (2009, p. 21) affirmed that “the Pragmatist concept of abduction takes account of this; insights can come from anywhere”. In other words, methodological approaches do not have sit at polar extremes of a spectrum, as implied by Glaser, where one end requires no familiarity with pre-existing literature and theory, and the other end is governed almost totally by pre-existing literature and theory. A true constructivist GTM means that ‘all’ really can be ‘data’. This means that the collection and analysis of data can happen concurrently, with outcomes guided by this process rather than a cleanly predetermined framework (Howard-Payne 2016). In grounded theory Heath & Cowley (2004) recommend that novice researchers select the variant that best suits their cognitive style, and in general the pragmatist perspective emphasises the importance of specific research communities that guide the nature of how to conduct inquiry. The Straussian variant of grounded theory adopted here does not ‘keep it simple’ – what Boychuk Duchscher & Morgan (2004) describe as Glaser’s motivation for upholding traditional grounded theory – however it does acknowledge the real-world complexities of performing research, particularly in the community of HF/E. What all GTM variants share is an encouragement to make a deliberate move away from a pure empiricist mindset, which was deeply engrained in most fields at the time of Glaser & Strauss’ original GTM. Human factors generally shares this criticality around whether the established way of doing things continues to be productive and valid (e.g. Salmon et al., 2017).The common criticism of grounded theory in general – that it can codify data but has failed to advance wider theory – can potentially be resolved by taking this route with a more abductive and formative approach than traditional grounded theory. Abductive and formative human factors methods are available, which can readily contribute to theoretical development (Timmermans & Tavory, 2012). In constructivist GTM, iterations between engagement with the research context and the conceptual analysis are the key to developing a grounded theory with ‘grab’ and ‘fit’ (Bryant 2009). Human factors methods are well-suited for this type of iterative, formative, flexible development of context-specific theory.

The flexibility inherent in a mixed methods toolkit is a fundamental component of human factors practice, which matches the complex and interdisciplinary nature of real-world conditions. This is reflective of a Pragmatist approach which requires grounding in and interaction with real-world practice, as new insights are evaluated through the practical differences they make to people’s thinking and behaviour (Bryant 2009).

In HF/E, a mix of methods are often applied ad-hoc based on practitioner expertise regardless of whether a single- or multi-method approach is used. In wider social science research the design of mixed methods research (Greene 2006; Johnson, Onwuegbuzie & Turner, 2007; Creswell & Plano Clark, 2011; Morgan 2014a) is described as either convergent parallel, sequential explanatory, sequential exploratory, embedded, transformative, or multiphase. Creswell & Plano Clark (2011) link the pragmatist paradigm to either a convergent parallel design or a multiphase design. The work of Carayon et al. (2015) further confirms these linkages, through the finding that 67% of existing HF/E mixed methods research follows a convergent parallel design. In this case, the research design explores the research question generally, and a cleanly sequential or parallel design may restrict this exploration. It is also expected that some HF/E outputs may be used as other HF/E inputs, for example in the use of a Hierarchical Task Analysis (HTA) for other methods. Furthermore as this work is sponsored by the multi-project Centre for Sustainable Road Freight, results must be mixed or integrated within a wider program-objective framework (Creswell & Plano Clark, 2011). For the above reasons a multiphase design will be taken, as a "combination of sequential and concurrent collection and analysis of qualitative and quantitative data over a period of time and within a major research program" (Carayon, et al., p. 296).

All of the above speak to a methodological position which acknowledges the real-world complexities of performing research, regardless of the subject or sector. The adopted methodology enables completion of Partington's research process elements as shown in Figure 3.5.

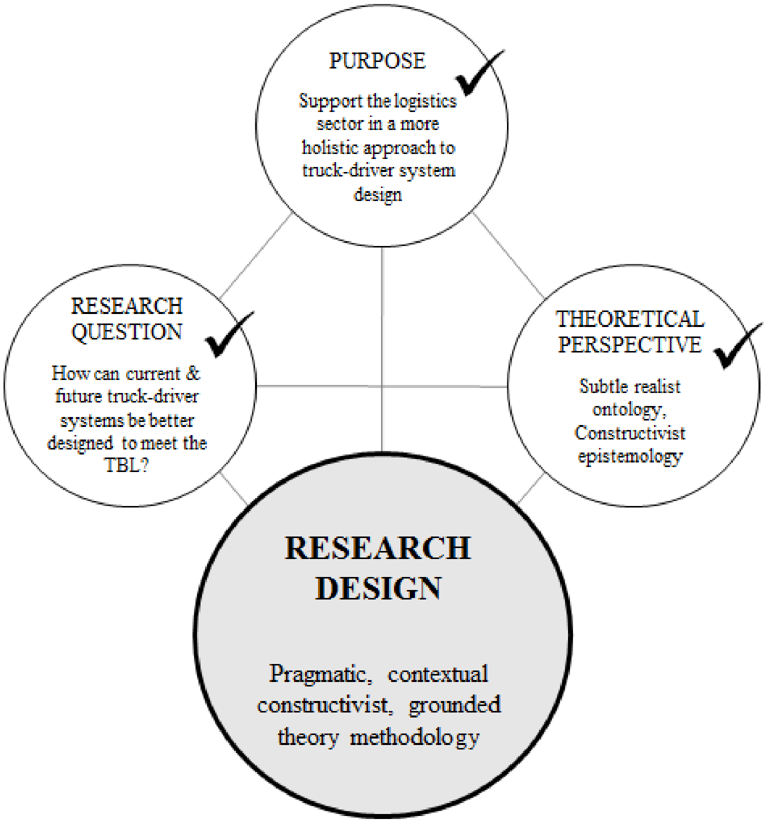


Figure 3.5: Research design, in Partington's four aligned elements of the research process (2002, p. 139)

3.4. Part 3: A methodological map for dealing with large CASTS

The need to engage in systems thinking (Part 1) and the research paradigm needed to do so (Part 2) both highlight a further gap in current knowledge. The need to overcome a lack of theory-based methodological structure to cope with large-scale complex adaptive socio-technical systems (CASTS). There have been recent calls for the development of complexity themes in HF/E and the associated methods by which to investigate them (Walker, et al., 2010). Nonetheless there exists a significant gap between the trends within academic literature which advocate for systems thinking (e.g. Dekker et al., 2013), and the current state of methodology and tools supporting real-world practice. The strategy of acknowledging human complexity within logistics at present relies heavily on the expertise and imagination of the human factors practitioner (Stanton & Young, 2003).

What methodological options currently exist? And perhaps more critically – to repeat the central pragmatist question – "how do researchers make choices about the way they do research?" (Morgan 2014b, p. 1051). Recent human factors methods reviews have focussed on appropriately matching methods to practical problems, increasingly from a systems perspective (Walker, et al., 2010; Thatcher & Yeow, 2016). This has in part been motivated by applied human factors research having little to no precedent in open systems at a large scale. This question is becoming a hot topic of review in HF/E (Waterson, et al., 2015; Salmon, et al., 2017), but the conversation currently lacks any formal reference to CASTS principles. As a result, it is valuable to perform a first-of-its-kind review relating HF/E methods to the characterisation of CAS boundaries and interactions.

3.4.1. HF/E methods review: accounting for system scale with STS & the ADS

To determine the extent of CAS coverage afforded by HF/E methods it is necessary to acknowledge the 'scaling out' of HF/E, and appropriately draw from CASTS principles to address these different scales. Karwowski (2012, p. 984) notes that "this scaling out of the HFE discipline theory and its applications has rapidly accelerated in recent years, with the focus on a very large system, that is, a system of systems, as well as a variety of other complex adaptive systems". Siemieniuch & Sinclair (2014) echo this sentiment with their recent 'system of systems' (SoS) approach. If a defining characteristic of CASTS are their heterogeneity of acting parts, the true challenge lies in dealing with these very large systems (e.g. logistics) and their overwhelming number of unknowns. Karwowski (2012, p. 989) points out further, “whereas any deterministic system is predictable on a short time scale, chaotic systems are not predictable on a long time horizon since their behavior is irregular and depends only on the uncertainty of the initial system conditions (Kleeman, 2011)”. Thus, for effective design and for anticipating long-term adaptivity, HF/E analysts need to understand a larger and larger set of behaviours. These behaviours occur in parallel and at different levels of scale, many of which are interdependent on one another to some degree. Walker et al. describe this challenge as addressing and navigating the study of ‘quantum behaviour’, i.e. that “systems have many different realities depending on the level of analysis” (Walker, et al., 2017, p. 158). This requires contextualising HF/E methods within a framework that acknowledges how nano- and macro-scale system behaviours are related, and how this contributes to the evolution of quantum systems over time.

Some guiding models and frameworks are relevant to this endeavour. For the purpose of creating a taxonomy by which HF/E methods can be reviewed for their coverage of systems analysis, two frameworks were considered. The first consideration was Rasmussen’s (2000) complex socio-technical systems model, which decomposes large systems into different levels of scale, as outlined in Figure 3.6 below. In relation to this model, Rasmussen points out that most disciplines restrict their research ‘horizontally’ within a single level of scale and ignore productive ‘bottom-level’ processes. This model emphasises that ‘vertically-oriented’ research is necessary to understand informational feedback loops in CASTS like logistics. In other words, to properly delve into CASTS and their interactions we must be able to acknowledge and capture these ‘vertically-oriented’ processes, and to move our focus and our toolkit easily between different levels of scale.

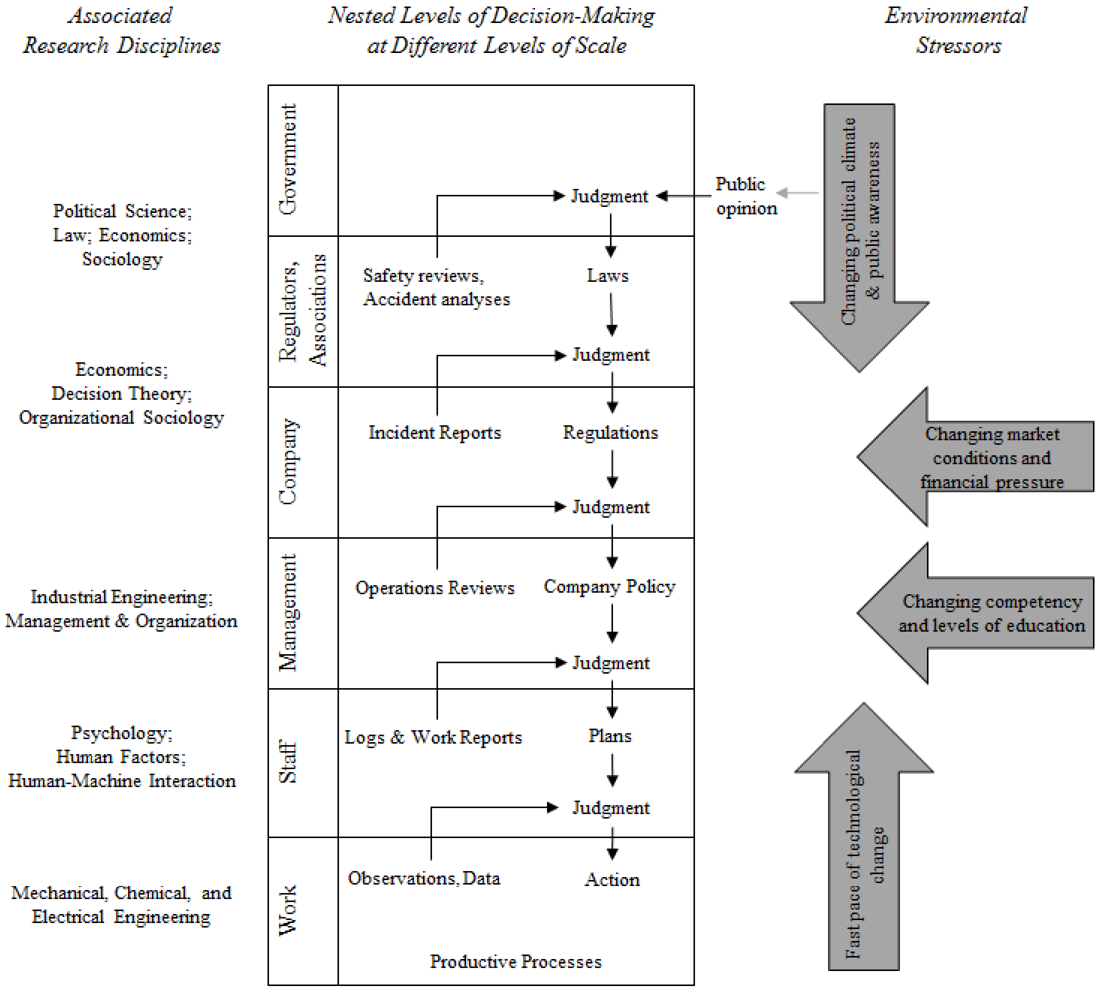


Figure 3.6: Rasmussen's (2000) model of nested decision-making in complex socio-technical systems

A similar style of system decomposition is also present in the Abstraction-Decomposition Space (ADS). This is part of the Cognitive Work Analysis (CWA) framework, and the second stage of Work Domain Analysis (WDA). In system design and evaluation, an ADS is created to break down system components into more manageable groups and gain insights on how the system might be viewed by different stakeholders. On the vertical axis there are five levels of abstraction (‘Functional Purpose’, ‘Values & Priority Measures’, ‘Purpose-Related Functions’, ‘Object-Related Processes’, and ‘Physical Objects’). On the horizontal axis there are five (or three) system levels: ‘Whole System’, ‘Subsystem’, ‘Functional Unit’, ‘Sub-assembly’, and ‘Individual’. Dul et al. (2012) use this approach to map stakeholders to different levels of the system as shown in Table 3.7. Here system groups have been interpreted as levels of abstraction, and system levels as levels of decomposition. This gives an abstraction-decomposition space ‘map’ of relevant stakeholders.

Table 3.7: System stakeholders mapped to ADS, with levels of abstraction & decomposition expressed as Dul et al.'s (2012) stakeholder groups & levels

		Whole System	Sub-System	Functional Unit	Sub-Assembly	Component
		Organisations Representing Individuals in the World	*Organisations Representing Individuals in a Country/Region*	*Organisations Representing Individuals in the Company*	*Individual*	
Functional Purpose	*System Influencers*	• International general public • International media • International governments • International standardisation bodies	• National/regional general public • National/regional media • National/regional governments • National/regional standardisation bodies	• Local community • Local media • Local government	• Any other person interested in systems design	
Values & Priority Measures	*System Decision-Makers*	• International employer organisation • International industry/trade orgs	• National/regional employer orgs • National/regional industry/trade organisations	• Management team • Purchasers of products / services	• Managers • Other decision-makers	
Generalised Functions	*System Experts*	• International research organisations (universities, research funding orgs) • International professional associations • International institutes for professional education	• National/regional institutes for professional education • National/regional research orgs (universities, research funding orgs) • National/regional professional associations	• Professional colleagues	• Professionals from the technical & social sciences, e.g.: *industrial engineering, IT/computer science, UX specialists, psychology, management consultancy, design, facility management, operations management, human resources, interior design, architecture*	
Object-Related Processes						
Physical Objects	*System Actors*	• International government/OHS /consumer safety legislation • International trade unions • International user groups • ILO • WHO • ICOH	• National/regional government/OHS /consumer safety legislation • National/regional user groups (e.g. patient associations) • National/regional trade unions • National/regional consumer org • National/regional org of OHS services	• Work councils • User groups • OHS service providers	• Actors of work systems (employees) • Actors of product systems (product users) • Actors of service systems (service receivers)	

Ultimately both Rasmussen's nested decision making model and the ADS influenced the procedure by which HF/E methods were reviewed. Both of these frameworks are in line with the underlying theory of CASTS, but have not been utilised to understand the coverage of HF/E methods or frame HF/E research design before. The ADS is used to structure a review of HF/E methods by defining distinct levels of granularity, while the STS model enables interactions between the levels of granularity defined by the ADS to be studied. The following section describes the procedure in detail.

3.4.2. HF/E methods review: procedure & materials

Informed by Rasmussen's STS model and the ADS, this review uses six independent levels of granularity to organise methods: whole system, subsystem, functional unit, sub-assembly, individual (theoretical/abstract), and individual (individual/contextual). Each of these levels of granularity has been described in the context of the total work system in Table 3.8.

Here, the 'whole system' is taken to include all activities (not limited to logistics) at a large (regional or even global) scale. This is a necessary precondition of a methods review for the study of CAS, due to the fact that the boundaries of CAS are fuzzy, and interactions which are meaningful (in that they lead to cascading system change) are sometimes at the edge of a fuzzy boundary (as referenced in the work of Holland, Cilliers, Pohl, Levin, and Gros in Table 3.1, point 7). In other words, in CAS it is difficult to discount the potentially significant influence of a superficially insignificant action, e.g. the 'butterfly effect' (as referenced in the work of Holland, Cilliers, Pohl, Levin, and Gros in Table 3.1, point 8). Pohl (1999, p. 3) contends that "even when attempts are made to model the boundary conditions, these models rarely reflect the dynamic nature of all of the external forces that impact the internal elements". The idea that theory and methods still need further development to effectively tell us how CAS boundaries are defined is echoed by Holland (2006). Section 3.4.1 outlays this need in an HF/E context, to consider larger and larger scales and sets of behaviours. This also directly addresses the fact that when the 'whole system' is taken at this large scale, agents experience the system from a localised perspective. In the above characterisation of a whole system, the net is cast wide to capture more than the traditional definition of a specific work system. This is a deliberate move away from a purely mathematical control theory approach, which assumes that any uncertainty can be converted into a definable set of parameters (Pohl, 1999).

At this scale, the existence of an accurate ‘whole systems’ method which can cover all resolutions (i.e. fine-grained as well as coarse-grained) would imply an omniscience that human beings are not capable of. As such under this definition of a ‘whole system’ within this particular review, it is not intended or expected that a ‘whole systems’ method does, or should, exist. Instead, this review is intended to shed light on what level of systems coverage HF/E methods afford, and critically, how different HF/E methods can be used together as building blocks for improved (but not necessarily total) systems coverage. In general this issue of matching methods to complex problems and ensuring they are compatible with systems thinking, particularly across traditional boundaries, is increasingly salient in the HF/E discipline (Carayon, 2006; Walker, et al., 2010; Karwowski, 2012; Le Coze, 2013; Salmon et al., 2017). More specifically Waterson et al. (2015) echo these needs in their review of sociotechnical systems methods for safety. They highlighted that (1) often HF/E methods ignore the wider context considered to be ‘external’ to the specific system under study, (2) future work to distinguish between system boundaries is needed, and (3) the best systems coverage was often afforded by frameworks that included multiple methods with different types of analysis.

A distinction between physical and informational interactions is made in the review to highlight the differences influencing reasoning and method approaches, and consequently validity and reliability in real-world application. Within this review, the ‘physical’ refers to any directly observable, measurable, physical behaviour. Or in other words, anything that can be easily noted by the analyst, and more or less consistently observed by multiple analysts. The ‘cognitive’ refers to indirectly observable, informational, cognitive, or culturally-driven aspects. Or in other words, these are the types of processes underlying behaviour which are more difficult for analysts to identify and characterise with consistency. Also within Table 3.8 are examples of their physical and cognitive aspects, and examples of corresponding HF/E method inputs.

Table 3.8: Levels of granularity used in HF/E methods review

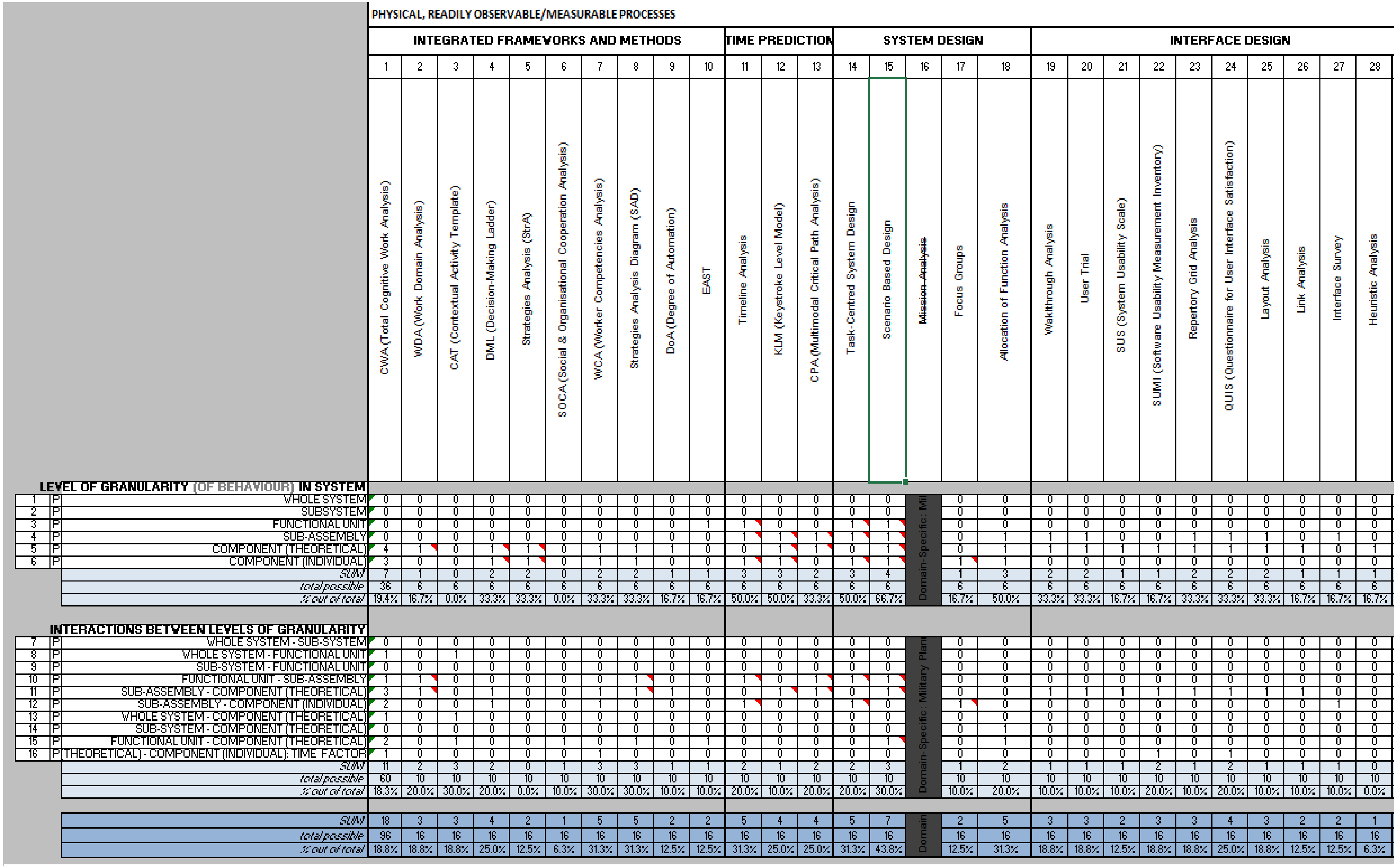
#	*Level of granularity*	*Description*	*Examples of physical or cognitive aspects*	*Example of data for an HF/E method*
1	Whole System	Capturing *all* actions, decision-making processes, and interactions, ideally with the potential to yield predictive power at any level of granularity (albeit, with potentially varying degrees of certainty within limitations of time); the definition of the system as closed or open will influence the ease of analysis at this level	*Physical:* Physical geography of a whole, large-scale transportation network, including all physical interactions between vehicles, infrastructure, climate, etc.	N/A (no such method exists)
			Cognitive: Trends in system culture & system behaviour	N/A (no such method exists)
2	Subsystem	Agents with high responsibility for decision-making; attempts to address current - or inform future - cultural values, decision-making criteria, and/or the high-level development of guidelines or procedures related to real-world operations	*Physical:* Physical documentation of legal rules for monitoring, governing, and influencing the system	Coordination Demands Analysis
			Cognitive: Decision-making processes utilised by agents with high decision-making capability; values and priority measures	Critical Decision Method
3	Functional Unit	Includes team behaviour among human and/or technological agents, and their interactions (usually attached to team-level task and bound by a specific space and time)	*Physical:* Physically observable task execution by a group or team, focusing on the completion of some function, rather than each agent's specific role attached to this function	Team Task Analysis
			Cognitive: Information networks which are requisite for adequate task completion among a group or team, rather than the specific information used by each agent	Team Workload Analysis
4	Sub-Assembly	Interactions between a small number of components focused on a lower-level sub-task, and usually considering very local allocation of function between one human and one technological agent (e.g. interface design)	*Physical:* Physical sub-tasks e.g. in operation of a control panel interface	Layout Analysis
			Cognitive: Information cues required for completion of a sub-task	System Usability Scale
5	Component (Abstract/ Theoretical)	Behaviour at the level of an individual human or technological agent, functionally independent of individual differences influenced by experience over time; in other words, this is the component's ideal 'designed' functionality	*Physical:* Ergonomic design considerations; designed physical behaviour or output of each individual human or technological agent (skill-based behaviour)	Worker Competencies Analysis
			Cognitive: Generalised 'ideal' decision-making ladders; algorithms ruling technological agents	Decision-Making Ladder
6	Component (Contextual/ Individual)	Elements of individual differences, or variations influenced by experience and time, at the level of an individual human or technological agent. This distinction from the 'abstract/theoretical' component is informed by developments in naturalistic decision-making (as in Rasmussen, 2000; Klein, et al., 1994)	*Physical:* Physical behaviour throughout task prior to or leading up to 'expert' level of experience (knowledge- or rule-based behaviour)	Focus Groups
			Cognitive: Decision-making ladder for non-experts; algorithms ruling technological agents	Task Centred System Design

Table 3.8 shows six discrete levels of granularity. Of course, levels can interact to create a further 10 levels listed below:

7. Whole System - Subsystem
8. Sub-system - Functional Unit
9. Whole system - Functional Unit
10. Functional Unit - Sub-assembly
11. Sub-assembly - Component (Abstract/Theoretical)
12. Sub-assembly - Component (Contextual/Individual)
13. Whole System - Component (Abstract/Theoretical)
14. Subsystem - Component (Abstract/Theoretical)
15. Functional Unit - Component (Abstract/Theoretical)
16. Component (Abstract/Theoretical) - Component (Contextual/Individual)

The main difference between the discreet levels (categories 1-6), and the interactions between levels (categories 7-16), is the shift in focus from a 'system' behaviour to a 'system-human' interaction which supports or influences system behaviour. In other words, the inclusion of interactions between levels (and particularly interactions with a component) shows the complex feedback loops in emergent behaviour within a system. Category 16 (last in the list above) demonstrates the difference between 'component' types which have been decomposed into two sub-categories: theoretical (category 5) vs. individual (category 6). The distinction between categories 5 and 6 is intended to show which methods reflect a general theoretical idea of the targeted work processes, and which methods rely heavily on input from experts in that type of work. Category 16, therefore, captures methods which look at learning effects, e.g. naturalistic decision-making styles moving through levels of knowledge, rule, and skill-based behaviour.

Overall, these classifications resulted in a taxonomy of 32 categories (16 physical and 16 cognitive). Using these categories 93 HF/E methods were reviewed. This compilation of methods was taken from a leading text on human factors methods for system design, compiled by Stanton et al. (2005). Four methods were excluded from the evaluation (Mission Analysis; Modified Cooper-Harper Scales; SASHA_L/SASHA_Q; Situation Awareness Rating Scale) due their specific data inputs and thus lack of transferability to the logistics domain. This gave a total of 89 methods reviewed in full. A description of each method was examined to determine which levels of granularity – as well as interactions between levels of granularity – were targeted by the data collection for each method. Applicable categories were marked down in an Excel matrix. This Excel matrix covered four parts (physical, cognitive, differential, and sum) and a sample is shown in Figure 3.7 below. Overall results for each of the 16 categories were calculated via this matrix.



PHYSICAL, READILY OBSERVABLE/MEASURABLE PROCESSES

			INTEGRATED FRAMEWORKS AND METHODS										TIME PREDICTION			SYSTEM DESIGN					INTERFACE DESIGN									
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
			CWA (Total Cognitive Work Analysis)	WDA (Work Domain Analysis)	CAT (Contextual Activity Template)	DML (Decision-Making Ladder)	Strategies Analysis (StrA)	SOCA (Social & Organisational Cooperation Analysis)	WCA (Worker Competencies Analysis)	Strategies Analysis Diagram (SAD)	DoA (Degree of Automation)	EAST	Timeline Analysis	KLM (Keystroke Level Model)	CPA (Multimodal Critical Path Analysis)	Task-Centred System Design	Scenario Based Design	~~Mission Analysis~~	Focus Groups	Allocation of Function Analysis	Walkthrough Analysis	User Trial	SUS (System Usability Scale)	SUMI (Software Usability Measurement Inventory)	Repertory Grid Analysis	QUIS (Questionnaire for User Interface Satisfaction)	Layout Analysis	Link Analysis	Interface Survey	Heuristic Analysis
		LEVEL OF GRANULARITY (OF BEHAVIOUR) IN SYSTEM																												
1	P	WHOLE SYSTEM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Domain-Specific: Mil	0	0	0	0	0	0	0	0	0	0	0	0
2	P	SUBSYSTEM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0
3	P	FUNCTIONAL UNIT	0	0	0	0	0	0	0	0	0	1	1	0	0	1	1		0	0	0	0	0	0	0	0	0	0	0	0
4	P	SUB-ASSEMBLY	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1		0	1	1	1	0	0	1	1	1	0	1	0
5	P	COMPONENT (THEORETICAL)	4	1	0	1	1	0	1	1	1	0	0	1	1	0	1		0	1	1	1	1	1	1	1	1	1	0	1
6	P	COMPONENT (INDIVIDUAL)	3	0	0	1	1	0	1	1	0	0	1	1	0	1	1		1	1	0	0	0	0	0	0	0	0	0	0
		SUM	7	1	0	2	2	0	2	2	1	1	3	3	2	3	4		1	3	2	2	1	1	2	2	2	1	1	1
		total possible	36	6	6	6	6	6	6	6	6	6	6	6	6	6	6		6	6	6	6	6	6	6	6	6	6	6	6
		% out of total	19.4%	16.7%	0.0%	33.3%	33.3%	0.0%	33.3%	33.3%	16.7%	16.7%	50.0%	50.0%	33.3%	50.0%	66.7%		16.7%	50.0%	33.3%	33.3%	16.7%	16.7%	33.3%	33.3%	33.3%	16.7%	16.7%	16.7%
		INTERACTIONS BETWEEN LEVELS OF GRANULARITY																												
7	P	WHOLE SYSTEM - SUB-SYSTEM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Domain-Specific: Military Plan	0	0	0	0	0	0	0	0	0	0	0	0
8	P	WHOLE SYSTEM - FUNCTIONAL UNIT	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0
9	P	SUB-SYSTEM - FUNCTIONAL UNIT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0
10	P	FUNCTIONAL UNIT - SUB-ASSEMBLY	1	1	0	0	0	0	0	1	0	0	1	0	1	1	1		0	0	0	0	0	0	0	0	0	0	0	0
11	P	SUB-ASSEMBLY - COMPONENT (THEORETICAL)	3	1	0	1	0	0	1	1	1	0	0	1	1	0	1		0	0	1	1	1	1	1	1	1	1	0	0
12	P	SUB-ASSEMBLY - COMPONENT (INDIVIDUAL)	2	0	0	1	0	0	1	0	0	0	1	0	0	1	0		1	0	0	0	0	0	0	0	0	0	1	0
13	P	WHOLE SYSTEM - COMPONENT (THEORETICAL)	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0
14	P	SUB-SYSTEM - COMPONENT (THEORETICAL)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	1	0	0	0	0	0	0	0	0	0	0
15	P	FUNCTIONAL UNIT - COMPONENT (THEORETICAL)	2	0	1	0	0	1	0	1	0	1	0	0	0	0	1		0	1	0	0	0	0	0	0	0	0	0	0
16	P	(THEORETICAL) - COMPONENT (INDIVIDUAL): TIME FACTOR	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0		0	0	0	0	0	1	0	1	0	0	0	0
		SUM	11	2	3	2	0	1	3	3	1	1	2	1	2	2	3		1	2	1	1	1	2	1	2	1	1	1	0
		total possible	60	10	10	10	10	10	10	10	10	10	10	10	10	10	10		10	10	10	10	10	10	10	10	10	10	10	10
		% out of total	18.3%	20.0%	30.0%	20.0%	0.0%	10.0%	30.0%	30.0%	10.0%	10.0%	20.0%	10.0%	20.0%	20.0%	30.0%		10.0%	20.0%	10.0%	10.0%	10.0%	20.0%	10.0%	20.0%	10.0%	10.0%	10.0%	0.0%
		SUM	18	3	3	4	2	1	5	5	2	2	5	4	4	5	7	Domain	2	5	3	3	2	3	3	4	3	2	2	1
		total possible	96	16	16	16	16	16	16	16	16	16	16	16	16	16	16		16	16	16	16	16	16	16	16	16	16	16	16
		% out of total	18.8%	18.8%	18.8%	25.0%	12.5%	6.3%	31.3%	31.3%	12.5%	12.5%	31.3%	25.0%	25.0%	31.3%	43.8%		12.5%	31.3%	18.8%	18.8%	12.5%	18.8%	18.8%	25.0%	18.8%	12.5%	12.5%	6.3%

Figure 3.7: Methods review matrix sample, showing methods reviewed for their capture of physical processes

3.4.3. HF/E methods review: results

Results show immediately that there is substantial opportunity in methodological development for true systems analysis. On the y-axis of Figure 3.8 is the extent to which methods reach across all 32 review categories (levels of system granularity *and* interactions between levels; physical *and* cognitive). For example, placement at 25% along the y-axis means that 8/32 categories have been covered. Each sphere represents a group of methods, with its attached label indicating % coverage, as well as the number of methods which have that % coverage. For example, the label "25%, 7" indicates there are 7 methods with 25% coverage. Thus the x-axis is simply expressed at the % of overall reviewed methods; for example, a sphere placed at 8% on the x-axis signifies 7/89 methods are in this group.

Individual HF/E methods cover up to 55% of the whole system, with the average coverage falling at 19% of the system. Full tables of individual methods' applicability at different levels can be found in Appendix B. Only two methods reach above the 50+% mark: Behavioural Observation Scales (BOS) and the Cognitive Reliability and Error Analysis Method (CREAM).

The finding that methods commonly thought of as HF/E systems approaches – such as Cognitive Work Analysis (CWA), Systems Theoretic Accident Modelling and Processes model (STAMP), and Functional Resonance Analysis Method (FRAM) – do not cover 100% of the 'whole system' is not because these methods fail to cover certain systems adequately (e.g. a nuclear power plant system). Many of the reviewed methods are important contributions which do cover a large proportion of a system, depending on how 'system' is defined. In the case of this thesis, the 'system' under study in Chapters 4-6 is a relatively small-scale, fine-grained one (i.e. how a truck and driver interact in the context of a road environment and a logistics organisation). However the wide-reaching definition of 'whole system' used in this methods review covers *all* dynamics at a *large* scale and at *all* resolutions (e.g. all economic, political, social, etc. activities across the globe that may influence UK truck-driver systems). As such the existence of a 'whole systems' method, with the capability to cover all aspects of systems at all resolutions is impossible – and even if possible would prove unwieldy for real-world practice. Indeed the results and conclusions within this methods review are echoed in other recent work. For example, Waterson et al. (2015, p. 592) found that sociotechnical systems methods often ignore the wider systems context, and that where it was addressed "much more work could be done examining the role played between ‘external’ system influences (e.g. political and economic influences) and organisation, group and individual levels of analysis”.

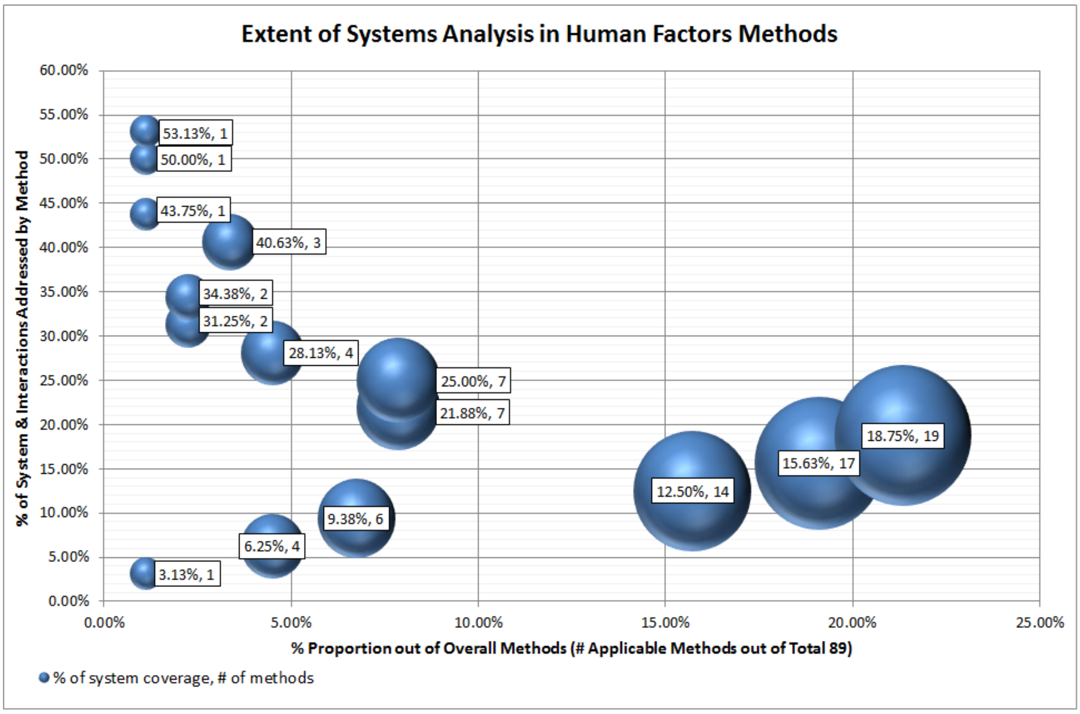


Figure 3.8: Extent of large-scale systems analysis in existing human factors methods

Instead of expecting a single method to capture the entirety of system behaviour, perhaps it is more useful to know which set of methods can give the greatest coverage, or certain types of coverage depending on the research aim. Outlined in Figure 3.9 are the physical and cognitive aspects addressed by all 89 methods, for each of the 16 scale categories. Lines indicate the number of methods relevant to a given scale, where one grid length represents one method. Dots indicate the average ‘lean’ of the methods at that scale towards the cognitive or the physical.

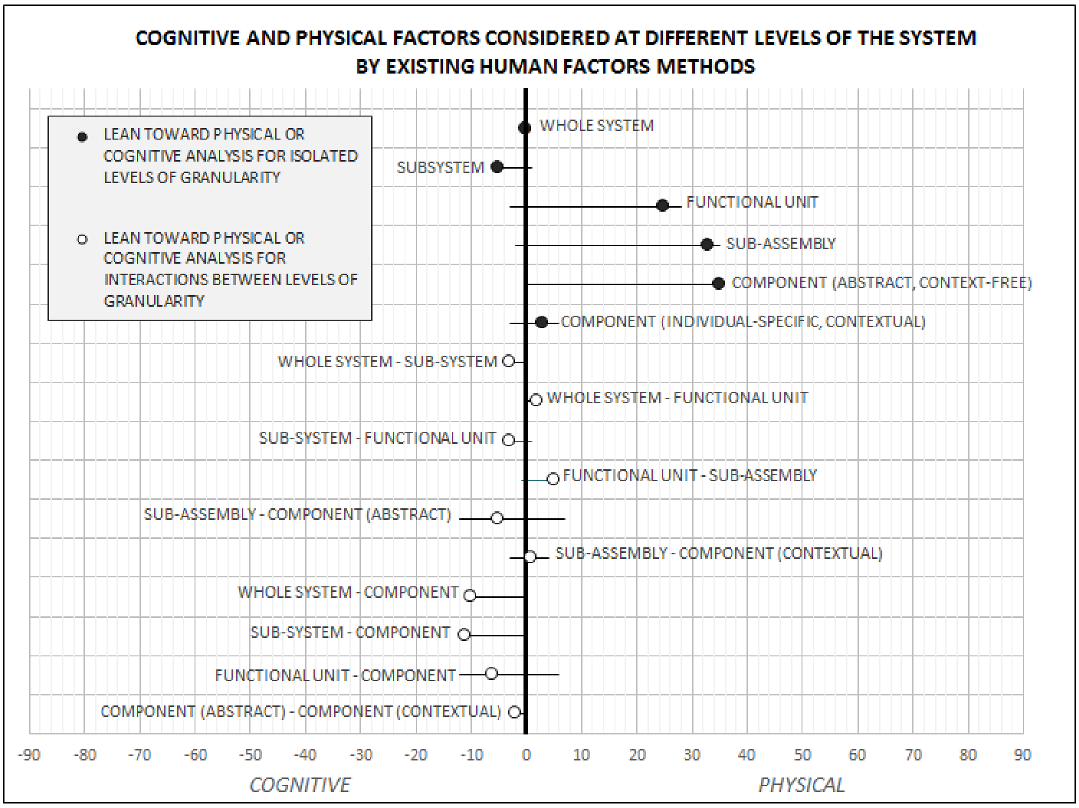


Figure 3.9: Cognitive and physical factors considered at different levels of the system by existing human factors methods

Results show there is a significant trend in how HF/E methods are applied to study interactions in a complex system. Isolated levels of granularity are studied through the investigation of physical measures. Based on Figure 3.3, this suggests that the study of isolated levels of granularity tends to adopt a normative (that is, descriptive or prescriptive) approach, particularly for finer levels of granularity with greater certainty. The study of interactions – which arguably yields more meaningful and enduring results for complex systems – focuses on cognitive, informational, or cultural aspects. The significance of ‘vertically-oriented’ information flows to the non-linear behaviour of CASTS could explain this tendency. Based on Figure 3.3, this suggests the use of mainly descriptive or, in areas of coarser granularity and thus greater uncertainty, formative approaches.

When considering both physical and cognitive aspects, methods which cover the greatest number of isolated levels of granularity (>40% of categories 1-6) include Allocation of Function (AoF) Analysis, the Behavioural Observation Scale (BOS), Coordination Demand Analysis (CDA), the Cognitive Reliability and Error Analysis Method (CREAM), Groupware Task Analysis (GTA), Hierarchical Task Analysis for Teams (HTA-T), the Mission Awareness Rating Scale (MARS), Scenario-Based Design (SBD), the Situation Awareness Global Assessment Technique (SAGAT), the Strategies Analysis Diagram (SAD), and Task-Centred Design (TCD).

Methods which cover the greatest number of interactions between levels of granularity (>40% of categories 7-16) include CDA, CREAM, and Worker Competencies Analysis (WCA). Methods which cover the greatest number of both interactions and isolated levels of granularity (>40% of all categories) include the BOS, CDA, CREAM, SBD, the SAD, and WCA. Methods which provided the highest rate (>19% of all categories) of coverage for both physical and cognitive aspects in each category of analysis includ: BOS, CDA, CREAM, the Human Error and Recovery Assessment Framework (HERA), SBD, WCA, and the Situation Awareness Behavioural Rating Scale (SABARS).

These results serve only to broadly characterise the nature of human factors methods, and to aid in matching methods to real-world issues within a systemic cognitive/behavioural ‘problem space’. Further reviews could address the five types of validity, and other considerations in Table 3.5, to examine the *effectiveness* of each method in capturing the 32 categories in this work. This is beyond the scope of the present review. These first steps, however, outline methodological trends and provide a guiding map for HF/E systems analysis. This map will be used in the following section to develop a specific research design targeting the effective design of current and future truck-driver systems consistent with the research aims set out in this thesis.

3.4.4. Methods selected from the map for this thesis

The goal of this thesis is not to optimise one single factor but three interlinked ones – safety, efficiency, and environmental impact – over the course of the next 15+ years. This inherently requires a systems approach which examines the truck *and* driver, and also allows room for future changes to existing technologies and practices. From the sections above, we now know there are significant gaps in HF/E-logistics research, even at the micro-scale. Taking this micro-scale – the truck-driver system – as a ‘starting point’ it is possible to begin with established and traditional methods to build up the evidence base. As the current state of commercial driving systems research only sporadically covers component or sub-assembly levels of granularity, the use of descriptive methods may be better suited to this stage of maturity in the field of commercial driver behaviour. As descriptive, micro-scale methods with wide-ranging usability, Hierarchical Task Analysis (HTA) and/or Training Needs Analysis (TNA) are an ideal place to begin. These methods also produce useful reference documents for wider research and practice, with HTA being an input to over 50 other HF/E methods. With a more solid foundation of knowledge on the commercial driving task, and mediating driver behaviour, larger-scale systems may be analysed more effectively.

The primary research question asks not only about the current state of affairs, but also about the design of future truck-driver systems. Using these same methods (HTA and TNA) we can look to the horizon and explore the truck-driver system of the future. By using the 'present-day' HTA and TNA results as a baseline, and the trajectory presented in Chapter 2 as an input, a forecast of typical working practices can be developed. Taking 'snapshots' of the future system in this way (at 5, 10, and 15 years into the future) illustrates the introduction of new technologies and their collective, systemic effects on operational practices.

With this new empirical knowledge base at a micro-level, other methods targeting interactions at higher levels of the system can be applied more reliably. For this we turn to the Cognitive Work Analysis framework. In order to design future truck-driver systems – particularly in light of the technology forecast, HTA, and TNA – methods can be applied to explore emergence and adaptivity. In collaboration with Scania, a leading European truck manufacturer, Work Domain Analysis (WDA), the Contextual Activity Template (CAT), and Strategies Analysis (StrAn) are applied. Critical work tasks are identified and a brand new next-generation truck technology designed from scratch for real-world industry use.

Extending the use of the CWA framework, the existing WDA for present-day truck-driver systems can also be adapted for future scenarios. WDA applied in this way serves to 'analytically prototype' future truck-driver systems. In addition to the standard format of WDA results, Social Network Analysis (SNA) metrics such as betweenness centrality can also be applied to the network, to quantify each part's degree of interdependence in the rest of the system. With a consistent, quantifiable, and reproducible measure as a guide, shifts in sociotechnical system functionality can be more easily identified and tracked over time. In this way, designers can look to the horizon of how truck-driver systems will be likely to function, with ample time for corrective co-evolution.

The proposed research plan begins with closing a crucial empirical gap, and pushing methodological boundaries slightly further at each step to design truck-driver systems which can help meet carbon reduction targets in addition to those offered by technology alone. Collectively, this strategy has the benefit of addressing both causes of Woods' "unanticipated perturbations", to ensure that (a) the system model in the competence envelope is 'complete' and (b) the system model is updated for new demands, pressures, and vulnerabilities (2006, p. 22). Table 3.9 clarifies which methods will be applied to current vs. future scenarios.

Table 3.9: Methods aimed at the representation & design of present & future truck-driver systems

		TYPICAL PAST APPLICATION OF METHOD		
		Normative		Formative
		Prescriptive	Descriptive	
TIMESCALE	Present System	▪ Hierarchical Task Analysis ▪ Training Needs Analysis	▪ Social Network Analysis (as applied to Abstraction Hierarchies)	▪ Cognitive Work Analysis (Work Domain Analysis; Contextual Activity Template; Strategies Analysis)
	Future Systems	▪ Hierarchical Task Analysis ▪ Training Needs Analysis	▪ Social Network Analysis (as applied to Abstraction Hierarchies)	▪ Technology Forecasting ▪ Cognitive Work Analysis (Work Domain Analysis)

Table 3.10 below also shows the selected methods in the context of their respective results from the methods review. This details their systems coverage individually, and demonstrates that as a whole the research design of this thesis covers 20/32 (63%) of the review categories. Ignoring the distinctions between physical and cognitive coverage, this thesis targets some aspect of 14/16 (88%) of the review categories. In other words, this thesis truly does engage systems thinking, to use systems methods.

Table 3.10: Systems coverage of planned research

Categories for Methods Review in Roughly Descending Order of Scale	Hierarchical Task Analysis		Training Needs Analysis		Work Domain Analysis		Contextual Activity Template		Strategies Analysis		SYSTEMS COVERAGE		TOTAL
	P	C	P	C	P	C	P	C	P	C	P	C	
Whole System											0	0	0
Whole System ←→ Subsystem						▨					0	1	1
Subsystem						▨					0	1	1
Whole System ←→ Functional Unit							▨				1	0	1
Subsystem ←→ Functional Unit						▨					0	1	1
Functional Unit	▨					▨					1	1	2
Functional Unit ←→ Sub-assembly					▨						1	0	1
Sub-assembly	▨										1	0	1
Whole System ←→ Component (Abstract/Theoretical)			▨	▨			▨	▨		▨	2	3	5
Subsystem ←→ Component (Abstract/Theoretical)			▨	▨						▨	1	2	3
Functional Unit ←→ Component (Abstract/Theoretical)		▨					▨			▨	1	2	3
Sub-assembly ←→ Component (Abstract/Theoretical)	▨	▨	▨	▨	▨					▨	3	3	6
Component (Abstract/Theoretical)	▨		▨	▨	▨				▨	▨	4	2	6
Sub-assembly ←→ Component (Contextual/Individual)										▨	0	1	1
Component (Contextual/Individual)									▨	▨	1	1	2
Component (Abstract/Theoretical) ← → Component (Contextual/Individual)											0	0	0
TOTAL SYSTEM COVERAGE	4	2	4	4	3	4	3	1	2	7	16	18	34

3.5. Conclusions

In this Chapter, four research sub-questions were asked to support the robustness and transparency of the thesis:

- *What theories or concepts draw together logistics & human factors literature? (SRQ1)*
- *What are the current logistics gaps which human factors is ideally suited to filling? (SRQ2)*
- *What is the research paradigm of human factors? (SRQ3)*
- *How can current logistics gaps be appropriately addressed by human factors methods? (SRQ4)*

To ensure this thesis adopts a strong research design, it was explored whether logistics and HF/E are truly engaging systems thinking and approaches. Logistics approaches to systems research were briefly reviewed, and complex adaptive systems was identified as a key area of underlying theory. It was found that HF/E also has implicit links to complex adaptive systems theory, and therefore potential to contribute to their study. However HF/E has not yet been regularly applied to logistics, and there is even a clear empirical gap at the micro-level of scale. Specifically, this means that individual drivers and their interactions with equipment, or the ‘truck-driver system’, requires our immediate attention. Therefore the two disciplines can (and should) be brought together.

To begin selecting methods targeting micro-scale studies, the HF/E research paradigm needs to be made explicit. The HF/E research paradigm was described as having an underlying philosophy of pragmatism; a subtle realist ontology; a constructivist epistemology; and a pragmatic, contextual constructivist, adapted grounded theory methodology. This proposed paradigm has been published in Walker et al. (2017), and described in the context of Partington’s four elements of the research process (shown in Figure 3.10 below).

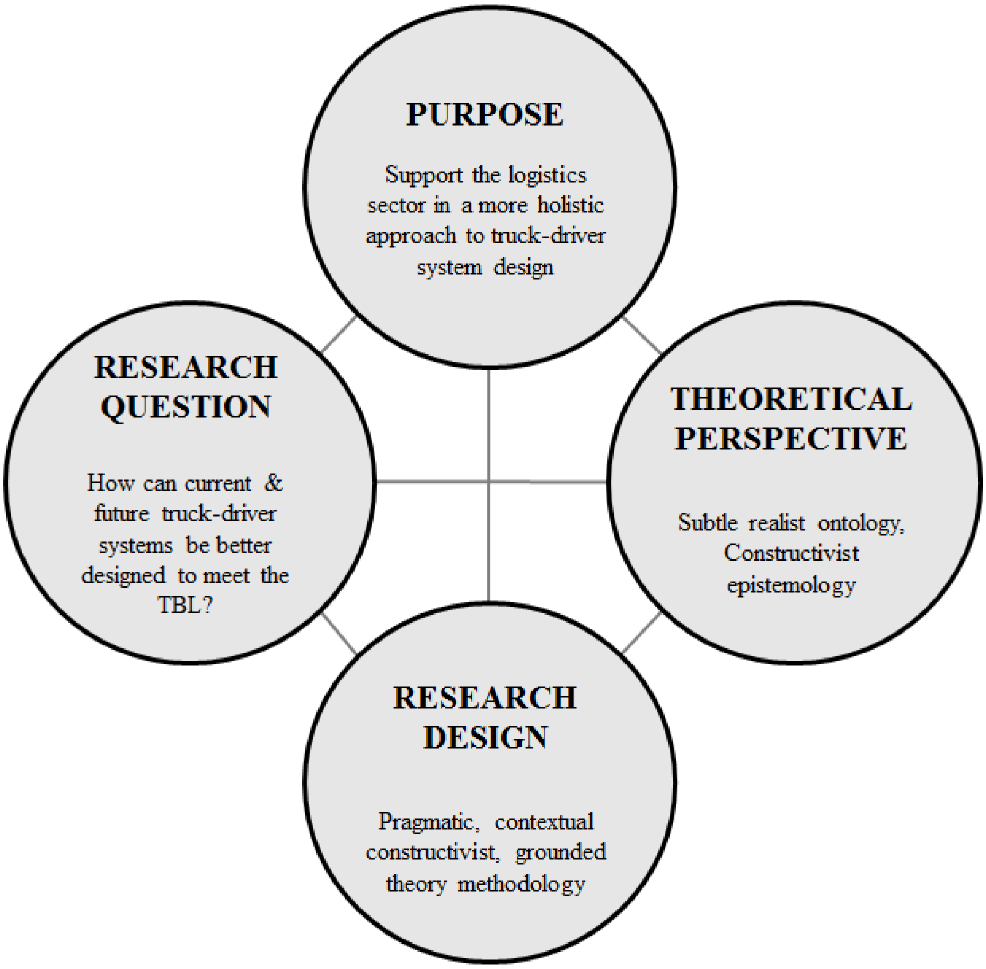


Figure 3.10: All four aligned elements of the research process for this thesis, as framed by Partington (2002, p. 139)

Using Partington's framework and looking toward the selection of methods for this thesis, a novel methodological contribution was provided for HF/E and the study of complexity in general by proposing that:

- different logic/reasoning approaches are connected to different method approaches (deductive-prescriptive; inductive-descriptive; abductive-formative);
- these approaches tend to suit different levels of granularity/scale within large, complex adaptive, socio-technical systems;
- the choice between qualitative vs. quantitative methods matters less to effective research than the choice between different reasoning and method approaches; and
- abductive-formative approaches tend to allow for the adaptivity and emergence of complex adaptive systems, particularly at higher levels of granularity, as they are the only approaches which are flexible and truly introduce novel ideas about system behaviour.

A novel, critical review of HF/E methods was performed to determine whether we are truly developing and employing 'systems approaches'. It was proposed that if different levels of scale are important for studying CASTS, and therefore for matching methods to problems, a structure to review methods based on different levels of scale is crucial. For the first time, the ADS was used as a basis for this methods review, dividing systems into theoretical and distinct levels of granularity. The results support the idea of a mixed method, toolkit approach for true systems analysis. The review also created a methodological contribution which provides much-needed structure for researchers; a reliable map of systems coverage provided by HF/E methods.

Using this map, methods were selected based on their coverage of system scale, coverage of both physical and cognitive system 'flows', and their potential to be applied as normative (prescriptive) to normative (descriptive) and formative approaches. Collectively, the selected methods also address both causes of Woods' "unanticipated perturbations", to ensure that (a) the system model in the competence envelope is 'complete' and (b) the system model is updated for new demands, pressures, and vulnerabilities (2006, p. 22). From this the following research strategy was developed:

- Hierarchical Task Analysis to build a solid, structured knowledge base of the commercial driving task and provide an input to over 50 other HF/E methods;
- Training Needs Analysis to define the Knowledge, Skills, and Attitudes (KSAs) required of the modern truck driver, as well as KSAs required in transitional stages from now to 2030;
- Work Domain Analysis, Control Task Analysis and Strategies Analysis to design new technologies and form strategies for prioritisation within very large systems;
- Work Domain Analysis to produce an analytical prototype of commercial driving systems against which current and future designs may be evaluated

These methods will be applied and extended in the Chapters which follow.

Chapter 4:
Identifying & Tracking the Future of Driver Training Needs

4.1. Introduction

Chapter 2 shows clearly that new commercial vehicle technologies will be coming forward over the next 15 years. The requirements placed on technology users (i.e. truck drivers) will also change. It is critical, therefore, not only to describe the current commercial driving task and its constituent training needs, but also how these might evolve over time. This will help to avoid skills gaps, skill degradation, and a wide range of other unintended effects. The latter point is especially important. Unanticipated system perturbations occur because (a) system models are incomplete, and (b) new demands arise that are outside current competence measures (Woods, 2006). Hierarchical Task Analysis (HTA) explicitly targets the incompleteness of pre-existing systems models, and Training Needs Analysis (TNA) explicitly targets new demands that are outside current competence measures. Both approaches will be used in this chapter to examine the impact of new technologies on the commercial driving task and how the road freight sector can prepare for these changes.

HTA is a foundational method in HF/E and used widely. That being said, previous task analyses specifically for commercial driving are few and far between. Published instances often cover specific ancillary tasks such as tanker filling (Salvendy, 2012, p. 755), refuelling errors in light vehicles (Adams & David, 2007), manual handling (Goode, et al., 2014), or more generic task analyses which do not cover sufficient depth to fully represent task complexity (Grove, 2008). Others include great depth but do not formally adhere to a consistent HTA structure (McKnight & Adams, 1970). The most comprehensive vehicle-related HTA published in the open literature covers private vehicle use in the United Kingdom by Walker et al. (Walker, Stanton, & Young, 2001; Walker, et al., 2015). The only existing publically available HTA specific to commercial driving was performed in the U.S. in 1996. While this is good groundwork it is now somewhat outdated in terms of truck technology, and irrelevant to activities governed by modern European regulations. An updated HTAoCD for UK operations will address these limitations.

TNA is also an approach used widely in HF/E to identify user requirements. In contrast to the UK's substantial number of prescriptive driving rules and recommendations, HF/E research exploring commercial driver requirements is sparse (e.g. Dubey & Gunasekaran, 2015). Methods like the Driver Skill Inventory (DSI) are broad by necessity of quick application to real-world drivers (e.g. Martinussen, et al., 2014), and by definition omit the knowledge and attitudes required for adequate task completion. The current training process for UK HGV drivers involves mandatory participation in the CPC driver certification scheme to ensure training is up to date. The breadth, depth and quality of what drivers are exposed to is relatively unknown. A formal TNA, driven from a robust HTA, enables current and future training needs to be captured in an exhaustive and systematic manner. As a novel forecasting technique it will be key to effective future system design. Forecasting commercial driver requirements relies on the technology forecast from Chapter 2, which can be used to inform the removal or addition of tasks from a current-day HTAoCD. Based on this, the corresponding TNA can be run (and re-run) and the changes in requirements and training needs captured. Forecasting the commercial driving task, and by extension their training needs, will highlight changes that need to be made, address new vulnerabilities, and allow decision-makers in the domain to revise competency measures before they become inappropriate.

A combination of HTA, TNA, and the technology forecast presented in Chapter 2 enables the needs and requirements of commercial drivers to be 'analytically prototyped'. This, turn, addresses the following sub-research questions:

- *How can the truck-driver system be represented in a functional, technologically agnostic way? (SRQ5)*
- *How can we estimate future system conditions, and test future system functionality before implementation? (SRQ6)*

This chapter will describe the tasks and competencies required for current commercial driving operations. It will also identify which tasks – or groups of tasks – are likely to be replaced by technology, what functionality will be provided, and what new tasks the future truck driver will be required to complete. Linked to these are new knowledge, skills, and attitudes, all of which need to be defined. In doing so future training needs are framed. As a result this chapter will present the most detailed, structured reference documents available for today's truck-driver systems. Equally important, this chapter also presents the first analytical prototypes of future truck driving, 'predicting the future' through 2020, 2025, and 2030.

4.2. Design & materials

4.2.1. Design

This study required a comprehensive HTA of truck driving to be constructed and the outputs used to drive a TNA. HTA is the most widely used of task analysis methods. It is designed to decompose a specified task into a hierarchical arrangement of goals, sub-goals, operations, and plans. When complete, this provides a technical reference based on a theory of goal-directed behaviour. According to Annett et al. (1971, p. 4, as cited in Stanton, 2006, p. 58), the original three principles governing a Hierarchical Task Analysis are the following:

1. *At the highest level we choose to consider a task as consisting of an operation and the operation is defined in terms of its goal. The goal implies the objective of the system in some real terms of production units, quality or other criteria.*
2. *The operation can be broken down into suboperations each defined by a sub-goal again measured in real terms by its contribution to overall system output or goal, and therefore measurable in terms of performance standards and criteria.*
3. *The important relationship between operations and sub-operations is really one of inclusion; it is a hierarchical relationship. Although tasks are often proceduralised, that is the sub-goals have to be attained in a sequence, this is by no means always the case.*

HTA details how tasks are expected to occur at a very granular level, but remains flexible to higher levels of granularity to fit the appropriate scope of research. Due to the high level of detail made possible by an HTA, and the iterative approach to refining it, it is advised to stop development of the HTA when both the analyst and the SME fully understand the sub-goal(s) (Stanton, 2006). Although the HTA does not speak to the frequency or duration of each task, it does provide a high degree of structure and documentation which can be referenced in an easily understandable format.

The scope of the following HTA(s) of commercial driving (HTAoCD) and TNA(s) of commercial driving (TNAoCD) encompassed right-hand-drive (RHD) articulated vehicles designed for driving on British roads with a C+E or C1+E license. Tractor units were assumed to be of Euro 6 emissions standard equipped with automatic transmission, dash-mounted handbrake, air braking system, breathalyser, and digital tachograph unit.

The use of technological systems such as lane departure warning systems (LDWS) and hands-free microphones were also included as such systems are commonin modern Euro 6 vehicles.

The TNAs addressed the knowledge, skills, and attitudes associated with each task in the corresponding HTA at each time step. Though knowledge, skills, and abilities were evaluated for each task step (down to the lowest level of granularity) it was presented at the third level of analysis (e.g. 1.1.1., 1.1.2, etc.) for clarity. Consistent with the research questions, this slightly higher-level perspective bestows a degree of technological agnosticism.

This process of HTA/TNA development/modification was repeated for three additional time steps in order to capture the future 2020, 2025 and 2030 scenarios identified in the earlier forecasting exercise (see Chapter 2). Practically this involved removing or adding tasks from the HTA and re-running the TNA to observe what changed.

4.2.2. Materials & procedure – Hierarchical Task Analysis of Commercial Driving (HTAoCD)

Feeding into this analysis of training needs is a complete Hierarchical Task Analysis of Commercial Driving (HTAoCD). After familiarisation with the domain and its operational diversity, an initial document review was performed. The researchers reviewed road freight sector regulations and available guidance documents, including an existing hierarchical task analysis of private vehicle driving (HTAoD) in the UK, undertaken by Walker et al. (Walker, Stanton, & Young, 2001; Walker, et al., 2015).

Also contributing to the development of the HTAoCD was the observation period (used also in Chapter 5). This covered day-to-day operations across multiple contexts including, but not limited to, waste management, timber/heavy haulage, postal, urban delivery, and long-haul night-time activities. Participants were recruited through dealership contacts available to the industry partner in Sweden, and both dealership contacts and direct contact with individual hauliers in Scotland. Managers were contacted via e-mail. In the e-mail of initial contact, a brief overview was provided to describe the research project, the planned use of any data collected, the option to ask questions or raise concerns during the observation period, and an assurance that all data will be anonymised. Managers then discussed this with individual drivers. This allowed participants to be provided information about the intended research, reflect fully on this under no time pressure from the researcher, and agree or disagree to the terms on their own time, before participating. No incentives were offered for participation in the study. Available drivers arranged to meet with either the author or Scania collaborator(s) at a time and location convenient to the participant, providing written consent via e-mail or verbal consent via phone. The observational approach required the researcher being present from start to finish of an entire driving shift. This typically involved an introduction to the driver as they signed in to their shift, riding along with the driver in the cab, taking required breaks at rest stops, observing non-driving activities such as unloading and delivering goods, and (for international multi-shift journeys) sometimes sleeping overnight in company barracks.

On meeting each participant, the researcher again provided a brief overview to describe the research project, the planned use of any data collected, the option to ask questions or raise concerns during the observation period, and an assurance that all data will be anonymised. The researcher's contact details were provided to management and reference to the overall research consortium was made such that participants were enabled to contact the researcher or project supervisors for further information or regarding any concerns. Participants were notified of their right to decline to participate, and notified of their right to withdraw at any time by contacting the researcher. The researcher encouraged each participant to go about their shift as normal. Data was collected during these activities to record the tasks being undertaken, rather than the specific driver's performance. Participant names were not taken down and only experience and gender were taken down in the researcher's notes. This data was collected as unobtrusively as possible, in the form of handwritten notes and sometimes digital photos in the researcher's personal notebook and digital camera. Full ethics approval was received from the Ethics Officer within the School of Management and Languages at Heriot-Watt University prior to beginning this work.

Details of observations and participants are presented in Table 4.1 below. In this case, age was not recorded but can be approximated through driver experience as nearly all drivers had been in the same profession since reaching driving age.

Table 4.1.: Observation period conducted by the author

Country	*Data Collection Period*	*Work Stage*	*Data Collection Type*	*# Drivers per Interview*	*Hours of Data Collection*	*Driving Experience (Yrs)*	*Gender*
Sweden	March 2015	WDA & ConTA	Observation	1	10	25	M
				1	10	5+	F
				1	10	5+	M
				1	10	5+	M
				1	7	35	M
				1	4	*Unknown*	M
				1	7	50+	M
Total				**7**	**58**	**125+**	
Average				**1**	**8**	**18**	**M**

To complete the analysis, the steps summarised by Stanton (2006) were followed:

1. Define the purpose of the analysis.
2. Define the boundaries of the system description.
3. Try to access a variety of sources of information about the system to be analysed.
4. Describe the system goals and sub-goals.
5. Try to keep the number of immediate sub-goals under any super-ordinate goal to a small number (i.e. between 3 and 10).
6. Link goals to sub-goals, and describe the conditions under which sub-goals are triggered (i.e. create plans as control structures).
7. Stop re-describing the sub-goals when you judge the analysis is fit-for-purpose (e.g. the analyst and the subject matter experts understand the sub-goal).
8. Try to verify the analysis with subject matter experts.
9. Be prepared to revise the analysis.

The resulting HTAoCD comprises over 70 pages of cross-referenced tabular analysis and featuring 2386 task steps and 534 plans. A summarised version of the analysis is presented in Table 4.2 below. The full HTAoCD is included in Appendix B.1.

Table 4.2: 2015 Hierarchical Task Analysis of Commercial Driving with Articulated HGV – Summary

TASK: Complete a shift driving a commercial heavy goods vehicle and performing delivery activities

CONTEXT: A standard heavy goods semi-truck-trailer combination vehicle for standard goods delivery*

PERFORMANCE CRITERIA: Configure and drive a standard heavy goods semi-truck-trailer combination vehicle for standard goods delivery in compliance with the EU Commission rules and guidelines (specifically the Worker Time Directive 2003, loading & unloading guidelines, tachograph guidelines, etc.), Department for Transport rules and guidelines, the UK Highway Code, and the Driving Standards Agency with respect to C+E licensing standards

**Specification includes an automatic transmission, dash-mounted manual handbrake, and fuel-injected Euro VI standard engine*

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0. Complete a shift driving a commercial heavy goods vehicle with articulated trailer and performing required delivery activities

Plan 0 – do 1, IF trailer is not connected to tractor unit THEN do 2, IF cargo is not loaded THEN do 3, THEN WHILE 4 do 5 AND 6 AND 7 AND 8, IF break/rest period OR end of shift THEN do 9, IF driving is otherwise required WHILE 5 do 6 AND 7 AND 8 at any stage

---

1. Perform pre-drive tasks

Plan 1 – WHILE 1 AND 2 AND 3, do 4 through 8 in order

1.1. Maintain safety
1.2. Limit engine run time for warm-up as much as possible, ideally according to the owner's manual/no more than 10 seconds
1.3. Avoid revving engine on start-up or during warm-up as much as possible
1.4. Locate and start vehicle
1.5. Check internal cab (vehicle-only) is functional/fit for purpose/compliant w/ regulations in countries of operation
1.6. Check vehicle-related paperwork
1.7. Check external cab (vehicle-only) is functional/fit for purpose/compliant w/ regulations in countries of operation
1.8. Load personal items

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2. Hook up trailer to vehicle cab and perform pre-drive checks

Plan 2 – IF no trailer is coupled to cab WHILE 1 do 2 through 5 in order

2.1. Maintain safety <<GO TO subroutine 1.1. 'Maintain safety' >>
2.2. Hook up vehicle cab to trailer
2.3. Check external truck-trailer configuration is functional/fit for purpose/compliant w/ regulations in countries of operation
2.4. Check internal truck-trailer configuration is functional/fit for purpose/compliant w/ regulations in countries of operation

2.5. Prepare to set off with trailer

3. Perform cargo handling activities

Plan 3 – WHILE 1 AND 2, do 3 AND 4 AND 5 AND 6 AND 7 AND 8 in any order as desired by driver/required by organisation or work conditions

3.1. Maintain safety <<GO TO subroutine 1.1. ‘Maintain safety’ >>
3.2. Perform steps flexibly as required by organisation or work conditions
3.3. Prepare for loading activities
3.4. Load normal goods cargo
3.5. Prepare to drive
3.6. Interact with customer(s)
3.7. Unload cargo scheduled for current destination
3.8. Uncouple trailer from vehicle

4. Perform strategic non-driving work tasks

Plan 4 – do 5, THEN IF fuel is required AND/OR schedule permits AND suitable refuelling station has been reached do 1 WHILE 7, IF route requires non-road transport do 2 WHILE 7, AND/OR IF vehicle configuration breaks down do 3 WHILE 7, AND/OR IF break/rest period is required by law OR desired by driver AND schedule permits do 4 WHILE 7, AND/OR IF driver in non-driving work environment do 6 WHILE 7

4.1. Perform refuelling activities
4.2. Book non-road transport
4.3. Deal with vehicle breakdowns
4.4. Take break/rest periods as required by law
4.5. Ensure driver passes medical requirements to hold and continue driving with a valid license
4.6. Perform surveillance in warehouse/storage/delivery/non-road transport lot/other work environment
4.7. Exhibit appropriate worker attitude/deportment

5. Perform basic vehicle control tasks

Plan 5 – IF pulling away at start of shift/drive WHILE 10, do 1 AND 2 in any order THEN do 3; ELSE WHILE 10 do 4 AND/OR 5 AND/OR 6 AND/OR 7 AND/OR 8 AND/OR 9 as required

5.1. Check that air brake/exhaust brake/engine retarder is engaged, if fitted
5.2. Check that power-assisted dynamic-force steering is functional/operating as normal, if fitted
5.3. Pull away from standstill
5.4. Perform steering manoeuvres
5.5. Control speed
5.6. Undertake directional control
5.7. Negotiate bends

5.8. Negotiate gradient
5.9. Reverse the vehicle
5.10. Avoid unnecessary idling wherever situation allows (e.g. parked/stopped/completing paperwork/e-mailing/phoning)

6. Perform operational driving tasks
Plan 6 – do 1 AND/OR 2 AND/OR 3 AND/OR 4 as required by road and traffic conditions
6.1. Enter traffic from roadside
6.2. Approach junctions (crossings, intersections, etc.)
6.3. Deal with junctions
6.4. Deal with crossings

7. Perform tactical driving tasks
Plan 7 – WHILE 1 do 2 AND/OR 3 AND/OR 4 AND/OR 5 as required by road and traffic conditions
7.1. Anticipate traffic, be alert, and adopt a predictive driving style
7.2. Deal with different road types/classifications
7.3. Deal with roadway-related hazards
7.4. Perform emergency manoeuvres

8. Perform strategic driving tasks
Plan 8 – WHILE 3 AND 6, do 1 AND 2 AND 4 AND 5 AND 7 as required
8.1. Perform surveillance
8.2. Perform navigation
8.3. Comply with rules
8.4. Respond to environmental conditions
8.5. Perform Institute of Advanced Motorists (IAM) system of vehicle control
8.6. Exhibit vehicle/mechanical sympathy
8.7. Exhibit appropriate driver attitude/deportment

9. Perform post-drive tasks
Plan 9 – do 1, IF preparing to leave vehicle out of eyeline OR driver prefers to secure vehicle THEN do 2
9.1. Park the vehicle
9.2. Leave and secure the vehicle

In comparison to the original HTAoD for private vehicles, several areas (operational and tactical driving task sub-goals) remained highly similar. However, the addition of sub-goal 4 (cargo handling tasks) and sub-goal 5 (strategic non-driving tasks) proved especially lengthy and complex compared to the more specific driving-related tasks. Some noticeable additions to the HTAoCD included the use of specific commercial driving systems such as:

- The requirement for breathalyser use to enable vehicle start-up
- Tractor/trailer hook-ups
- Ancillary warehouse equipment (e.g. forklifts) required for loading and unloading heavy cargo
- Hydraulic systems for vehicle lifting and ramp use
- Communications technologies for booking intermodal transport links ahead (e.g. ferry transport)

While operational driving sub-tasks (sub-goal 6) remained of a more or less similar nature and number when compared to the HTAoD completed by Walker et al. (Walker, Stanton & Young, 2001; Walker, et al., 2015) higher-level strategic tasks required much greater specificity in the associated plans. Indeed, the higher the level of decomposition, the more sophisticated plans must become to cope with system-wide complexities. This reflects the complexity of large-scale road freight transport systems.

4.2.3. Materials & procedure – Training Needs Analysis (TNA)

TNA aims to define the required knowledge, skills, and attitudes for a particular role, and the potential means by which they could be acquired. Many different TNA approaches exist. Here the TNA approach used by Stanton et al. (2010, p. 71) was employed. The first step involves using an HTA to inform the task steps which the operator or user must perform, which has been covered above. The second step – organisation analysis – involves using a Work Domain Analysis (WDA; developed separately and described in detail in Chapter 5). The WDA is a hierarchical representation of the functions which take place within the commercial driving 'system', from the most abstract of purposes to the most specific of activities. For the purposes of TNA one particular layer of the hierarchy was used. This layer represented the values & priority measures of the system, or the ways in which success in meeting the system's high level functional purposes could be measured. The full set of values and priority measures comprised: 'ensure provision of goods to customer', 'maximise gentle, forbearing driving style', 'maximise safety', 'minimise financial cost/loss of time', 'maximise user/worker health/comfort', 'maximise vehicle/system reliability', 'maximise efficiency/miles driven loaded', and 'maximise flexibility in routine'. These were used to define the required user attitudes at each task step. Following this the person analysis phase of TNA was undertaken. This involved filling in the knowledge and skills required of the user to complete tasks from the HTAoCD effectively. The final TNA step is to identify appropriate means of assessment. These enable evaluations of whether or not a specific user or operator has attained all Knowledge, Skills, and Attitudes (KSAs) required for their role.

The structure of how these 'task', 'person', and 'organisation' components build up into a complete TNA can be seen in Table 4.3 below. The full TNAoCD comprises over 90 pages of cross-referenced tabular analysis and is included in Appendix D.1.

Table 4.3.: Example extract of Training Needs Analysis of Commercial Driving (2015)

TASK ANALYSIS	**PERSON ANALYSIS**		**ORGANISATION ANALYSIS**	
TASK	KNOWLEDGE	SKILLS	ATTITUDES	ASSESSMENT METHODS
1 Perform pre-drive tasks				
1.1 Maintain safety	▪ Knowledge of system/work environment ▪ Knowledge of tools and equipment		▪ Maximise safety ▪ Minimise financial cost/loss of time ▪ Maximise user/worker health/comfort ▪ Maximise vehicle/system reliability ▪ Maximise flexibility in routine	▪ Talk-throughs ▪ Observation ▪ Verbal knowledge tests by experts ▪ Simulated exercises ▪ Pen and paper tests ▪ Shadowed work
1.1.1 Wear appropriate high-visibility clothing and personal protective clothing as required by law	▪ Knowledge of safety gear	▪ Ability to locate and put on safety gear	▪ Maximise safety ▪ Maximise user/worker health/comfort	
1.1.2 Avoid walking underneath equipment (e.g. trailer)	▪ Knowledge of equipment and trailer dimensions ▪ Knowledge of variations to set-up of equipment	▪ Spatial awareness ▪ Ability to react quickly & smoothly to avoid obstacles	▪ Maximise safety ▪ Maximise user/worker health/comfort	
1.1.3 Observe and assess risk in work environment	▪ Knowledge of system/work environment & likely risk factors to own safety ▪ Knowledge of system/work environment & likely risk factors to others' safety	▪ Ability to observe environment ▪ Ability to note risky factors or situations ▪ Ability to determine situations where risk necessitates proceeding with caution ▪ Ability to determine situations where risk necessitates aborting work	▪ Maximise safety ▪ Minimise financial cost/loss of time ▪ Maximise user/worker health/comfort ▪ Maximise vehicle/system reliability ▪ Maximise flexibility in routine	

4.2.4. Materials & procedure – Forecasting the future task & associated training needs

Once the HTA and TNA phases are complete it is possible to move to the analytical prototyping phase. This involved taking the future logistics technology scenarios from Chapter 2 and using them as inputs to mark changes in the HTA over time. This was done by reviewing the technology trajectory one time step at time (using Figures 2.1, 2.2, and 2.3 as guidance for individual time steps), and reading through the HTA page by page, while considering one future technology at a time in rough order of their likely implementation. For example, to adapt the present-day HTA for the 2020 time step, the first technology considered was ‘aerodynamic fittings’. With ‘aerodynamic fittings’ in mind, the entirety of the present-day HTA was read, and wherever this technology would have an effect on the nature or structure of the task – i.e. where it would change or replace an existing task, or add a new task – this was highlighted in the original document and changed in the next time step. The same procedure was used for adapting TNAs, with regard to the technology’s effect on knowledge, skills, or abilities.

This was undertaken to show the evolution of the driver’s task (via HTAs) and associated training needs (via TNAs) for 2020, 2025, and 2030. Due to the heavily interrelated nature of driving task analyses, any cross-references which were affected by future technology changes were also tracked through a series of tables. In essence this was done to give a broad indication of potential knock-on effects elsewhere in the driving task. Full analyses, with changes highlighted throughout various time steps, are available in Appendices C.1 through D.4.

4.3. Results

4.3.1. Current day: Scenario 2015

The HTA created for the current 2015 scenario is over 70 cross-referenced pages, including a total of 2386 task steps and 534 plans. Tables 4.4 and 4.5 provide a short descriptive summary of the size and structure of the analysis. The full analysis is presented in Appendix B.1. The present-day HTA descended to nine levels of goal decomposition. The fourth level of the hierarchy included the highest number of plans (158) and the fifth level of the hierarchy included the highest number of tasks (695). The seventh level of the hierarchy included the lowest number of plans (2), and the ninth level of the hierarchy included the lowest number of tasks (9).

Table 4.4: Breakdown of HTAoCD tasks by level of hierarchy and sub-goal number

		SUB-GOAL										
		1	2	3	4	5	6	7	8	9	Total N	Total %
LEVEL	1	1	1	1	1	1	1	1	1	1	9	0.4%
	2	8	5	8	7	10	4	5	7	2	56	2.4%
	3	27	14	30	38	40	17	14	28	11	219	9.2%
	4	52	41	105	70	87	66	57	82	30	590	24.7%
	5	65	34	57	22	103	88	201	123	2	695	29.1%
	6	46	39	69	0	57	84	202	74	0	571	23.9%
	7	6	3	13	0	5	15	134	31	0	207	8.7%
	8	0	0	0	0	0	4	29	2	0	35	1.5%
	9	0	0	0	0	0	0	4	0	0	4	0.2%
	Total N	205	137	283	138	303	279	647	348	46	**2386**	
	Total %	8.6%	5.7%	11.9%	5.8%	12.7%	11.7%	27.1%	14.6%	1.9%		

Table 4.5: Breakdown of HTAoCD plans by level of hierarchy and sub-goal number

		SUB-GOAL										
		1	2	3	4	5	6	7	8	9	Total N	Total %
LEVEL	1	1	1	1	1	1	1	1	1	1	9	1.7%
	2	6	4	6	7	9	4	4	7	2	49	9.2%
	3	11	6	19	13	22	16	14	19	9	129	24.2%
	4	11	7	17	5	32	16	39	30	1	158	29.6%
	5	11	6	12	0	16	19	50	19	0	133	24.9%
	6	1	1	5	0	1	4	34	8	0	54	10.1%
	7	0	0	0	0	0	1	0	1	0	2	0.4%
	8	0	0	0	0	0	0	0	0	0	0	
	9	0	0	0	0	0	0	0	0	0	0	
	Total N	41	25	60	26	81	61	142	85	13	**534**	
	Total %	7.7%	4.7%	11.2%	4.9%	15.2%	11.4%	26.6%	15.9%	2.4%		

An excerpt of the TNA addressing driving surveillance tasks is shown in Table 4.6 below as an example (the full TNA is presented in Appendix D.1). In terms of knowledge, the task involved the system having or acquiring 'knowledge of local area', 'knowledge of vehicle configuration dimensions/weight', and 'knowledge of instrument panel display components (and location)'. In terms of skills, the task required the system having the 'ability to detect wind/gusts', 'ability to feel location of pedals', 'ability to gauge whether headway distance is causing glare for lead vehicle'. Knowledge and skills across the full breadth and depth of the HTA were extracted and it was noted how requirements for both varied significantly depending on the task. Interestingly, attitudes varied to a lesser extent due to the fact these were drawn from a smaller set.

Table 4.6: Example extract of Training Needs Analysis (2015), task 8.1.

TASK	KNOWLEDGE	SKILLS	ATTITUDES	ASSESSMENT METHODS
8 Perform strategic driving tasks				
8.1 Perform surveillance	▪ Knowledge of system/work environment ▪ Knowledge of tools and equipment ▪ Knowledge of self (physical/mental limits) ▪ Knowledge of typical driving risks	▪ Ability to observe environment ▪ Ability to note risky factors or situations	▪ Maximise ‘forbearing, gentle driving style’ ▪ Maximise safety ▪ Minimise financial cost/loss of time ▪ Maximise user/worker health/comfort ▪ Maximise vehicle/system reliability ▪ Maximise efficiency/miles driven loaded ▪ Maximise flexibility in routine	▪ Talk-throughs ▪ Observation ▪ Verbal knowledge tests by experts ▪ Simulated exercises ▪ Pen and paper tests ▪ Shadowed work
8.1.1 Perform visual surveillance	▪ Knowledge of typical health and safety hazard warning signs ▪ Knowledge of different traffic features (junctions, etc.) ▪ Knowledge of traffic lane separators ▪ Knowledge of blind spots	▪ Ability to perform visual observation ▪ Ability to note health and safety hazards (e.g. black ice, wires, etc.) ▪ Ability to shift gaze frequently ▪ Ability to adjust focal distance relative to speed ▪ Ability to differentiate traffic lanes ▪ Ability to observe trajectory and behaviour of other work vehicles/workers (e.g. vehicles which frequently change speed, neglect to signal, brake suddenly, have unconfident/unsure/aggressive/inattentive drivers) ▪ Ability to use mirror system to maximum advantage ▪ Ability to glance quickly over shoulder(s) ▪ Ability to open window(s)	▪ Maximise safety ▪ Maximise user/worker health/comfort ▪ Maximise vehicle/system reliability ▪ Maximise flexibility in routine	
8.1.2 Perform auditory surveillance	▪ Knowledge of typical vehicle/work-related sounds	▪ Ability to perform auditory observation ▪ Ability to monitor sounds emitted by own vehicles, work-related events ▪ Ability to monitor sounds emitted by other vehicles, work-related events ▪ Ability to determine location, trajectory, and intensity of detected noise ▪ Ability to open window(s)	▪ Maximise safety ▪ Maximise user/worker health/comfort ▪ Maximise vehicle/system reliability ▪ Maximise flexibility in routine	
8.1.3 Perform olfactory surveillance	▪ Knowledge of typical vehicle/work-related smells	▪ Ability to perform olfactory observation ▪ Ability to determine location and trajectory of detected scent(s)	▪ Maximise safety ▪ Maximise user/worker health/comfort ▪ Maximise vehicle/system reliability ▪ Maximise flexibility in routine	
8.1.4 Perform standard surveillance of own vehicle	▪ Knowledge of instrument panel display components (and location) ▪ Knowledge of breathalyser system ▪ Knowledge of trailer security measures ▪ *Knowledge of blind spots*	▪ Ability to perform visual observation ▪ Ability to perform auditory observation ▪ Ability to see/hear instrument panel information ▪ Ability to detect changes in speed limit ▪ Ability to detect changes in lead vehicle/traffic flow speed ▪ Ability to react to anything in cabin which might adversely affect driving performance ▪ *Ability to observe trajectory and behaviour of other work vehicles/workers* ▪ *Ability to use mirror system to maximum advantage* ▪ *Ability to glance quickly over shoulder(s)* ▪ *Ability to open window(s)*	▪ Maximise ‘forbearing, gentle driving style’ ▪ Maximise safety ▪ Minimise financial cost/loss of time ▪ Maximise user/worker health/comfort ▪ Maximise vehicle/system reliability ▪ Maximise efficiency/miles driven loaded ▪ Maximise flexibility in routine	

4.3.2. Time step 1: Scenario 2020

The baseline HTA for present-day operations was then revised according to the technological changes projected in Chapter 2 to occur by 2020. All 'new' added technologies can be seen in Chapter 2 where they are fully described in terms of their intended functionality. Their collective impact on the driver's task is depicted below in Table 4.7.

In total there were 13 technologies added to the system between 2015 and 2020, of which just six technologies necessitated direct consideration of the driving task. Other 'enabling' technologies such as electrification of hotel loads, or engine heat management, are less intrusive to the nature of the present-day driving task, and arguably present greater change to the vehicle maintenance team. The presence of these six technologies resulted in a total of 35 revisions to task steps within the HTA. Revisions took place at a more detailed level of the hierarchy such that the original 2015 HTA summary presented above in Table 4.1 remained unchanged. While 16 of these revisions took the form of a simple change to an existing HTA component, 19 revisions were in fact additions of entirely new steps that required adjustments to task plans.

All changes and additions to the HTA in 2020 are shown in Table 4.7. This table outlines each new technology; the number of changes it caused to the HTA; whether this was simply a change to an existing step or an addition of a brand new step; and where in the HTA this change occurred. In 2020, the introduction of the advanced driver assistance system (ADAS) required the driver to maintain near constant awareness of the warnings and alerts from the new system. Automated emergency braking replaces the need for the driver to brake in an emergency, and eliminates one element of the driver's task in taking evasive actions. The new collision avoidance warning system compensates or replaces the driver's need to continuously observe for hazardous objects in the environment, including debris, potholes, parked vehicles, pedestrians, cyclists, animals, vehicle doors being opened, vehicle preparing to pull out from the roadside, large vehicles (e.g. buses) preparing to make a stop, and existing accidents or emergencies on the roadway. The fact that the collision avoidance warning system is intended to be additional to drivers' existing surveillance tasks means that individual drivers will adapt to this in different ways. Without additional guidance and training, drivers will rely to different degrees on the CAW system, and their own visual and auditory surveillance. The addition of real-time traffic data capability to existing GPS routing systems will have little direct effect on the driving task, but the accuracy and reliability of the technological advance may create variant adaptations in driver behaviour. In other words, if the routing technology is found to be less accurate or less reliable than driver knowledge in different situations, it may be ignored. New on-board cameras are additional to the existing mirror design to form an improved visual surveillance support system. This adds an extra task for the driver in checking the alignment and angles of the overall system as well as wiping down camera lenses, before setting off so that it is correctly set for mirror-signal-manoeuvre routines while driving. In terms of effects on driving tasks, the on-board camera system adds to rearward-facing visual surveillance. Driving tasks where the on-board camera system will have a specific direct effect include surveillance tasks specifically for entering on-slips, entering main carriageways, turning left or right at crossroads, reacting to being followed, and responding to being passed by other vehicles. Finally, the topographical cruise control system fully controls the speed of the vehicle, negotiating different gradients, in situations where traffic conditions allow and the driver has initiated the system. This means that in calm traffic scenarios, the driver relegates control of the vehicle to the topographical cruise control system and relies on this to react to the vehicle ahead, until a directional or drastic speed change is required which the driver must be vigilant to throughout. Three of these 19 additions related to topographical cruise control and caused important changes in associated task plans. The old way of working (i.e. the existing 2015 steps relevant to HTA sections 5.5., 5.8., and 7.4.1.2.) have in 2020 become back-up functions to be performed manually in cases where the new automation is unsuitable or fails. In short, this technology may appear to fully automate a task but the driver must be monitoring on ‘standby’.

Task steps which were changed or added were also regularly cross-referenced elsewhere in the document due to the interrelated nature of the driving task. These cross-references do not always occur at the same level of decomposition as the original task step, instead appearing at various levels of decomposition throughout. To determine the extent to which a new technology had indirect knock-on effects throughout the analysis, Table 4.7 shows the number of times a new/changed step is cross-referenced elsewhere in the HTA. These counts are collected at the level of the specific task change/addition, and up to 5 levels of decomposition above the change/addition. This shows how and to what extent a change propagates through other, related tasks.

Changes and additions to the TNA in 2020 are shown in Table 4.8. These changes created 19 new points of knowledge and 50 new instances of skills required of the driver, and these are shown in Table 4.9. 2020 was also the only time step in which a new attitude was added: ‘minimise emissions/environmental impact’. Six instances where this attitude was added are shown in Table 4.8; however this attitude was also added on to 127 existing steps in the TNA as an additional consideration. In essence, where previously a task step focused on minimising operator costs, in 2020 ‘minimise emissions’ was also applicable as an organisational goal/required attitude.

One striking result was that the KSAs required for dealing with new technologies – particularly technologies that allocate large task sections to the truck, rather than the driver – were not addressed by the majority of UK commercial driver training schemes. This included, for example, recognising contexts in which topographical adaptive cruise control (TACC) would not be at full functionality (e.g. inconsistent GPS connection, unclear roadside markings) where the driver would have to regain control of the vehicle.

The full revised HTAoCD and TNAoCD for the 2020 scenario can be found in Appendices C.2 and D.2 respectively.

Table 4.7: Changes to HTAoCD, 2015–2020 (shading indicates no change from previous time step)

Technology	Change to HTA	Type of Change (change to existing step OR addition of new step)	HTA Step #		# of Times Cross-Referenced Elsewhere in HTA					
				Specifically Referenced Elsewhere	1 Level Up Referenced Elsewhere	2 Levels Up Referenced Elsewhere	3 Levels Up Referenced Elsewhere	4 Levels Up Referenced Elsewhere	5 Levels Up Referenced Elsewhere	Total # Cross-References
ADAS	1	Addition	8.6.1.							
	SUB-TOTAL									
	AVERAGE CROSS-REFERENCES									
Automated Emergency Braking	1	Addition	7.5.1.1.		7					7
	SUB-TOTAL				*7*					*7*
	AVERAGE CROSS-REFERENCES				*7*					*7*
Collision Avoidance Warnings	1	Addition	7.3.3.1.1.4.							
	2	Addition	7.4.1.1.5.				2			2
	3	Addition	7.4.1.5.5.				2			2
	4	Addition	7.4.1.5.11.4.1.						2	2
	5	Addition	7.4.1.5.11.5.1.						2	2
	6	Addition	7.4.1.6.1.1.1.						2	2
	7	Addition	7.4.2.1.1.1.				1	2		3
	8	Addition	7.4.2.3.1.1.				1	2		3
	9	Addition	7.4.2.4.1.1.				1	2		3
	10	Addition	7.4.3.1.3.				2			2
	11	Addition	8.1.1.1.		1	28				29
	12	Addition	8.1.2.1.			28				28
	SUB-TOTAL				*1*	*56*	*9*	*6*	*6*	*82*
	AVERAGE CROSS-REFERENCES				*0.08*	*4.67*	*0.75*	*0.50*	*0.50*	*6.83*
GPS-Enabled Real-Time Traffic Data	1	Revision	8.2.1.5.			5				5
	2	Addition	8.2.2.1.		1	5				6
	SUB-TOTAL				*1*	*10*				*11*
	AVERAGE CROSS-REFERENCES				*0.5*	*5*				*5.5*
On-board Camera System	1	Revision	1.4.7.3.	1						1
	2	Revision	1.4.7.3.1.		1					1
	3	Addition	1.4.7.3.5.		1					1
	4	Revision	2.4.3.							
	5	Revision	5.9.1.5.2.							
	6	Revision	6.2.2.1.							

	7	Revision	6.3.1.1.1.5.2.							
	8	Revision	6.3.1.1.1.5.3.							
	9	Revision	6.3.1.1.3.4.							
	10	Revision	6.3.2.2.2.							
	11	Revision	6.3.2.3.2.							
	12	Revision	7.4.1.3.3.				2			2
	13	Revision	7.4.1.5.1.				2			2
	14	Revision	8.1.1.3.3.		21	1	28			50
	15	Revision	8.1.1.3.4.		21	1	28			50
	16	Revision	8.4.1.1.3.2.							
			SUB-TOTAL	*1*	*44*	*2*	*60*			*107*
			AVERAGE CROSS-REFERENCES	*0.06*	*2.75*	*0.13*	*3.75*			*6.69*
Topographical Cruise Control	1	Addition*	5.5.1.		4					4
	2	Addition*	5.8.1.							
	3	Addition*	7.4.1.2.1.		1		2			3
			SUB-TOTAL		*5*		*2*			*7*
			AVERAGE CROSS-REFERENCES		*1.67*		*0.67*			*2.33*
			TOTAL	*1*	*58*	*68*	*71*	*6*	*6*	*203*
			AVERAGE (out of 35 total changes)	*0.03*	*1.66*	*1.94*	*2.03*	*0.17*	*0.17*	*5.80*

*becomes default

**potentially competes with other steps

Table 4.8: Number of new points of knowledge, skills, and attitudes required by changes to the driving task in 2020

TASK #	TASK DESCRIPTION	# NEW KNOWLEDGE	# NEW SKILLS	# NEW ATTITUDES	TOTAL ADDITIONS
1.4.7.3.	Check and adjust mirrors and camera system		1		1
1.4.7.3.1.	Check visual field is adequate with current mirror and camera system positioning		1		1
1.4.7.3.5.	Adjust camera angles		1		1
2.4.3.	Check and adjust mirrors and camera system to ensure adequate visual field for truck-trailer configuration		2		2
5.5.1.	Use topographical adaptive cruise control (TACC) wherever possible	1	1	1	3
5.5.8.	Use topographical adaptive cruise control (TACC) wherever possible	1	1	1	3
5.9.1.5.2.	Turn head and check mirrors and/or camera system		1		1
6.2.2.1.	Assess rearward traffic speed and conditions using side mirrors and/or camera system		1		1
6.3.1.1.1.5.2.	Glance/look in offside mirrors/camera angle		1		1
6.3.1.1.1.5.3.	Glance/look in nearside mirrors/camera angle		1		1
6.3.1.1.3.4.	Recheck following vehicle in gap using mirrors and/or camera system		1		1
6.3.2.2.2.	Check all mirrors and camera angles before moving away		1		1
6.3.2.3.2.	Check all mirrors and camera angles before moving away		1		1
7.3.3.1.1.4.	Stay aware of and heed collision avoidance warnings (CAW)	1	2		3
7.4.1.1.5.	Stay aware of and heed collision avoidance warnings (CAW)	1	2		3
7.4.1.2.1.	Use topographical cruise control (TACC) wherever possible	1	1	1	3
7.4.1.3.3.	Check mirrors and camera system frequently		1		1
7.4.1.5.1.	Check mirrors and camera system frequently		1		1
7.4.1.5.5.	Stay aware of and heed collision avoidance warnings (CAW)	1	2		3
7.4.1.5.11.4.1.	Stay aware of and heed collision avoidance warnings (CAW)	1	2		3
7.4.1.5.11.5.1.	Stay aware of and heed collision avoidance warnings (CAW)	1	2		3
7.4.1.6.1.1.1.	Stay aware of and heed collision avoidance warnings (CAW)	1	2		3
7.4.2.1.1.	Stay aware of and heed collision avoidance warnings (CAW)	1	2		3
7.4.2.3.1.1.	Stay aware of and heed collision avoidance warnings (CAW)	1	2		3
7.4.2.4.1.1.	Stay aware of and heed collision avoidance warnings (CAW)	1	2		3
7.4.3.1.3.	Stay aware of and heed collision avoidance warnings (CAW)	1	2		3
7.5.1.1.	Allow automated emergency braking to stop vehicle	1	2		3
8.1.1.1.	Stay aware of and heed collision avoidance warnings (CAW) and other visual alerts from ADAS	1	2		3
8.1.1.3.3.	Glance/look in offside mirrors/camera angles		1		1
8.1.1.3.4.	Glance/look in nearside mirrors/camera angles		1		1
8.1.2.1.	Stay aware of and heed collision avoidance warnings (CAW) and other visual alerts from ADAS	1	2		3
8.2.1.5.	Use global positioning system (GPS) with real-time traffic data	1	1	1	3
8.2.2.1.	Take into account updates from GPS applications fed by real-time traffic data	1	1	1	3
8.4.1.1.3.2.	Use cloth to clean/wipe down mirrors and camera lenses as required		1		1
8.6.1.	Stay aware of and heed warnings and alerts from advanced driver assistance system (ADAS)	1	2	1	4
TOTAL		**19**	**50**	**6**	**75**

Table 4.9: Example extract of Training Needs Analysis (2020), task 8.1., with changes highlighted in green

TASK	KNOWLEDGE	SKILLS	ATTITUDES	ASSESSMENT METHODS
8 Perform strategic driving tasks				
8.1 Undertake directional control	▪ Knowledge of system/work environment ▪ Knowledge of tools and equipment ▪ Knowledge of self (physical/mental limits) ▪ Knowledge of typical driving risks	▪ Ability to observe environment ▪ Ability to note risky factors or situations	▪ Maximise 'forbearing, gentle driving style' ▪ Maximise safety ▪ Minimise financial cost/loss of time ▪ Maximise user/worker health/comfort ▪ Maximise vehicle/system reliability ▪ Maximise efficiency/miles driven loaded ▪ Maximise flexibility in routine ▪ Minimise emissions/environmental impact	• Talk-throughs • Observation • Verbal knowledge tests by experts • Simulated exercises • Pen and paper tests • Shadowed work
8.1.1 Perform visual surveillance	▪ Knowledge of typical health and safety hazard warning signs ▪ Knowledge of different traffic features (junctions, etc.) ▪ Knowledge of traffic lane separators ▪ Knowledge of blind spots ▪ Knowledge of collision avoidance warning (CAW) system	▪ Ability to perform visual observation ▪ Ability to note health and safety hazards (e.g. black ice, wires, etc.) ▪ Ability to shift gaze frequently ▪ Ability to adjust focal distance relative to speed ▪ Ability to differentiate traffic lanes ▪ Ability to observe trajectory and behaviour of other work vehicles/workers (e.g. vehicles which frequently change speed, neglect to signal, brake suddenly, have unconfident/unsure/aggressive/inattentive drivers) ▪ Ability to use mirror/camera system to maximum advantage ▪ Ability to glance quickly over shoulder(s) ▪ Ability to open window(s) ▪ Ability to recognise and heed collision avoidance warnings (CAWs) ▪ Ability to maintain adequate attention during driving tasks	▪ Maximise safety ▪ Maximise user/worker health/comfort ▪ Maximise vehicle/system reliability ▪ Maximise flexibility in routine ▪ Minimise emissions/environmental impact	
8.1.2 Perform auditory surveillance	▪ Knowledge of typical vehicle/work-related sounds ▪ Knowledge of collision avoidance warning (CAW) system	▪ Ability to perform auditory observation ▪ Ability to monitor sounds emitted by own vehicles, work-related events ▪ Ability to monitor sounds emitted by other vehicles, work-related events ▪ Ability to determine location, trajectory, and intensity of detected noise ▪ Ability to open window(s) ▪ Ability to recognise and heed collision avoidance warnings (CAWs) ▪ Ability to maintain adequate attention during driving tasks	▪ Maximise safety ▪ Maximise user/worker health/comfort ▪ Maximise vehicle/system reliability ▪ Maximise flexibility in routine ▪ Minimise emissions/environmental impact	
8.1.3 Perform olfactory surveillance	▪ Knowledge of typical vehicle/work-related smells	▪ Ability to perform olfactory observation ▪ Ability to determine location and trajectory of detected scent(s)	▪ Maximise safety ▪ Maximise user/worker health/comfort ▪ Maximise vehicle/system reliability ▪ Maximise flexibility in routine ▪ Minimise emissions/environmental impact	

8.1.4 Perform standard surveillance of own vehicle	▪ Knowledge of instrument panel display components (and location) ▪ Knowledge of breathalyser system ▪ Knowledge of trailer security measures ▪ *Knowledge of blind spots*	▪ Ability to perform visual observation ▪ Ability to perform auditory observation ▪ Ability to see/hear instrument panel information ▪ Ability to detect changes in speed limit ▪ Ability to detect changes in lead vehicle/traffic flow speed ▪ Ability to react to anything in cabin which might adversely affect driving performance ▪ *Ability to observe trajectory and behaviour of other work vehicles/workers (e.g. vehicles which frequently change speed, neglect to signal, brake suddenly, have unconfident/unsure/aggressive/inattentive drivers)* ▪ *Ability to use mirror/camera system to maximum advantage* ▪ *Ability to glance quickly over shoulder(s)* ▪ *Ability to open window(s)*	▪ Maximise ‘forbearing, gentle driving style’ ▪ Maximise safety ▪ Minimise financial cost/loss of time ▪ Maximise user/worker health/comfort ▪ Maximise vehicle/system reliability ▪ Maximise efficiency/miles driven loaded ▪ Maximise flexibility in routine ▪ Minimise emissions/environmental impact	

4.3.3. Time step 2: Scenario 2025

In the 2025 scenario eight direct revisions were made to the HTAoCD, falling across Task 2 ‘hook up trailer to vehicle cab and perform pre-drive checks’, Task 5 ‘perform basic vehicle control tasks’, Task 7 ‘perform tactical driving tasks’, and Task 8 ‘perform strategic driving tasks’.

All changes to the HTA are displayed below in Table 4.10. The highest-level revisions referred to active steering dolly systems. These were the only additions in any future scenario which resulted in changes to the original HTA summary presented in Table 4.1. This resulted in nine new points of knowledge and 13 new skills required of the driver, as shown in Table 4.11. Table 4.12 shows the added Task 2.6 ‘hook up active steering dolly’.

In 2025, the introduction of an active dolly adds pre-driving tasks to locate and hook up the dolly to the rest of the vehicle configuration. Throughout driving tasks, this technology requires the driver to bear in mind that the active dolly enables a tighter trajectory of motion that avoids the trailer running to the inside or outside when driving in a 360* circle (such as through a roundabout). The incorporation of vehicle-specific data (i.e. vehicle dimensions and current weight) into GPS routing systems simply updated an existing technology rather than causing any task additions. A more sophisticated advanced driver assistance system with head-up display creates new visual alerts to guarantee the driver’s attention without diverting the driver’s glance away from the road environment, but the individual designs of head-up displays may be highly variable and contribute to different levels of distraction for different drivers. The introduction of an active collision avoidance system enables not only emergency braking but also trajectory control in the event of any emergency requiring an evasive manoeuvre. Notably this integrates collision avoidance warnings with the triggering of automated vehicle control. When considered together, this may over time cause the driver to neglect warnings not only regarding collision avoidance but potentially other issues. Overall the changes predicted for 2025 highlight the importance of re-evaluating the truck design as an integrated system, versus approving a collection of individual components – as well as the need for rigorous testing amongst a diverse set of drivers in a diverse set of trucking scenarios.

The 2025 scenario also underscores the interconnected nature of the driving task. While active steering dolly systems could appear at first glance to mark a significant change in commercial driving operations in the future, the changes caused by this technology were not actually heavily interlinked to other tasks within the HTA and TNA documents. Active Collision Avoidance Systems, on the other hand, had much more profound effect. This systems had the highest number of cross-references (7), despite causing just one direct change to a task step. Additionally, the one task addition caused by the presence of Collision Avoidance Systems became the default option, replacing similar manual tasks in most conditions. As in the 2020 scenario, this highlights the increasingly automated nature of future driving systems, and exactly how drivers will be required to adapt around them.

As a result of this structured method of analysis, the importance of associated KSAs – such as 'ability to maintain attention' and 'ability to determine if visibility allows for use of automated technology', etc. – come forward as priorities for the design of future training schemes.

The full revised HTAoCD and TNAoCD for the 2025 scenario can be found in Appendices C.3 and D.3 respectively.

Table 4.10: Changes to HTAoCD, 2020–2025 (shading indicates no change from previous time step)

Technology	Change to HTA	Type of Change (change to existing step OR addition of new step)	HTA Step #		# of Times Cross-Referenced Elsewhere in HTA					
				Specifically Referenced Elsewhere	1 Level Up Referenced Elsewhere	2 Levels Up Referenced Elsewhere	3 Levels Up Referenced Elsewhere	4 Levels Up Referenced Elsewhere	5 Levels Up Referenced Elsewhere	Total # Cross-References
Active Dolly System	1	Addition	2.5.							
	2	Addition	2.6.							
	3	Addition	5.7.4.6.5.							
	SUB-TOTAL									
	AVERAGE CROSS-REFERENCES									
ADAS	1	Revision	8.1.1.1.	3	1					4
	2	Revision	8.1.2.1.							
	SUB-TOTAL			*3*	*1*					*4*
	AVERAGE CROSS-REFERENCES			*1.5*	*0.5*					*2*
Collision Avoidance System	1	Addition*	7.5.1.		7					7
	SUB-TOTAL				*7*					*7*
	AVERAGE CROSS-REFERENCES				*7*					*7*
GPS-Enabled Real-Time Vehicle-Specific Routing	1	Revision	8.2.1.5.			5				5
	2	Revision	8.2.2.1.		1	5				6
	SUB-TOTAL				*1*	*10*				*11*
	AVERAGE CROSS-REFERENCES				*0.5*	*5*				*5.5*
TOTAL CROSS-REFERENCES				*3*	*9*	*10*				*22*
AVERAGE CROSS-REFERENCES (out of 8 total changes)				*0.38*	*1.13*	*1.25*				*2.75*

*becomes default

**potentially competes with other steps

Table 4.11: Number of new points of knowledge, skills, and attitudes required by changes to the driving task in 2025

TASK #	TASK DESCRIPTION	# NEW KNOWLEDGE	# NEW SKILLS	# NEW ATTITUDES	TOTAL ADDITIONS
2.5.	Locate dolly				
2.6.	Hook up active steering dolly	1	1		2
5.7.4.6.5.	Bear in mind any active dolly used enabled 2nd trailer wheels to follow trajectory lines of 1st trailer wheels, i.e active steering makes sure that the train runs on an inner radius of 7.2 m without the semi-trailer running to the inside or outside when driving a 360-degree circle	1	3		4
7.5.1.	Allow active collision avoidance system (ACAS) to perform evasive manoeuvre	1	1		2
8.1.1.1.	Stay aware of and heed collision avoidance warnings (CAW) and other visual alerts from the ADAS	2	3		5
8.1.2.1.	Stay aware of and heed collision avoidance warnings (CAW) and other visual alerts from the ADAS	2	3		5
8.2.1.5.	Use vehicle-specific global positioning system (GPS) with real-time traffic data	1	1		2
8.2.2.1.	Take into account updates from vehicle-specific GPS applications fed by real-time traffic data	1	1		2
TOTAL		**9**	**13**		**22**

Table 4.12: Example extract of Training Needs Analysis (2025), task 2.6., with changes highlighted in green

TASK	KNOWLEDGE	SKILLS	ATTITUDES	ASSESSMENT METHODS
2 Hook up trailer to vehicle cab and perform pre-drive checks				
2.6 Hook up active steering dolly			▪ Ensure provision of goods to customer ▪ Maximise safety ▪ Minimise financial cost/loss of time ▪ Maximise user/worker health/comfort ▪ Maximise vehicle/system reliability ▪ Maximise efficiency/miles driven loaded ▪ Maximise flexibility in routine	• Talk-throughs • Observation • Verbal knowledge tests by experts • Simulated exercises • Pen and paper tests • Shadowed work
2.6.1 Maintain safety	▪ Knowledge of system/work environment ▪ Knowledge of tools and equipment ▪ Knowledge of self (physical/mental limits) ▪ Knowledge of safety gear ▪ Knowledge of equipment and trailer dimensions ▪ Knowledge of variations to set-up of equipment ▪ Knowledge of system/work environment & likely risk factors to own safety ▪ Knowledge of system/work environment & likely risk factors to others' safety ▪ *Knowledge of typical health and safety hazard warning signs* ▪ *Knowledge of traffic lane separators* ▪ *Knowledge of typical driving risks*	▪ Ability to locate and put on safety gear ▪ Spatial awareness ▪ Ability to react quickly & smoothly to avoid obstacles ▪ Ability to observe environment ▪ Ability to note risky factors or situations ▪ Ability to determine situations where risk necessitates proceeding with caution ▪ Ability to determine situations where risk necessitates aborting work ▪ *Ability to perform visual observation* ▪ *Ability to perform auditory observation* ▪ *Ability to perform olfactory observation* ▪ *Ability to note health and safety hazards (e.g. black ice, wires, etc.)* ▪ *Ability to shift gaze frequently* ▪ *Ability to adjust focal distance relative to speed* ▪ *Ability to differentiate traffic lanes* ▪ *Ability to observe trajectory and behaviour of other work vehicles/workers (e.g. vehicles which frequently change speed, neglect to signal, brake suddenly, have unconfident/unsure/aggressive/inattentive drivers)* ▪ *Ability to monitor sounds emitted by other vehicles, work-related events* ▪ *Ability to determine location, trajectory, and intensity of detected noise* ▪ *Ability to open window(s)* ▪ *Ability to detect smoke/steam from surrounding area*	▪ Maximise safety ▪ Minimise financial cost/loss of time ▪ Maximise user/worker health/comfort ▪ Maximise vehicle/system reliability ▪ Maximise flexibility in routine	

		▪ *Ability to determine location and trajectory of detected scent*		
2.6.2 Ensure work gloves are on	▪ Knowledge of tools and equipment	▪ Ability to find work gloves	▪ Maximise safety ▪ Maximise user/worker health/comfort	
2.6.3 Get out of cab	▪ Knowledge of self (limits to own abilities) ▪ Knowledge of tools & equipment (e.g. door weight) ▪ Knowledge of system/work environment ▪ Knowledge of typical health and safety hazard warning signs ▪ Knowledge of different road features (junctions, etc.) ▪ Knowledge of traffic lane separators ▪ Knowledge of blind spots	▪ Ability to perform visual observation ▪ Ability to perform auditory observation ▪ Ability to perform olfactory observation ▪ Flexibility/ability to reach/untie/tie shoes and store/retrieve quickly ▪ Spatial awareness ▪ Ability to react quickly & smoothly to avoid meeting or creating obstacles ▪ Ability to support self physically into truck cab ▪ Ability to reach truck cab supports ▪ Ability to reach light settings and adjust lights as required ▪ Ability to note health and safety hazards (e.g. black ice, wires, etc.) ▪ Ability to shift gaze frequently ▪ Ability to adjust focal distance relative to speed ▪ Ability to differentiate traffic lanes ▪ Ability to observe trajectory and behaviour of other work vehicles/workers (e.g. vehicles which frequently change speed, neglect to signal, brake suddenly, have unconfident/unsure/aggressive/inattentive drivers) ▪ Ability to use mirror/camera system to maximum advantage ▪ Ability to glance quickly over shoulder(s) ▪ Ability to open window(s)	▪ Maximise safety ▪ Minimise financial cost/loss of time ▪ Maximise user/worker health/comfort ▪ Maximise vehicle/system reliability ▪ Maximise flexibility in routine	
2.6.4 Pick up front end and manually move dolly toward end (5” wheel) of 1” of trailer	▪ Knowledge of safe manual handling procedures	▪ Ability to lift reasonable weight ▪ Ability to pull dolly behind, into position	▪ Maximise safety ▪ Minimise financial cost/loss of time ▪ Maximise user/worker health/comfort ▪ Maximise vehicle/system reliability ▪ Maximise efficiency/miles driven loaded ▪ Maximise flexibility in routine	
2.6.5 Attach dolly to 5th wheel of 1st trailer	▪ Knowledge of safe manual handling procedures ▪ Knowledge of tools and equipment ▪ Knowledge of system/work environment	▪ Ability to reach and control interfaces (e.g. dolly connection)	▪ Maximise safety ▪ Minimise financial cost/loss of time ▪ Maximise user/worker health/comfort ▪ Maximise vehicle/system reliability ▪ Maximise efficiency/miles driven loaded ▪ Maximise flexibility in routine	

4.3.4. Time step 3: Scenario 2030

In the 2030 scenario two major revisions were made, both within Task 5 ‘perform basic vehicle control tasks’. The highest-level revision can be seen in Table 4.13 below which displays Task 5.9 ‘reverse vehicle’. The only technology to have direct impact on the HTAoCD and TNAoCD was an automated low-speed manoeuvring system. The addition of this new technology had the greatest direct change on driving at extremely low speeds, bringing the vehicle to a halt, and reversing the vehicle. In all scenarios where these tasks are required, the technology completely replaces the manual procedure. This single technology also proved to have the greatest knock-on effect throughout the driving task and associated KSAs, as it was associated with an average of 11.5 task cross-references per change. This signals that although a completely autonomous road transport system will not be in place until 2050 or later, by 2030 we can expect the nature of commercial driving to become increasingly automated compared to today’s operations. At this point in time, the tasks related to monitoring the surrounding environment, gradient negotiation, speed control, braking, evasive manoeuvres, low-speed manoeuvring and parking will all be the primary responsibility of the commercial vehicle first, with the driver in a supervisory monitoring role.

At this time step just four new KSAs were added to the TNA. As outlined in Table 4.14, these were two new points of knowledge and two new skills. All new KSAs related to new automated low-speed manoeuvring technology. It is worth noting that although new KSAs were limited at this stage, suggesting that future changes will slow after 2025, these were based on new technologies alone. Potential changes to legally-required organisational practices could have a much more widespread effect. Forecasting this aspect at a 15-year timescale proves challenging for SMEs and thus cannot be included at present.

Consequent revisions to the TNA are demonstrated in an excerpt of Task 5.9 related to reversing the vehicle. This excerpt is displayed below in Table 4.15 with the year 2030 changes highlighted in green.

The full revised HTAoCD and TNAoCD for the 2030 scenario can be found in Appendices C.4 and D.4 respectively.

Table 4.13: Changes to HTAoCD, 2025–2030 (shading indicates no change from previous time step)

Technology	Change to HTA	Type of Change (change to existing step OR addition of new step)	HTA Step #		# of Times Cross-Referenced Elsewhere in HTA					
				Specifically Referenced Elsewhere	1 Level Up Referenced Elsewhere	2 Levels Up Referenced Elsewhere	3 Levels Up Referenced Elsewhere	4 Levels Up Referenced Elsewhere	5 Levels Up Referenced Elsewhere	Total # Cross-References
Automated Low-Speed Manoeuvring	1	Addition	5.5.5.1.		23					23
	2	Addition	5.9.2.							
	SUB-TOTAL				*23*					
	AVERAGE CROSS-REFERENCES				*11.5*					
TOTAL CROSS-REFERENCES					*23*					*23*
AVERAGE CROSS-REFERENCES (out of 2 total changes)					*11.5*					*11.5*

*becomes default

**potentially competes with other steps

Table 4.14: Number of new points of knowledge, skills, and attitudes required by changes to the driving task in 2030

TASK #	TASK DESCRIPTION	# NEW KNOWLEDGE	# NEW SKILLS	# NEW ATTITUDES	TOTAL ADDITIONS
5.5.5.1.	Engage automated low-speed manoeuvring	1	1		2
5.9.2.	Engage automated low-speed manoeuvring	1	1		2
TOTAL		**2**	**2**		**4**

Table 4.15: Example extract of Training Needs Analysis (2030), with changes highlighted in green

TASK	KNOWLEDGE	SKILLS	ATTITUDES	ASSESSMENT METHODS
5 Perform basic vehicle control tasks				
5.9 Reverse the vehicle			▪ Ensure provision of goods to customer ▪ Maximise 'forbearing, gentle driving style' ▪ Maximise safety ▪ Minimise financial cost/loss of time ▪ Maximise user/worker health/comfort ▪ Maximise vehicle/system reliability ▪ Maximise efficiency/miles driven loaded ▪ Minimise emissions/environmental impact	• Talk-throughs • Observation • Verbal knowledge tests by experts • Simulated exercises • Pen and paper tests • Shadowed work
5.9.1 Prepare to back up	▪ Knowledge of truck cab layout ▪ Knowledge of vehicle/system ▪ *Knowledge of typical health and safety hazard warning signs* ▪ *Knowledge of different road features (junctions, etc.)* ▪ *Knowledge of traffic lane separators* ▪ *Knowledge of blind spots* ▪ *Knowledge of organisation rules and procedures for dealing with broken or malfunctioning equipment* ▪ *Knowledge of self (limits to own abilities)*	▪ Ability to reach/feel brake pedal ▪ Ability to reach interfaces (e.g. horn) ▪ Ability to detect potential obstructions ▪ Ability to perform auditory observation (e.g. horn sound) ▪ Ability to glance quickly over shoulder(s) ▪ *Ability to perform visual observation* ▪ *Ability to note health and safety hazards (e.g. black ice, wires, etc.)* ▪ *Ability to shift gaze frequently* ▪ *Ability to adjust focal distance relative to speed* ▪ *Ability to differentiate traffic lanes* ▪ *Ability to observe trajectory and behaviour of other work vehicles/workers (e.g. vehicles which frequently change speed, neglect to signal, brake suddenly, have unconfident/unsure/aggressive/inattentive drivers)* ▪ *Ability to use mirror/camera system to maximum advantage* ▪ *Ability to open window(s)* ▪ *Ability to determine when breakdown or malfunction requires expert attention* ▪ *Ability to contact expert assistance*	▪ Maximise 'forbearing, gentle driving style' ▪ Maximise safety ▪ Minimise financial cost/loss of time ▪ Maximise user/worker health/comfort ▪ Maximise vehicle/system reliability ▪ Maximise efficiency/miles driven loaded ▪ Maximise flexibility in routine	
5.9.2 Engage automated low-speed manoeuvring	▪ Knowledge of automated low-speed manoeuvring system ▪ Knowledge of tools and equipment	▪ Ability to reach and control interfaces (e.g. automated low-speed manoeuvring controls)	▪ Maximise 'forbearing, gentle driving style' ▪ Maximise safety ▪ Minimise financial cost/loss of time ▪ Maximise user/worker health/comfort ▪ Maximise vehicle/system reliability	

5.9.3 Begin reverse manoeuvre	▪ Knowledge of truck cab layout ▪ Knowledge of truck cab dial, lever, and other control mechanisms ▪ Knowledge of own physical dimensions ▪ *Knowledge of specific truck cab pedal mechanisms* ▪ *Knowledge of vehicle configuration weight* ▪ *Knowledge of roadway gradient and conditions* ▪ *Knowledge of truck cab dial, lever, and other control mechanisms* ▪ *Knowledge of analogue clock hand positioning system* ▪ *Knowledge of system/work environment* ▪ *Knowledge of tools and equipment* ▪ *Knowledge of self (physical/mental limits)* ▪ *Knowledge of typical driving risks* ▪ *Knowledge of typical health and safety hazard warning signs* ▪ *Knowledge of different traffic features (junctions, etc.)* ▪ *Knowledge of traffic lane separators* ▪ *Knowledge of blind spots* ▪ *Knowledge of typical vehicle/work-related sounds* ▪ *Knowledge of typical vehicle/work-related smells* ▪ *Knowledge of instrument panel display components (and location)* ▪ *Knowledge of breathalyser system* ▪ *Knowledge of trailer security measures*	▪Ability to reach interfaces (e.g. steering wheel) ▪Ability to sense grip pressure ▪Ability to operate vehicle smoothly ▪Spatial awareness ▪Ability to sense grip pressure ▪Ability ▪*Ability to 'feel' location of pedals* ▪*Ability to operate pedals based on 'feel' of resistance* ▪*Ability to assess required vehicle dynamics for desired movement and trajectory* ▪*Ability to observe environment* ▪*Ability to note risky factors or situations* ▪*Ability to note health and safety hazards (e.g. black ice, wires, etc.)* ▪*Ability to shift gaze frequently* ▪*Ability to adjust focal distance relative to speed* ▪*Ability to differentiate traffic lanes* ▪*Ability to observe trajectory and behaviour of other work vehicles/workers (e.g. vehicles which frequently change speed, neglect to signal, brake suddenly, have unconfident/unsure/aggressive/inattentive drivers)* ▪*Ability to use mirror/camera system to maximum advantage* ▪*Ability to glance quickly over shoulder(s)* ▪*Ability to open window(s)* ▪*Ability to perform auditory observation* ▪*Ability to monitor sounds emitted by own vehicles, work-related events* ▪*Ability to monitor sounds emitted by other vehicles, work-related events* ▪*Ability to determine location, trajectory, and intensity of detected noise* ▪*Ability to open window(s)* ▪*Ability to perform olfactory observation* ▪*Ability to determine location and trajectory of detected scent(s)* ▪*Ability to see/hear instrument panel information* ▪*Ability to detect changes in speed limit* ▪*Ability to detect changes in lead vehicle/traffic flow speed* ▪*Ability to react to anything in cabin which might adversely affect driving performance*	▪ Maximise 'forbearing, gentle driving style' ▪ Maximise safety ▪ Minimise financial cost/loss of time ▪ Maximise user/worker health/comfort ▪ Maximise vehicle/system reliability ▪ Maximise efficiency/miles driven loaded ▪ Maximise flexibility in routine ▪ Minimise emissions/environmental impact	
5.9.4 Complete	▪ Knowledge of specific truck cab pedal mechanisms ▪ Knowledge of truck cab layout	▪Spatial awareness ▪Ability to 'feel' location of pedals ▪Ability to operate pedals based on 'feel' of resistance	▪ Maximise 'forbearing, gentle driving style' ▪ Maximise safety ▪ Minimise financial cost/loss of time ▪ Maximise user/worker health/comfort	

reversing manoeuvre	▪ Knowledge of truck cab dial, lever, and other control mechanisms ▪ *Knowledge of vehicle configuration weight* ▪ *Knowledge of roadway gradient and conditions* ▪ *Knowledge of analogue clock hand positioning system* ▪ *Knowledge of system/work environment* ▪ *Knowledge of tools and equipment* ▪ *Knowledge of self (physical/mental limits)* ▪ *Knowledge of typical driving risks* ▪ *Knowledge of typical health and safety hazard warning signs* ▪ *Knowledge of different traffic features (junctions, etc.)* ▪ *Knowledge of traffic lane separators* ▪ *Knowledge of blind spots* ▪ *Knowledge of typical vehicle/work-related sounds* ▪ *Knowledge of typical vehicle/work-related smells* ▪ *Knowledge of instrument panel display components (and location)* ▪ *Knowledge of breathalyser system* ▪ *Knowledge of trailer security measures*	▪ Ability to reach and operate interfaces (e.g. steering wheel, handbrake) ▪ *Ability to assess required vehicle dynamics for desired movement and trajectory* ▪ *Ability to reach and control interface settings (e.g. handbrake)* ▪ *Ability to operate vehicle smoothly/avoid abrupt changes in pressure applied to pedals* ▪ *Ability to observe environment* ▪ *Ability to note risky factors or situations* ▪ *Ability to perform visual observation* ▪ *Ability to note health and safety hazards (e.g. black ice, wires, etc.)* ▪ *Ability to shift gaze frequently* ▪ *Ability to adjust focal distance relative to speed* ▪ *Ability to differentiate traffic lanes* ▪ *Ability to observe trajectory and behaviour of other work vehicles/workers (e.g. vehicles which frequently change speed, neglect to signal, brake suddenly, have unconfident/unsure/aggressive/inattentive drivers)* ▪ *Ability to use mirror/camera system to maximum advantage* ▪ *Ability to glance quickly over shoulder(s)* ▪ *Ability to open window(s)* ▪ *Ability to perform auditory observation* ▪ *Ability to monitor sounds emitted by own vehicles, work-related events* ▪ *Ability to monitor sounds emitted by other vehicles, work-related events* ▪ *Ability to determine location, trajectory, and intensity of detected noise* ▪ *Ability to open window(s)* ▪ *Ability to perform olfactory observation* ▪ *Ability to determine location and trajectory of detected scent(s)* ▪ *Ability to see/hear instrument panel information* ▪ *Ability to detect changes in speed limit* ▪ *Ability to detect changes in lead vehicle/traffic flow speed* ▪ *Ability to react to anything in cabin which might adversely affect driving performance*	▪ Maximise vehicle/system reliability ▪ Maximise efficiency/miles driven loaded ▪ Maximise flexibility in routine ▪ Minimise emissions/environmental impact	

4.4. Conclusions

Current and future driving tasks, and associated training needs, were examined through the following research sub-questions:

- *How can the truck-driver system be represented in a functional, technologically agnostic way? (SRQ5)*
- *How can we estimate future system conditions, and test future system functionality before implementation? (SRQ6)*

In doing so a substantial empirical contribution to the intersection of logistics and HF/E is made. The work presented in this Chapter advances our understanding of truck-driver systems with 680 pages of detailed, exhaustive, systematic and cross-referenced documentation. This includes the most comprehensive and current HTAoCD currently in existence within the publically available literature; the first and most comprehensive TNAoCD; and the first analytical prototype of future truck driving operations including the training needs required for 2020, 2025, and 2030. The full background analysis appears in Appendices C and D but a quantitative summary of changes highlighted by the analytical prototyping can be seen in Table 4.16 below.

Table 4.16: Number of projected changes to the truck driving task & training needs, 2015 – 2030

TIME STEP	HTA CHANGES		TNA CHANGES			**TOTAL CHANGES**
	# NEW TASKS	# CHANGES TO EXISTING TASKS	# NEW KNOWLEDGE	# NEW SKILLS	# NEW ATTITUDES	
2020	19	16	19	50	6	110
2025	4	4	9	13		30
2030	2		2	2		6
TOTAL	25	20	30	65	6	**146**

In 2020, an overwhelming number of changes for trucking are forecasted to occur, with some more in tension than others. The HTA had the greatest number of additions overall, but these were generally at low levels of task decomposition. Five of the 13 new technologies were enabling i.e. supporting electrical or mechanical processes in the ‘background’ of the truck-driver system. When transparent or opaque technologies were introduced and necessitated greater driver interaction, traditional ways of working became back-up functions to be performed manually when the new automation becomes unsuitable or fails. In the TNA, these changes caused the greatest number of additional KSAs – mainly in the introduction of new ‘skills’ in 50 instances. In contrast to these lower-level ‘skill’ changes, a high-level ‘attitude’ change stressed minimising environmental impact. This places responsibility not just on green driving technology but also on drivers’ individual and situational sense of what green driving is. New ‘knowledge’ and ‘skills’ placed emphasis on recognising when automated technologies would not be at full functionality, and when the driver would have to regain control of the vehicle. This provides support for an area of concern in HF/E research: understanding errors in takeovers from automation (e.g. Zeeb, et al., 2015; 2016). Despite these technologies being forecast for widespread use by 2020, current commercial driver training schemes do not generally cover these important (and sometimes in tension) KSA changes. The analysis reported in this chapter identifies them and enables them to be incorporated in future.

In 2025 the interrelated nature of the driving task was evidenced at higher levels of decomposition in the HTA. The propagation of change to higher levels of decomposition showed the increasing importance of drivers’ ability to identify different situations and adjust their tasks and behaviours accordingly. More specifically, changes showed even more relegation of manual tasks to automation. The ‘ability to maintain attention’, the ‘ability to determine if visibility allows for use of automated technology’, and similar abilities related to cognitive demands gained even more emphasis than in 2020. There is clearly a critical need for driver training programmes to recognise this trend.

In 2030 a noteworthy change involved a high-level revision to reversing the vehicle, as this task is forecasted to be fully automated. This technology caused a low quantity of changes, but also had the highest number of cross-references in the HTA for any technology in any time step. As this activity also relates to nearly a quarter of all deaths in driving work (Health and Safety Executive, 2019), low-speed and reversing tasks are a clear topic of importance for future work. Generally, fewer changes to tasks and corresponding KSAs were found in 2030 than in previous time steps. This may, however, tell us more about the nature of the commercial driving industry, and the limited foresight it allows, than actual operations in 2030. Based on the relatively low quantity of expert responses for the 2030 scenario in Chapter 2, it appears the optimal time length for logistics forecasting is around 10 years into the future (in this thesis, between 2015-2025). To account for this it is recommended that technology forecasts be updated in 2020-2025 to continue building an accurate and iterative picture of work scenarios in the longer-term.

The overall picture to emerge from the analytical efforts presented in this Chapter is an increasing reliance on automation. This is not unexpected. What is new are the detailed insights into the cognitive demands placed on future drivers and how to cope with them. The format of the HTA made clear that some traditional manual tasks will soon be allocated to technology, without necessarily easing the driver's workload. Higher levels of HTA decomposition required more elaborate plans to cope with variations in situations, and the high rate of information available to, and required by the driver, especially in comparison to private vehicle use. These plans represent the underlying theory of HTA and are direct measures of the human decision-making required by the system. The more elaborate HTA plans signify that future technology changes cause truck driving to transition in a fundamental way, from a visuo-spatial 'doing' task, to a task with greater emphasis on 'thinking'.

For most researchers and technologists working at the cutting edge of road transport, these results may appear to overestimate the driver's future role. It is therefore important to note that rather than focusing on a fully connected and autonomous 'end' state, this thesis focuses on the transition states on the horizon of the next 5-20 years. This means that results presented above are heavily reliant on the technology trajectory presented in Chapter 2, and thus on the selection and expertise of participants contributing to the trajectory. In general, autonomous road transport research emphasises the 'end' state (e.g. Banks et al., 2018; Banks & Stanton, 2019), focusing on what is *technologically possible* through advances in science and engineering. The participants contributing to the technology trajectory were selected specifically because they are embedded in real-world industry and practice, with a grounded perspective on what is *realistically viable* for wide market uptake, taking into account a wide range of economic, regulatory, sectoral culture, and other factors. In short, this ensured the trajectory was not limited to an idealised picture of what is possible, assuming that all relevant actors would immediately take up new technologies and practices as they became available. Instead the trajectory went a step further to incorporate what is likely to be implemented, and which measures may take more time to gain momentum of uptake, in the real-world UK context. Technology trajectory participants held a collective 370 years of road freight experience, across a wide spectrum ranging from policy all the way down to technology design, speaking to their ability to accurately estimate road transport transitions. A wider circle of participants (i.e. including academics and futurists) may have brought about different results, showing a faster pace of change and reaching a longer timeframe (e.g.

to 2100), but with increasing uncertainty as to the technological readiness and likelihood of uptake. As such Chapter 2 recommends limiting the trajectory participants to those embedded in industry in some way, and ensuring ongoing accuracy by updating the results through further interviews every 5-10 years.

These results sound an alarm for truck-driver systems, and the logistics industry more widely. Attention has been drawn to future system interactions we are not currently accounting for. The proposed HTA/TNA approach detects these warning signs through its structure, fine level of granularity, and acknowledgment of cross-references. Both the HTAoCD and TNAoCD provide a robust descriptive characterisation of commercial driving which can now frame real-world industry experiences with a functional and consistent structure.

The HTAoCD in particular serves as a reference for over 50 other HF/E methods which can be used for more comprehensive and 'technologically agnostic' system development. As useful as these methods may be, technologies, tasks, and KSAs are characterised in a way which is rooted in our understanding of how systems should currently work (Salmon, et al., 2010). The methods used in this chapter take us so far, but they do not tell us how systems could work, or necessarily how to design them better for an increasingly complex adaptive environment. Marrying these analyses with the study of system functionality through frameworks such as Cognitive Work Analysis (CWA), provides a formative approach to anticipate unexpected adaptations within the truck-driver system.

Perhaps more importantly, these detailed methods required over 680 pages – and countless hours – of analysis. Walker et al. (2016) found that a similar set of HTA-based methods – HE-HAZOP analysis, which uses HTA as an input and follows an HTA structure – required seven times as much analyst time when compared to CWA. Furthermore the HTA-based methods was able to cover less of the system, even when allotted seven times as much analyst time. CWA is not only significantly quicker, but also succeeded in detecting system vulnerabilities to a greater degree, and had greater relative predictive efficiency (Walker, et al., 2016). The HTAoCD and TNAoCD were required to gain a detailed picture of the operational environment, and the use of HTA-based methods with or alongside CWA has proven complementary in past applications (Salmon, et al., 2010). On this basis CWA can be justified as a resource-efficient way forward to gaining powerful new insights and feeding into real-world design processes. In Chapter 5 the HTAoCD is used to inform the first three stages of CWA, to holistically model the system and enable joint-optimisation of a real-world next-generation truck technology.

Chapter 5:

Evaluating the Truck-Driver System & Strategising the Design of New Technology with CWA

5.1. Why are we still designing poor systems?

The Chapters so far have succeeded in revealing significant interdisciplinary gaps. The road freight sector is actively searching for the solutions that HF/E can offer. Chapter 2 identified the powerful trends driving near term changes to the commercial driving task and the significant HF/E risks bound up in them. Chapter 3 put forward the research strategy for mitigating these risks ad capitalising on an important opportunity to leverage HF/E insights in a new domain. Chapter 4, to some extent, brings to bear established and proven HF/E techniques to provide a systematic diagnosis of the commercial driver and their training needs. This Chapter, consistent with the research strategy, shifts focus. In HF/E being applied to a new domain there is an opportunity for the road freight sector to ‘leap frog’ the existing state of practice in other sectors and benefit from cutting edge HF/E techniques. These techniques can respond to long-standing and fundamental questions in the design of future truck technology.

Given the dearth of HF/E insights and methods available, it is only natural to question “why [..]poor systems are still being designed” (Maguire, 2014, p. 168). In the road freight sector this includes distracting alert systems, routing systems which do not allow for the vehicle configuration (e.g. in Figure 5.1), and telematics feedback systems which give instructions that do not take the full driving context into account.

Figure 5.1: HGV wedged in an alley, after the driver faithfully followed satnav instructions (Gye, 2011)

The risks involved in persisting with existing practices are that the driver will be overwhelmed by the fitment of ad-hoc technology which is poorly integrated and not referenced to their task, jeopardising safety and environmental outcomes. The commercial risk, stated simply, is that significant investments in new technologies are made which nonetheless do not function as expected and will ultimately fail in the marketplace. These risks are clearly evident in the previous Chapter where it is seen how apparently dramatic technological changes can, in fact, have minor impacts on the actual driving task, but also vice versa. These risks present two fundamental challenges to HF/E-logistics research.

The first challenge is an obligation to capture systems complexity in our methods. In Chapter 4, 680 pages of descriptive HF/E analysis built a foundation to aid our understanding of the future truck driver. But what about the future truck? Designing systems for what 'should' happen is certainly one way to approach the problem, one with significant merit. It is, however, possible to go further and in doing so leap-frog practices and procedures in common use in other sectors. To avoid the financial, environmental, and safety-related costs of poorly designed technology, we need to explore complex adaptive socio-technical interactions in a more comprehensive and formative manner. Instead of basing the HF/E analysis on what ‘should’ happen; base it on what ‘could’ happen. It is for this reason that some commercial vehicle manufacturers are turning to methods like Cognitive Work Analysis (CWA), more often regarded as a research tool, to drive out practical insights around technology strategy.

This links to a second challenge, which is to resolve tensions between pragmatism vs. theoretical rigour in real-world technology design. In other words, does capturing system complexity mean our methods must be time-intensive and generally unwieldy? Is it possible to draw from HF/E theory to inform industry practice which is *both* more efficient *and* more effective? This challenge is echoed in recent literature which identifies a gap between CWA and real-world design, and calls for additional guidance in using its outputs in the design processes (Read, et al., 2015a).

Collaboration with a leading European HGV manufacturer – Scania – makes it possible to explore these challenges in a very direct sense. Dul et al. (2012) in their HF/E strategy paper called for wider stakeholder involvement in the discipline, not only acknowledging the user but also the product manufacturer. This Chapter describes how a unique opportunity to do just this was used. The collaboration with Scania was funded by two exchange grants (HFES Europe) and allowed the following sub-research questions to be further addressed:

- *How can current logistics gaps be appropriately addressed by human factors methods? (SRQ4)*
- *How can the truck-driver system be represented in a functional, technologically agnostic way? (SRQ5)*
- *How can we estimate future system conditions, and test future system functionality before implementation? (SRQ6)*

As a result this Chapter shifts focus to formatively model the commercial driving ‘work system’, and leverage this new understanding to inform next-generation truck design. CWA is used to evaluate the current truck-driver system; find the most critical activities occurring within that system; and design a new technology to support selected activities. Thus this chapter demonstrates CWA as a tool not only to evaluate existing systems, but also to design new parts for that system ‘from scratch’.

To determine what type of technology would be most helpful to the driver, a method of navigating very large and complex work systems to identify critical activities is developed. This offers a more manageable strategy for CWA application, which can be easily navigated by members of industry in the course of designing future real-world systems, but without taking a reductionist approach.

Once a critical activity is identified, a new technology complementing the functions of that activity can be proposed. CWA can then be used to ensure the proposed technology is fit-for-purpose, supporting holistic next-generation truck design. The result of this work is a new truck technology for Scania timber vehicles, a technology which will appear on vehicles before 2020, alongisde a substantial methodological contribution for real-world CWA applications. In other words, this Chapter responds to both challenges of poorly designed systems.

5.2. Why use CWA? Preventing methodological reductionism and practical intractability

The CWA method has been used previously in the domain of eco-driving (Birrell, et al., 2011), road infrastructure (Cornelissen, et al., 2015), and intelligent transport systems (Salmon, et al., 2007), but CWA has not so far been applied to the design of commercial vehicles. Cognitive Work Analysis and the acronym ‘CWA’ have been mentioned on a few occasions in this thesis so far, and this chapter is an ideal place to describe the framework.

CWA is a cognitive systems engineering framework which is used to model complex sociotechnical systems in terms of what constrains (or enhances) behaviours within them. The framework was originally developed to understand nuclear power systems that had robust technical designs, but continually experienced accidents attributed to ‘human error’ (Rasmussen, 1986). CWA differs significantly from the methods used in Chapter 4 in order to expand understanding of the system. Whereas methods like HTA rely on hierarchical actions that are required to complete higher-level goals, CWA can illustrate the structural degrees of freedom available in the system to achieve higher-level purposes (Jenkins, et al., 2009). Because CWA does not rely on a structure of specific actions or events, trajectories of behaviour can be defined outside of normal situations, goals, and work requirements, even for unanticipated events (Naikar, et al., 2005). In other words, benefits of the CWA framework include its ability to model constraints and flexibilities of socio-technical systems, and examine what could (rather than what should) happen.

CWA is “a mature analytical framework which can more extensively address system design issues than other methods from cognitive engineering” (Lintern, 2008 as cited in Read, et al., 2015a, p. 154). This is confirmed by the methods review performed in Chapter 3, which shows how CWA affords better-than-average coverage of different system scales, whilst also acknowledging both physical and cognitive aspects of systems. In short, CWA has high potential to capture system complexity, meeting the first challenge for well-designed systems.

The framework offers a toolkit in five phases, which can be applied selectively and in almost any order:

1. Work Domain Analysis (WDA),
2. Control Task Analysis (ConTA),
3. Strategies Analysis (StrAn),
4. Social Organisation & Cooperation Analysis (SOCA), and
5. Worker Competencies Analysis (WCA).

The following sub-sections briefly outline why different stages across Cognitive Work Analysis (CWA) are used.

5.2.1. Evaluating the current system

Work Domain Analysis (WDA) is the first step of CWA which aims to model the affordances and constraints of the system in a technologically agnostic manner. WDA “addresses not only what is performed, but also, how and why” (Jenkins, et al., 2009, p. 18). Typically this includes both an Abstraction Hierarchy (AH) and an Abstraction-Decomposition Space (ADS). Each of these representations is needed to decompose the system into discrete parts existing at different levels of granularity in the system, and to show how these parts are connected by means-end relationships between each level.

In the AH, objects within the system form the bottom layer (‘Physical Objects’ or PO). The next level (‘Object-Related Processes’ or ORP) explains what each of the objects can physically do. The third level (‘Generalised Functions’ or GF) shows what tasks can be accomplished by using these physical processes. The fourth level (‘Values & Priority Measures’ or VPM) represents criteria by which we can determine if a system is fulfilling its ‘Functional Purposes’ (or FP), the top level of the hierarchy that identifies why the system exists. Nodes at each level are connected through means-ends links in order to capture functionality, with the functions being increasingly abstracted with each layer of the hierarchy. These links are as important as the entities themselves, as they represent “the ‘means’ that a system can use in order to achieve defined ‘ends’” (Beevers et al., 2016). As shown in Figure 5.2, the AH is bi-directional. Working from the bottom of the hierarchy upwards answers the question of how an object achieves higher-level functions; traveling from the top downwards answers the question of why the system exists and how it functions.

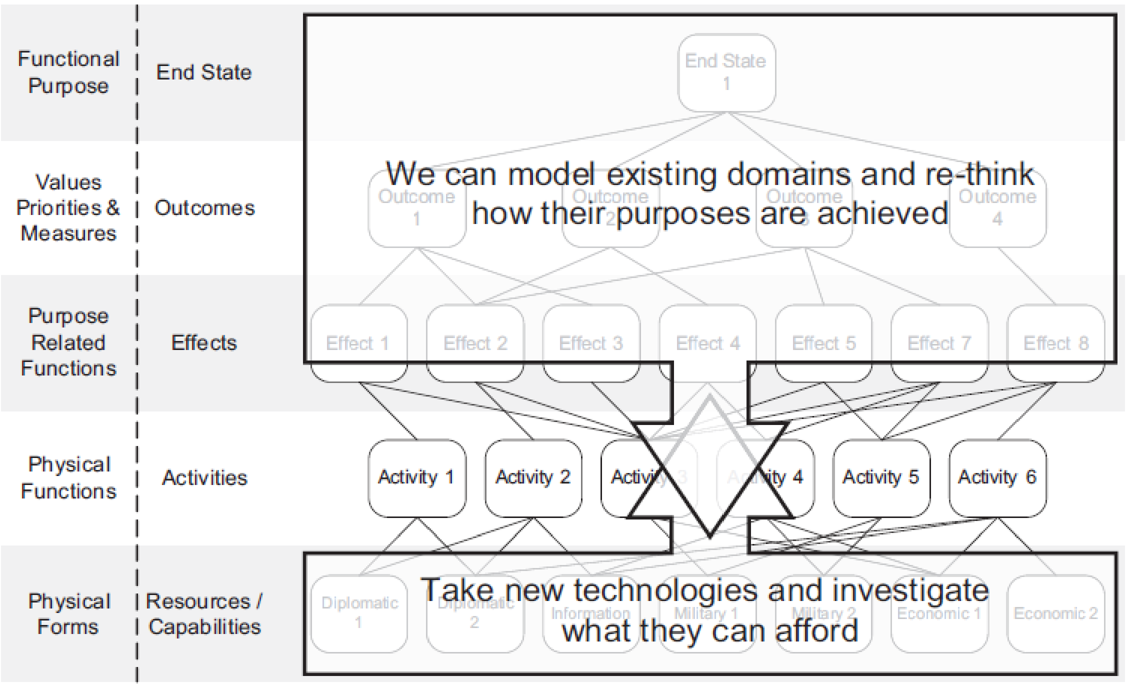

Figure 5.2: Bottom-up vs. top-down explorations of the abstraction hierarchy (Jenkins, et al., 2009)

The ADS breaks down these entities and explicitly categorises them into distinct system scales. The inherent acknowledgment of system scales, and interconnections between them, are unique WDA properties which enable a more accurate study of complex systems.

The next stage of CWA is Control Task Analysis, which is designed to understand the task and how operations may vary because of recurring types of situations. This addresses what tasks need to be performed, not how they must be performed or who they must be performed by. Typically, this includes the development of a Contextual Activity Template (CAT) and/or Decision-Making Ladder (DML), both of which represent activity within different work situations and work functions. Of particular interest to this study is the CAT, which represents how work functions and work situations intersect. Functions are activities characterised by their content, independent of temporal or spatial characteristics, which are often informed by the GF level of the AH. Situations are, essentially, the different physical or temporal contexts in which functions might occur. By characterising whether these intersections between functions and situations are impossible, possible, or typical, the system constraints are captured. A typical CAT is shown in Figure 5.3 below.

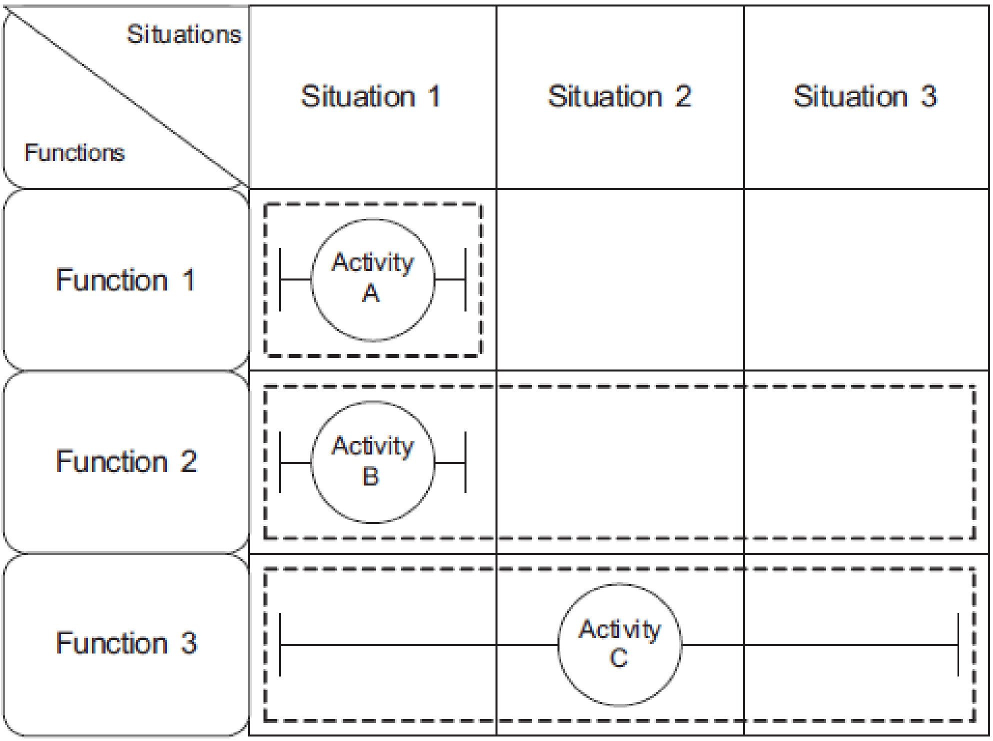

Figure 5.3: System constraints represented by a Contextual Activity Template (Jenkins, et al., 2009) The circle and whiskers shows in which situation the function typically occurs; the dotted box shows where it 'could' occur

In the wider logistics system, technologies are sensitive to situational factors and targets (Ricardo AEA, 2012) and thus cannot be optimised when detached from these. Through the VPM of the AH, multiple (sometimes competing) criteria of system success can be considered. Through the situations in the CAT, situational influences can be explored. However, in most if not all applications of CWA, ConTA is performed for all possible activities or simply those thought to be of value to the analyst, without any structured selection guidance. Due to the deep interconnections within the logistics system, this presents a challenge for truck-driver systems, and indeed any road freight sub-system at a higher level of granularity.

5.2.2. Finding critical work tasks/functions

The introduction to this chapter put forth two crucial challenges for well-designed systems. CWA clearly meets the first of these, the need to capture complexity in our methods. The second challenge – ensuring methods are tractable for real-world use, without resorting to reductionism – remains a grey area. Chapter 3 showed that the effective theoretical study of complexity relies on the application of formative methods on a wide range of scales. CWA is a prime candidate for meso-ergonomic inquiry and to map research findings directly to real, future systems (Dekker & Nyce, 2004). To make the necessary jumps in scale of analysis – from driver, to company operations, to truck-driver configuration, to company-wide operations, etc. – more structured guidance is necessary. Without guidance, scaling up the typically localised scope of CWA (e.g. interface design) to a wider system (e.g. distribution optimisation) could flood the analyst with information.

It is for this reason that practitioners, to quote the title of a paper on this topic, do not often 'go all the way with CWA', instead completing only one or two stages (McIlroy & Stanton, 2011)(Naikar, 2017). Though WDA and ConTA are considered to be better developed and explained than the later stages of CWA (Cornelissen, et al., 2013; Read, et al., 2015a; Salmon, et al., 2010), these have not been widely applied to very large-scale complex systems. In such large systems, the relatively high number of functions and situations (and therefore activities) found by the Contextual Activity Template have potential to inflict a sort of 'option paralysis'. In these cases hundreds of activities could be explored, and the time resource required to work through these one-by-one is simply impractical.

Thus, some decision-making must occur to select key activities and move forward. Here the overwhelming amount of information further stresses the importance of 'grey' additional processes used (consciously or not) by system designers. The usually implicit and unchecked nature of additional 'design supporting' processes opens up the design to inconsistency and lack of theoretical rigour. Further advice on how to 'zoom in and out' on system components critical to overall functionality will undoubtedly strengthen the ability to carry analysis through to latter stages of CWA. Thus, additional guidance is required to move through to later stages, to 'go all the way' with CWA, in an effective and cost-beneficial manner.

Prior to beginning this study the research team were aware of this need. The complex requirements of truck-driver systems were discussed, and it was acknowledged that application of CWA would require some non-reductive means of prioritising which system ‘parts’ are most critical to overall functionality. The Birrell method (Birrell, et al., 2011) was suggested as a recently peer-reviewed approach to prioritisation. This method was loosely adapted from the Failure Modes and Effects Analysis (FMEA) method, which systematically identifies potential failures in a system or process. In this way, critical system processes and objects could be identified. Birrell et al. (2011) set the scope of their WDA at the level of a single technological application, with a function which was pre-specified at the outset of their study.

The current study took a wider scope. The boundary was not set around a single technology but around the entire truck driving system; our aim was to identify *activities* within that system which would benefit most from the development of a new technology. This would enable the definition of a compatible new technology’s functional purpose, and only *then* begin a process of requirements specification. To prioritise ‘critical functions’ the Values & Priority Measures of the Abstraction Hierarchy completed in Stage 1 were referred to. Scania aimed to optimise the truck-driver system with maximum impact, and the VPM were thought to reflect both the main criteria for the truck-driver system and the main commercial aims of the business. Based on their experience Scania team members chose the Values & Priority Measures related to system efficiency and system safety as being of most importance to their customers, and therefore their business. As such, rating Contextual Activity Template functions based on how much they are perceived to contribute to *efficiency* or *safety* was proposed as one way of locating prime areas for technology development. Although safety and efficiency would likely be of high importance to most socio-technical systems, the proposed prioritisation method is flexible to industry partners selecting alternative VPMs as desired. For instance, if an industry partner placed high importance on environmental impact and regulating activities, system end users could be asked to rate the extent to which CAT functions contributed to these. This is, therefore, a flexible yet structured industry-led approach to the problem space.

The high number of situations (and therefore activities) found by the Contextual Activity Template in Stage 1 posed an additional challenge. It was clear that prioritising only functions would not sufficiently reduce the problem space. To prioritise ‘critical functions’ additional criteria were brought to bear. Frequency and effort were both considered. Based on complex systems and mental workload literature (Young &

Stanton, 2001; Young & Stanton, 2002a; Young & Stanton, 2002b; Young & Stanton, 2002c; Young, et al., 2009; Hajek, et al., 2013; de Winter, et al., 2014; Hassall & Sanderson, 2014), the frequency of situations drivers find themselves in, and the effort required to deal with them, are thought to contribute significantly to performance. One conceptualisation of how frequency and effort affect performance is highlighted in Table 5.1 below.

Table 5.1: Worker capability, familiarity and task complexity as contributing factors to task difficulty (adapted from Hassall & Sanderson, 2012)

Familiarity/situational stability	Worker capability (knowledge, skills, aptitude, and attitudes relevant to the task)	Task complexity	
		Low	High
Familiar and stable situation	High worker capability	Low difficulty	Low-medium difficulty
	Low worker capability	Low-medium difficulty	Medium-high difficulty
Unfamiliar and unstable situation	High worker capability	Medium-low difficulty	Medium-high difficulty
	Low worker capability	Medium-high difficulty	High difficulty

As such, potentially critical situations might include high frequency situations which require a high amount of effort (addressing mental overload), and low frequency situations which require a high amount of effort (addressing mental underload, e.g. in the case of driver-automation transitions such as unexpected takeover tasks). Rating Contextual Activity Template situations by how *frequent* or *effortful* they are was proposed. By finding intersections between the most safety/efficiency-critical functions and the most frequent/effortful situations, the approach enables the analysts to zoom in on an appropriate, potentially critical, problem space.

5.2.3. Selecting a critical activity & design supporting technology

Once the problem space is reduced further CWA stages can be applied to explore human behaviour within these critical areas. Strategies Analysis is the "investigation of the different ways that a control task could be performed, and an analysis of their consequences, performed to uncover ideas for improving system design" (Hassall & Sanderson, 2012, p. 3). The analysis is centred around eight main strategy types, outlined in Table 5.2 below. The typical context in which these strategies are used (in terms of a combination of time pressure, risk level, and difficulty) is also described, and shown in Figure 5.4.

Table 5.2: Strategy types (adapted from Hassall & Sanderson, 2012)

Strategy type	*Description*	*Typical context where strategy is used*		
		Time pressure	*Risk level*	*Difficulty*
Avoidance	Approaches to a task that include, delaying, deferring or not performing the task	High	Low	High
Intuitive	Approaches to a task that are executed automatically and include habitual responses	Low	Low	Low
Arbitrary-choice	Approaches to a task that are scrambled, ad hoc or haphazard and that do not include consideration of options or cues	High	High	High
Imitation	Approaches to a task that are adopted or copied, usually from another worker or from an approach that has been successful in a similar situation	Low	High	Low
Option-based	Approaches to a task where the worker selects from a set of alternatives an action option that meets some minimum requirement	High	Low	Low
Cue-based	Approaches to a task where the worker takes into account apparently relevant evidence from the environment that lets them include or exclude action possibilities, so guiding their responses	Low	High	High
Compliance	Approaches to a task that conform to rules and procedures	Low	High	Low
Analytical reasoning	Approaches to a task where the worker uses reason to carry out the task	Low	Low	High

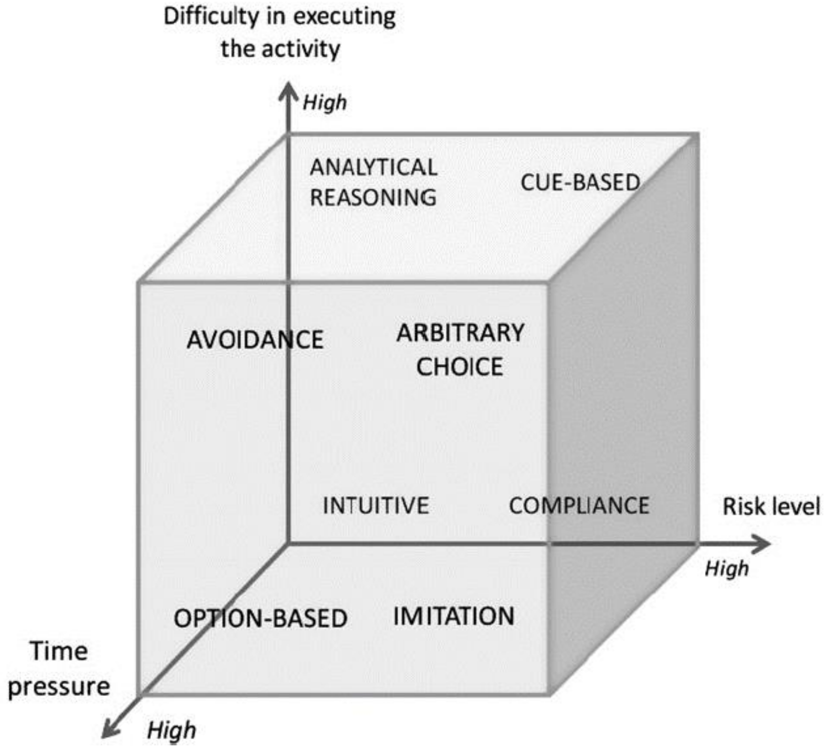

Figure 5.4: Hassall & Sanderson's (2012) Strategy Cube with all eight strategy types

This method explores human behaviour through these strategy types, and whether different strategy types are possible, acceptable, or preferable to the user during a specific activity. By gaining insights into which strategy types could, but should not, be promoted by the future system we can eliminate the risk of alienating the user and fostering undesirable emergent behaviours. By applying Strategies Analysis and utilising the taxonomy of strategies outlined above in Table 5.2, a direct link can be made between CWA and existing commercial design approaches (e.g. HMI design workshops typically run by Scania, the industry partner).

5.3. Methods

5.3.1. Design

CWA and prioritisation methods were applied in three stages: evaluate the system, identify critical tasks/activities, and design the supporting technology. A summary of this process is shown in Figure 5.5 below.

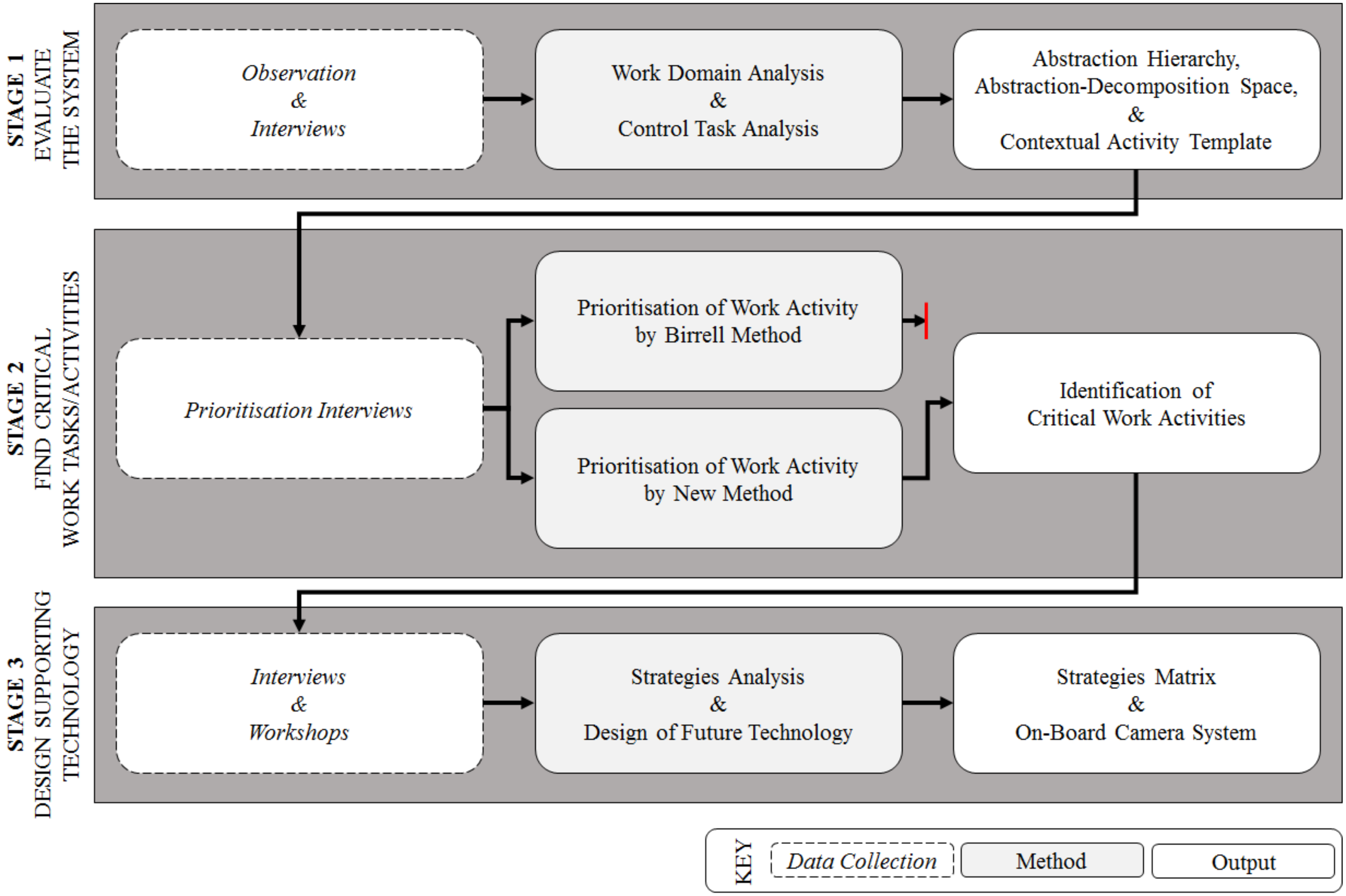

Figure 5.5: Design of CWA application for development of next-generation truck technology

5.3.2. Materials

5.3.2.1. Vehicles & equipment

Scania selected timber vehicle drivers as a key end user group on which to focus this study. This may appear a strange case study but in fact it serves as an excellent example of the need to prioritise the development of individual technologies, and how to integrate them into a jointly optimised system. Timber driving often involves maintaining a self-owned or specifically allocated truck (see Figure 5.6 for an example), and travelling between remote rural points and a local mill or transport centre to perform two to three pick-ups per day. Qualities which distinguish it from other road freight sectors are the use of particularly risk-inherent machinery (e.g. double trailers to accommodate large loads, and trailer cranes for moving timber) in dangerous terrain (often muddy and unstable) during lone, independent, relatively flexible work. For this reason, the key challenge for a timber freight company is balancing worker safety with maximum "loads per day".

Figure 5.6: Scania R-730 with 16-litre V8 520/580 horsepower Euro 6 engine, fitted for timber (Scania, 2013)

Participants were based in Sweden or Scotland, and either owned their vehicle or were personally responsible for a single assigned company vehicle. Most common was the Scania

R-series with high-set cab, configured with a V8 engine for heavy-duty operations. Frequently this was a Euro V standard R-620, or the most recent Euro VI standard R-730, an example of which can be seen in Figure 5.6 above. These were specified as rigid vehicles with timber storage and loading crane attached to the cab section of the vehicle. In Scotland these were accompanied by a single additional timber trailer. In Sweden, these were often accompanied by a B-double trailer with extendable floor for ease of loading, with a crane affixed to the cab section of the configuration.

5.3.2.2. Analysis & prioritisation aids

To familiarise the reader with the sector, Figures 5.7 and 5.8 have been included below. Typical processes involved in timber trucking operations are shown in Figure 5.7 below. This includes typical timber pick-up points (boxes 1-3), timber loading and securing processes (boxes 4-6), completing timber pick-up via GPS-enabled tracking system (box 7), driving loaded to the timber processing point (box 8), completing required paperwork at timber processing point (box 9), unloading timber at the processing point (boxes 10-11), and locating and driving to the next pick-up point using GPS-enabled tracking system (box 12).

Typical road environments encountered are shown in Figure 5.8 below. This includes rural, unpaved and private paths (row 1), public paved roads (row 2), roundabouts, town centre, and rail crossings (row 3), and private industrial work and break sites (row 4).

Interview questionnaires used for abstraction hierarchy development as well as two separate prioritisation methods are shown in Table 5.3 below.

Table 5.3: Driver interview questionnaire

Interview stage	*Question(s)*	*Application*
Abstraction Hierarchy development	What has the truck-driver system been designed to achieve? / What is the purpose of your work?	Prompts including but not limited to these central examples, from or inspired by Naikar (2005), facilitated discussion of the work system
	What criteria can be used to judge whether the work system is achieving its purposes? / How do you know things are going well?	
	What functions are performed in the work system? / What do you do in a typical work day?	
	What are the functional capabilities and limitations of physical objects in the work system? / How do the physical objects (e.g. ___) you use work?	
	What physical objects are necessary to enable the processes and functions of the work system? / What physical objects and tools do you use to do the job?	
Birrell prioritisation method	Is [abstraction hierarchy node description] high, medium or low priority to your work / fulfilling the purpose of the overall system?	Repeated for all nodes at FP, VPM, & GF levels
New prioritisation method	On a scale of 1-10 (with 1 being no impact, and 10 being very large impact), how much do you think your ability to [function description] affects overall safety?	Repeated for all CAT functions
	On a scale of 1-10 (with 1 being no impact, and 10 being very large impact), how much do you think your ability to [function description] affects overall efficiency?	
	How many hours/minutes per shift do you spend [situation description]?	Repeated for all CAT situations
	On a scale of 1-10 (with 1 being no effort, and 10 being extreme effort), how much effort do you think it requires to deal with this situation?	

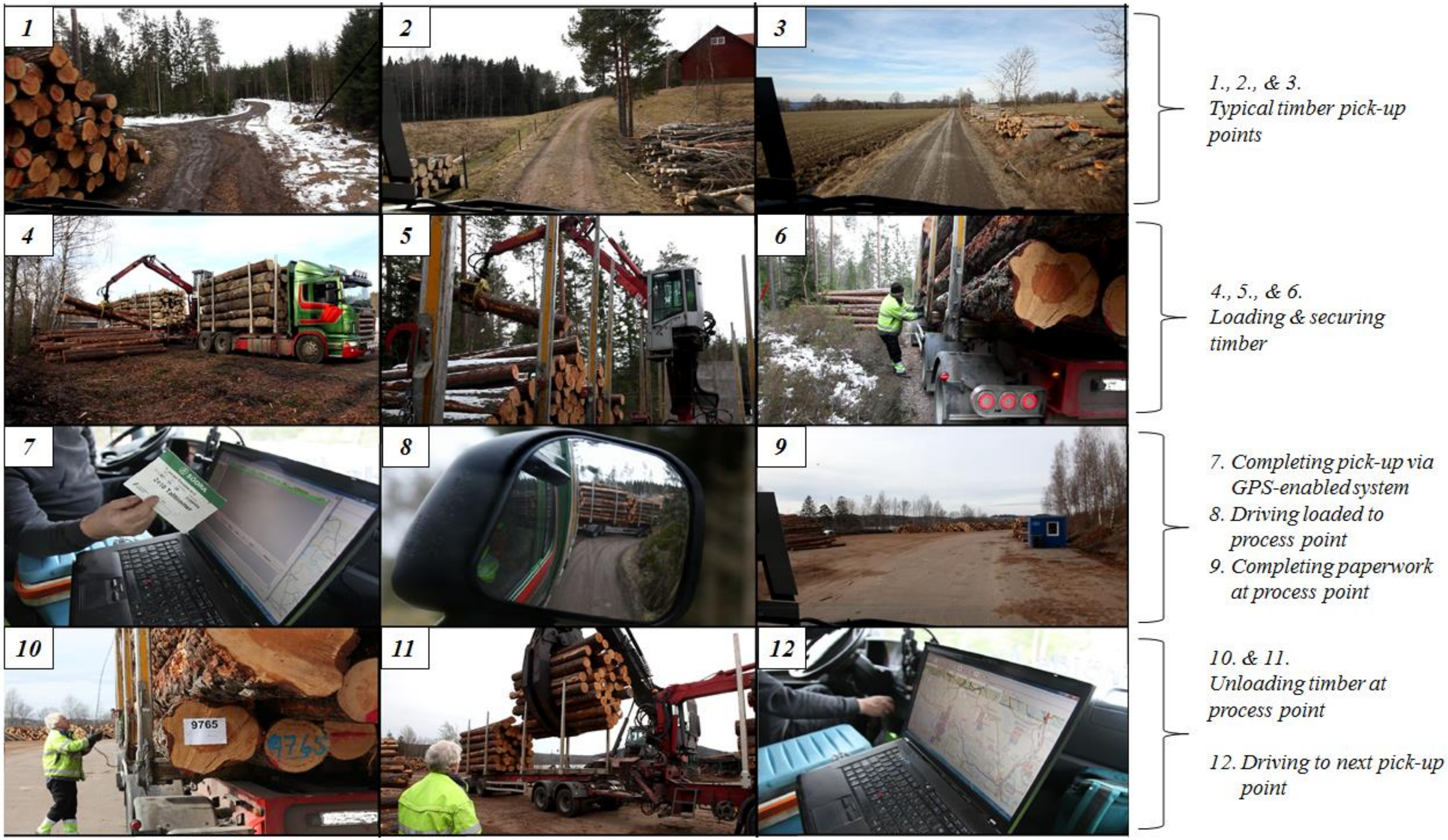

Figure 5.7: Typical timber trucking operations

Figure 5.8: Road environment encountered in typical timber trucking operations
Row 1 – rural/unpaved/private paths, Row 2 – public/paved roads, Row 3 – roundabouts, town centre, rail crossings, Row 4 – industrial/work/break sites

5.3.3. Participants

In total, 22 individual SME drivers contributed to various stages of the CWA. Participants were recruited through dealership contacts available to the industry partner in Sweden, and both dealership contacts and direct contact with individual hauliers in Scotland. Managers were contacted via e-mail. In the e-mail of initial contact, a brief overview was provided to describe the research project, the planned use of any data collected, the option to ask questions or raise concerns during the observation period, and an assurance that all data will be anonymised. Managers then discussed this with individual drivers. This allowed participants to be provided information about the intended research, reflect fully on this under no time pressure from the researcher, and agree or disagree to the terms on their own time, before participating. No incentives were offered for participation in the study. Available drivers arranged to meet with either the author or Scania collaborator(s) at a time and location convenient to the participant, providing written consent via e-mail or verbal consent via phone. On meeting each participant, the researcher again provided a brief overview to describe the research project, the planned use of any data collected, the option to ask questions or raise concerns during the observation period, and an assurance that all data will be anonymised. The researcher's contact details were provided to management and reference to the overall research consortium was made such that participants were enabled to contact the researcher or project supervisors for further information or regarding any concerns. Participants were notified of their right to decline to participate, and notified of their right to withdraw at any time by contacting the researcher. Full ethics approval was received from the Ethics Officer within the School of Management and Languages at Heriot-Watt University prior to beginning this work.

Table 5.4 below shows a timeline of data collection activities performed by the author to generate the CWA outputs. In this case, age was not recorded but can be approximated through driver experience as nearly all drivers had been in the same profession since reaching driving age. Table 5.5 on the following page shows aligned data collection by Scania which focused more heavily on specific technology designs.

Before beginning formal interviews, the author observed 7 Swedish drivers for a total of 58 working hours – drawing from a collective 125 years' professional driving experience. After the observation period 15 hours of formal interviews were conducted with an additional 11 drivers, drawing from a collective 278 years' professional driving experience. On average, drivers had about 24 years' experience, with about 4 hours spent with each participant.

Table 5.4: Data collection conducted or co-conducted by the author

Country	*Data Collection Period*	*Work Stage*	*Data Collection Type*	*# Drivers per Interview*	*Hours of Data Collection*	*Driving Experience (Yrs)*	*Gender*
Sweden	March 2015	WDA & ConTA	Observation	1	10	25	M
				1	10	5+	F
				1	10	5+	M
				1	10	5+	M
				1	7	35	M
				1	4	*Unknown*	M
				1	7	50+	M
	June 2015	WDA & ConTA	Interview	1	1+	19	M
				1	1+	47	M
				1	1+	43	M
				1	1+	10	M
				1	1+	30	M
				1	1+	15+	M
				1	1+	54	M
Scotland	September 2015	WDA & ConTA (Validation & Prioritisation)	Interview	1	2+	15+	M
				1	2+	15+	M
				1	2+	15+	M
		StrAn	Interview	1	2+	15+	M
Total				**18**	**73+**	**403+**	
Average				**1**	**4**	**24+**	**M**

Interviews and workshops conducted by the industry partner included 14 participants, with slightly less allotted time per driver. Descriptive data about the below participants in Table 5.5 cannot be included as the researcher was not present during the data collection efforts and this was not collected by the industry partner. In addition the workshop stage of data collection to translate CWA outputs into a real-world HMI design is commercially sensitive and cannot be fully outlined in this thesis.

Table 5.5: Data collection conducted by the industry partner

Country	*Data Collection Period*	*Work Stage*	*Data Collection Type*	*# Drivers per Interview*	*Hours of Data Collection*	*Driving Experience (Yrs)*	*Gender*
Scotland	July 2015	ConTA & Early HMI Discussions	Interview	3	2	*Unknown*	*Unknown*
				1	1		
				1	1		
				1	1		
				1	1		
				1	1		
				1	1		
				2	2		
				1	1		
				1	1		
				1	1		
Sweden	September 2015	StrAn & HMI Feedback	Workshop	*Unknown*	*Unknown*	*Unknown*	*Unknown*
Total				**14+**	**13+**	**Unknown**	
Average				**1**	**1**	**Unknown**	**Unknown**

5.3.4. Procedure

5.3.4.1. Stage 1: Work Domain Analysis & Contextual Activity Template

After familiarisation with the domain and its operational diversity, aided by an observation period, an initial review of documents and regulations was performed as described in Chapter 4. This included familiarisation with the comprehensive HTAoCD and TNAoCD for 2015 general commercial driving operations as completed in Chapter 4, which naturally fed into the researcher's system knowledge prior to beginning CWA.

Individual semi-structured interviews were then conducted with seven drivers using traditional CWA prompts (included in Appendix E) (Naikar, et al., 2005, pp. 33-34). Each interview covered the nature of day-to-day operations and lasted between 1-2 hours.

Insights gained from both the HTAoCD, TNAoCD, and interviews were used by the researcher to sketch a first-draft AH for current truck-driver systems. The HTAoCD and TNAoCD provided a strong foundational understanding of system operations as typically done, informing the content of the AH nodes and some of the means-end links at lower levels of the hierarchy. The interview responses clarified where in the AH (i.e. what level of the hierarchy) the nodes belonged, confirming the means-end links between them, and distinguishing nodes at different levels of decomposition.

When integrating the observations with the interview responses, there were no discrepancies in the technologies, processes, functions and tasks, values and priority measures, or purposes. This was partially due to the fact that the CWA performed in Chapter 5 is within a specific sector – forestry – which has a generally consistent application of technology and work practice even across multiple countries within the EU. It is also possible that despite encouragement to perform 'work-as-done' i.e. as the driver would do regardless of the study, the presence of the researcher in the truck cab during the observations could have affected driver behaviour and task completion in such a way that deviations and discrepancies from 'work-as-imagined' were muted.

After this initial draft was completed by hand, it was cross-checked and developed further based on guidance from Bodin (2013), before being drawn up in Microsoft Visio. After several drafts these analyses were printed off on A3 paper and validated by reviewing the outputs with a further three drivers. Validation was performed during one-on-one sessions, where drivers were given an explanation of the AH as a systems model. They were then led through the nodes at each level of the AH one by one, and asked if these should be included or excluded. At the finish of each AH level, and the close of the session overall, drivers were also asked to reflect on whether any parts of the system (nodes or means-end links) were missing from the AH. Outputs were accepted with no suggested changes.

A CAT was completed by the author, building upon the situations and functions within Bodin's (2013) CAT, and developed further based on operations specific to timber driving. The CAT was completed by using a numerical system, where 0 = function cannot occur (represented by dark shading), 1 = function can occur, and 2 = function always occurs. The CAT was then reviewed by a Scania collaborator and validated by one SME driver through an interview lasting 1-2 hours.

5.3.4.2. Stage 2: Prioritisation of critical activities

5.3.4.2.1. Option A: Birrell Method

The Birrell method (Birrell, et al., 2011) was initially proposed as a way to prioritise user requirements from the AH. Unfortunately, in this application it did not provide enough discrimination and left a very large problem space. It was decided to develop an alternative prioritisation method.

5.3.4.2.2. Option B: New Method

To incorporate the user into the prioritisation of critical work activities, semi-structured interviews were conducted with SMEs. This captured not just ratings related to a specific situation but allowed drivers to discuss their day-to-day activities, thus putting their responses in the context of their typical transitions between situations and/or functions.

Participants were also asked about the relationships between each function in the Contextual Activity Template and the two specific VPMs (safety and efficiency) selected by the manufacturer. Drivers were asked questions modelled on the format: *On a scale of 1-10 (with 1 being no impact, and 10 being very large impact), how much do you think your ability to [function description] affects overall safety [and separately, efficiency]?* Where drivers believed that the function in question did not have any impact on safety/efficiency, their response was entered as “N/A”.

Lastly, the driver participants were asked about the frequency and effort required in each driving situation defined by the CAT. Drivers first verified that a typical shift lasted approximately 13 hours, and were then asked questions modelled on the format: *How many hours/minutes per shift do you spend [situation description]?* After the approximate frequency of each situation was established, drivers were asked questions modelled on the format: *On a scale of 1-10 (with 1 being no effort, and 10 being extreme effort), how much effort do you think it requires to deal with this situation?* Where drivers had no direct or translatable experience of encountering the situation in question, their response was entered as “N/A”.

The mean of driver responses for each function were calculated to give an overall mean rating for safety, and then efficiency. The mean of driver responses were then calculated for each situation to derive an overall mean rating for required effort. Responses for frequency in hours per shift were first converted into percentages based on a 13-hour day, and the mean calculatedto derive an overall mean rating for frequency in each situation. These were cross-checked to ensure potentially critical situations lined up with these functions, i.e. that the activity could or always occurred (has a 1 or 2 in CAT). If these intersections of potentially critical situations and functions never occurred, they were omitted and the next potentially critical activity was selected.

Cut-off points for the highest and lowest safety/efficiency functions and frequency/effort situations were determined by calculating the mean +/- ½ the standard deviation, as shown in Table 5.6 below.

Table 5.6: Calculation of cut-off points for 'high' and 'low'

	Frequency	Effort
Mean	1.305	5.617
0.5*SD	0.986894741	0.902834244
Mean + (0.5*SD)	2.292	6.520
Mean – (0.5*SD)	0.318	4.715

The activities which did not meet these 'cut-off' points, and were thus excluded from the 'most critical' activities, were not by their exclusion deemed unimportant or negligible. The omitted activities could still be integral to an effective work system, and even warrant the addition of new supportive technology; however the aim of this study was to employ a quick, manageable, industry-friendly process of prioritisation to strategise which activities should be focused on first.

5.3.4.3. Stage 3: Strategies Analysis & technology design

The Strategies Analysis phase normally involves the exploration of possible strategies actors may use to complete an activity within the CAT. Scania developed a variation on this approach in order, again, to make the method's application more manageable for employees. The first step of the matrix (shown in Table 5.7) was to define the activity (task), in this case the activity or activities identified as potentially critical. The second step involves dividing the matrix into eight strategies based on time pressure, risk level, and difficulty level (as seen below), and defining each strategy type in terms of the domain/context if required.

Table 5.7: Blank Strategies Analysis worksheet Excel matrix

Task	Description of the Task	Time Pressure	Risk Level (Hassall & Sanderson, 2012)	Difficulty Level	Strategy Prompt (Why Use This Strategy?)	Strategy Categories (Hassall & Sanderson, 2012)	Description of Strategy Categories (Hassall & Sanderson, 2012)	Strategies	Accepted?	Preferred?
		High	High	High		Arbitrary-choice	Tasks that are uncommon and random and without considerations of options (e.g. pressing a button to cancel an alarm)			
				Low		Imitation	Approach to task copied from another worker or similar situation			
			Low	High		Avoidance	Delaying or not performing the task			
				Low		Option-based	One option for action is selected from alternatives that matches some criteria			
		Low	High	High		Cue-based	Include and exclude possible actions by taking relevant evidence from the environment into account			
				Low		Compliance	Follow rules and procedures (read and follow a written procedure)			
			Low	High		Analytical reasoning	Analytical reason is used to carry out the task, based on fundamental principles of the work system or mental simulation of possible outcomes			
				Low		Intuitive	Tasks executed automatically (routine tasks)			

Individual interviews were carried out with two SME drivers, lasting 2-3 hours each. The aim of these interviews was to understand strategy prompts or pre-conditions for the worker to ‘activate’ each category of strategy. The participant was also asked if each strategy type was acceptable, and if so, if it was preferred. This line of questioning enabled the analyst to identify strategies which are most natural to the user, and thus support their use in future designs. Strategies not accepted or preferred should therefore not be promoted in the future system.

Once existing cues, strategies, and acceptability were defined in the StrAn matrix, Scania was able to move on to their in-house design process. This involved an additional set of 14 individual timber drivers participating in feedback workshops for potential HMI designs, either one-on-one or in small groups of 2-3 dependent on availability. These lasted for approximately 1-2 hours. Based on these sessions, one technological application was selected and a more detailed design was fleshed out to be incorporated into the next generation of the manufacturer’s HGVs.

5.4. Results

5.4.1. Stage 1: Work Domain Analysis & Contextual Activity Template

The AH for timber driving can be seen in Figure 5.9, with the functional purpose of the system defined as ‘deliver timber to customer/process point’. Values and priority measures included ‘ensure provision of goods to customer’, ‘maximise forbearing, gentle driving style’, ‘maximise safety’, ‘minimise financial cost/loss of time’, ‘maximise user/worker health/comfort’, ‘maximise vehicle/system reliability’, ‘maximise efficiency/miles driven loaded’, and ‘maximise flexibility in routine’. All in all, the top three levels of the AH included 23 nodes, while the bottom two levels included 191 nodes. An example highlighting the functionality of the physical object ‘steering wheel’ is illustrated in Figure 5.10. The ADS associated with this AH provides more legible detail, and can be found in Tables 5.8 through 5.10 below.

In the ConTA (shown in Table 5.11), a total of 46 situations and 15 functions were included, totalling to 690 possible activities. 131 activities were given a score of 0 (indicating that these cannot occur), bringing the number of total possible activities down by 19% to 558 cells. This was still an extremely large problem space to navigate, and clearly justified initial concerns that some approach to prioritisation would be necessary to hone in on critical areas for future design.

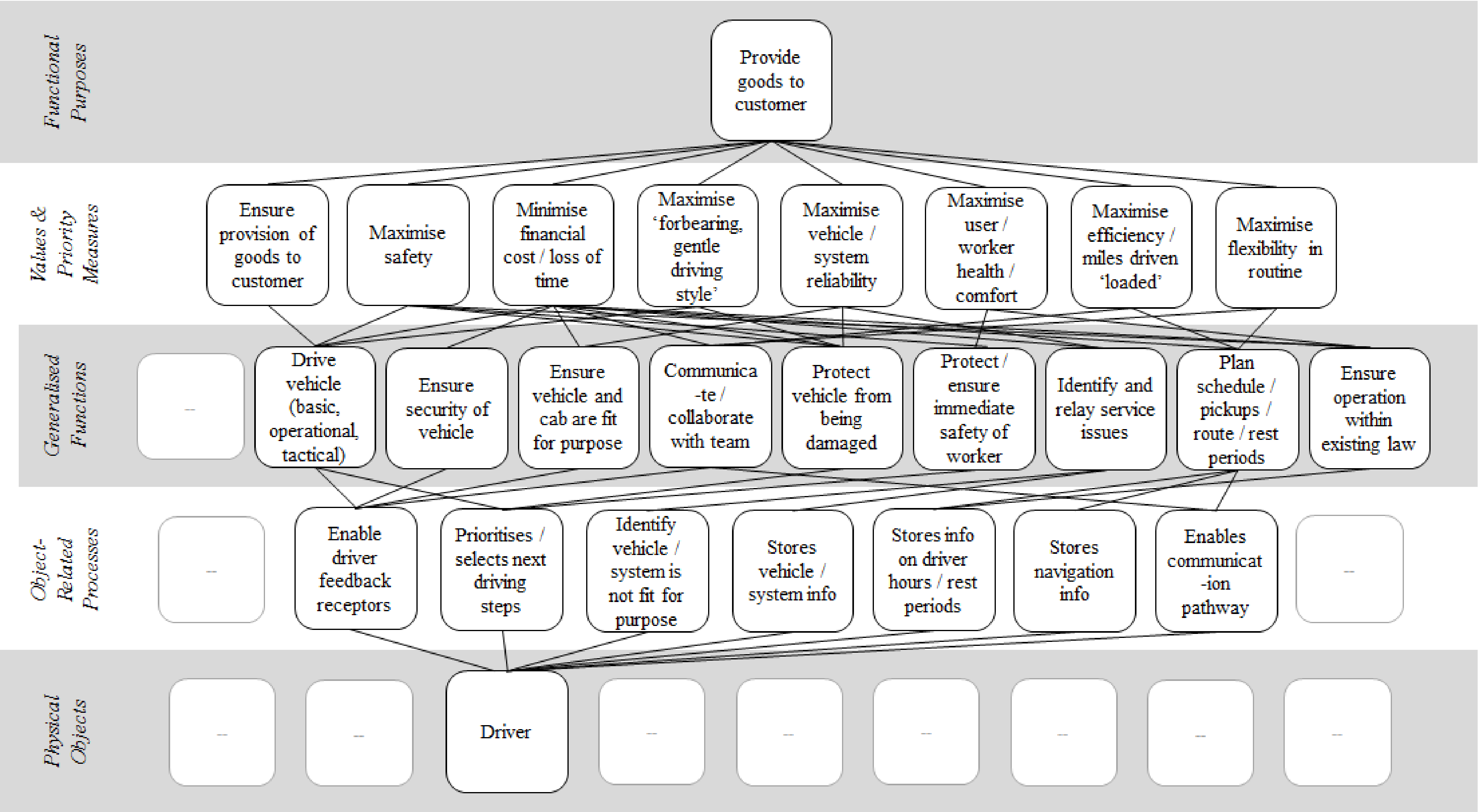

Figure 5.9: Abstraction Hierarchy for timber truck driving, highlighted example – driver

Table 5.8: 2015 ADS Part 1 – Functional Purposes at whole system level, Values & Priority Measures at sub-system level, & Generalised Functions at functional unit level

	Whole System	Sub-System	Functional Unit	SA	C
Functional Purpose	• Deliver timber to customer/process point				
Values & Priority Measures		• Ensure provision of goods to customer • Maximise “forebearing, gentle driving style” • Maximise safety • Minimise financial coast / loss of time • Maximise user/worker health/comfort • Maximise vehicle/system reliability • Maximise efficiency / miles driven loaded • Maximise flexibility in routine			
Generalised Functions			• Connect trailer to vehicle / enable delivery • Pick up / load vehicle with goods • Unload goods • Fuel/refuel • Drive vehicle • Ensure operation within existing law • Protect/ensure immediate safety of worker • Protect vehicle from being damaged • Ensure occ. health / comfort of worker • Identify and relay service issues • Ensure security of vehicle • Ensure vehicle / cab fit for purpose • Plan schedule / pickups/route/breaks • Communicate / collaborate w/ team		
ORP					
PO					

Table 5.9: 2015 ADS Part 2 – Object-Related Processes at the sub-assembly level

	WH	SS	FU	Sub-Assembly	C
FP					
VPM					
GF					
Object-Related Processes				• Adjusts seat • Fulfil order • Stores cargo • Secures cargo • Secures trailer • Deploys airbag • Alerts to smoke • Enables start-up • Minimises noise • Stabilises human • Connects air lines • Stores fuel/power • Provides traction • Connects brakes • Connects power • Connects trailer • Stores cargo info • Provides fuel/power • Enables locomotion • Provides RPM info • Provides speed info • Alerts to door status • Provides traffic info • Attaches label to goods • Protects vehicle body • Stores navigation info • Provides info on temp. • Alerts others to presence • Provides cargo area info • Protects worker's hands • Stabilises/protects tools • Maintains temp./climate • Alerts to lack of seatbelt • Alerts to brake pad wear • Provides info on oil level • Provides info on location • Provides oil pressure info • Presents coolant level info • Alerts to low tyre pressure • Provides info on fuel level • Controls vehicle trajectory • Facilitates refuelling point • Enables trailer locomotion • Stores vehicle / system info • Provides info on current time • Facilitates work environment • Enables vehicle speed change • Provides air line pressure info • Prevents dirt/water/ice build-up • Lifts/adjusts cargo to/from trailer • Enables driver feedback receptors • Alerts to status of cab area hazards • Enables worker to get into position • Presents info on sub-system fitness • Stores cargo description & location • Identifies system not fit for purpose • Prioritises/selects next driving steps • Provides current ignition setting info • Provides vehicle & trailer weight info • Provides info on current day/driver drive times • Provides info on other system/vehicle characteristics • Acts as supporting infrastructure for communications • Enables communication pathway/ passage of information	
PO					

Table 5.10: 2015 ADS Part 3 – Physical Objects at the component level

	WH	SS	FU	SA	Component
FP					
VPM					
GF					
ORP					
Physical Objects					• Fuel tank • Battery • Gear box • Clutch • Fuel • Tyres • Airbags • Horn • Ignition • Steps • Keys • Crane • Laptop • Satellite • Mirrors • Bumper • Driver • Paper • Ink • Printer • Clock • Map • Seatbelts • Hand rails • Break area • Generator • Cargo/goods • Brake pedal • Steering wheel • External lights • Internal lights • Vehicle seats • Hazard lights • Work gloves • Seat controls • Radio/media • Mobile phone • Laptop mount • Trailer body • Fuel station • GPS system • Indicators • Alarm (doors) • Alarm (smoke) • Pen/pencil • Gear stick • Food/drink • Adhesive/staple • Roadway/path • Trailer sheeting • Temperature controls • Windscreen wipers • High vis vest, etc • Accelerator pedal • Vehicle suspension • Front grill/bull bar • Engine (mechanical) • Mill/processing site • Window adjusters • Drawbar/kingpin • Breathalyser unit • Digital tachograph • Display (fuel level) • Display (RPM) • Display (speed) • Alarm (ignition) • Alarm (cab area) • Sensors (oil level) • Sensors (coolant) • Sensors (doors) • Sensors (other) • Sensors (smoke) • Sensors (ignition) • Trailer suspension • Trailer side barrier • Trailer ABS input • Driver tachograph card • Brake system hardware • Road navigation signs • Vehicle parking brake • Vehicle user manual • Ridged floor mats • Personal belongings • Windscreen defogger • GPS-enabled software • Orange traffic triangle • Central locking system • White smoke limiter button • Display (oil pressure) • Display (temperature) • Mech. warnings (on/off) • Display (coolant level) • Display (tyre pressure) • Alarm/display (other) • Sensors (brake pads) • Sensors (oil pressure) • Sensors (temperature) • Sensors (seat/seatbelts) • Trailer light hook-ups • Trailer parking brake • Trailer air hook-ups • Trailer ABS hook-ups • Roadside clearing/loading point • Cab (incl. windscreen/windows) • Cab heating & cooling systems • Land-based communications tower • Electricity fuses/connectors • Engine Control Unit (ECU) • Cargo paperwork/ID tags • Alarm (seatbelt reminder) • Alarm to indicate reversal • Display (vehicle/trailer weight) • Display (current fuel consumption) • Display (brake pad warning) • Display (oil level warning) • Display (air line pressure) • Mech. warning (not functional) • Mech. warning (comms. failure) • Sensors (air line pressure) • Tyre pressure monitoring sensors • Sensors (vehicle & trailer weight) • Sensors (cargo area issues) • Sensors (cab area e.g. grill) • Cargo chain hooks/clips/fasteners • Trailer air hook-up inputs • Trailer electricity hook-up inputs • Trailer steel wire adjusting button • Trailer cargo chains/straps, etc.

Table 5.11: Contextual Activity Template for timber driving operations, where 0 = cannot occur (represented by dark shading), 1 = can occur, 2 = always occurs

FUNCTION → SITUATION	Drive vehicle	Plan route/break/ schedule/pickup	Connect & use trailer	Load timber	Unload timber	Fuel/refuel	Ensure immediate safety of worker	Ensure occupational health/comfort	Ensure safety of others	Ensure vehicle fit for purpose	Protect vehicle from damage	Identify & relay service issues	Ensure security of vehicle	Ensure operation within existing law	Communicate/ collaborate with team	*SUM*	*% OUT OF TOTAL POSSIBLE (15x2=30)*
Driving (generally)	2	1	1	■	■	■	2	2	2	2	2	2	2	2	1	*21*	*70*
Loading	■	1	2	2	■	■	2	2	2	2	2	1	1	2	1	*20*	*67*
Unloading	■	1	2	■	2	■	2	2	2	2	2	1	1	2	1	*20*	*67*
Other worker unloads cargo	■	1	2	■	■	■	2	2	2	2	2	1	1	2	1	*18*	*60*
Driving (loaded)	2	1	2	■	■	■	2	2	2	2	2	2	2	2	1	*22*	*73*
Driving (unloaded)	2	1	2	■	■	■	2	2	2	2	2	2	2	2	1	*22*	*73*
Driving (trailer not connected)	2	1	1	■	■	■	2	2	2	2	2	2	2	2	1	*20*	*67*
Driving on highway (low traffic)	2	1	1	■	■	■	2	2	2	2	2	2	2	2	1	*21*	*70*
Driving on highway (high traffic)	2	1	1	■	■	■	2	2	2	2	2	2	2	2	1	*21*	*70*
Driving on highway (changing lanes)	2	1	1	■	■	■	2	2	2	2	2	2	2	2	1	*21*	*70*
Driving on country road (low traffic)	2	1	1	■	■	■	2	2	2	2	2	2	2	2	1	*21*	*70*
Driving on country road (high traffic)	2	1	1	■	■	■	2	2	2	2	2	2	2	2	1	*21*	*70*
Driving on 'timber road'/off-road path	2	1	1	■	■	■	2	2	2	2	2	2	2	2	1	*21*	*70*
Dealing with junctions (with traffic light)	2	1	1	■	■	■	2	2	2	2	2	2	2	2	1	*21*	*70*
Dealing with junctions (without traffic light)	2	1	1	■	■	■	2	2	2	2	2	2	2	2	1	*21*	*70*
Dealing with roundabout	2	1	1	■	■	■	2	2	2	2	2	2	2	2	1	*21*	*70*
Driving/loading/unloading on hilly terrain	2	1	1	1	1	■	2	2	2	2	2	2	2	2	1	*23*	*77*
Driving/loading/unloading on slippery terrain	2	1	1	1	1	■	2	2	2	2	2	2	2	2	1	*23*	*77*
Driving/loading/unloading in poor visibility	2	1	1	1	1	■	2	2	2	2	2	2	2	2	1	*23*	*77*
Driving/loading/unloading in wind	2	1	1	1	1	■	2	2	2	2	2	2	2	2	1	*23*	*77*
Driving in convoy (leading)	2	1	1	■	■	■	2	2	2	2	2	2	2	2	2	*22*	*73*
Driving in convoy (following)	2	1	1	■	■	■	2	2	2	2	2	2	2	2	2	*22*	*73*

Driving through tunnels	2	1	1	■	■	■	2	2	2	2	2	2	2	2	1	*21*	*70*
Driving under low bridges	2	1	1	■	■	■	2	2	2	2	2	2	2	2	1	*21*	*70*
Dealing with rail level crossings	2	1	1	■	■	■	2	2	2	2	2	2	2	2	1	*21*	*70*
Dealing with crash/incident (involved)	1	1	1	■	■	■	2	2	2	2	2	2	1	2	1	*19*	*63*
Dealing with non-crash incident (e.g. trailer flips)	1	1	1	■	■	■	2	2	2	2	2	2	1	2	1	*19*	*63*
Stopped (attending to accident/first on scene)	■	1	1	■	■	■	2	2	2	2	2	2	1	2	1	*18*	*60*
Stopped (waiting for traffic/accident to clear)	■	1	1	■	■	■	2	2	2	2	2	2	1	2	1	*18*	*60*
Being overtaken	1	1	1	1	1	1	2	2	2	2	2	2	1	2	1	*22*	*73*
Overtaking any other vehicle	2	1	1	■	■	■	2	2	2	2	2	2	2	2	1	*21*	*70*
Navigating obstacles in path	2	1	1	1	1	■	2	2	2	2	2	2	2	2	1	*23*	*77*
Vehicle is driving close in front	2	1	1	■	■	■	2	2	2	2	2	2	2	2	1	*21*	*70*
Vehicle is following close to back	2	1	1	■	■	■	2	2	2	2	2	2	2	2	1	*21*	*70*
Parking	2	1	1	■	■	■	2	2	2	2	2	2	2	2	1	*21*	*70*
Dealing with vehicle/trailer/equipment breakdown	1	1	1	1	1	1	2	2	2	2	2	2	2	2	1	*23*	*77*
Washing vehicle/trailer/equipment	■	1	1	■	■	1	2	2	2	2	2	2	2	2	1	*20*	*67*
Dealing with roadworks	1	1	1	■	■	■	2	2	2	2	2	2	1	2	1	*19*	*63*
Dealing with stolen truck	■	1	■	■	■	■	1	■	1	■	■	■	■	2	2	*7*	*23*
Dealing with loose cargo	■	1	2	■	■	1	2	2	2	2	2	1	1	2	1	*19*	*63*
Dealing w/ other timber vehicles using same loading path	1	1	2	■	■	■	2	2	2	2	2	1	1	2	2	*20*	*67*
Waiting in queue to unload at mill	1	1	2	■	■	■	2	2	2	2	2	1	1	2	1	*19*	*63*
Refuelling	■	1	1	■	■	2	2	2	2	2	2	1	1	2	1	*19*	*63*
Stopped (other work)	■	1	1	1	1	1	2	2	2	2	2	1	1	2	1	*20*	*67*
Stopped (rest period)	■	1	1	■	■	■	2	2	2	2	2	1	1	2	1	*17*	*57*
Stopped (pre-/post- shift)	■	2	1	■	■	■	2	2	2	2	2	2	2	2	2	*21*	*70*
SUM	*61*	*47*	*52*	*10*	*10*	*7*	*91*	*90*	*91*	*90*	*90*	*81*	*75*	*92*	*51*		
% OUT OF TOTAL POSSIBLE (46x2 =92)	*66*	*51*	*57*	*11*	*11*	*8*	*99*	*98*	*99*	*98*	*98*	*88*	*82*	*100*	*55*		

5.4.2. Stage 2: Prioritisation of critical activities

5.4.2.1. Critical functions (safety)

The functions identified by drivers as having the greatest impact on safety within the work system were ‘ensure occupational health/comfort of worker’ and ‘communicate/collaborate with team’ , ‘ensure service issues are identified and relayed’, and ‘drive vehicle’. Table 5.12 ranks orders the priority functions from greatest to least impact on operational safety.

Table 5.12: Driver-rated impact of functions on safety of work system (from 1-10), in descending order

FUNCTION	SAFETY RATING* *0 = no effect on safety* *1 = very little effect on safety* *10 = very large effect on safety* *N/A = driver does not typically encounter the function*			
	Driver 1	Driver 2	Driver 3	Average
Ensure occupational health/comfort of worker	**9**	**9**	**9**	**9.00**
Communicate/collaborate with team	**9**	**9**	**N/A**	**9.00**
Identify & relay service issues	**7**	**9**	**N/A**	**8.00**
Drive vehicle	**9**	**9**	**5**	**7.67**
Ensure security of vehicle	6	9	N/A	7.50
Ensures vehicle and cab are fit for purpose	7.5	7	N/A	7.25
Plan schedule/ pickups/ route/ rest periods	7	9	5	7.00
Protect vehicle from damage	6	7	N/A	6.50
Ensure operation within existing law	4	9	N/A	6.50
Ensure immediate safety of worker	1	9	9	6.33
Ensure safety of others	1	9	9	6.33
Pick up/load vehicle with timber	3	9	5	5.67
Unload timber	3	9	5	5.67
Connect & use trailer	2	9	2	4.33
Fuel/ refuel	1	7	1	2.67

**dark grey shading indicates GF was not applicable to driver; light grey shading indicates GFs rated as most and least important to safety*

When it comes to impacts on system safety, standard deviations were highest for ‘ensure immediate safety of worker’ and ‘ensure safety of others’. This was a surprising result, as these are functions which appear directly related to safety. Perhaps this speaks to the operational viewpoint of the driver (focusing on *how* to achieve maximum safety, rather than simply agreeing that safety is important). Standard deviations were lowest for ‘ensure occupational health/comfort of worker’ and ‘communicate/collaborate with team’. The distinction between ‘immediate safety’ and ‘occupational health’ here is an important one; while ‘immediate safety’ often relies on an intervening technology (e.g. collision avoidance systems, or something as simple as a seatbelt), ‘occupational health’ is much more user-flexible. Many timber drivers serve lifetime roles within a company and become extremely familiar with local routes and practices, and the findings may be an artefact of this. Timber driving work is also relatively rural and off-road, at a slower and more deliberate pace than, say, urban logistics. As a result, threats perceived by drivers are less likely to involve high-speed vehicle collisions and more likely to involve aspects over which the driver perceives they have more control (e.g. non-driving accidents or cumulative musculoskeletal strains over time).

5.4.2.2. Critical functions (efficiency)

The functions rated by drivers as having the greatest impact on the efficiency were ‘drive vehicle’, ‘communicate/collaborate with team’, and ‘plan schedule/pickups/route/breaks’ and ‘ensure service issues are identified and relayed’ Table 5.13 shows the values of functions from of greatest to least impact on operational efficiency.

Table 5.13: Driver-rated impact of functions on efficiency of work system (from 1-10, where 10 is highest impact), in descending order

FUNCTION	EFFICIENCY RANKING* *0 = no effect on efficiency* *1 = very little effect on efficiency* *10 = very large effect on efficiency* *N/A = driver does not typically encounter the function*			
	Driver 1	Driver 2	Driver 3	Average
Drive vehicle	**9**	**9**	**5**	**7.67**
Communicate/collaborate with team	**9**	**6**	**N/A**	**7.50**
Plan schedule/ pickups/ route/ rest periods	**7**	**9**	**5**	**7.00**
Identify & relay service issues	**7**	**7**	**N/A**	**7.00**
Ensures vehicle and cab are fit for purpose	7	5	N/A	6.00
Ensure security of vehicle	6	6	N/A	6.00
Ensure occupational health/ comfort of worker	9	3	3	5.00
Protect vehicle from damage	6	4	N/A	5.00
Ensure operation within existing law	4	4	N/A	4.00
Connect & use trailer	2	7	2	3.67
Pick up/load vehicle with timber	3	4	4	3.67
Unload timber	3	4	4	3.67
Ensure safety of others	5	1	2	2.67
Ensure immediate safety of worker	0	4	2	2.00
Fuel/ refuel	0	4	1	1.67

**dark grey shading indicates GF was not applicable to driver; light grey shading indicates GFs rated as most and least important to safety*

Standard deviations were highest for ‘connect & use trailer’, ‘drive vehicle’, and ‘plan schedule/pickups/route/breaks’. These responses are likely to be heavily dependent on individual routes and typical company procedures, hence the wide variance in responses. Standard deviations were lowest for ‘ensure operation within existing law’, ‘ensure security of vehicle’, and ‘ensure service issues are identified and relayed’. It would appear, intuitively, that these functions are highly constrained, having severe consequences to the completion of the functional purpose if their affordances are removed. Three potentially critical functions were found to have the highest impact on *both* safety *and* efficiency. These were: ‘ensure service issues are identified and relayed’, ‘communicate/collaborate with team’, and (unsurprisingly) ‘drive vehicle’.

In Table 5.14 below, the mean responses for both safety and efficiency can be seen. Interestingly, ‘communicate/collaborate with team’ emerges as having the most impact on both VPMs.

Table 5.14: Critical functions (greatest effect on Values & Priority Measures of safety & efficiency)

FUNCTION	VPM	RANKING* *0 = no effect on VPM* *1 = very little effect on VPM* *10 = very large effect on VPM* *N/A = driver does not typically encounter the function*				
		Driver 1	Driver 2	Driver 3	Average	Total Average
Communicate/ collaborate with team	*Safety*	9	9	N/A	9.00	**8.25**
	Efficiency	9	6	N/A	7.50	
Drive vehicle	*Safety*	9	9	5	7.67	**7.67**
	Efficiency	9	9	5	7.67	
Identify & relay service issues	*Safety*	7	9	N/A	8.00	**7.50**
	Efficiency	7	7	N/A	7.00	

**dark grey shading indicates GF was not applicable to driver; light grey shading indicates GFs rated as most and least important to safety*

5.4.2.3. Critical situations

Situations which accounted for greater than 2.29 hours per shift were considered high frequency; situations below 0.32 hours per shift were considered low frequency. Any situations above a 6.52 ranking were considered high effort (see method section for detailed explanation). ‘

Driving (generally)’ was naturally the situation with the highest frequency. Moving down the rankings the situations included more specificity. The second most frequent situation was ‘driving/loading/unloading on hilly terrain’, which makes intuitive sense within a sector dependent on forestry, typically in rural mountainous areas. The six least frequent situations returned 0 values from all three drivers, indicating these were never encountered. They included such things as dealing with a stolen truck or negotiating a railway level crossing. Arguably, these situations could occur in future, but would be intermittent and very rare given the significant collective driving experience of the participants.[2] Table 5.15 presents these findings in full.

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[2] For example, according to the technology trajectory developed in Chapter 2, driving in convoys will be increasingly encouraged in the logistics sector, but timber companies operate in such a way that this will not be highly integrated into daily procedures.

Table 5.15: Situations ranked by drivers for high & low frequency (% based on typical 13-hour shift), in descending order

		FREQUENCY RATING* (% based on a typical 13-hour shift)							
		Driver 1		Driver 2		Driver 3		Average	
	SITUATION	hrs/day	%	hrs/day	%	hrs/day	%	hrs/day	%
High Frequency (x > 2.29)	Driving (generally)	8.00	61.54	9.50	73.08	8.00	61.54	**8.50**	65.38
	Driving/loading/unloading on hilly terrain	6.00	46.15	9.50	73.08	6.00	46.15	**7.17**	55.13
	Driving (loaded)	4.00	30.77	7.13	54.81	4.00	30.77	**5.04**	38.78
	Driving/loading/unloading on slippery terrain	9.00	69.23	2.40	18.46	1.00	7.69	**4.13**	31.79
	Driving/loading/unloading in poor visibility	2.40	18.46	8.40	64.62	1.00	7.69	**3.93**	30.26
	Being overtaken	4.00	30.77	6.50	50.00	1.00	7.69	**3.83**	29.49
	Driving (unloaded)	4.00	30.77	2.38	18.27	4.00	30.77	**3.46**	26.60
	Driving/loading/unloading in wind	6.00	46.15	0.60	4.62	1.00	7.69	**2.53**	19.49
	Driving on 'timber road'/off-road path	2.00	15.38	2.50	19.23	3.00	23.08	**2.50**	19.23
Low Frequency (x < 0.32)	Driving on highway (changing lanes)	0.50	3.85	0.02	0.13	0.03	0.26	**0.18**	1.41
	Stopped (pre-/post- shift)	0.08	0.64	0.12	0.900	0.33	2.56	**0.18**	1.37
	Navigating obstacles in path	0.17	1.28	0.02	0.13	0.33	2.56	**0.17**	1.32
	Dealing with roundabout	0.25	1.92	0.05	0.38	0.20	1.54	**0.17**	1.28
	Parking	0.08	0.64	0.30	2.31	0.10	0.77	**0.16**	1.24
	Washing vehicle/trailer/equipment	0.20	1.54	0.00	0.00	0.20	1.54	**0.13**	1.03
	Dealing with vehicle/trailer/equipment breakdown	0.02	0.13	0.17	1.28	0.17	1.28	**0.12**	0.90
	Dealing with non-crash incident (e.g. trailer flips)	0.02	0.13	0.25	1.92	0.00	0.00	**0.09**	0.68
	Driving (trailer not connected)	0.00	0.00	0.00	0.00	0.26	2.00	**0.09**	0.67
	Dealing with junctions (with traffic light)	0.17	1.28	0.08	0.64	0.00	0.00	**0.08**	0.64
	Dealing w/ timber vehicles using same loading path	0.08	0.64	0.03	0.26	0.08	0.64	**0.07**	0.51
	Driving under low bridges	0.08	0.64	0.08	0.64	0.02	0.13	**0.06**	0.47
	Vehicle is driving close in front	0.17	1.28	0.00	0.00	0.00	0.00	**0.06**	0.43
	Overtaking any other vehicle	0.03	0.26	0.03	0.26	0.05	0.38	**0.04**	0.30
	Dealing with crash/incident (involved)	0.02	0.13	0.02	0.13	0.00	0.00	**0.01**	0.09
	~~Driving in convoy (leading)~~	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**	0.00
	~~Driving in convoy (following)~~	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**	0.00
	~~Driving through tunnels~~	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**	0.00
	~~Dealing with rail level crossings~~	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**	0.00
	~~Stopped (attending to accident/first on scene)~~	0.00	0.01	0.00	0.00	0.00	0.00	**0.00**	0.00
	~~Dealing with stolen truck~~	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**	0.00

**where grey shading indicates a situation not encountered by drivers*

In terms of effort, the situations which returned the highest values were ‘dealing with a stolen truck’, ‘dealing with rail level crossings’, ‘stopped (attending to accident/first on scene)’ and ‘dealing with non-crash incident (e.g. trailer flips). However, the top three situations were based on only one driver response, and none of the participants had ever encountered them. On this basis they were omitted. For the ratings included in the analysis it was noted that situations rated as requiring the most effort had smaller standard deviations compared to the same metric for both high- and low-effort situations. The results presented in Table 5.16 seem to have a relatively high level of agreement between drivers.

Table 5.16: Potentially critical situations further narrowed down by prioritising situations ranked by drivers as high effort

	SITUATION	EFFORT RATING* *1 = extremely easy* *10 = extremely difficult* *N/A = driver does not encounter the situation*			
		Driver 1	Driver 2	Driver 3	Average
High Effort (x>6.52)	Dealing with stolen truck	9	N/A	N/A	**9.00**
	Dealing with rail level crossings	N/A	N/A	8	**8.00**
	Stopped (attending to accident/first on scene)	8	N/A	N/A	**8.00**
	Dealing with non-crash incident (e.g. trailer flips)	8	8	N/A	**8.00**
	Driving on country road (high traffic)	7	8	8	**7.67**
	Dealing with crash/incident (involved)	8	7	N/A	**7.50**
	Driving/loading/unloading on slippery terrain	4	9	9	**7.33**
	Vehicle is driving close in front	7	7	8	**7.33**
	Driving/loading/unloading in poor visibility	5	8	9	**7.33**
	Driving on 'timber road'/off-road path	5	9	8	**7.33**
	Dealing with roadworks	7	6	8	**7.00**
	Driving/loading/unloading in wind	7	5	9	**7.00**
	Navigating obstacles in path	6	7	7	**6.67**
	Dealing with junctions (without traffic light)	6	7	7	**6.67**
	Driving (loaded)	7	6	7	**6.67**
	Dealing with junctions (with traffic light)	4	9	7	**6.67**

**where grey shading indicates a situation not encountered by drivers*

It is also worth noting that when converting the averages of standard deviations in each factor to a 1-10 scale, safety was the highest at 2.37, with effort following at 1.55, efficiency at 1.53, and frequency at 0.53. The frequency of situations/functions seems to have the most consensus among participants.

The notion that less frequent situations require more effort was also explored. No strong linear, exponential, logarithmic, or power relationship was observed – even when removing 0 frequency situations. This supports the idea that the effort required of in a situation is not necessarily correlated with the drivers’ familiarity with that situation, and further contextual factors should be considered. Situations were also categorised by type, including: crash/incident, infrastructure, load handling, manoeuvre, road type, service, and waiting/stopped. Environment-related manoeuvres such as driving on slippery or hilly terrain had highest average effort ratings, highest average frequency ratings, and also the highest variance in ratings for both categories.

5.4.2.4. Critical activities

The top three functions were selected for consideration: ‘communicate/collaborate with team’, ‘drive vehicle’, and ‘ensure service issues are identified and relayed’. Situations with 0 values for frequency were omitted as drivers agreed these were never encountered. Table 5.17 presents the results in full.

Table 5.17: Situations identified as potentially critical; grey shading indicates situation not encountered by drivers

SITUATION	Average Frequency *(hrs/day)*	Average Effort *(1-10 scale)*	Type of Potential Criticality *(based on limits of mean +/- 0.5*SD)*
~~Dealing with stolen truck~~	~~0.000~~	~~9.000~~	~~Low frequency - high effort~~
~~Dealing with rail level crossings~~	~~0.000~~	~~8.000~~	~~Low frequency - high effort~~
~~Stopped (attending to accident/first on scene)~~	~~0.000~~	~~8.000~~	~~Low frequency - high effort~~
Dealing with crash/incident (involved)	0.011	7.500	Low frequency - high effort
Vehicle is driving close in front	0.056	7.333	Low frequency - high effort
Dealing with junctions (with traffic light)	0.083	6.667	Low frequency - high effort
Dealing with non-crash incident (e.g. trailer flips)	0.089	8.000	Low frequency - high effort
Navigating obstacles in path	0.172	6.667	Low frequency - high effort
Dealing with roadworks	0.211	7.000	Low frequency - high effort
Driving on 'timber road'/off-road path	2.500	7.333	High frequency - high effort
Driving/loading/unloading in wind	2.533	7.000	High frequency - high effort
Driving/loading/unloading in poor visibility	3.933	7.333	High frequency - high effort
Driving/loading/unloading on slippery terrain	4.133	7.333	High frequency - high effort
Driving (loaded)	5.042	6.667	High frequency - high effort

The effect of the prioritisation method can be clearly seen, in that this step reduced the number of potential activities from 558/690 cells within the CAT, to 33/690 cells. Table 5.18 on the following page is an abridged CAT with potentially critical activities highlighted in red.

Table 5.18: Critical activities highlighted in an abridged CAT

		Functions with high impact on both safety AND efficiency			*Functions with high impact on safety OR efficiency*			
	SITUATION / FUNCTION →	Communicate/ collaborate with team	Drive vehicle	Identify & relay service issues	~~Plan schedule/ pickups/route/breaks~~	~~Ensure occ. health/ comfort of worker~~	*SUM*	*% OUT OF TOTAL POSSIBLE (15x2=30)*
Situations with 0 frequency	~~Dealing with stolen truck~~	2	■	■	1	■	*7*	*23*
	~~Dealing with rail level crossings~~	1	2	2	1	2	*21*	*70*
	~~Stopped (attending to accident/first on scene)~~	1	■	2	1	2	*18*	*60*
Situations with low frequency AND high effort	Dealing with crash/incident (involved)	1	1	2	1	2	*19*	*63*
	Vehicle is driving close in front	1	2	2	1	2	*21*	*70*
	Dealing with junctions (with traffic light)	1	2	2	1	2	*21*	*70*
	Dealing with non-crash incident (e.g. trailer flips)	1	1	2	1	2	*19*	*63*
	Navigating obstacles in path	1	2	2	1	2	*23*	*77*
	Dealing with roadworks	1	1	2	1	2	*19*	*63*
Situations with high frequency AND high effort	Driving on 'timber road'/off-road path	1	2	2	1	2	*21*	*70*
	Driving/loading/unloading in wind	1	2	2	1	2	*23*	*77*
	Driving/loading/unloading in poor visibility	1	2	2	1	2	*23*	*77*
	Driving/loading/unloading on slippery terrain	1	2	2	1	2	*23*	*77*
	Driving (loaded)	1	2	2	1	2	*22*	*73*
	SUM	*51*	*61*	*81*	*47*	*90*		
	% OUT OF TOTAL POSSIBLE (46x2 =92)	*55*	*66*	*88*	*51*	*98*		

5.4.2.5. Final selection of activity

Although the prioritisation process managed to reduce the problem space by a remarkable 94%, making this systemic method 'much' more tractable, performing StrAn for 33 activities was still outside the scope of this study. When presented with these 33 activities the following questions arose from discussions regarding further prioritisation:

1. Is the activity too general to generate a specific, effective new technology design?
2. Does an associated technology have potential to help the driver, compared to the current vehicle configuration?
3. Do existing technologies sufficiently cover the activity?
4. According to the technology forecast, is this technology already being developed for future systems?

5. Is adding a new technological application in this situation likely to create mental overload?
6. Would this novel application require an unrealistic change in working practices or jump in technological sophistication?

These extra considerations were applied to each of the thirty three critical functions to evaluate available opportunities for future systems. Though generic, ‘drive vehicle’ was selected as a core and wide-reaching function. Only one situation would be exempt from the function ‘drive vehicle’ (the situation ‘dealing with crash incident (involved)’ and that will be addressed by collision avoidance systems in the near future. The remaining ten activities under the umbrella of ‘drive vehicle’ could all be investigated for future improvements to the system as shown in Table 5.19 below.

Table 5.19: Ten critical activities

		Functions with high impact on both safety AND efficiency
	FUNCTION → SITUATION	Drive vehicle
Situations with low frequency AND high effort	Dealing with crash/incident (involved)	1
	Vehicle is driving close in front	2
	Dealing with junctions (with traffic light)	2
	Dealing with non-crash incident (e.g. trailer flips)	1
	Navigating obstacles in path	2
Situations with high frequency AND high effort	Driving on 'timber road'/off-road path	2
	Driving/loading/unloading in wind	2
	Driving/loading/unloading in poor visibility	2
	Driving/loading/unloading on slippery terrain	2
	Driving (loaded)	2

5.4.3. Stage 3: Strategies Analysis & technology design

From the ten potential activities put forward by the prioritisation process, it was concluded that StrAn for three activities would sufficiently represent different strategy styles within the system. These were:

1. Driving the vehicle on slippery terrain (high frequency-high effort, environment-related)

2. Driving the vehicle on timber/off-road paths (high frequency-high effort, road type), and
3. Driving the vehicle behind a lead vehicle which suddenly become close to front (low frequency-high effort, traffic-related).

The results of these analyses can be found in the Table 5.20 through 5.22 below.

Table 5.20: Strategies Analysis for driving a vehicle safely and efficiently on slippery terrain (such as mud or ice)

TIME PRESSURE	RISK LEVEL	DIFFICULTY LEVEL	STRATEGY PROMPT	ACCEPTED	PREFERRED	STRATEGY TYPE	STRATEGY TYPE DESCRIPTION
HIGH	HIGH	HIGH	If driver is running late/new/tired/unfamiliar with terrain AND if a corner is more slippy than it first looks OR if it rains after a dry spell the road gets greasy	Yes	Yes	ARBITRARY	Performed quickly without relevant experience OR consideration of options
		LOW	If the driver is running late AND driver has seen this done before	Yes; only if done correctly	No; not necessarily	IMITATION	Copying what you've seen another worker do in a similar situation
	LOW	HIGH	If driver trying to make it home on time (i.e. running late) AND does not have required knowledge of route OR when environment is potentially dangerous e.g. icy	Yes	Yes; under right conditions	AVOIDANCE	Delaying/not performing task
		LOW	If driver is running late, and/or there is someone nearby to help guide vehicle into position (reducing risk of incident), and/or driver has done this before	Yes	Yes	OPTION-BASED	Process of elimination of options by reasoning, evaluation or 'rule-of-thumb'
LOW	HIGH	HIGH	If cues are consistently present and accessible (e.g. nature of sky/ tree branches in wind/snow gathered in branches, haptic feel from steering wheel, sound from engine revs/speed, indications that Opticruise is not working quickly enough)	Yes	No; not necessarily	CUE-BASED	Include & exclude possible actions by taking signals from environment into account
		LOW	If weather conditions dictate AND/OR if law dictates	No; not always	No; not preferred	COMPLIANCE	Follow a written procedure
	LOW	HIGH	"Basically, all the time you've got to do that" E.g. if driver is coming to a corner, needs to think about a proper speed to negotiate the curve and conditions	Yes	Yes	ANALYTICAL REASONING	Involves mental simulation of possible outcomes
		LOW	"Most times it is this one" Especially if vehicle configuration has good tyres	Yes	Yes	INTUITIVE	Tasks executed automatically (i.e. routine tasks)

Table 5.21: Strategies Analysis for driving the vehicle gently, safely and efficiently on a timber/off-road path, pre- or post-pickup

TIME PRESSURE	RISK LEVEL	DIFFICULTY LEVEL	STRATEGY PROMPT	ACCEPTED	PREFERRED	STRATEGY TYPE	STRATEGY TYPE DESCRIPTION
HIGH	HIGH	HIGH	Not applicable	N/A	N/A	ARBITRARY	Performed quickly without relevant experience OR consideration of options
		LOW	Not applicable	N/A	N/A	IMITATION	Copying what you’ve seen another worker do in a similar situation
	LOW	HIGH	If on a road that’s been heavily tracked (i.e. with harvesting machines which take mud out onto road)	Yes	Yes; for those situations	AVOIDANCE	Delaying/not performing task
		LOW	Not applicable	N/A	N/A	OPTION-BASED	Process of elimination of options by reasoning, evaluation or ‘rule-of-thumb’
LOW	HIGH	HIGH	If road condition, curvature, space, weather, timber configuration, steering feel necessitates	Yes	Yes	CUE-BASED	Include & exclude possible actions by taking signals from environment into account
		LOW	Not applicable	N/A	N/A	COMPLIANCE	Follow a written procedure
	LOW	HIGH	If in extreme weather conditions (e.g. torrential rain or a freak snow storm usually on high altitude ground) If the vehicle configuration/set up isn’t appropriate	Yes; for those situations	No	ANALYTICAL REASONING	Involves mental simulation of possible outcomes
		LOW	Mostly	Yes	Yes	INTUITIVE	Tasks executed automatically (i.e. routine tasks)

Table 5.22: Strategies Analysis for driving the vehicle gently, safely and efficiently while lead vehicle drives close in front

TIME PRESSURE	RISK LEVEL	DIFFICULTY LEVEL	STRATEGY PROMPT	ACCEPTED	PREFERRED	STRATEGY TYPE	STRATEGY TYPE DESCRIPTION
HIGH	HIGH	HIGH	If coming on to a motorway AND driver on inside lane AND driver doesn’t move out by time you are at end of slip road OR if another driver cuts you off AND/OR if you get a fright	Yes	No	ARBITRARY	Performed quickly without relevant experience OR consideration of options
		LOW	Not applicable	N/A	N/A	IMITATION	Copying what you've seen another worker do in a similar situation
	LOW	HIGH	If trying to maintain momentum	Yes	Yes	AVOIDANCE	Delaying/not performing task
		LOW	If you notice foreign license plates/caravanette/bicycles AND/OR if you notice make of car AND/OR if you can gauge driver age/experience/ “dottery”	Yes	Yes	OPTION-BASED	Process of elimination of options by reasoning, evaluation or 'rule-of-thumb'
LOW	HIGH	HIGH	If you notice vehicle is too close in mirror AND/OR if vehicle sensors alert AND/OR if windows are open and can hear approaching vehicle	Yes	Yes	CUE-BASED	Include & exclude possible actions by taking signals from environment into account
		LOW	If vehicle is not acting erratically	Yes	No	COMPLIANCE	Follow a written procedure
	LOW	HIGH	If weather conditions necessitate (e.g. ice or rain)	Yes	No	ANALYTICAL REASONING	Involves mental simulation of possible outcomes
		LOW	Most of the time he's using this strategy	Yes	Yes	INTUITIVE	Tasks executed automatically (i.e. routine tasks)

The process of completing an AH, ADS, CAT, followed by the prioritisation of functions and situations, enabled the problem space to be reduced and for specific design interventions to emerge. In this case, the combination of risks, difficulty, and strategies pointed to an optimised on-board camera system. The optimised system would provide different perspectives to enable drivers to manoeuvre with precision on slippery and/or off-road terrain. Indeed, several participants throughout the CWA commented informally on the usefulness of better visibility in such a large and unwieldy vehicle configuration. Based on the StrAn outputs, Scania only supported strategy types accepted and preferred by the user, which were: avoidance, cue-based, analytical reasoning, and intuitive. Three out of four of these accepted strategy types are defined by Hassall et al. (2012) as applying to high difficulty activities, confirming the accuracy of our method of selecting high effort situations. Likewise, Scania gained insight into which strategy types should not be promoted by the future system, at the risk of alienating the user and fostering undesirable emergent behaviours.

5.4.4. Final product: Camera system for precision-manoeuvring of timber trucks

This analysis led to the development of a camera system designed to enable the precision-manoeuvring of timber trucks. Configurations of these camera systems will vary with the specifications of different timber haulage vehicles (placement and dimensions of lifting cranes, trailer(s), external cab accessories etc.). General promotional descriptions of the multi-lens on-board camera system is featured in Figures 5.11 and 5.12 below.

REAR VIEW CAMERAS

When manoeuvring a truck at loading bays or in tight spaces there is always a risk of cosmetic damage or broken lights. Up to three cameras can be linked to the same monitor. These extra eyes show what is happening around the truck and make the driver's job easier, safer and more effective. Improving visibility means improving safety. The cameras are 100% waterproof and feature heated lenses that eliminate frost and moisture problems. Scania camera systems conform to the latest CE, ADR, RFI, VDE and EMC specifications.

Figure 5.10: Description of Scania rear view cameras available for inclusion on multi-lens on-board camera system for precision manoeuvring

THE AUTOMATIC SOLUTION

Sustainability is the key challenge facing global transport. We need to find new, more efficient and environmentally viable ways to move goods and people. Scania embraces this challenge.

Welcome to **Autonomous Transport Systems** Scania's latest contribution to the future of sustainable transport.

GPS
The GPS gives the vehicle's position down to a few metres and allows the vehicle to plan its route. The manoeuvring required to follow the route is supported by the sensors and data fusion.

AUTOMATION CONTROL UNIT
Houses the vehicle's on-board intelligence and executes all automation and assistance functions. Collects data from the vehicle's numerous sensors and combines it to give a comprehensive view of the surrounding area. The control unit also receives transport missions from the off-board logistics system and translates them into instructions that the vehicle systems can understand.

MOBILE DATA LINK
The mobile data link is the vehicle's communication channel for receiving transport missions, reporting its status and performance, and sharing perception data with other autonomous vehicles.

POWERTRAIN SYSTEM
Scania's intelligent powertrain handles the truck's propulsion with the highest precision and energy efficiency. The central powertrain control system controls the engine, gearbox, clutch and auxiliary brakes.

SHORT RANGE RADAR
Mounted at each corner of the vehicle, the short-range radars provide 360-degree detection of other vehicles and pedestrians. They function in all weathers and light conditions.

INERTIAL SENSORS
The inertial sensors measure the rotation and acceleration of the vehicle to help the automation control unit calculate how it is moving.

WHEEL SPEED SENSORS
By measuring the rotation of each wheel, the automation control unit can calculate how the vehicle moves and turns.

LONG RANGE RADAR
With its range of up to 200 metres in front of the vehicle, the long-range radar enables high speed driving.

ELECTRONICALLY ASSISTED STEERING
EAS is an electrohydraulic system that enables the automation and assistance functions to safely steer the vehicle along roads and around obstacles.

MULTI-LENS CAMERA
Mounted behind the windscreen, the multi-lens camera monitors the area in front of the vehicle to detect objects, vehicles, pedestrians and lane markings. With stereoscopic vision, it can see the shape of the ground in much the same way a human can.

Figure 5.11: Multi-lens camera system featured in next-generation Scania HGVs

5.5. Conclusions

A first of its kind WDA for truck-driver systems was developed in this Chapter to model the truck driving work system. The associated CAT generated a monstrous 690 possible intersections between functions and situations. The prioritisation method developed by the author and Scania collaborators narrowed this down by well over 90% to a much more manageable 33 cells. Not only did this method significantly reduce the number of activities to be considered, it did so in a way that carefully considered concepts of complexity and emergence. This approach provides a dual contribution to theoretical study (navigation of complexity between scales) and practical design (enabling a faster – and still effective – approach for design within large-scale systems). Further discussion put these activities in the context of current and future technology, explored the ripple effects of new designs on wider organisational practices, and considered different situation types. These discussions, and the selected strategy types (intuitive, cue-based, and analytical reasoning) informed the final technology, led by Scania's in-house design process. As a direct result of this research an optimised on-board camera system designed to assist precision-manoeuvring on slippery and/or off-road terrain will be included in Scania's next generation of heavy timber vehicles.

This Chapter has clearly demonstrated the power of CWA in guiding the design of future technologies in large-scale and complex systems. Whilst HF/E insights in the logistics domain are not mature, the advantage is it becomes possible to leap frog the current state of science and alight on cutting edge approaches like CWA. The user-centred design of the camera system to be implemented by Scania has been driven directly from this approach, demonstrating a significant original contribution to practice and methodology. From this work it is clear that human factors methods have an impactful role to play in practical and holistic design in every corner of logistics systems. Past applications of CWA have successfully evaluated and redesigned systems which have already experienced an unexpected or even dangerous incident. In this chapter CWA has been newly applied to robustly design truck technology in a way that promotes user adaptability and system resilience before an incident occurs. In doing so, this chapter has made progress on the following research sub-questions:

- *How can current logistics gaps be appropriately addressed by human factors methods? (SRQ4)*

- *How can the truck-driver system be represented in a functional, technologically agnostic way? (SRQ5)*
- *How can we estimate future system conditions, and test future system functionality before implementation? (SRQ6)*

This Chapter has introduced the power of human factors methods to the practical reality of the truck-driver system, and developed a new more tractable approach to CWA for large-scale systems. In doing so it meets both challenges presented in the introduction. It shows how HF/E methods can cope with complexity, whilst at the same time being tractable and usable. Inspired by this, the next chapter will move beyond a specific design case study to investigate how the domain at large is likely to change over time. Moreover, how social and technical factors will co-evolve with future logistics systems.

Chapter 6:

Analytically Prototyping Truck-Driver Systems with WDA & Network Analysis

6.1. Introduction

The evolution of the future truck as forecast in Chapter 2 describes a logistics landscape with increasingly complex automation. The nature of this increasing reliance on technology, as seen in Chapters 4 and 5, is very likely to increase negative effects on system performance without HF/E insights. This is a universal theme. At the turn of the 21st century one of the pioneers of cognitive systems engineering, Jens Rasmussen (2000, p. 869), warned that increased automation could promote unexpected, emergent behaviours if we do not track and strategise behavioural co-evolution along with our technological systems. The HTAoCD and TNAoCD outputs presented in Chapter 4 provide a view of future scenarios, highlighting the changing requirements of future truck drivers (and the associated training needs). Chapter 5 went further with a CWA-based approach which examined the constraints and affordances within the commercial driving system and how technology could be implemented in a way that avoids unexpected outcomes. The use of CWA need not be confined to the development of a specific technology in a specific domain of commercial driving. It has wide applicability which can be exploited in this Chapter, due to the fact that it is ‘technologically agnostic’, i.e. according to Jenkins et al. (2011, p. 4) CWA can model change where “new technology has been introduced to perform the same processes as the legacy system in a different way”. A first of its kind formative view of future truck-driver scenarios will be developed through the application of WDA and social network analysis. This enables a highly novel analytical prototyping approach to be applied to the truck-driver ‘work system’. In the course of this chapter, therefore, the following research sub-questions will once again be addressed:

- *How can the truck-driver system be represented in a functional, technologically agnostic way? (SRQ5)*
- *How can we estimate future system conditions, and test future system functionality before implementation? (SRQ6)*

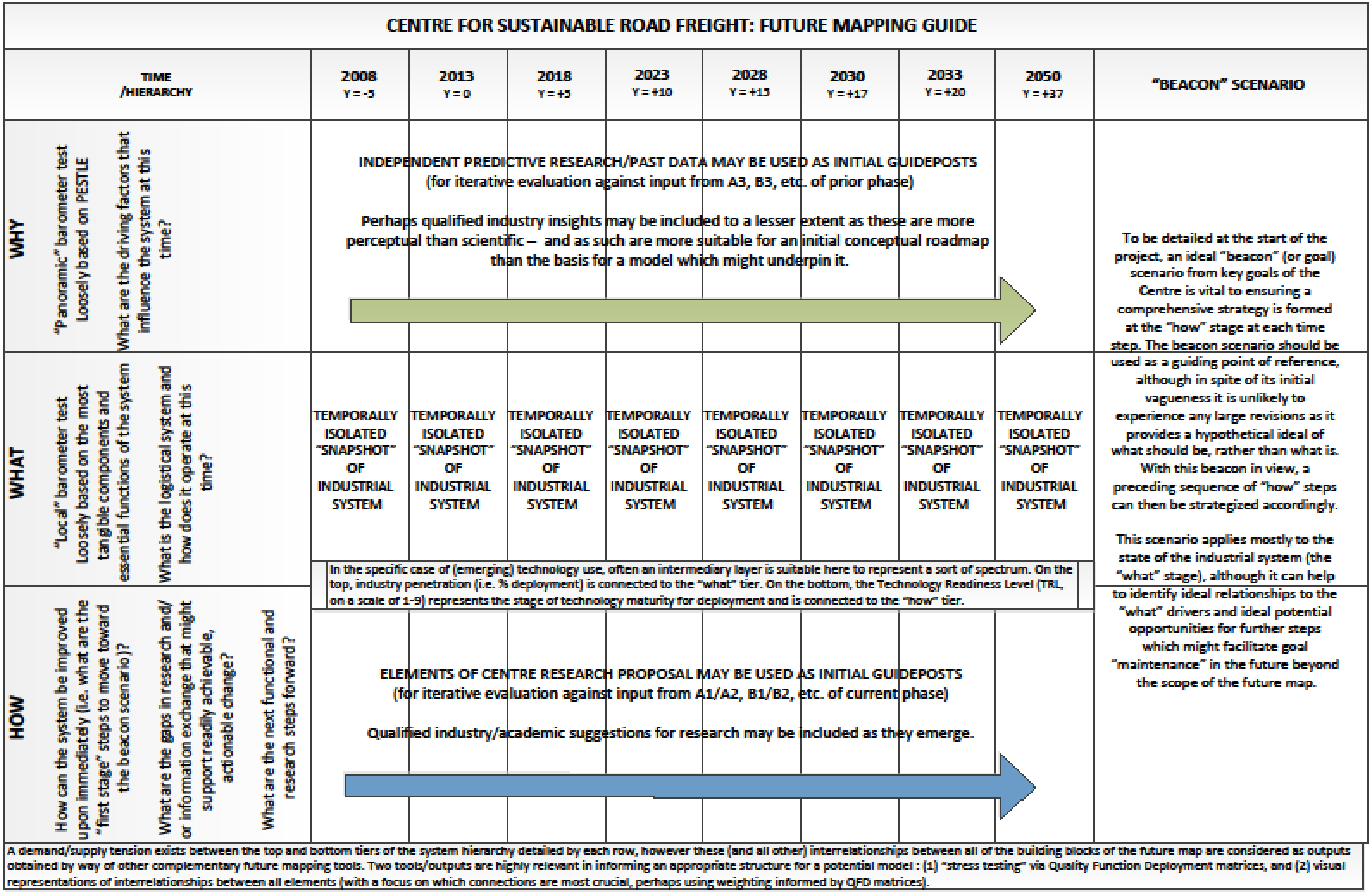
6.1.1. Potential for road-mapping

As we have seen throughout this thesis, forecasting future scenarios will critically influence the success of future system designs. Approaches such as scenario planning are increasingly being used as tools for learning, foresight, and strategic leadership (Farber & Lakhtakla, 2009). Currently requirements generation occurs for products or systems during or after a system is already in the design stage or even in widespread use; there is a distinct lack of cases where this occurs prior to the realisation of a system (McIlroy & Stanton, 2012). Forecasting future scenarios can circumvent this by analytically prototyping the resultant future systems.

Logistics and operations management research has utilised road-mapping as a strategic planning tool to determine optimal next steps (an example is shown in Figure 6.1 below). Generally, data collection takes the form of an interactive workshop where SMEs populate a working model of the system, highlight and timeline the most salient problems ahead, and brainstorm steps to work toward solutions. Participants normally include individual stakeholders representative of different viewpoints of this system to produce the most complete 'model' possible.

To resolve the Triple Bottom Line (TBL) operational tensions which have persisted for decades, and which guide this entire research endeavour, it has been argued we need a new kind of system model (Rasmussen, 2000) and a new kind of scenario planning (Masys, 2012). Not necessarily to predict what will certainly happen, but to explore and prepare for what might happen (Chapman, 2005). In order to accomplish this, there is a need to shift to greater use of formative rather than normative methods, an approach adopted by this thesis in every chapter including but not limited to the frequent use of Cognitive Work Analysis.

As can be seen in Figure 6.1, strategic future-mapping exercises aimed at guiding effective interventions appear to have some superficial similarities to an Abstraction-Decomposition Space.



CENTRE FOR SUSTAINABLE ROAD FREIGHT: FUTURE MAPPING GUIDE

TIME /HIERARCHY	2008 Y = -5	2013 Y = 0	2018 Y = +5	2023 Y = +10	2028 Y = +15	2030 Y = +17	2033 Y = +20	2050 Y = +37	"BEACON" SCENARIO
WHY "Panoramic" barometer test Loosely based on PESTLE What are the driving factors that influence the system at this time?	INDEPENDENT PREDICTIVE RESEARCH/PAST DATA MAY BE USED AS INITIAL GUIDEPOSTS (for iterative evaluation against input from A3, B3, etc. of prior phase) Perhaps qualified industry insights may be included to a lesser extent as these are more perceptual than scientific – and as such are more suitable for an initial conceptual roadmap than the basis for a model which might underpin it.								To be detailed at the start of the project, an ideal "beacon" (or goal) scenario from key goals of the Centre is vital to ensuring a comprehensive strategy is formed at the "how" stage at each time step. The beacon scenario should be used as a guiding point of reference, although in spite of its initial vagueness it is unlikely to experience any large revisions as it provides a hypothetical ideal of what should be, rather than what is. With this beacon in view, a preceding sequence of "how" steps can then be strategized accordingly. This scenario applies mostly to the state of the industrial system (the "what" stage), although it can help to identify ideal relationships to the "what" drivers and ideal potential opportunities for further steps which might facilitate goal "maintenance" in the future beyond the scope of the future map.
WHAT "Local" barometer test Loosely based on the most tangible components and essential functions of the system What is the logistical system and how does it operate at this time?	TEMPORALLY ISOLATED "SNAPSHOT" OF INDUSTRIAL SYSTEM	TEMPORALLY ISOLATED "SNAPSHOT" OF INDUSTRIAL SYSTEM	TEMPORALLY ISOLATED "SNAPSHOT" OF INDUSTRIAL SYSTEM	TEMPORALLY ISOLATED "SNAPSHOT" OF INDUSTRIAL SYSTEM	TEMPORALLY ISOLATED "SNAPSHOT" OF INDUSTRIAL SYSTEM	TEMPORALLY ISOLATED "SNAPSHOT" OF INDUSTRIAL SYSTEM	TEMPORALLY ISOLATED "SNAPSHOT" OF INDUSTRIAL SYSTEM	TEMPORALLY ISOLATED "SNAPSHOT" OF INDUSTRIAL SYSTEM	
	In the specific case of (emerging) technology use, often an intermediary layer is suitable here to represent a sort of spectrum. On the top, industry penetration (i.e. % deployment) is connected to the "what" tier. On the bottom, the Technology Readiness Level (TRL, on a scale of 1-9) represents the stage of technology maturity for deployment and is connected to the "how" tier.								
HOW How can the system be improved upon immediately (i.e. what are the "first stage" steps to move toward the beacon scenario)? What are the gaps in research and/ or information exchange that might support readily achievable, actionable change? What are the next functional and research steps forward?	ELEMENTS OF CENTRE RESEARCH PROPOSAL MAY BE USED AS INITIAL GUIDEPOSTS (for iterative evaluation against input from A1/A2, B1/B2, etc. of current phase) Qualified industry/academic suggestions for research may be included as they emerge.								

A demand/supply tension exists between the top and bottom tiers of the system hierarchy detailed by each row, however these (and all other) interrelationships between all of the building blocks of the future map are considered as outputs obtained by way of other complementary future mapping tools. Two tools/outputs are highly relevant in informing an appropriate structure for a potential model : (1) "stress testing" via Quality Function Deployment matrices, and (2) visual representations of interrelationships between all elements (with a focus on which connections are most crucial, perhaps using weighting informed by QFD matrices).

Figure 6.1: Typical road-mapping process for logistics & operations management research

Firstly, road-maps like these are often constrained to one possible set of outcomes, being flexible only in the timeline by which these events will occur. This is because strategic future-mapping exercises are designed to construct an ideal 'end state' and hypothesise the optimal way to achieve it. This is useful in describing shared goals between stakeholders and triangulating the most realistic timeline for all involved parties, but it is only a framing exercise for high-level decision-makers. In reality, operational "snapshots" defined in the middle row of the road-map should be treated as whole systems in and of themselves from the first workshop, not just when revisiting the model years later. This is the only way to truly test system functionality for vulnerability to non-designed behaviours. This would also enable the estimation of when transitional stages, brought about by non-designed "tipping points", are most likely to occur. In other words, existing future-mapping approaches represent systems as complicated, not complex, and certainly not adaptive.

Secondly, traditional road-mapping approaches at best mix – and at worst, confuse – action-oriented and means-end links within the same model without differentiating the two. While action-oriented links describe the *tasks or activities* required to achieve an end, structural means-end links (such as those in an Abstraction Hierarchy) describe the *properties of an environment* required for achieving an end (Naikar, 2013, p. 31). If these two types of connections were used separately, the use of action-oriented links on the x-axis only and means-end links on the y-axis only would perhaps alleviate this methodological concern. However, the structure of the road-map is further muddled by using means-end links between the top two rows of the road-map, and action-oriented links between the bottom two rows of the road-map.

Thirdly, SME participants are often new to this type of road-mapping technique and have limited time to devote to learning it. The theoretical concern about link types presents a practical challenge, in that the traditional method (let alone some future method) necessitates complicated instructions in an approach designed to grapple with an already complex system.

The question arises, based on experience in the previous Chapter, whether CWA, and WDA specifically, can address these three concerns. Scenario mapping has been carried out using WDA approaches to test pre-existing activities such as training exercises (Burns, et al., 2001), but so far at least it has not been extended to likely future scenarios. It has been suggested that CWA/WDA has the potential to map research findings directly to real, future systems (Dekker & Nyce, 2004; Jenkins, et al., 2011), but applied examples are rare. A research gap therefore emerges into which the work of this Chapter can fill.

6.1.2. WDA 2.0: New insights for social network analysis

All of this makes clear a need for better, more structured road-mapping tools, potentially by extending an existing human factors method like the Abstraction Hierarchy (AH). The principle in play is whether there is a way to quantify the structure of an AH, and to systematically explore what happens to that structure when functions and/or means/ends links are added or removed under future scenarios. In other words, how does the 'space of possible behaviours' change. Indeed, are new behaviours enabled or desired behaviours restricted? An AH is, in essence, a form of network. It comprises nodes and links. A method that can use the disposition of nodes and links as an input is Social Network Analysis (SNA). SNA has been exploratvely applied to action-oriented networks in Social and Organisational Cooperation Analysis (SOCA), a latter stage of CWA (Houghton, et al., 2015). It has also recently been applied directly to AH-based analyses in order to investigate flood vulnerability (Beevers, et al., 2016). It is therefore possible to apply the same technique to an AH of the commercial driving system and use it to analytically prototype a range of future 'functional' scenarios and to test, in a very direct way, what desirable and undesirable behaviours may emerge under different future conditions.

In this Chapter, truck-driver work systems from 2015, 2020, 2025, and 2030 will again be analytically prototyped but this time using a highly novel combined WDA/road-mapping/SNA approach. This has the potential to explore if some constraints are functionally more critical than, or otherwise different from, others. Using network metrics to analyse the AH is also a unique way of characterising how changes elsewhere in the work system affect 'system schema' (represented by VPM). The following sections test this functionality, reveal interactions and unintended impacts, and provide insights which might allow system designers to co-evolve with future operations. This approach also has the benefit of making extremely large and complex systems more tractable for analysts and other stakeholders by taking a reproducible, quantifiable approach which pinpoints specific areas for further research. This will reflect the evolution of the system over time with a more structured, yet still formative, approach.

6.2. Methods

6.2.1. Design

As seen in Chapter 5, Abstraction Hierarchies (and other CWA outputs) for truck-driver systems can become extremely large and intractable. This calls for some additional methodological structure to be developed in order to obtain meaningful real-world outputs. Not only is the present-day (2015) logistics scenario large and intractable, future scenarios (as suggested in Chapter 5 for 2020, 2025, and 2030) present new and potentially complex challenges for system design. To better grasp these changes and challenges, the following study harnesses the metrics used in network theory, namely betweenness centrality, and applies them to the AH. Betweenness centrality provides a numeric value for the relative importance of an AH node to the functionality of the overall AH as a whole. Betweenness centrality is given by the formula:

$$g(v) = \sum_{s \neq v \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}}$$

where σ_{st} is the total number of shortest paths from node s to node t and $\sigma_{st}(v)$ is the number of those paths that pass through v.

Centrality score results were analysed in two ways. The first method was to report the top three nodes at each level of the AH, for each time step (2020, 2025 and 2030). This was due to the fact that the imposed hierarchical structure of the AH ‘network’ disallowed the possibility for all nodes to be connected all other nodes as would be the case for a typical social network. Centrality scores would be mathematically disadvantaged in this case, particularly those at the FP and PO levels which are placed at the ‘edge’ of the network and thus limited in their potential connectivity. The second method was to present a high-level overview of the top 25 nodes in each network. This way of tracking system changes was possible by comparing a network against another version of itself.

6.2.2. Materials & procedure

In order to complete this study the following steps were performed:

1. The WDA for timber trucking was adapted from Chapter 5 to widen its applicability to general truck-driver systems.

2. The technology trajectory presented in Chapter 2 was then used as an input to adapt the general trucking WDA for future scenarios in 2020, 2025, and 2030. This was done by reviewing the technology trajectory one time step at time (using Figures 2.1, 2.2, and 2.3 as guidance for individual time steps), considering one future technology at a time in rough order of their likely implementation, and adding this to the Physical Objects (PO) level. Where a new technology also enabled a new Object-Related Process (ORP), Generalised Function (GF), Value and Priority Measure (VPM), or Functional Purpose (FP), this was also included. For example, aerodynamic fittings enable the ORP 'reduces drag', which is only newly required due to the VPM 'minimise emissions/environmental impact'.
3. An open-source Excel software add-on – NodeXL – was used for all AH network calculations and visualisations. Each scenario (2015, 2020, 2025, and 2030) was analysed for betweenness centrality of all network nodes. Relevant results are reported in this Chapter; however full data and results tables can be found in Appendix F.
4. For each time step, the top three most central nodes at each level of the hierarchy were presented in tables. The FP level was disregarded, as it included just one node. From 2020 onward, the three 'most changed' nodes at each level of the hierarchy were also reported.
5. To gain an overall view of the network and changes over time, the top 25 nodes regardless of AH level were reported for each time step.
6. Abstraction Hierarchies for each time step were displayed. From 2020, new additions to the network were indicated by shading. For 2020, this shading is red; in 2025, orange; and in 2030, yellow.
7. Abstraction-Decomposition Spaces (ADS) were displayed for each time step. To illustrate 'where' the top 25 nodes were located within the overall network, these were indicated in the ADS by shading. In the 2015 scenario purple shading indicates a node which is highly central to the AH. For 2020, this 'highly critical' shading is red; in 2025, orange; and in 2030, yellow. After 2015, blue shading was used to highlight nodes which had fallen from the top 25 highest centrality rankings at each time step (e.g. a node which was highly central in the previous scenario but was no longer highly central in the current scenario). For clarity this was presented in 'concertina style' tables which open and collapse different levels of the network.

6.3. Results & discussion

6.3.1. Current day: Scenario 2015

The 2015 scenario was first adapted from the existing timber trucking WDA presented in Chapter 5. This involved minor changes to nodes and their descriptions at the Physical Objects and Object-Related Processes levels – e.g. 'crane' was deleted, and 'pick up/load vehicle with timber' became 'pick up/load vehicle with goods' – but did not involve any structural changes to the means-end links. In the general 2015 scenario the abstraction hierarchy (portrayed in Figure 6.2 further below) consists of 219 individual nodes and 329 distinct edges; this is an enormous and heavily interconnected system. The top three nodes at each AH level (aside from the FP level, which consists of only one node) are shown here in Table 6.1.

Table 6.1: Top three nodes at each level of 2015 abstraction hierarchy

Level of Abstraction Hierarchy	Top three nodes at each level (by betweenness centrality score)		
	1	2	3
Values & Priority Measures	Minimise financial cost/loss of time (6249.66)	Maximise safety (1756.8)	Ensure provision of goods to customer (621.32)
Generalised Functions	Drive vehicle (basic, operational, & tactical tasks) (10263.42)	Connect trailer to vehicle/enable delivery to site (3304.97)	Plan schedule/ pickups/ route/ rest periods (3041.09)
Object-Related Processes	Provides visual or auditory alerts others to presence (2250.95)	Provides info on vehicle & trailer weight (1803.18)	Enables driver feedback receptors (vision, hearing, and/or proprioception) (1789.89)
Physical Objects	Engine Control Unit/ computer (2740.79)	Driver (891.32)	Cab (including windows/ windscreen) (144.08)

Overall, the nodes with the top 25 greatest values for betweenness centrality can be seen in Table 6.2 below. We do not need a method to tell us that the most important element of the current truck-driver system is the function of driving a vehicle, however, some other nodes in this ranked table may be slightly more surprising. The driver does have a place in the top 25, but it is lower on the list than we might imagine. This could be in part because the technologically agnostic approach of WDA means all objects which complete the same process are treated equally. Nevertheless, the driver's place in contrast to the Engine Control Unit (the other 'decision-making' object) is striking. These are the only two nodes from the Physical Objects level included in the top 25, yet the ECU is ranked 17 positions above the driver and has over 3x the centrality value.

Table 6.2.: Top 25 nodes with greatest centrality, 2015

Rank	Node	Betweenness Centrality
1	Drive vehicle (basic, operational, & tactical)	10263.42
2	Minimise financial cost/loss of time	6249.66
3	Connect trailer to vehicle/ enable delivery	3304.97
4	Plan schedule/pickups/route/rest periods	3041.09
5	Engine Control Unit/computer	2740.79
6	Identify and relay service issues	2619.13
7	Provides visual or auditory alerts others to presence	2250.95
8	Pick up/load vehicle with goods	1852.19
9	Provides info on vehicle & trailer weight	1803.18
10	Enables driver feedback receptors (vision, hearing, proprioception)	1789.89
11	Communicate/collaborate w/ drivers/transport dispatcher	1765.10
12	Maximise safety	1756.81
13	Ensure occupational health/comfort of worker	1726.98
14	Unload goods	1602.16
15	Protect/ensure immediate safety of worker	1564.14
16	Facilitates work environment	1509.06
17	Enables change in vehicle speed	1412.79
18	Ensure operation within existing law	1233.78
19	Provides info on cargo area	1105.47
20	Stabilises/secures cargo	1089.48
21	Protect vehicle from being damaged	1004.49
22	Driver	891.32
23	Enables vehicle start-up	849.99
24	Prioritises/selects next driving steps	788.68
25	Ensures vehicle and cab are functional/fit for purpose	758.50
	SUM TOTAL ALL NODES IN NETWORK	76800.24

The abstraction-decomposition space for this time step can be seen across Tables 6.3 through 6.5.

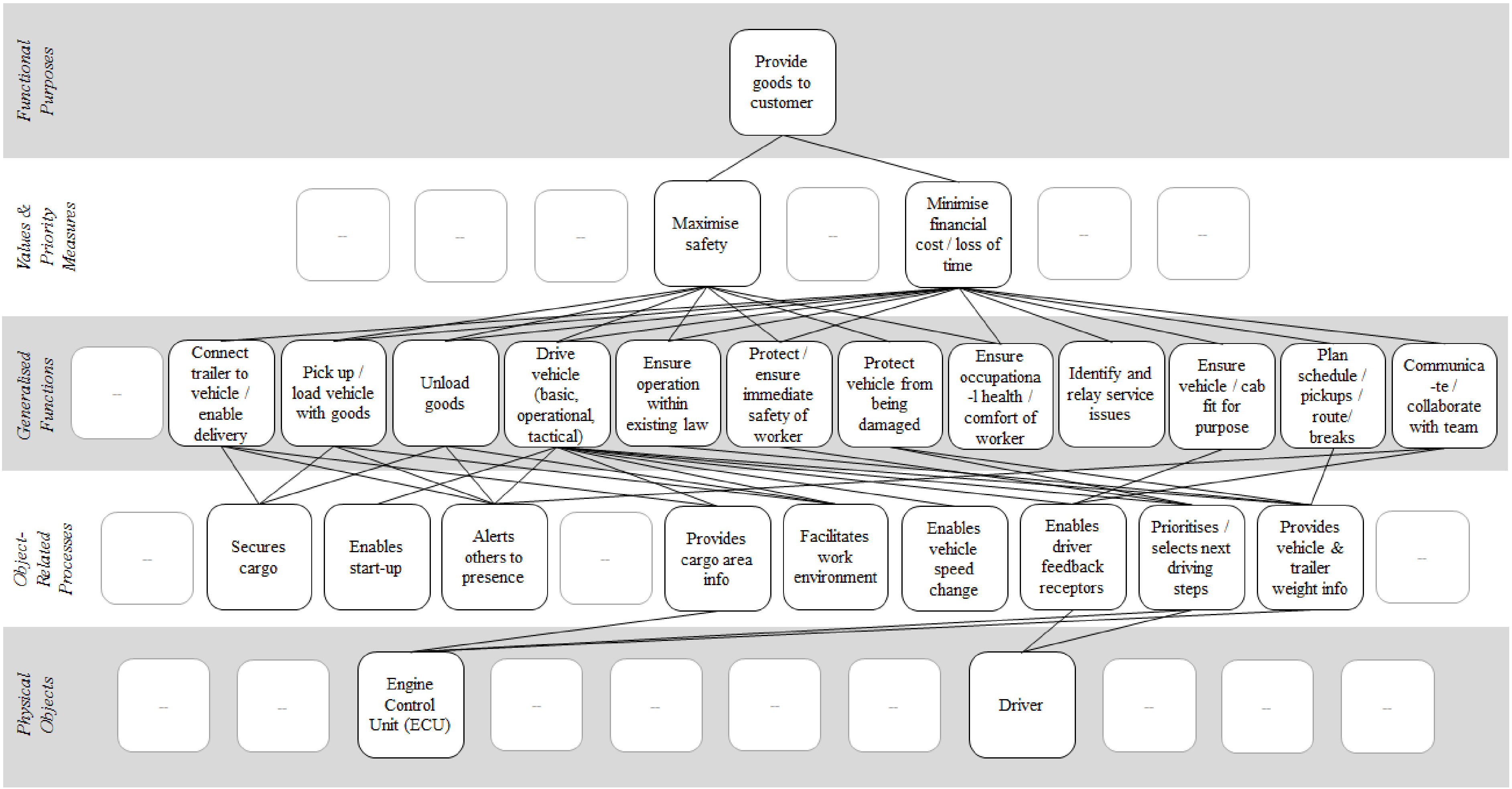


Figure 6.2: Excerpt of Abstraction Hierarchy for truck-driver systems (2015) highlighting high centrality nodes

Table 6.3: 2015 Abstraction-Decomposition Space Part 1 – Functional Purposes at whole system level, Values & Priority Measures at sub-system level, & Generalised Functions at functional unit level

	Whole System	Sub-System	Functional Unit	SA	C
Functional Purpose	• Provide goods to customer				
Values & Priority Measures		• Ensure provision of goods to customer • Maximise "forebearing, gentle driving style" • **Maximise safety** • **Minimise financial coast / loss of time** • Maximise user/worker health/comfort • Maximise vehicle/system reliability • Maximise efficiency / miles driven loaded • Maximise flexibility in routine			
Generalised Functions			• **Connect trailer to vehicle / enable delivery** • **Pick up / load vehicle with goods** • **Unload goods** • Fuel/refuel • **Drive vehicle** • **Ensure operation within existing law** • **Protect/ensure immediate safety of worker** • **Protect vehicle from being damaged** • **Ensure occ. health / comfort of worker** • **Identify and relay service issues** • Ensure security of vehicle • **Ensure vehicle / cab fit for purpose** • **Plan schedule / pickups/route/breaks** • **Communicate / collaborate w/ team**		
ORP					
PO					

***bold font in purple shading** indicates one of top 25 high centrality nodes in current (2015) scenario

Table 6.4: 2015 Abstraction-Decomposition Space Part 2 – Object-Related Processes at the sub-assembly level

	WH	SS	FU	Sub-Assembly			C
FP							
VPM							
GF							
Object-Related Processes				• Adjusts seat	• Alerts to door status	• Enables trailer locomotion	
				• Fulfil order	• Provides traffic info	• Stores vehicle / system info	
				• Stores cargo	• Attaches label to goods	• Provides info on current time	
				• Secures cargo	• Protects vehicle body	**• Facilitates work environment**	
				• Secures trailer	• Stores navigation info	**• Enables vehicle speed change**	
				• Deploys airbag	• Provides info on temp.	• Provides air line pressure info	
				• Alerts to smoke	**• Alerts others to presence**	• Prevents dirt/water/ice build-up	
				• Enables start-up	**• Provides cargo area info**	• Lifts/adjusts cargo to/from trailer	
				• Minimises noise	• Protects worker's hands	**• Enables driver feedback receptors**	
				• Stabilises human	• Stabilises/protects tools	• Alerts to status of cab area hazards	
				• Connects air lines	• Maintains temp./climate	• Enables worker to get into position	
				• Stores fuel/power	• Alerts to lack of seatbelt	• Presents info on sub-system fitness	
				• Provides traction	• Alerts to brake pad wear	• Stores cargo description & location	
				• Connects brakes	• Provides info on oil level	• Identifies system not fit for purpose	
				• Connects power	• Provides info on location	**• Prioritises/selects next driving steps**	
				• Connects trailer	• Provides oil pressure info	• Provides current ignition setting info	
				• Stores cargo info	• Presents coolant level info	**• Provides vehicle & trailer weight info**	
				• Provides fuel/power	• Alerts to low tyre pressure	• Provides info on current day/driver drive times	
				• Enables locomotion	• Provides info on fuel level	• Provides info on other system/vehicle characteristics	
				• Provides RPM info	• Controls vehicle trajectory	• Acts as supporting infrastructure for communications	
				• Provides speed info	• Facilitates refuelling point	• Enables communication pathway/ passage of information	
PO							

***bold font in purple shading** indicates one of top 25 high centrality nodes in current (2015) scenario

Table 6.5: 2015 Abstraction-Decomposition Space Part 3 – Physical Objects at the Component Level

	WH	SS	FU	SA	Component
FP					
VPM					
GF					
ORP					
Physical Objects					• Fuel tank • Battery • Gear box • Clutch • Fuel • Tyres • Airbags • Horn • Ignition • Steps • Keys • Crane • Laptop • Satellite • Mirrors • Bumper • **Driver** • Paper • Ink • Printer • Clock • Map • Seatbelts • Hand rails • Break area • Generator • Cargo/goods • Brake pedal • Steering wheel • External lights • Internal lights • Vehicle seats • Hazard lights • Work gloves • Seat controls • Radio/media • Mobile phone • Laptop mount • Trailer body • Fuel station • GPS system • Indicators • Alarm (doors) • Alarm (smoke) • Pen/pencil • Gear stick • Food/drink • Adhesive/staple • Roadway/path • Trailer sheeting • Temperature controls • Windscreen wipers • High vis vest, etc • Accelerator pedal • Vehicle suspension • Front grill/bull bar • Engine (mechanical) • Mill/processing site • Window adjusters • Drawbar/kingpin • Breathalyser unit • Digital tachograph • Display (fuel level) • Display (RPM) • Display (speed) • Alarm (ignition) • Alarm (cab area) • Sensors (oil level) • Sensors (coolant) • Sensors (doors) • Sensors (other) • Sensors (smoke) • Sensors (ignition) • Trailer suspension • Trailer side barrier • Trailer ABS input • Driver tachograph card • Brake system hardware • Road navigation signs • Vehicle parking brake • Vehicle user manual • Ridged floor mats • Personal belongings • Windscreen defogger • GPS-enabled software • Orange traffic triangle • Central locking system • White smoke limiter button • Display (oil pressure) • Display (temperature) • Mech. warnings (on/off) • Display (coolant level) • Display (tyre pressure) • Alarm/display (other) • Sensors (brake pads) • Sensors (oil pressure) • Sensors (temperature) • Sensors (seat/seatbelts) • Trailer light hook-ups • Trailer parking brake • Trailer air hook-ups • Trailer ABS hook-ups • Roadside clearing/loading point • Cab (incl. windscreen/windows) • Cab heating & cooling systems • Land-based communications tower • Electricity fuses/connectors • **Engine Control Unit (ECU)** • Cargo paperwork/ID tags • Alarm (seatbelt reminder) • Alarm to indicate reversal • Display (vehicle/trailer weight) • Display (current fuel consumption) • Display (brake pad warning) • Display (oil level warning) • Display (air line pressure) • Mech. warning (not functional) • Mech. warning (comms. failure) • Sensors (air line pressure) • Tyre pressure monitoring sensors • Sensors (vehicle & trailer weight) • Sensors (cargo area issues) • Sensors (cab area e.g. grill) • Cargo chain hooks/clips/fasteners • Trailer air hook-up inputs • Trailer electricity hook-up inputs • Trailer steel wire adjusting button • Trailer cargo chains/straps, etc.

***bold font in purple shading** indicates one of top 25 high centrality nodes in current (2015) scenario

6.3.2. Time step 1: Scenario 2020

In the 2020 scenario (highlighted in red in Figure 6.3), the technology trajectory from Chapter 5 was used as input to add 14 new nodes and 57 new edges. An excerpt of these additions is shown in Figure 6.3, showing direct network changes. Due to some outdated forms of technology being removed in 2020, the net change from the 2015 case involved a 7.4% decrease in nodes and an 8.2% increase in edges. The distribution of added nodes was 78.6% at the physical objects level, 7.1% at the object-related processes level, 7.1% at the generalised function level, and 7.1% at the values and priorities level. The distribution of added edges was 78.9% connecting physical objects to object-related processes, 8.8% connecting object-related processes to generalised functions, and 12.3% connecting generalised functions to values & priority measures.

One noteworthy change from the 2015 scenario is the shift of many individual alarms and displays to a concentrated Advanced Driver Assistance System. With the introduction of objects which serve the sole purpose of minimising fossil fuel use, 2020 also sees the introduction of environmental impact considerations at a higher level (values & priority measures). The corresponding abstraction-decomposition space for this time step can be seen in Tables 6.9 through 6.11.

The top node at each level of the hierarchy remained stable between 2015 and 2020 but the second and third highest nodes for each level did experience changes in 2020. ‘Minimise emissions/environmental impact’ was a newly introduced node, and overtook the 2015 ‘Ensure provision of goods to customer’ as the third highest VPM. At the GF level, ‘Pick up/load vehicle with goods’ was a pre-existing node from 2015, but due to wider network changes in 2020, overtook ‘Plan schedule/pickups/route/rest periods’. At the ORP level, ‘Enables driver feedback receptors’ increased from third place in 2015 to second place in 2020, with ‘Enables change in vehicle speed’ being added as third.

Table 6.6: Top three nodes at each level of 2020 abstraction hierarchy

Level of Abstraction Hierarchy	Top three nodes at each level (by betweenness centrality score)		
	1	2	3
Values & Priority Measures	Minimise financial cost/loss of time (4033.49)	Maximise safety (1371.15)	Minimise emissions/environmental impact (929.30)
Generalised Functions	Drive vehicle (basic, operational, & tactical tasks) (7960.46)	Connect trailer to vehicle/enable delivery to site (2989.10)	Pick up/load vehicle with goods (1801.61)
Object-Related Processes	Provides visual or auditory alerts others to presence (1943.39)	Enables driver feedback receptors (vision, hearing, and/or proprioception) (1876.46)	Enables change in vehicle speed (1481.12)
Physical Objects	Engine Control Unit/ computer (1072.38)	Driver (432.11)	Cab (including windows/ windscreen) (120.20)

The introduction of ‘Minimise emissions/environmental impact’ nearby in the network, as well as other system changes in more distal areas of the network, contributed to the VPM ‘Minimise financial cost/loss of time’ being significantly reduced. The GF ‘Drive vehicle’ and the ORP ‘Provides info on vehicle & trailer weight’ were also heavily reduced.

Table 6.7: Three ‘most changed’ nodes between 2015 & 2020

Level of Abstraction Hierarchy	Nodes with largest difference in centrality at each level		
	1	2	3
Values & Priority Measures	Minimise financial cost/loss of time (-2216.27)	Minimise emissions/ environmental impact (+929.30)	Maximise safety (-385.66)
Generalised Functions	Drive vehicle (basic, operational, & tactical tasks) (-2302.97)	Identify and relay service issues (-1763.03)	Plan schedule/ pickups/ route/ rest periods (-1356.13)
Object-Related Processes	Provides info on vehicle & trailer weight (-880.33)	Presents info on driver’s hours/rest periods (-644.3)	Stores info on driver’s hours/rest periods (-341.85)
Physical Objects	ADAS feedback system with collision avoidance warnings (+2618.27)	Engine Control Unit/ computer (-1668.41)	Driver (-459.21)

Overall network metrics for the 2020 scenario (shown in Table 6.8) returned the same top 3 most central nodes as found in the 2015 base case – ‘drive vehicle’, ‘minimise financial cost/loss of time’, and ‘connect trailer to vehicle/enable delivery’. A few minor ranking adjustments were found thereafter, most notably the increased centrality of ‘enables change in vehicle speed’ and ‘provides fuel/power’ nodes.

Table 6.8: Top 25 nodes with greatest centrality, 2020

Rank	Node	Centrality	Change in Centrality from 2015	% Change in Centrality from 2015	Change in Rank from 2015
1	Drive vehicle (basic, operational, & tactical)	7960.46	-2302.97	-22.44%	0
2	Minimise financial cost/loss of time	4033.39	-2216.27	-35.46%	0
3	Connect trailer to vehicle/ enable delivery	2989.10	-315.87	-9.56%	0
4	ADAS feedback system w/ collision avoidance warnings	2618.27	*NEW*	*NEW*	*NEW*
5	Provides visual or auditory alerts others to presence	1943.39	-307.56	-13.66%	2
6	Enables driver feedback receptors (vision, hearing, proprioception)	1876.46	86.57	4.84%	4
7	Pick up/load vehicle with goods	1801.61	-50.58	-2.25%	1
8	Plan schedule/pickups/route/rest periods	1684.96	-1356.13	-44.59%	-4
9	Communicate/collaborate with other drivers/transport dispatcher	1496.04	-269.06	-15.24%	2
10	Enables change in vehicle speed	1481.12	68.34	4.84%	7
11	Maximise safety	1371.15	-385.66	-21.95%	1
12	Facilitates work environment	1360.90	-148.16	-9.82%	4
13	Ensure occupational health/comfort of worker	1339.01	-387.97	-22.47%	0
14	Unload goods	1317.32	-284.84	-17.78%	0
15	Protect/ensure immediate safety of worker	1298.36	-265.78	-16.99%	0
16	Engine Control Unit/computer	1072.38	-1668.41	-60.87%	-11
17	Stabilises/secures cargo	1019.88	-69.59	-6.39%	3
18	Prioritises/selects next driving steps	1018.40	229.71	29.13%	6
19	Provides info on cargo area	986.94	-118.53	-10.72%	0
20	Provides fuel/power	942.20	294.20	45.40%	13
21	Protect vehicle from being damaged	939.87	-64.62	-6.43%	0
22	Minimise emissions/environmental impact	929.30	*NEW*	*NEW*	*NEW*
23	Provides info on vehicle & trailer weight	922.84	-880.33	-48.82%	-14
24	Ensure operation within existing law	896.71	-337.07	-27.32%	-6
25	Identify and relay service issues	856.10	-1763.03	-67.31%	-19
	SUM TOTAL ALL NODES IN NETWORK	64819.00			

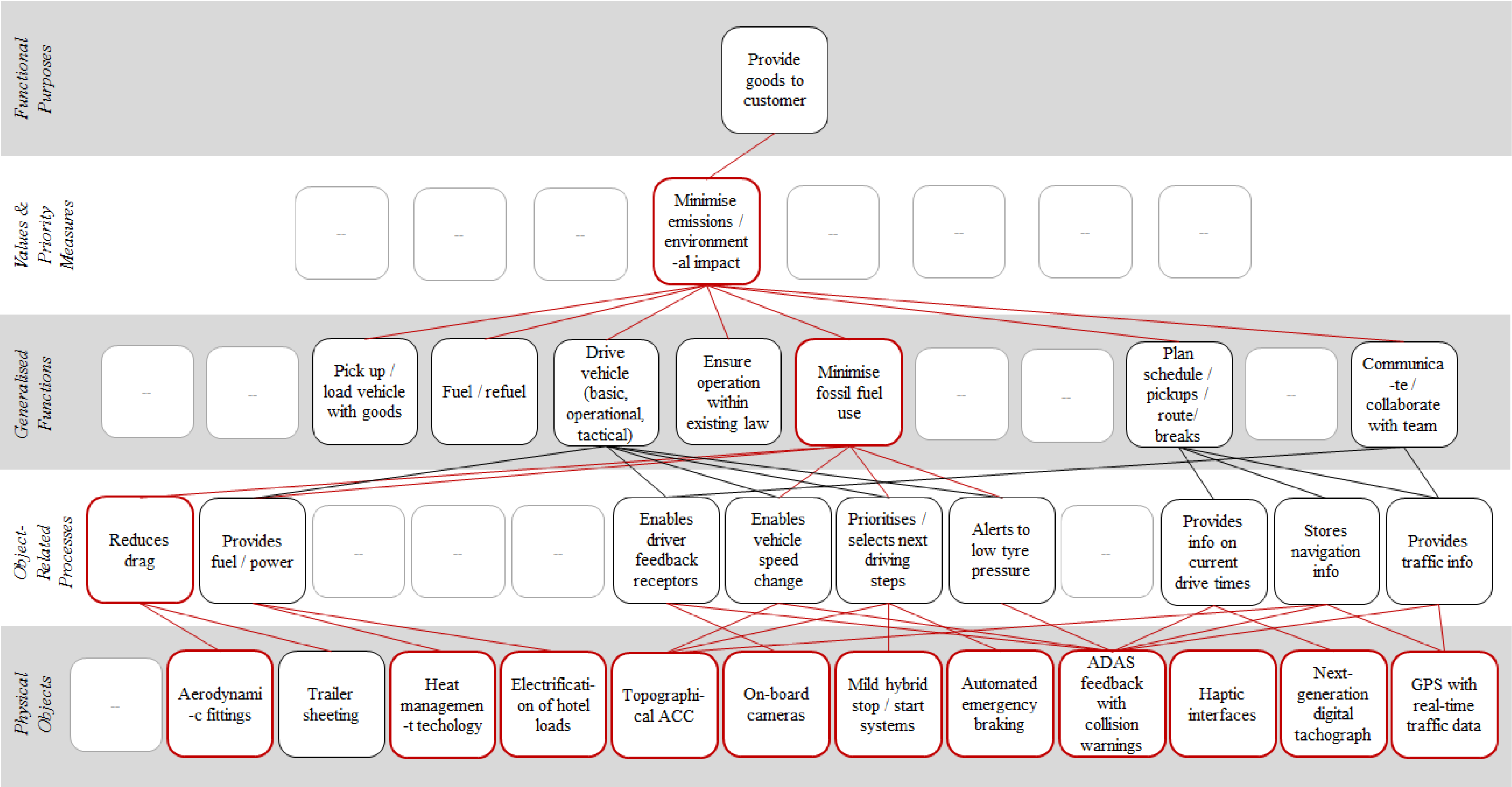


Figure 6.3: Excerpt of Abstraction Hierarchy for truck-driver systems (2020), with additions highlighted in red

Table 6.9: 2020 Abstraction-Decomposition Space Part 1 – Functional Purposes at whole system level, Values & Priority Measures at sub-system level, & Generalised Functions at functional unit level

	Whole System	Sub-System	Functional Unit	SA	C
FP	• Provide goods to customer				
Values & Priority Measures		• Ensure provision of goods to customer • Maximise “forebearing, gentle driving style” • **Maximise safety** • **Minimise financial coast / loss of time** • Maximise user/worker health/comfort • Maximise vehicle/system reliability • Maximise efficiency / miles driven loaded • Maximise flexibility in routine • **+ Minimise emissions / environmental impact**			
Generalised Functions			• **Connect trailer to vehicle / enable delivery** • **Pick up / load vehicle with goods** • **Unload goods** • Fuel/refuel • **Drive vehicle** • **Ensure operation within existing law** • **Protect/ensure immediate safety of worker** • **Protect vehicle from being damaged** • **Ensure occ. health / comfort of worker** • **Identify and relay service issues** • Ensure security of vehicle • Ensure vehicle / cab fit for purpose • **Plan schedule / pickups/route/breaks** • **Communicate / collaborate w/ team** • + Minimise fossil fuel use		
ORP					
PO					

***bold font in red shading** indicates one of top 25 high centrality nodes in current (2020) scenario;
blue shading indicates node which has fallen from top 25 most central nodes since previous scenario (2015); + indicates node added in current (2020) scenario

Table 6.10: 2020 Abstraction-Decomposition Space Part 2 – Object-Related Processes at sub-assembly level

	WH	SS	FU	Sub-Assembly	C
FP					
VPM					
GF					
Object-Related Processes				• Adjusts seat • Fulfil order • Stores cargo **• Secures cargo** • Secures trailer • Deploys airbag • Alerts to smoke • Enables start-up • Minimises noise • Stabilises human • Connects air lines • Stores fuel/power • Provides traction • Connects brakes • Connects power • Connects trailer • Stores cargo info **• Provides fuel/power** • Enables locomotion • Provides RPM info • Provides speed info • + Reduces drag • Alerts to door status • Provides traffic info • Attaches label to goods • Protects vehicle body • Stores navigation info • Provides info on temp. **• Alerts others to presence** **• Provides cargo area info** • Protects worker's hands • Stabilises/protects tools • Maintains temp./climate • Alerts to lack of seatbelt • Alerts to brake pad wear • Provides info on oil level • Provides info on location • Provides oil pressure info • Presents coolant level info • Alerts to low tyre pressure • Provides info on fuel level • Controls vehicle trajectory • Facilitates refuelling point • Enables trailer locomotion • Stores vehicle / system info • Provides info on current time **• Facilitates work environment** **• Enables vehicle speed change** • Provides air line pressure info • Prevents dirt/water/ice build-up • Lifts/adjusts cargo to/from trailer **• Enables driver feedback receptors** • Alerts to status of cab area hazards • Enables worker to get into position • Presents info on sub-system fitness • Stores cargo description & location • Identifies system not fit for purpose **• Prioritises/selects next driving steps** • Provides current ignition setting info **• Provides vehicle & trailer weight info** • Provides info on current day/driver drive times • Provides info on other system/vehicle characteristics • Acts as supporting infrastructure for communications • Enables communication pathway/ passage of information	
PO					

***bold font in red shading** indicates one of top 25 high centrality nodes in current (2020) scenario;
bBlue shading indicates node which has fallen from top 25 most central nodes since previous scenario (2015); + indicates node added in current (2020) scenario

Table 6.11: 2020 Abstraction-Decomposition Space Part 3 – Physical Objects at Component Level

	WH	SS	FU	SA	Component				
FP									
VPM									
GF									
ORP									
Physical Objects					• Fuel tank • Battery • Gear box • Clutch • Fuel • Tyres • Airbags • Horn • Ignition • Steps • Keys • Crane • Laptop • Satellite • Mirrors • Bumper • Driver • Paper • Ink • Printer • Clock • Map • Seatbelts • Hand rails • Break area	• Generator • Cargo/goods • Brake pedal • Steering wheel • External lights • Internal lights • Vehicle seats • Hazard lights • Work gloves • Seat controls • Radio/media • Mobile phone • Laptop mount • Trailer body • Fuel station • Indicators • Sensors (doors) • Sensors (other) • Pen/pencil • Gear stick • Food/drink • Adhesive/staple • Roadway/path • Trailer sheeting • + Haptic interfaces	• Temperature controls • Windscreen wipers • High vis vest, etc • Accelerator pedal • Vehicle suspension • Front grill/bull bar • Engine (mechanical) • Mill/processing site • Window adjusters • Drawbar/kingpin • Breathalyser unit • Ridged floor mats • Vehicle user manual • Sensors (oil level) • Sensors (coolant) • Trailer ABS hook-ups • Trailer air hook-ups • Sensors (smoke) • Sensors (ignition) • Trailer suspension • Trailer side barrier • Trailer ABS input • Central locking system • + Topographical ACC • + Aerodynamic fittings	• Driver tachograph card • Brake system hardware • Road navigation signs • Vehicle parking brake • Electricity fuses/connectors • Roadside clearing/loading point • Personal belongings • Windscreen defogger • GPS-enabled software • Orange traffic triangle • White smoke limiter button • Mech. warnings (on/off) • Sensors (cab area e.g. grill) • Sensors (brake pads) • Sensors (oil pressure) • Sensors (temperature) • Sensors (seat/seatbelts) • Trailer air hook-up inputs • + Next-gen digital tachograph • + On-board cameras • + Electrification of hotel loads • + Heat management technology • + Mild hybrid stop/start systems • + Next-gen digital tachograph	• Cargo paperwork/ID tags • Cab (incl. windscreen/windows) • Cab heating & cooling systems • Land-based communications tower • Alarm to indicate reversal • **Engine Control Unit (ECU)** • Mech. warning (not functional) • Mech. warning (comms. failure) • Sensors (air line pressure) • Tyre pressure monitoring sensors • Sensors (vehicle & trailer weight) • Sensors (cargo area issues) • Cargo chain hooks/clips/fasteners • Trailer electricity hook-up inputs • Trailer steel wire adjusting button • Trailer cargo chains/straps, etc. • Trailer light hook-ups • Trailer parking brake • + Heat management technology • + GPS system w real-time traffic data • **+ ADAS feedback system** • + Automated emergency braking • + GPS system w real-time traffic data • + Automated emergency braking

***bold font in red shading** indicates one of top 25 high centrality nodes in current (2020) scenario;
blue shading indicates node which has fallen from top 25 most central nodes since previous scenario (2015); + indicates node added in current (2020) scenario

6.3.3. Time step 2: Scenario 2025

In the 2025 scenario (highlighted in orange in Figure 6.4), the technology trajectory from Chapter 5 was used as input to add 17 new nodes and 41 new edges. When considering other eliminations, this resulted in a net 5.4% increase in nodes and a net 8.4% increase in edges compared to the 2020 case. The distribution of added nodes was 70.6% at the physical objects level, 17.6% at the object-related processes level, and 11.8% at the generalised functions level. The distribution of added edges was 39% connecting physical objects to object-related processes, 14.6% connecting object-related processes to generalised functions, and 46.3% connecting generalised functions to values & priority measures. Much of this restructuring relates to increasingly sophisticated, real-time data-driven technology (e.g. DSRC technology for V2X communications). The corresponding Abstraction Decomposition Space (ADS) for this time step can be seen in Tables 6.15 through 6.17.

The top node at the VPM, GF, and ORP levels remained stable between 2020 and 2025. The GF node 'Plan schedule/pickups/routes/rest periods' returned to third place, overtaking 'Pick up/load vehicle goods'. In terms of POs, in the 2020 scenario a new ADAS system experienced the highest change but didn't make the top three nodes at that level. In the 2025 scenario the ADAS system was replaced by a new 'ADAS feedback system via head-up display with collision avoidance warnings', which had sufficient connectivity not only to be in the top three, but to be the number one node at the PO level. This relegated 'Engine Control Unit/computer' and 'Driver' to 2nd and 3rd place respectively.

Table 6.12: Top three nodes at each level of 2025 abstraction hierarchy

Level of Abstraction Hierarchy	Top three nodes at each level (by betweenness centrality score)		
	1	2	3
Values & Priority Measures	Minimise financial cost/loss of time (4672.0)	Maximise safety (1591.4)	Minimise emissions/environmental impact (775.6)
Generalised Functions	Drive vehicle (basic, operational, & tactical tasks) (8633.9)	Connect trailer to vehicle/enable delivery to site (3250.7)	Plan schedule/ pickups/ route/ rest periods (1656.9)
Object-Related Processes	Provides visual or auditory alerts others to presence (2165.5)	Enables driver feedback receptors (vision, hearing, and/or proprioception) (2071.1)	Enables change in vehicle speed (1625.4)
Physical Objects	ADAS feedback system via head-up display with collision avoidance warnings (2887.6)	Engine Control Unit/ computer (1126.0)	Driver (452.8)

'Minimise financial cost/loss of time', 'Maximise safety', and 'Minimise fossil fuel use' increased, likely due to knock-on effects triggered by new lower-level technology interventions. The importance of communication (between both human and technological agents) is highlighted by an increase in 'Enables communication pathway/passage of info'.

Table 6.13: Three 'most changed' nodes between 2020 & 2025

Level of Abstraction Hierarchy	Nodes with largest difference in centrality at each level		
	1	2	3
Values & Priority Measures	Minimise financial cost/loss of time (+638.6)	Maximise safety (+220.2)	Minimise emissions/ environmental impact (-153.7)
Generalised Functions	Drive vehicle (basic, operational, & tactical tasks) (+673.5)	Minimise fossil fuel use (+451.1)	Pick up/load vehicle with goods (-281.2)
Object-Related Processes	Enables communication pathway/passage of info (+291.2)	Enables driver feedback receptors (vision, hearing, and/or proprioception) (+289.1)	Provides info on cargo area (+267.8)
Physical Objects	ADAS feedback system via head-up display with collision avoidance warnings (+2887.6)	ADAS feedback system with collision avoidance warnings (-2618.3)	Cab (including windows/windscreen) with integrated aerodynamic design and lightweighting (+212.1)

Overall network metrics for the 2025 scenario (shown in Table 6.14) returned the same top three most central nodes as found in the 2020 case – 'drive vehicle', 'minimise financial cost/loss of time', and 'connect trailer to vehicle/enable delivery'. The aforementioned ADAS system was highly connected enough to be ranked as fourth in the overall network.

Table 6.14: Top 25 nodes with greatest centrality, 2025

Rank	Node	Centrality	Change in Centrality from 2020	% Change in Centrality from 2020	Change in Rank from 2020
1	Drive vehicle (basic, operational, & tactical)	8633.94	673.48	8.46%	0
2	Minimise financial cost/loss of time	4672.01	638.62	15.83%	0
3	Connect trailer to vehicle/ enable delivery	3250.73	261.63	8.75%	0
4	ADAS system via head-up display w/ collision avoidance warnings	2887.64	269.37	10.29%	0
5	Enables driver feedback receptors (vision, hearing, proprioception)	2165.53	289.07	14.87%	1
6	Provides visual or auditory alerts others to presence	2071.11	127.72	6.57%	-1
7	Plan schedule/pickups/route/rest periods	1656.89	-28.08	-1.67%	1
8	Enables change in vehicle speed	1625.40	144.28	9.74%	2
9	Maximise safety	1591.35	220.20	16.06%	2
10	Communicate/collaborate with other drivers/transport dispatcher	1583.16	87.12	5.82%	-1
11	Pick up/load vehicle with goods	1520.45	-281.16	-15.61%	-4
12	Unload goods	1520.45	203.12	15.42%	2
13	Facilitates work environment	1441.77	80.87	5.94%	-1
14	Ensure occupational health/comfort of worker	1399.02	60.01	4.48%	-1
15	Protect/ensure immediate safety of worker	1369.98	71.62	5.52%	0
16	Provides info on cargo area	1254.70	267.77	27.13%	3
17	Provides fuel/power	1201.87	259.67	27.56%	2
18	Prioritises/selects next driving steps	1165.64	147.25	14.46%	0
19	Engine Control Unit/computer	1126.03	53.64	5.00%	-3
20	Ensure operation within existing law	1107.63	210.92	23.52%	4
21	Minimise fossil fuel use	1063.22	451.06	73.68%	9
22	Stabilises/secures cargo	1028.65	8.77	0.86%	-5
23	Protect vehicle from being damaged	992.41	52.54	5.59%	-2
24	Provides info on vehicle & trailer weight	967.41	44.56	4.83%	-1
25	Enables communication pathway/passage of info	948.59	291.16	44.29%	3
	SUM TOTAL ALL NODES IN NETWORK	71789.00			

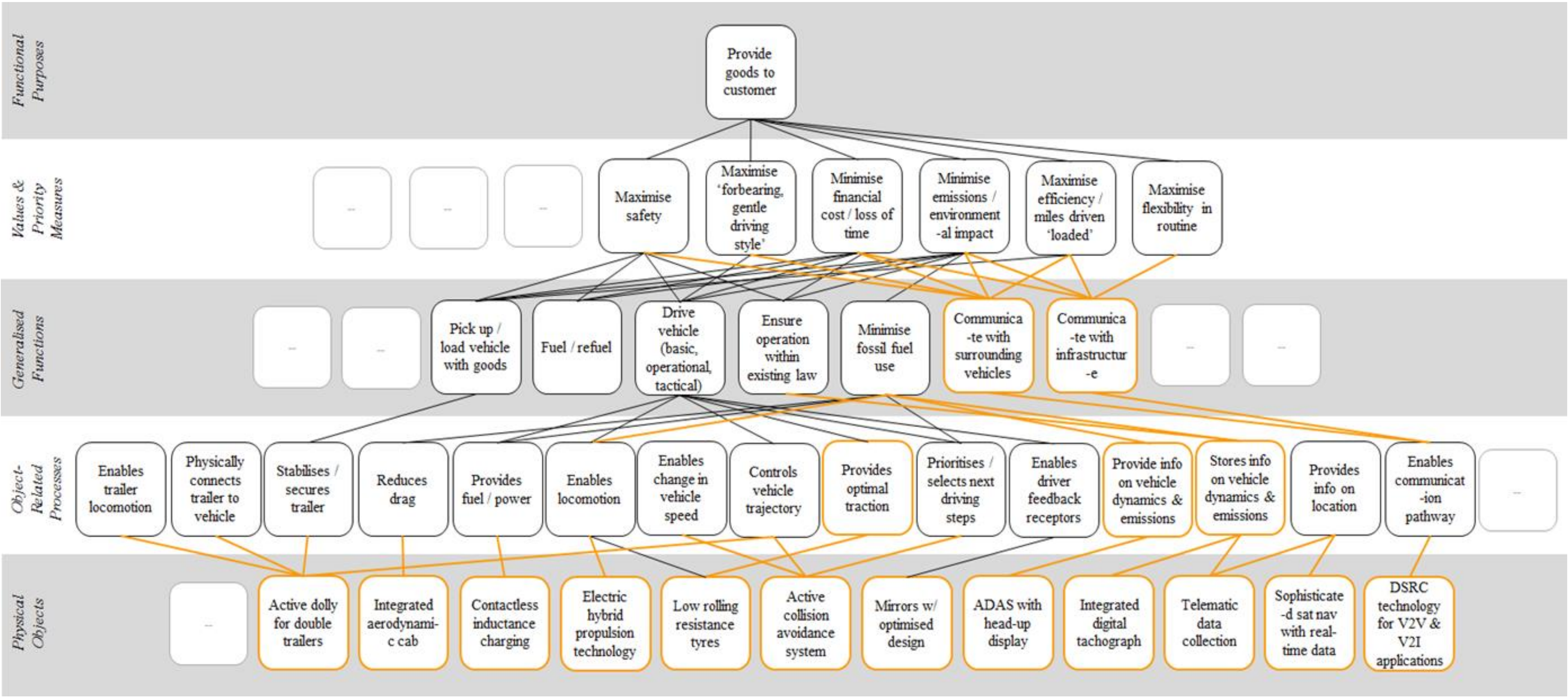


Figure 6.4: Excerpt of Abstraction Hierarchy for truck-driver systems (2025) with additions shaded in orange

Table 6.15: 2025 Abstraction-Decomposition Space Part 1 – Functional Purposes at whole system level, Values & Priority Measures at sub-system level, & Generalised Functions at functional unit level

	Whole System	Sub-System	Functional Unit	SA	C
FP	• Provide goods to customer				
Values & Priority Measures		• Ensure provision of goods to customer • Maximise “forebearing, gentle driving style” • **Maximise safety** • **Minimise financial coast / loss of time** • Maximise user/worker health/comfort • Maximise vehicle/system reliability • Maximise efficiency / miles driven loaded • Maximise flexibility in routine • Minimise emissions / environmental impact			
Generalised Functions			• **Connect trailer to vehicle / enable delivery** • **Pick up / load vehicle with goods** • **Unload goods** • Fuel/refuel • **Drive vehicle** • **Ensure operation within existing law** • **Protect/ensure immediate safety of worker** • **Protect vehicle from being damaged** • **Ensure occ. health / comfort of worker** • Identify and relay service issues • Ensure security of vehicle • Ensure vehicle / cab fit for purpose • **Plan schedule / pickups/route/breaks** • **Minimise fossil fuel use** • **Communicate / collaborate w/ team** • + Communicate w/ surrounding vehicles • + Communicate with infrastructure		
ORP					
PO					

***bold font in orange shading** indicates one of top 25 high centrality nodes in current (2025) scenario;
blue shading indicates node which has fallen from top 25 most central nodes since previous scenario (2020); + indicates node added in current (2025) scenario

Table 6.16: 2025 Abstraction-Decomposition Space Part 2 – Object-Related Processes at sub-assembly level

	WH	SS	FU	Sub-Assembly			C
FP							
VPM							
GF							
Object-Related Processes				• Adjusts seat • Fulfil order • Stores cargo • **Secures cargo** • Secures trailer • Deploys airbag • Alerts to smoke • Enables start-up • Minimises noise • Stabilises human • Connects air lines • Stores fuel/power • Provides traction • Connects brakes • Connects power • Connects trailer • Stores cargo info • **Provides fuel/power** • Enables locomotion • Provides RPM info • Provides speed info • Reduces drag	• Alerts to door status • Provides traffic info • Attaches label to goods • Protects vehicle body • Stores navigation info • Provides info on temp. • **Alerts others to presence** • **Provides cargo area info** • Protects worker's hands • Stabilises/protects tools • Maintains temp./climate • Alerts to lack of seatbelt • Alerts to brake pad wear • Provides info on oil level • Provides info on location • Provides oil pressure info • Presents coolant level info • Alerts to low tyre pressure • Provides info on fuel level • Controls vehicle trajectory • Facilitates refuelling point • + Provides optimal traction	• Enables trailer locomotion • Stores vehicle / system info • Provides info on current time • **Facilitates work environment** • **Enables vehicle speed change** • Provides air line pressure info • Prevents dirt/water/ice build-up • Lifts/adjusts cargo to/from trailer • **Enables driver feedback receptors** • Alerts to status of cab area hazards • Enables worker to get into position • Presents info on sub-system fitness • Stores cargo description & location • Identifies system not fit for purpose • **Prioritises/selects next driving steps** • Provides current ignition setting info • **Provides vehicle & trailer weight info** • Provides info on current day/driver drive times • Provides info on other system/vehicle characteristics • Acts as supporting infrastructure for communications • **Enables communication pathway/ passage of information** • + Provide info on vehicle dynamics & emissions • + Stores info on vehicle dynamics & emissions	
PO							

***bold font in orange shading** indicates one of top 25 high centrality nodes in current (2025) scenario;
blue shading indicates node which has fallen from top 25 most central nodes since previous scenario (2020); + indicates node added in current (2025) scenario

Table 6.17: 2025 Abstraction-Decomposition Space Part 3 – Physical Objects at component level

	WH	SS	FU	SA	Component				
FP									
VPM									
GF									
ORP									
Physical Objects					• Fuel tank • Battery • Gear box • Clutch • Fuel • Tyres • Airbags • Horn • Ignition • Steps • Keys • Crane • Laptop • Satellite • Mirrors • Bumper • Driver • Paper • Ink • Printer • Clock • Map • Seatbelts • Hand rails • Break area • + DSRC	• Generator • Cargo/goods • Brake pedal • Steering wheel • External lights • Internal lights • Vehicle seats • Hazard lights • Work gloves • Seat controls • Radio/media • Mobile phone • Laptop mount • Trailer body • Fuel station • Indicators • Sensors (doors) • Sensors (other) • Pen/pencil • Gear stick • Food/drink • Adhesive/staple • Roadway/path • Trailer sheeting • High vis vest, etc • Haptic interfaces	• Temperature controls • Windscreen wipers • Accelerator pedal • Vehicle suspension • Front grill/bull bar • Engine (mechanical) • Mill/processing site • Window adjusters • Drawbar/kingpin • Breathalyser unit • Ridged floor mats • Vehicle user manual • Sensors (oil level) • Sensors (coolant) • Trailer ABS hook-ups • Trailer air hook-ups • Sensors (smoke) • Sensors (ignition) • Trailer suspension • Trailer side barrier • Trailer ABS input • Central locking system • Topographical ACC • On-board cameras • Aerodynamic fittings • Personal belongings	• Driver tachograph card • Brake system hardware • Road navigation signs • Vehicle parking brake • Electricity fuses/connectors • Roadside clearing/loading point • Windscreen defogger • GPS-enabled software • Orange traffic triangle • White smoke limiter button • Mech. warnings (on/off) • Sensors (cab area e.g. grill) • Sensors (brake pads) • Sensors (oil pressure) • Sensors (temperature) • Sensors (seat/seatbelts) • Trailer air hook-up inputs • Next-gen digital tachograph • Electrification of hotel loads • Heat management technology • Mild hybrid stop/start systems • + Mirrors w/ optimised design • + Active collision avoidance • + Low rolling resistance tyres • + Electric hybrid propulsion • + Active dolly for double trailer	• Cargo paperwork/ID tags • Heat management technology • Cab heating & cooling systems • Land-based communications tower • Alarm to indicate reversal • **Engine Control Unit (ECU)** • Mech. warning (not functional) • Mech. warning (comms. failure) • Sensors (air line pressure) • Tyre pressure monitoring sensors • Sensors (vehicle & trailer weight) • Sensors (cargo area issues) • Cargo chain hooks/clips/fasteners • Trailer electricity hook-up inputs • Trailer steel wire adjusting button • Trailer cargo chains/straps, etc. • Trailer light hook-ups • Trailer parking brake • Automated emergency braking • + Contactless inductance charging • + Cab (w/ lightweighting & aerodynamics) • + Sat nav w/ veh spec & real-time traffic data • + Telematic data collection device • + Integrated tachograph w/ telematics • **+ ADAS w/ head-up display & CA warnings**

***bold font in orange shading** indicates one of top 25 high centrality nodes in current (2025) scenario;
blue shading indicates node which has fallen from top 25 most central nodes since previous scenario (2020); + indicates node added in current (2025) scenario

6.3.4. Time step 3: Scenario 2030

In the final 2030 scenario (highlighted in yellow in Figure 6.5), the technology trajectory from Chapter 5 was used as input to add 7 new nodes and 16 new edges. Inclusive of eliminations of outdated technologies, this resulted in a 3.3% net increase in nodes and a 4.1% net increase in edges compared to the 2025 network. The distribution of added nodes was 71.4% at the physical objects level, and 28.6% at the object-related processes level. The distribution of added edges was 50% connecting physical objects to object-related processes, and 50% connecting object-related processes to generalised functions. Perhaps the most impactful additions to the hierarchy are those related to fatigue detection technology, which contributed 60.9% of node and link additions when compared to the 2025 case. The corresponding abstraction-decomposition space for this time step can be seen in Tables 6.21 through 6.23. ‘Plan schedule/pickups/route/rest periods’ returned again to the top three GFs, indicating that this node and ‘Pick up/load vehicle goods’ are consistently close enough in centrality that these remain fairly stable in the system. At the ORP level, ‘Enables driver feedback receptors’ moved from the second to the first rank, relegating ‘Provides visual or auditory alerts to alert others to presence’ to second place. ‘Provide fuel/power’ experienced a significant increase in centrality, becoming the third most critical ORP node. The ‘ADAS feedback system via head-up display with collision avoidance warning’ not only remained the top PO node in 2030, its centrality also increased the most out of any PO.

Table 6.18: Top three nodes at each level of 2030 abstraction hierarchy

Level of Abstraction Hierarchy	Top three nodes at each level (by betweenness centrality score)		
	1	2	3
Values & Priority Measures	Minimise financial cost/loss of time (4642.4)	Maximise safety (1546.5)	Minimise emissions/environmental impact (810.9)
Generalised Functions	Drive vehicle (basic, operational, & tactical tasks) (9764.3)	Connect trailer to vehicle/enable delivery to site (3301.6)	Plan schedule/ pickups/ route/ rest periods (1706.2)
Object-Related Processes	Enables driver feedback receptors (vision, hearing, and/or proprioception) (2249.6)	Provides visual or auditory to alert others to presence (2134.1)	Provides fuel/power (1668.6)
Physical Objects	ADAS feedback system via head-up display with collision avoidance warnings (3107.9)	Engine Control Unit/ computer (1138.9)	Driver (469.6)

Table 6.19: Three nodes with largest difference in centrality between 2025 & 2030

Level of Abstraction Hierarchy	Nodes with largest difference in centrality at each level		
	1	2	3
Values & Priority Measures	Maximise efficiency/ miles driven loaded (+168.3)	Maximise safety (-44.8)	Ensure provision of goods to customer (+39.5)
Generalised Functions	Drive vehicle (basic, operational, & tactical tasks) (+1130.3)	Pick up/load vehicle with goods (+185.7)	Ensure operation within existing law (+171.8)
Object-Related Processes	Alerts and wakes driver (+523.3)	Provides fuel/power (+466.7)	Detects driver drowsiness/ sleep (+309.4)
Physical Objects	ADAS feedback system via head-up display with collision avoidance warnings (+220.3)	Low rolling resistance tyres (-73.7)	Active dolly for double trailers (+66.1)

The above tables show that new additions resulted in some restructuring of the AH. The top 25 nodes from 2025, however, remained in the same ranked positions as in the 2030 scenario. As in all previous stages, network metrics for the 2030 scenario again returned the same top three most central nodes as found in the 2025 case – ‘drive vehicle’, ‘minimise financial cost/loss of time’, and ‘connect trailer to vehicle/enable delivery’.

Table 6.20: Top 25 nodes with greatest centrality, 2030

Rank	Node	Centrality	Change in Centrality from 2025	% Change in Centrality from 2025	Change in Rank from 2025
1	Drive vehicle (basic, operational, & tactical)	9764.28	1130.34	13.09%	0
2	Minimise financial cost/loss of time	4642.41	-29.60	-0.63%	0
3	Connect trailer to vehicle/ enable delivery	3301.58	50.84	1.56%	0
4	ADAS system via head-up display w/ collision avoidance warnings	3107.93	220.29	7.63%	0
5	Enables driver feedback receptors (vision, hearing, proprioception)	2249.56	84.03	3.88%	0
6	Provides visual or auditory alerts others to presence	2134.14	63.03	3.04%	0
7	Pick up/load vehicle with goods	1706.15	185.70	12.21%	4
8	Plan schedule/pickups/route/rest periods	1700.30	43.41	2.62%	-1
9	Provides fuel/power	1668.56	466.68	38.83%	8
10	Communicate/collaborate with other drivers/transport dispatcher	1590.64	7.48	0.47%	0
11	Enables change in vehicle speed	1561.47	-63.92	-3.93%	-3
12	Maximise safety	1546.54	-44.80	-2.82%	-3
13	Facilitates work environment	1507.84	66.07	4.58%	0
14	Unload goods	1491.32	-29.12	-1.92%	-2
15	Ensure occupational health/comfort of worker	1390.54	-8.48	-0.61%	-1
16	Prioritises/selects next driving steps	1356.92	191.28	16.41%	2
17	Protect/ensure immediate safety of worker	1341.60	-28.38	-2.07%	-2
18	Provides info on cargo area	1295.04	40.34	3.21%	-2
19	Ensure operation within existing law	1279.40	171.77	15.51%	1
20	Engine Control Unit/computer	1138.88	12.86	1.14%	-1
21	Minimise fossil fuel use	1137.62	74.40	7.00%	0
22	Stabilises/secures cargo	1137.51	108.86	10.58%	0
23	Protect vehicle from being damaged	1097.35	104.94	10.57%	0
24	Enables communication pathway/passage of info	977.77	29.17	3.08%	1
25	Provides info on vehicle & trailer weight	945.10	-22.31	-2.31%	-1
	SUM TOTAL ALL NODES IN NETWORK				

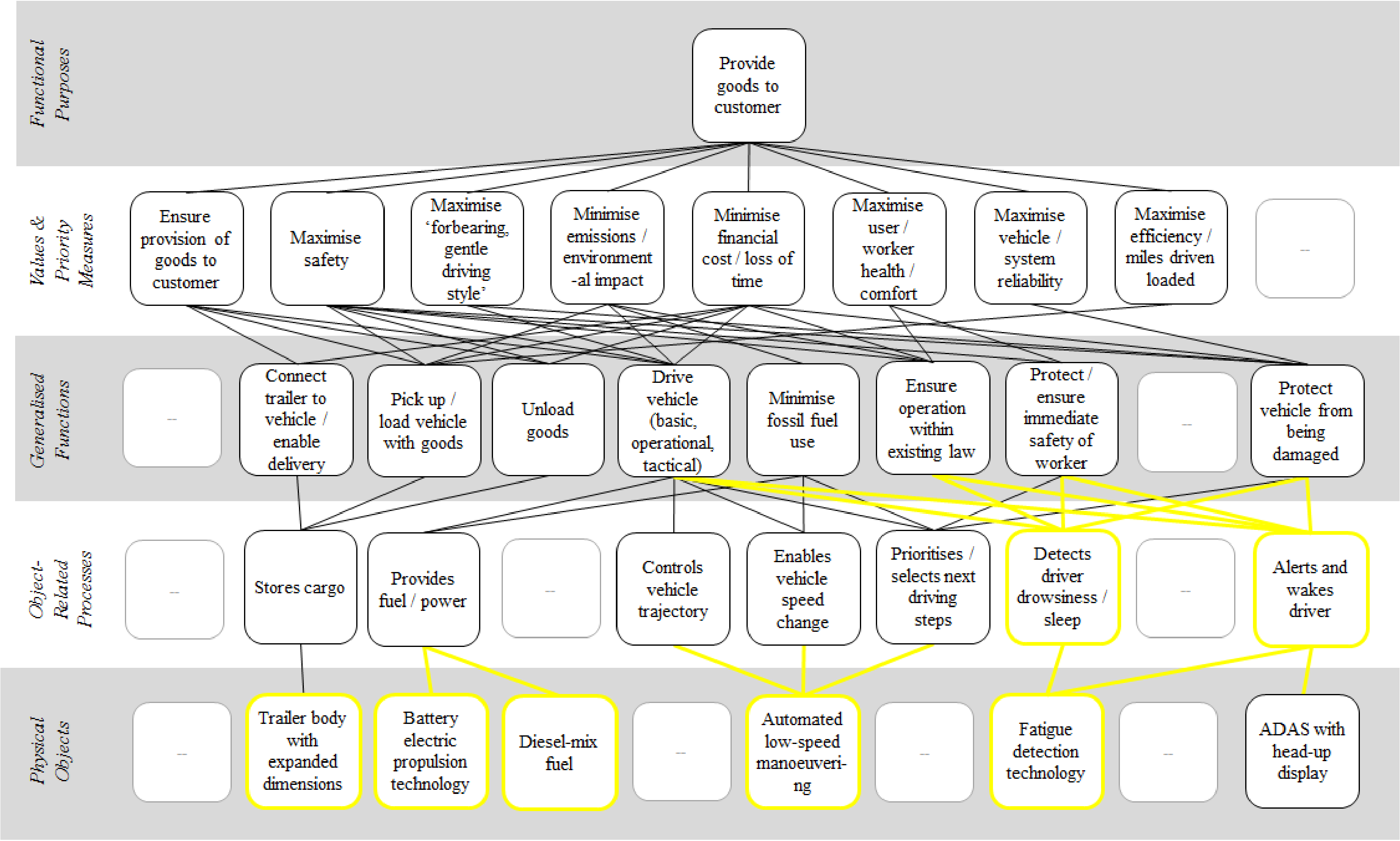


Figure 6.5: Excerpt of Abstraction Hierarchy for truck-driver systems (2030) with additions shaded in yellow

Table 6.21: 2030 Abstraction-Decomposition Space Part 1 – Functional Purposes at whole system level, Values & Priority Measures at sub-system level, & Generalised Functions at functional unit level

	Whole System	Sub-System	Functional Unit	SA	C
FP	• Provide goods to customer				
Values & Priority Measures		• Ensure provision of goods to customer • Maximise "forebearing, gentle driving style" • **Maximise safety** • **Minimise financial coast / loss of time** • Maximise user/worker health/comfort • Maximise vehicle/system reliability • Maximise efficiency / miles driven loaded • Maximise flexibility in routine • Minimise emissions / environmental impact			
Generalised Functions			• **Connect trailer to vehicle / enable delivery** • **Pick up / load vehicle with goods** • **Unload goods** • Fuel/refuel • **Drive vehicle** • **Ensure operation within existing law** • **Protect/ensure immediate safety of worker** • **Protect vehicle from being damaged** • **Ensure occ. health / comfort of worker** • Identify and relay service issues • Ensure security of vehicle • Ensure vehicle / cab fit for purpose • **Plan schedule / pickups/route/breaks** • **Minimise fossil fuel use** • **Communicate / collaborate w/ team** • Communicate w/ surrounding vehicles • Communicate with infrastructure		
ORP					
PO					

***bold font in yellow shading** indicates one of top 25 high centrality nodes in current (2030) scenario;
blue shading indicates node which has fallen from top 25 most central nodes since previous scenario (2025); + indicates node added in current (2030) scenario

Table 6.22: 2030 Abstraction-Decomposition Space Part 2 – Object-Related Processes at the sub-assembly level

	WH	SS	FU	Sub-Assembly	C
FP					
VPM					
GF					
Object-Related Processes				• Adjusts seat • Fulfil order • Stores cargo • **Secures cargo** • Secures trailer • Deploys airbag • Alerts to smoke • Enables start-up • Minimises noise • Stabilises human • Connects air lines • Stores fuel/power • Provides traction • Connects brakes • Connects power • Connects trailer • Stores cargo info • **Provides fuel/power** • Enables locomotion • Provides RPM info • Provides speed info • Reduces drag • + Alerts & wakes driver • Alerts to door status • Provides traffic info • Attaches label to goods • Protects vehicle body • Stores navigation info • Provides info on temp. • **Alerts others to presence** • **Provides cargo area info** • Protects worker's hands • Stabilises/protects tools • Maintains temp./climate • Alerts to lack of seatbelt • Alerts to brake pad wear • Provides info on oil level • Provides info on location • Provides oil pressure info • Presents coolant level info • Alerts to low tyre pressure • Provides info on fuel level • Controls vehicle trajectory • Facilitates refuelling point • Provides optimal traction • + Detects driver drowsiness • Enables trailer locomotion • Stores vehicle / system info • Provides info on current time • **Facilitates work environment** • **Enables vehicle speed change** • Provides air line pressure info • Prevents dirt/water/ice build-up • Lifts/adjusts cargo to/from trailer • **Enables driver feedback receptors** • Alerts to status of cab area hazards • Enables worker to get into position • Presents info on sub-system fitness • Stores cargo description & location • Identifies system not fit for purpose • **Prioritises/selects next driving steps** • Provides current ignition setting info • **Provides vehicle & trailer weight info** • Provides info on current day/driver drive times • Provides info on other system/vehicle characteristics • Acts as supporting infrastructure for communications • **Enables communication pathway/ passage of information** • Provide info on vehicle dynamics & emissions • Stores info on vehicle dynamics & emissions	
PO					

***bold font in yellow shading** indicates one of top 25 high centrality nodes in current (2030) scenario;
blue shading indicates node which has fallen from top 25 most central nodes since previous scenario (2025); + indicates node added in current (2030) scenario

Table 6.23: 2030 Abstraction-Decomposition Space Part 3 – Physical Objects at component level

	WH	SS	FU	SA	Component
FP					
VPM					
GF					
ORP					
Physical Objects					• Fuel tank • Battery • Gear box • Clutch • Fuel • Tyres • Airbags • Horn • Ignition • Steps • Keys • Crane • Laptop • Satellite • Mirrors • Bumper • Driver • Paper • Ink • Printer • Clock • Map • Seatbelts • Hand rails • Break area • DSRC • Generator • Cargo/goods • Brake pedal • Steering wheel • External lights • Internal lights • Vehicle seats • Hazard lights • Work gloves • Seat controls • Radio/media • Mobile phone • Laptop mount • Fuel station • Indicators • Sensors (doors) • Sensors (other) • Pen/pencil • Gear stick • Food/drink • Adhesive/staple • Roadway/path • Trailer sheeting • High vis vest, etc • Haptic interfaces • Ridged floor mats • Temperature controls • Windscreen wipers • Accelerator pedal • Vehicle suspension • Front grill/bull bar • Engine (mechanical) • Mill/processing site • Window adjusters • Drawbar/kingpin • Breathalyser unit • Vehicle user manual • Sensors (brake pads) • Sensors (oil level) • Sensors (coolant) • Trailer ABS hook-ups • Trailer air hook-ups • Sensors (smoke) • Sensors (ignition) • Trailer suspension • Trailer side barrier • Trailer ABS input • Central locking system • Topographical ACC • On-board cameras • Aerodynamic fittings • Personal belongings • + Diesel-mix fuel • Driver tachograph card • Brake system hardware • Road navigation signs • Vehicle parking brake • Electricity fuses/connectors • Roadside clearing/loading pt • Windscreen defogger • GPS-enabled software • Orange traffic triangle • White smoke limiter button • Mech. warnings (on/off) • Sensors (cab area e.g. grill) • Sensors (oil pressure) • Sensors (temperature) • Sensors (seat/seatbelts) • Trailer air hook-up inputs • Next-gen digital tachograph • Electrification of hotel loads • Heat management technology • Mild hybrid stop/start systems • Mirrors w/ optimised design • Active collision avoidance • Low rolling resistance tyres • Electric hybrid propulsion • Active dolly for double trailer • + Fatigue detection technology • + Battery electric propulsion • Cargo paperwork/ID tags • Heat management technology • Cab heating & cooling systems • Land-based communications tower • Alarm to indicate reversal • **Engine Control Unit (ECU)** • Mech. warning (not functional) • Mech. warning (comms. failure) • Sensors (air line pressure) • Tyre pressure monitoring sensors • Sensors (vehicle & trailer weight) • Sensors (cargo area issues) • Cargo chain hooks/clips/fasteners • Trailer electricity hook-up inputs • Trailer steel wire adjusting button • Trailer cargo chains/straps, etc. • Trailer light hook-ups • Trailer parking brake • Automated emergency braking • Contactless inductance charging • Cab (w/ lightweighting & aerodynamics) • Sat nav w/ veh spec & real-time traffic data • Telematic data collection device • Integrated tachograph w/ telematics • **ADAS w/ head-up display & CA warnings** • + Automated low-speed manoeuvring • + Trailer body w/ expanded dimensions

***bold font in yellow shading** indicates one of top 25 high centrality nodes in current (2030) scenario;
blue shading indicates node which has fallen from top 25 most central nodes since previous scenario (2025); + indicates node added in current (2030) scenario

6.3.5. Overall net changes

6.3.5.1. Content of the abstraction hierarchy

These results may surprise researchers and technologists in the domain of road transport, showing a picture of road logistics which is either slower or faster in progress than some expect. In comparison to the research on private motor vehicles (e.g. Banks et al., 2018; Banks & Stanton, 2019), these results may appear to overestimate the continued role of the driver. This may be due to the fact that in such research on private vehicles, comparisons are often made between the current state of road transport and an assumed 'end' state of a fully connected autonomous system. This jump from current to 'end' state has been necessary to draw focus to the changing nature of road transport, and urge researchers and practitioners to begin preparatory efforts. This thesis does not argue that a fully connected autonomous system will never be reached, or that consideration of this 'end' state is unnecessary. Instead, it adds to the existing body of work, by focusing on the transition states on the horizon of the next 5-20 years. By clarifying the specific nature and timing of transition states between the current and 'end' states – informed by over 370 years of collective road freight experience – researchers and practitioners now have a more realistic picture of what is to come, when it is coming, and how we should prioritise our efforts at each stage.

To many familiar with the industry, it is no shock that driving the vehicle, minimising time and cost, and connecting the trailer(s) to the vehicle are the most basic and integral building blocks of logistics work. These three nodes were – predictably, but for the first time with a robust method – found to have the greatest centrality throughout 2015 – 2030. This provides reassurance of face validity.

Overall the period between 2015 and 2030 saw a net 1.4% increase in nodes and a 22.2% net increase in edges. By 2030, 29 nodes from the physical objects level are removed, and 32 new nodes are added at various levels of the hierarchy. A slowing of centrality changes at the lower levels, and the PO level in particular, in 2030 is particularly interesting because it occurs in contrast to how nodes were added through the time steps. For instance, 2020 saw nodes added at the VPM, GF, ORP, and PO levels; 2025 saw nodes added at the GF, ORP, and PO levels; and 2030 saw nodes added at the ORP and PO levels. Despite system interventions being introduced in this way, summed centrality changes for each level do not reflect this. Thus the analyses capture some system complexities we are not currently accounting for by simply reporting the quantity of new interventions.

The results realise Rasmussen’s hypothesis that the digital age brings increased interconnectivity and propagates functionality into the higher cognitive levels, which require inclusion in higher levels of abstraction. As the number and diversity of system functions increases, objects will be consolidated into fewer yet more sophisticated physical systems responsible for carrying out these functions. This is an issue which has foundational implications for the design of future transport technology, and emphasises the need for increasing adoption of interdisciplinary systems tools such as CWA.

Not only can this approach validate or critique our vague suspicions about the future of the industry, it can also tell us when to expect the most challenging transitions, and which parties might hold the most potential for adaptation. The period from 2015 to 2020 saw the addition of the most edges, while the period from 2020 to 2025 saw the addition of the most nodes. All of this suggests that current systems are being continually retrofitted and adapted from the ‘bottom up’ to cope with deeply embedded habitual constraints, by innovating new applications for existing technologies. Consequently the old (2015) system will be ‘maxed out’ at some time between 2020 and 2025, requiring a significant shift to avoid pushing the envelope of acceptable behaviours and inadvertently encouraging undesirable behaviours. We can see this reflected in changes between 2020 and 2030, particularly in higher levels of abstraction.

As the system reaches its functional limits between 2020 and 2025, policy and management stakeholders must begin adapting the socio-technical system from the ‘top down’, making more organisational rather than operational interventions a reality. Even a few additions at this level of influence result in significant changes to how the system functions by 2025, and from this work it is expected that the transitional period between 2020 and 2025 will be the busiest period of adjustment with the most potential for truly impactful decision-making.

As a result, acknowledgment of, and guidance for, systems design tools such as CWA would be well placed amongst ‘top down’ stakeholders such as driver managers, technology strategists, and policy-makers starting from 2020 (at the latest). This road-mapping insight could be further guided by Dul et al.’s (2012) representation of stakeholder groups and system levels. In Table 6.24, Dul et al.'s system groups have been inferred into levels of abstraction, and system levels have been interpreted as levels of decomposition. This gives an abstraction-decomposition space 'map' of relevant stakeholders.

Table 6.24: System stakeholders mapped to ADS, with levels of abstraction & decomposition expressed as Dul et al.'s (2012) stakeholder groups & levels

		Whole System	Sub-System	Functional Unit	Sub-Assembly	Component
		Organisations Representing Individuals in the World	*Organisations Representing Individuals in a Country/Region*	*Organisations Representing Individuals in the Company*	*Individual*	
Functional Purpose	*System Influencers*	• International general public • International media • International governments • International standardisation bodies	• National/regional general public • National/regional media • National/regional governments • National/regional standardisation bodies	• Local community • Local media • Local government	• Any other person interested in systems design	
Values & Priority Measures	*System Decision-Makers*	• International employer organisation • International industry/trade orgs	• National/regional employer orgs • National/regional industry/trade organisations	• Management team • Purchasers of products / services	• Managers • Other decision-makers	
Generalised Functions Object-Related Processes	*System Experts*	• International research organisations (universities, research funding orgs) • International professional associations • International institutes for professional education	• National/regional institutes for professional education • National/regional research orgs (universities, research funding orgs) • National/regional professional associations	• Professional colleagues	• Professionals from the technical & social sciences, e.g.: *industrial engineering, IT/computer science, UX specialists, psychology, management consultancy, design, facility management, operations management, human resources, interior design, architecture*	
Physical Objects	*System Actors*	• International government/OHS /consumer safety legislation • International trade unions • International user groups • ILO • WHO • ICOH	• National/regional government/OHS /consumer safety legislation • National/regional user groups (e.g. patient associations) • National/regional trade unions • National/regional consumer org • National/regional org of OHS services	• Work councils • User groups • OHS service providers	• Actors of work systems (employees) • Actors of product systems (product users) • Actors of service systems (service receivers)	

6.3.5.2. Structure of the abstraction hierarchy

Figure 6.9 (further below) shows pictorially how the AH changes from 2015 to 2030. Figures 6.6 and 6.7 show these changes in the form of graphs, portraying results related to betweenness centrality. Figure 6.6 shows the top 30 nodes for the different time periods, rank ordered according to their betweenness centrality value. While there was significant restructuring of the AH network throughout 2015 to 2030 values for betweenness centrality (independent of the specific AH nodes they represent) were similar in all four cases. This seems to suggest some form of invariance, or 'core stability' in the network structure.

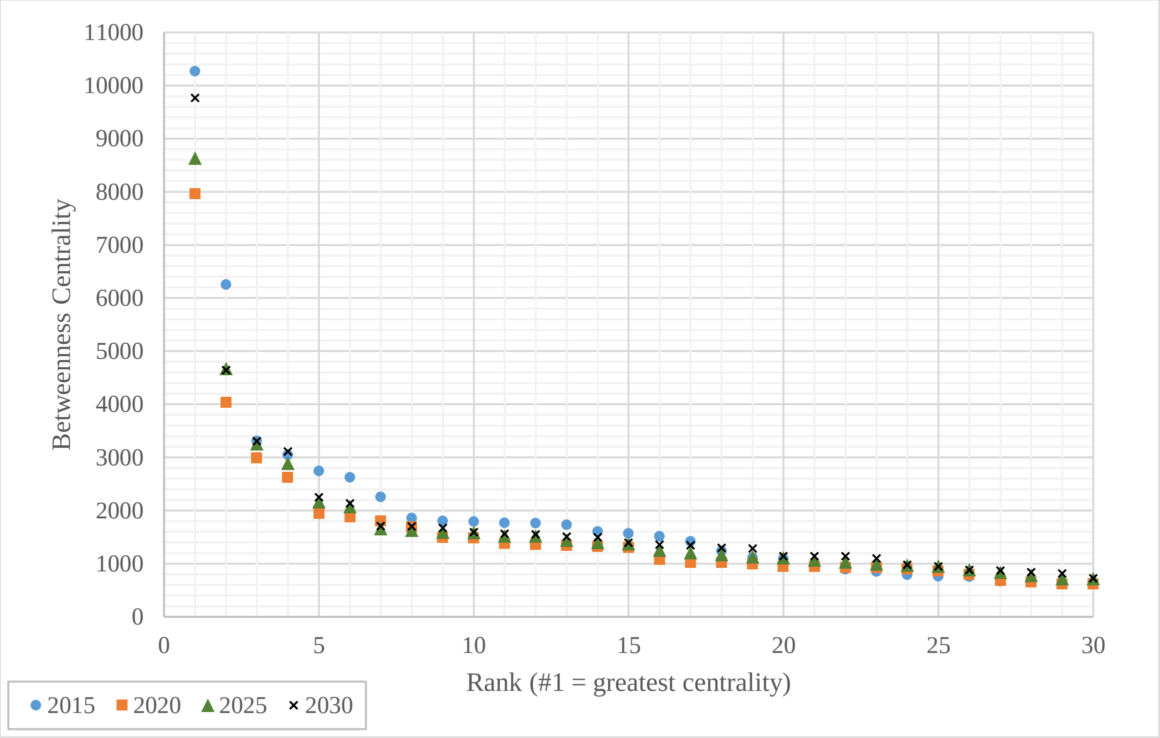


Figure 6.6: Top 30 nodes of greatest centrality in four scenarios

Figure 6.7 rank orders the top 121 nodes according to the mean and standard deviation of betweenness centrality scores. What is interesting to note is that at approximately the 80th ranked position, standard deviations decouple from the rate of decline in centrality values, and rise sharply above average. The standard deviation results only return to below average around the 115th ranked position, at the very low end of ranked positions. This might suggest a form of flexibility or 'give' in the system.

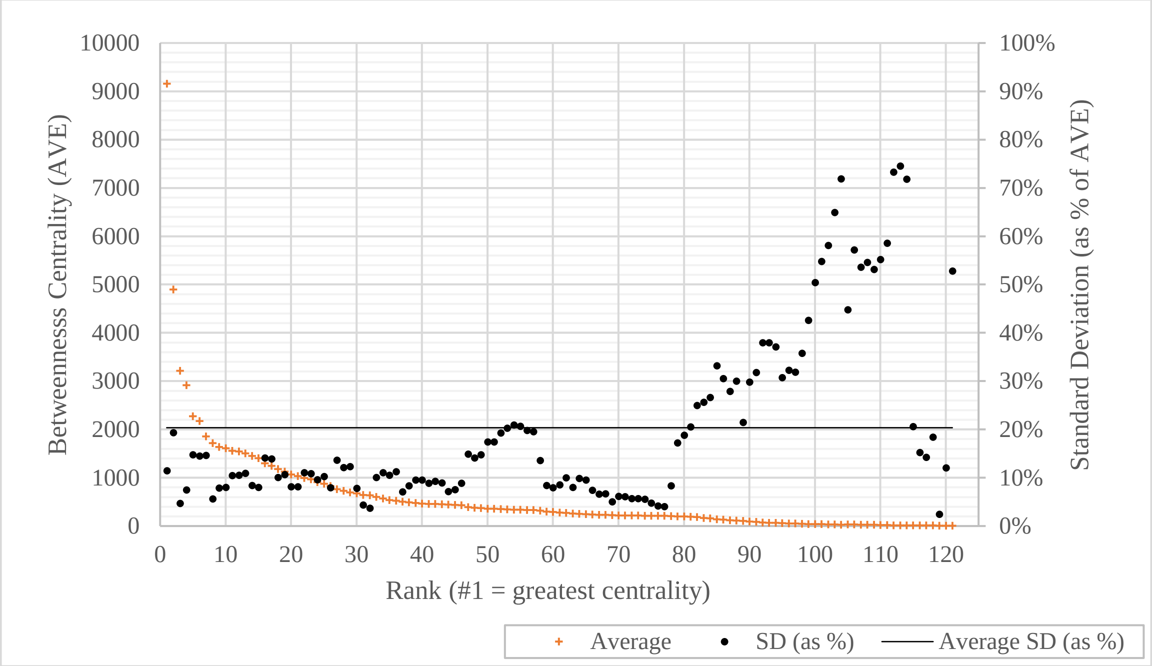


Figure 6.7: Standard deviation of centrality values between 2015-2030 for each ranked position, expressed as a % of averaged centrality values for each ranked position

When considering potential changes to the state of the system over time, the most central 80 nodes in each scenario are unlikely to change significantly and provide core system stability. The top 80 ranked positions for betweenness centrality are more robust to changes, while positions for centrality after this position are more sensitive to system changes and restructuring.

The more meaningful theoretical takeaway from this finding of 'core stability' is that these top 80 nodes (whatever they may be at any given time) are the constraints which are most fixed in the system, and around which the remaining nodes must adapt, or at the very least have the most 'give'. While these nodes will 'set' the system structure, the nodes which do not reach the top 80 will be the ones most likely to provide flexibility. This structural property might nurture adaptive and emergent behaviours. For example, the nodes 'Engine Control Unit' and 'Driver' serve similar Object-Related Processes. When the node 'Engine Control Unit' remains in the top 80 over time, and the node 'Driver' does not, the node 'Driver' adapts (or is adapted) around the constraints of the node 'Engine Control Unit'. This brings us one step closer to a potential understanding of how adaptive behaviour manifests around different types of constraints. Moreover, this understanding itself emerges from a structured approach (quantitative network metrics) that might allow us to systematically address adaptive behaviour before it is expected to occur.

Of course, it would be unlikely that ‘core stability’ would remain at a static number (e.g. 80 in this study) for any given system or sector, and this analysis is exploratory. Nonetheless it is one which might add to theoretical discussions around CASTS emergence, as well as methodological discussion around measurement of WDA inter-rater reliability. Looking through a more practical lens, perhaps more salient for real-world outcomes is the investigation of what network metrics mean for *how* the network changes qualitatively, rather than *whether* the network changes quantitatively.

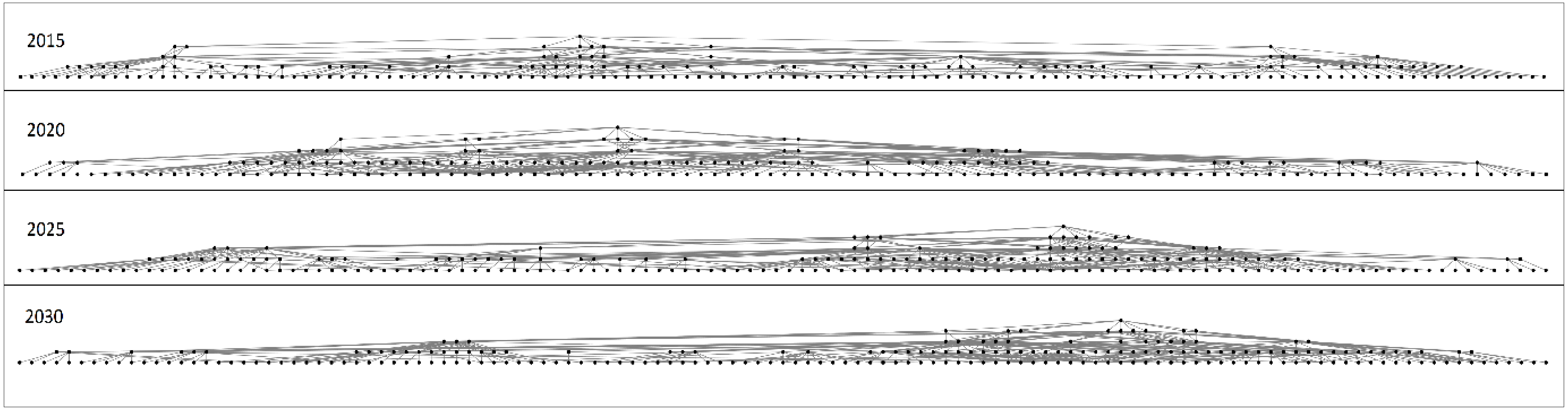


Figure 6.8: Overall transformation of the abstraction hierarchy from 2015-2030, including 1.4% net increase in nodes & 22.2% net increase in edges

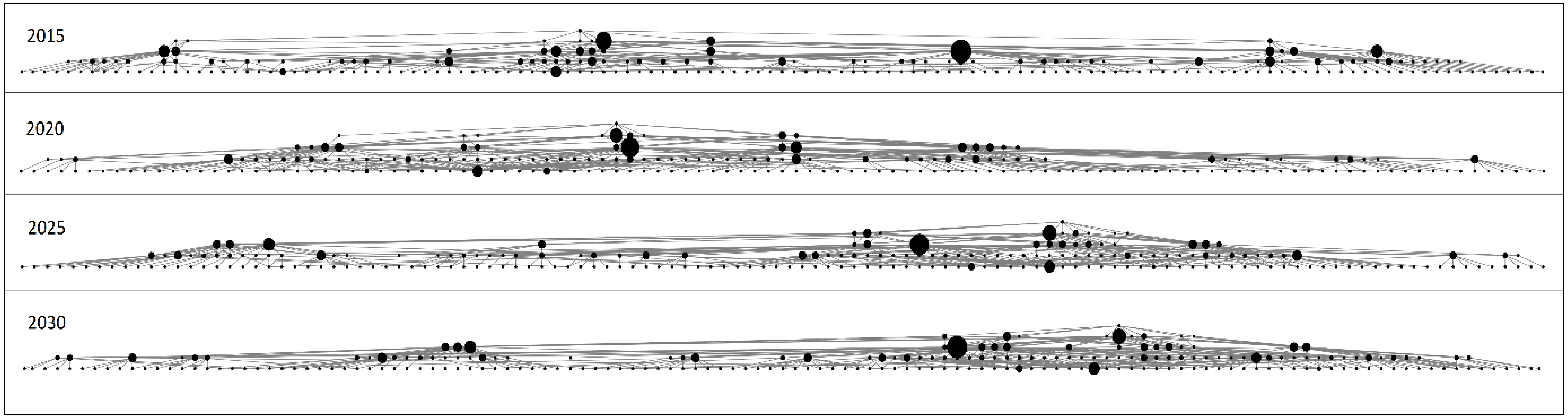


Figure 6.9: Changes to network, where node size indicates its betweenness centrality score, 2015-2030

6.4. Conclusions

There is a great deal of literature chronicling the pitfalls of system design approaches which have failed to acknowledge the role of complexity and emergence. In order to avoid taking the age-old approach and expecting different results, this chapter addressed the following research sub-questions in an attempt to gain greater foresight regarding truck-driver systems:

- *How can the truck-driver system be represented in a functional, technologically agnostic way? (SRQ5)*
- *How can we estimate future system conditions, and test future system functionality before implementation? (SRQ6)*

The main impacts of projected interventions on truck-driver system functionality, and potential responses to these impacts, are described in Table 6.25. From this work it is expected that the transitional period between 2020 and 2025 will be the busiest period of adjustment with the most potential for truly impactful decision-making. However, all transitional periods through the next 15 years will require some (and at times intensive) HF/E evaluation. Thus, road freight stakeholders should be planning for these changes *now*, and coming to grips with HF/E practice, so that responses can be effectively initiated *before* the system reaches its functional limits. Likewise, HF/E practitioners will need to prioritise the advancement of methods aimed at organisational- or sectoral-level technology integration, to effectively understand and influence these higher levels of system scale.

Table 6.25: Main impacts of interventions on truck-driver systems, and potential responses

Transitional Period	Main Impact of Projected Interventions	Potential Response (required before end of transitional period)
2015 – 2020	Retrofitting and adapting current systems, with new applications of existing technologies	Ensure individual technical interventions are well-considered and well-designed, with HF/E approaches
2020 – 2025	Old (2015) system is functionally 'maxed out' on technical constraints, and potential for emergent behaviours is high	System adaptations from the 'top down' i.e. organisational (rather than technical) system interventions
2025 – 2030	Many old (2015) system processes become fully automated (e.g. fatigue detection technology) and system connectivity is wider	Heavy-duty, detailed HF/E evaluations of newly automated processes, and design considerations for widespread organisational and sectoral integration (i.e. 'Intelligent Transport Systems' or ITS)

In general the patterns observed within these analyses suggest that not only will there there be a consolidation of existing technologies into more centralised systems (e.g. ADAS) but also that new technologies will be increasingly complex and interconnected in future systems. This complexity is deepened by the fact it will occur across the purview of multiple industry stakeholders (truck manufacturers, ITS engineers, etc.) which traditionally develop technology in relative isolation. By viewing commercial driving as a complex adaptive socio-technical system it could be argued that the engine management designer is as important as the driver – and becomes increasingly so over time. As such, the marriage of forecasting and WDA demonstrated within this chapter could be a powerful tool in managing technology strategy from many different viewpoints within the larger logistics system.

In Chapter 4, it was argued that while HTA-based methods and CWA are complementary (Salmon, et al., 2010), CWA holds greater promise in terms of resource efficiency for good system coverage, the detection of system vulnerabilities, and relative predictive efficiency (Walker, et al., 2016). All of the above are crucial to identifying critical system components quickly, as well as tracking future system change, and this Chapter presents an opportunity to further compare HTA-based methods with CWA on this basis. Generally speaking, while the results in Chapter 4 showed the impact of technology changes on different tasks, knowledge, skills, and attitudes, the results in Chapter 6 showed the impact of technology, task, knowledge, and attitude change on the wider sociotechnical system. The transition to the 2025 scenario presents a prime example of the differences between HTA-based and CWA outputs. HTA-based methods found specific areas where task changes will propagate into higher levels of the HTA and require adjustments to future driver training programmes, while CWA showed that at a broader level the system may be functionally ‘maxed out’ on technical constraints and encourage emergent behaviours. Both of these lead to similar conclusions with nuanced differences in perspective – ‘top down’ organisational changes will be required, including but not limited to new requirements for driver training programmes.

This comparison can not only be made when examining the speed and quality of analysis, but also the speed and quality of interpreting results. In the HTA-based methods, changes were represented in disparate portions of analysis across 680 pages. Any knock-on effects within the wider sociotechnical system were represented by the number of cross-referenced tasks, in a somewhat removed manner (e.g. the final right-hand column in

Table 4.7). In contrast, CWA enables the reader to visualise knock-on effects relatively quickly through means-end links, and track their relative impact through network metrics.

Both HTA-based methods and CWA contribute valuable insights. However this work reiterates that CWA continues to provide better resource efficiency for total systems coverage, with higher potential for identification of critical system vulnerabilities, and more accessible visualisation of results for large CASTS. The point of relative predictive efficiency has yet to be tested, either through a future programme of simulator-based testing, or as the projected future scenarios unfold 'in the wild' of real-world traffic conditions.

The introduction of a quantifiable metric to the AH also revealed new insights about the functional structure of truck-driver work systems. By developing and comparing AH outputs for several timesteps, it was found that a certain number of top ranked nodes provide core system stability. As such, betweenness centrality can not only identify which nodes may be more interdependent within the system (and therefore more critical) than others, it can also characterise which nodes represent 'core' or 'flexible' constraints. This distinction informs which constraints will have to be adapted around the more stable nodes during periods of disturbance, potentially leading to emergent or adaptive system behaviour.

Furthermore this approach is one that may be useful as we usher truck-driver systems into an age of digital interconnectivity. At the turn of the 21st century, Rasmussen (2000, p. 869) wrote:

> *…The workplace of a large proportion of the population had been dramatically influenced by computerization. A very pronounced effect of this development was a diversification of work. When elementary work routines are mechanized and automated, the work domain of the individual becomes wider, and the task moves to a higher cognitive level.*

Nearly twenty years after this proposition, the results within this chapter appear to confirm Rasmussen's hypothesised scenario. He also wrote that, as a result of this transition, "problem-solving and creative improvisation become essential ingredients of the work content" (p. 869). This was a warning that unexpected, emergent behaviour will arise if we do not track and strategise behavioural co-evolution with our technological systems. Now more than ever it is crucial to safe, effective operations to integrate human factors into the design process, and the contributions of this chapter speak to this aim. Overall, the approach taken in this chapter has resulted in a method to represent and model the propensity of a system to exhibit emergence but, more importantly, to identify exactly where and what form it could take.

Chapter 7:
Conclusions

7.1. Answering the research question

At the outset of this thesis, a pattern was identified in the logistics industry which has previously occurred in other sociotechnical systems: a rapid pace of technological advancement, and an assumption that technology users are ‘hyper-rational’ machines. It was also noted that unanticipated system perturbations come from an incomplete or outdated understanding of the system’s ‘competence envelope’ measures (Woods, 2006). As such, sociotechnical competencies of truck-driver systems must be acknowledged and tracked. The need for more holistic system design was made clear, and the question was asked: *How can current & future truck-driver systems be better designed to meet the triple bottom line of safety, efficiency environment?*

From the above context and research question, three objectives were put forward. Objective 1 was to overview the potential fit of HF/E principles and methods to solving problems within road freight systems. Objective 2 was to apply specific HF/E methods to formalise and expand our understanding of the truck-driver system, ensuring that it is not “incomplete, limited, or wrong” (Woods, 2006, p. 22), and addressing the first condition of unanticipated system disruption. Objective 3 was to gain foresight into future system conditions, and incorporate these into adapted versions of present-day analyses, for future scenarios. These adapted analyses for future scenarios respond to “new demands, pressures, and vulnerabilities that undermine the effectiveness of competence measures in play”, thus addressing the second condition of unanticipated system disruption (Woods, 2006, p. 22).

Practically speaking, these were addressed by providing a behaviour-sensitive and thoroughly documented understanding of the truck-driver system – both present and future. The practical contributions mainly addressed Objectives 2 and 3. This work marked a significant shift from the existing knowledge base which has a heavy, nearly exclusive, emphasis on physical ergonomics. First-of-a-kind, exhaustive reference documents on the truck driving task (Hierarchical Task Analysis or HTA), associated knowledge, skills, and abilities (Training Needs Analysis or TNA), and overall system functionality (CWA) were produced. Not only was this reference documentation meticulously developed, it was also applied in the design of a ‘real’ future truck. In particular the work described in Chapter 5 employed CWA to help design a concept truck technology for a specialist market in 2015. Without these analyses, design efforts might have focused on technology which in this sectoral context would have been less useful (e.g. convoy driving) or even distracting (e.g. rail level crossing alerts). Instead, expert drivers and a new prioritisation method identified the need for increased visual capability, leading to a precision manoeuvring camera system.

To envision future scenarios, these analyses were adapted to reflect the introduction of new technologies and policies identified in the expert-led technology trajectory from Chapter 2. Overall the empirical results highlighted that in the road freight sector:

- An abundance of new technologies and policies are on the horizon for 2020–2050, and these carry associated human factors issues;
- Technology alone will not be enough to meet carbon reduction targets, thus the driver will be under pressure to close this gap;
- Driving tasks are highly interdependent on one another;
- Redundancies in the driving task – i.e. 'back up' options if new technology fails – will be reduced over the next 15 years;
- Changes in specific technologies and wider truck-driver systems are significant enough to necessitate the development of new training that incorporates a fuller understanding of required knowledge, skills, and attitudes (KSAs), particularly to recognise contexts in which:
    - The driver is unable to maintain attention;
    - Newly automated processes would not be at full functionality (e.g. inconsistent GPS connection, unclear roadside markings) where the driver would have to regain control of the vehicle;
- Real-world manufacturers can use HF/E methods to design user-centred technologies 'from scratch' (not just evaluate or retrofit old systems)
- The period 2020–2025 will require substantial 'top down' organisational- or sectoral-level changes to UK logistics (vs. the technical operational interventions common to the sector)
- The predicted trajectory of logistics necessitates ongoing HF/E expertise

Methodologically speaking, these objectives – namely Objectives 1 and 3 – were addressed in three ways. First, by reviewing human factors & ergonomics (HF/E) methods for suitability to different system scales, so that different aspects of logistics could be studied appropriately (Objective 1). Comparisons were also enabled between HTA-based methods and CWA, finding that CWA affords better resource efficiency for total systems coverage, with higher potential for detection of critical system vulnerabilities, and more accessible visualisation of results for large CASTS (Objective 1). Second, by employing increasingly formative approaches which had the ability to envision what *could* happen instead of simply what *should* happen (Objective 3). Third, by extending methods which were already ‘complexity-smart’ to cope with very large-scale systems, prioritise design issues, and track projected future changes (Objective 3). All of these methodological aspects formally acknowledged system complexity – including the sometimes competing priorities of a triple bottom line – and thus improved the traditional way of approaching truck-driver systems. In other words, confronting the reality that humans in the logistics socio-technical system are not ‘hyper-rational’.

Though the primary purpose of this thesis – to support more holistic design of truck-driver systems – emphasised the practical and methodological aspects of research, several theoretical contributions were also made through this process. Theoretically speaking, Objectives 1 and sometimes 3 were addressed. Research gaps and compatibilities between human factors, road freight, and complex systems were detailed to show that the logistics system exhibits complex behaviour and needs to be studied as a complex adaptive, socio-technical system (CASTS). This is particularly relevant for future efforts beyond this thesis, as research begins to account for increasing system depth and/or multiple scales. The HF/E paradigm was also explicated for the first time, clarifying the ontology, epistemology, and methodology commonly adopted by the field in general. This described HF/E as having an underlying philosophy of pragmatism; a subtle realist ontology; a constructivist epistemology; and a pragmatic, contextual constructivist, adapted grounded theory methodology. Finally, in Chapter 6, some emergence-related concepts around the structure of the abstraction hierarchy were offered. In particular, the idea that systems changing over time have a number of ‘core stability’ nodes (vs. flexible nodes) was presented, for further investigation in future research.

The specific theoretical, methodological, and practical contributions have been summarised with respect to each thesis chapter in Table 7.1 below.

Table 7.1: Theoretical, methodological & practical contributions of the thesis

CHAPTER	NOVEL CONTRIBUTION		
	THEORETICAL	METHODOLOGICAL	PRACTICAL / EMPIRICAL
Chapter 1: Introduction			
Chapter 2: A Trajectory for 21st Century Trucking			• Technology forecast of road logistics (2015–2050) • Associated trajectory of human factors issues • Associated trajectory of CO_2 emissions
Chapter 3: Human Factors in Complex Adaptive Socio-technical Systems – Developing a Research Paradigm	• Identification of logistics as a Complex Adaptive Socio-technical System (CASTS) • Definition of the Human Factors research paradigm (ontology, epistemology, & methodology)	• Review of Human Factors methods (extent of systems coverage)	
Chapter 4: Tracking the Future of Driver Training Needs		• Analytically prototyping future systems with Hierarchical Task Analysis • Analytically prototyping future systems with Training Needs Analysis	• Detailed description of present-day truck driving tasks • Detailed description of present-day training needs for truck drivers • Forecast of how truck driving tasks will change (2020-2050) • Forecast of how truck driver training needs will change (2020-2050)
Chapter 5: Evaluating the Truck-Driver System & Strategising the Design of New Technology with CWA		• Prioritisation appproach for Control Task Analysis as applied to large CASTS	• Formative characterisation & evaluation of current truck-driver system functionality • Novel design for a real-world truck technology
Chapter 6: Analytically Prototyping Truck-Driver Systems with WDA		• Analytically prototyping future systems with Work Domain Analysis • Network analysis of abstraction hierarchies • Identification of 'stable' and 'flexible' abstraction hierarchy nodes, & implications for adaptive behaviour	• Forecast of truck-driver system functionality (2015–2050) • Identification of most interdependent components in truck-driver systems (2015–2050)
Chapter 10: Conclusions			

The overall research question this thesis set out to explore was: How can current & future truck-driver systems be better designed to meet the triple bottom line of safety, efficiency environment? As a whole this thesis demonstrated that in logistics, it is possible – and much-needed – for HF/E methods to address both conditions of unanticipated system perturbations put forward by Woods (2006). That is, tools have been applied in a road freight context to (1) understand the current competence envelope and (2) scan the horizon for how this may change. Looking forward, it is clear that the most agile and intelligent agent in the logistics system – the human – will face an increasingly supervisory role in driving tasks. Responsibilities will be increasingly centralised and allocated to the rules of the vehicle's Engine Control Unit (ECU), making a successful drive heavily reliant on the effective design of both the ECU and the Advanced Driver Assistance Systems which interfaces with the driver. This thesis revealed the high potential for driver adaptation to this changing role.

This, in turn, leads to the conclusion that in order for the UK road freight sector – and those extolling the virtues of self-driving vehicles more generally – to negotiate this change, further applications of HF/E principles and methods will be needed. Without them, the road freight sector may implement technologies, training, and organisational measures that exacerbate existing issues (such as a disproportionate number of cyclist deaths), or create entirely new ones. Studies are now needed in a wide range of contexts, with a wide range of users, to effectively design future semi-autonomous systems. This means 'systems thinking' not only in terms of an individual technology or vehicle, but also in the context of a wider and less predictable logistics system. HF/E systems methods (and combined approaches) will be required which cover interactions between as many levels of granularity as possible, such as the remaining stages of CWA – and other methods which have yet to be developed, including those which leverage the potential of big data in transport. The key contribution this thesis makes is to open up an important new frontier for HF/E – one that could be explored first by the suggestions provided in section 7.2.2 below.

7.2. Now what?

7.2.1. Limitations of the completed research

This thesis presents a bold first attempt to embed cutting-edge HF/E theories and methods into a new sector. Whilst it presents an exciting demonstration of HF/E's very real contribution, and puts forward an equally exciting research agenda, it does by its nature have limitations which require future researchers to confront. First, it is important to note a few limitations of this work. One minor limitation is that these analyses apply only to UK truck-driver systems, and will require adjustments for internationalisation.

A second limitation is the possibility – however unlikely – that the truck-driver system was not represented sufficiently, or rather not in its entirety. In Chapters 2, 5, and 6, participant groups were small, and were often drawn from a small number of organisations (i.e. stakeholders from the Centre for Sustainable Road Freight). This is often the case for HF/E methods which seek to capture deep insights about system behaviour, rather than sample a broad range of the general public. However, this risk was mitigated through the selection of subject matter experts with key perspectives and/or extensive experience – as well as thorough industry document reviews to triangulate the boundaries of the typical truck-driver system.

A related limitation is the unknown horizon-scanning capability of SMEs in the logistics sector, on which the forecasting in this thesis relies. No party has a complete view of the whole system in its entirety, and furthermore changes occur rapidly and not always in a way that it is easily visible. This is a challenge in any forecasting effort, but one that is worth the powerful insights gained from using forecasts as inputs to HF/E methods, in order to produce 'analytical prototypes' of future work contexts.

Though not necessarily a limitation, it is important also to note that the methodological extensions developed in this thesis are exploratory. Coping with and navigating large complex adaptive socio-technical systems (CASTS) requires bold experimentation, and every empirical study of this thesis delivers it. This was primarily done by extending methods to prioritise system parts, or to adapt systems to future contexts, or both. The deep methodological review in Chapter 3 served as a guiding compass for this experimentation, but this remains a new area of research. Repeating these approaches in other sectors, and where necessary adapting them with careful consideration of underlying complexity concepts, is highly encouraged.

7.2.2. Implications of the thesis & a new research agenda

The research has succeeded in driving out some useful practical tools and analyses, with a new research agenda on the horizon. The Hierarchical Task Analysis (HTA), Training Needs Analysis (TNA), Work Domain Analysis (WDA), Control Task Analysis

(ConTA), & Strategies Analysis (StrAn) produced here can all be used as reference points for a wide range of truck-driver system design activities. These analyses covered commercial driving in general, and one specialist sector (timber driving). Future work could expand or adapt these for other sectors (e.g. livestock transport; frozen goods). In general results could lead to – and indeed already have – improved technological systems and training measures targeting the operational aspects of road freight.

Looking forward would, first of all, include efforts to update the technology trajectory outlined in Chapter 2. To maintain accuracy of the projections, further document reviews and interviews should be carried out every 5-10 years, looking ahead 15-20 years. In doing so, a wider circle of participants could be incorporated, and their perspectives of the system as (optimistic) technologists or (sceptical) logistics managers could be compared.

More widely, this thesis has implications for the study of other CASTS. The map of methods' fit to system scales (and interactions) developed in Chapter 3 can be easily repurposed in the study of other large, complex adaptive socio-technical systems, where researchers might have otherwise grasped in the dark for structure. However much further work on the HF/E research paradigm can be done. At the least, the methods review outlined in Chapter 3 should be updated as sociotechnical systems methods are created or extended, and validity, reliability, and other criteria for method selection should be incorporated.

The HTA-based outputs found in Chapter 4 are offered as inputs to a vast array of other HF/E methods – including but not limited to human error approaches, accident causation models, and interface analyses – as well as practitioner design of technology and training. As an example of this, the TNAoCD can be used as a reference for the design of truck driver training programmes, including but not limited to short eco-driving courses (e.g. refresher certificates of professional competence otherwise known in the UK as CPC training). Indeed, this has already been used in a real-world CPC training scheme, trialled in a real-world logistics company, with successful outcomes. (This study was outwith the scope of the thesis, as the TNAoCD informed the content but several other lengthy processes informed the delivery and evaluation of the training scheme.) This evidences the usefulness of the TNAoCD and shows promise for widespread improvements to truck driver training – a sometimes overlooked component of road freight systems that we know from Chapters 4 and 6 will be integral to deal with upcoming change.

The real-world technology designed in Chapter 5 is of particular note as it is now in widespread production by truck manufacturer Scania. This bears out the face validity, acceptability, and cost-effectiveness of the HF/E approach. Other potentially critical activities identified in Chapter 5 could also be explored, to design more supportive technologies 'from scratch' and avoid the pitfalls of continually retrofitting systems. Based on the above, the latter steps of CWA not within the time scope of this thesis could easily be applied (e.g. Decision-Making Ladders; Social & Organisational Cooperation Analysis; Workers Competencies Analysis). These are likely provide useful insights into decision-making, and allocation of function. On a methodological level, the prioritisation method developed in Chapter 5 can now be applied to other CASTS domains, to be widely tested and fine-tuned.

At a macro-scale, using the network analysis approach developed in Chapter 6 could test other combinations of technological – and policy – interventions, other than those currently planned. This would explore the nature of future system states in order to find the best possible 'target' state. From this logistics decision-makers would be enabled to trial interventions in a risk-free way, then work backwards with strategic goals at different time steps to achieve a targeted system design. At a micro-scale, the intermediary connections between 'core' and 'flexible' abstraction hierarchy nodes could be explored with additional HF/E methods. This would test the theoretical suggestion that the network analysis approach can identify how adaptive behaviours will manifest. The network analysis approach to WDA should be trialled in any available existing or planned CWA. Doing so would enable the exploration of systems of various sizes, the sensitivity of different network metrics, and the general robustness of the 'core stability' concept presented in Chapter 6. A review of existing abstraction hierarchies, and computation of their network analysis outputs, might prove an interesting study for future work.

Future work should not only aim to repeat the above methods at the operational level, either for alternate logistics issues or for entirely new sectors. It should also expand the scope of HF/E-logistics research to the tactical and strategic levels, by using existing (or extended) methods at higher levels of scale. Not only does there remain a clear gap in the literature relevant to this scale, we also now know from Chapter 6 that these higher levels of scale will be critical to system functionality in the next transitional period (2020–2025). To give just one example of a potential study, the HTAoCD hinted at the importance of interconnecting tasks, including information gained from an external dispatcher responsible for assigning deliveries and specific routes to the driver. The methods review points to the Event Analysis of Systemic Teamwork (EAST) method as just one option to gain insights into that tactical level, by exploring its combined information, task, and social networks. On an even larger scale, future work might address the increasingly connected transport systems predicted in future scenarios. Integrating and revising the tools within this thesis with information systems and decision support could be essential to achieving the triple bottom line in the age of the Intelligent Transport System (ITS). With the view expanding from individual drivers to the larger system of traffic networks, the careful investigation of surrounding driver behaviour and technologically agnostic scenarios will continue to be imperative.

In general, this thesis demonstrated that HF/E can provide powerful insights for logistics, by first demonstrating this power with truck-driver systems. Deeper integration of HF/E evaluations into sector-wide design standards, and informal normalisation of these techniques throughout the industry, would clearly benefit both HF/E and road freight. In other words, considerable potential exists to not just apply HF/E to the logistics sector in order to help it achieve the triple bottom line, but for this novel domain to drive equally novel enhancements in theory and method. This includes but is not limited to testing of the presented models through driver simulator studies; linking of organisational culture to various truck driver outcomes; and quantitative analysis of driver data.

7.3. Final remarks

This thesis contributes a novel, and exhaustive, foundation of knowledge on UK truck-driver systems using ‘technologically agnostic’ methods. Because logistics is a large, complex adaptive socio-technical system, it is prone to rapid evolutions. Thus a technology forecast, and a methodological strategy to expand and update the knowledge base, are also provided to guide future work. Taken together, these theoretical, methodological, and practical contributions acknowledge logistics system complexity, and effectively leverage the most agile agent in that system – the human.

Without this direction of travel, truck-driver systems (and perhaps logistics systems as a whole) would continue on a trajectory headed for substantial sociotechnical issues, and costly real-world consequences. Instead this work has enabled a more holistic design approach for both current and future truck-driver systems, and firmly established the potential of HF/E methods for wider logistics research. Other researchers are invited to participate in this exciting new research agenda.

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APPENDIX A:

Degree of Automation Calculations

TIMELINE	TECHNOLOGY	STAGE OF AUTOMATION				SUM	% OUT OF TOTAL POSSIBLE (3 LEVELS OF AUTOMATION * 4 STAGES = 12 TOTAL)	DEGREE OF AUTOMATION (0 = NO; 0-33% = LOW; 33-66% = MODERATE; 66-100% = HIGH)
		STAGE 1	STAGE 2	STAGE 3	STAGE 4			
		INFORMATION ACQUISITION	INFORMATION ANALYSIS	DECISION & ACTION SELECTION	ACTION IMPLEMENTATION			
2020	Aerodynamic Fittings	0	0	0	0	0	0.00%	No
	Heat Management	0	0	0	0	0	0.00%	No
	Electrification of Hotel Loads	0	0	0	3	3	25.00%	Low
	Haptic Interfaces	0	0	0	2	2	16.67%	Low
	Next-Generation Digital Tachograph	2	0	0	0	2	16.67%	Low
	On-Board Safety Cameras	2	0	0	0	2	16.67%	Low
	Real-Time Traffic Data	3	0	0	0	3	25.00%	Low
	Simulator Training	1	1	0	0	2	16.67%	Low
	Collision Avoidance Warning Systems	3	3	2	0	8	66.67%	Moderate to High
	Mild Hybrid & Stop/Start Systems	2	2	2	2	8	66.67%	Moderate to High
	Advanced Driver Assistance System (ADAS) Feedback	3	3	2	1	9	75.00%	High
	Automated Emergency Braking	3	3	3	3	12	100.00%	High
	Topographical Adaptive Cruise Control	3	3	3	2	11	91.67%	High
2021	Low Rolling Resistance Tyres	0	0	0	0	0	0.00%	No
	Telematic Data Collection	3	3	1	0	7	58.33%	Moderate
2022	Advanced Satellite Navigation & Routing Systems	3	3	1	0	7	58.33%	Moderate
	Integrated Aerodynamic Design	0	0	0	0	0	0.00%	No
2020	Lightweighting	0	0	0	0	0	0.00%	No

CONT.	Active Dolly Steering	2	2	1	1	6	50.00%	Moderate
	Active Steering	2	2	1	1	6	50.00%	Moderate
	Infrastructure-to-Vehicle (I2V) Communications	3	2	1	1	7	58.33%	Moderate
2023	Active Collision Avoidance Systems (ACAS)	3	3	3	3	12	100.00%	High
2025	Reduction of Rearward Amplification	0	0	0	0	0	0.00%	No
	Contactless Inductance Charging	0	0	0	3	3	25.00%	Low
	Head-Up Displays	2	1	0	0	3	25.00%	Low
	Optimised Mirror Design	1	1	1	1	4	33.33%	Low to Moderate
	Integrated Tachograph & Telematic Data Collection	3	3	1	0	7	58.33%	Moderate
	Electric Hybrid Propulsion	2	2	2	2	8	66.67%	Moderate to High
2026	Expansion of Truck or Trailer Dimensions	0	0	0	0	0	0.00%	No
2027	Battery Electric Propulsion	2	2	2	2	8	66.67%	Moderate to High
	Diesel-Mix Fuel Use	0	0	0	0	0	0.00%	Moderate to High
	Fatigue Detection Technology	3	3	2	0	8	66.67%	Moderate to High
	Automated Low-Speed Maneuvering	3	3	3	3	12	100.00%	High
2033	Heavy Goods Vehicle (HGV) Platooning	3	3	3	2	11	91.67%	High
2034	Dedicated Gas Propulsion	2	2	2	2	8	66.67%	Moderate to High
2036	Dual Fuel Propulsion	2	2	2	2	8	66.67%	Moderate to High
2037	Natural Gas Infrastructure	0	0	0	0	0	0.00%	No
	Hydrogen Fuel Cell Propulsion	2	2	2	2	8	66.67%	Moderate to High

APPENDIX B:
Human Factors Methods Review

METHOD TYPE	METHOD		APPLICABLE LEVEL OF SYSTEM GRANULARITY (PHYSICAL)						SUM	TOTAL POSSIBLE
			1 WHOLE SYSTEM	2 SUBSYSTEM	3 FUNCTIONAL UNIT	4 SUBASSEMBLY	5 COMPONENT (THEORETICAL)	6 COMPONENT (CONTEXTUAL)		
INTEGRATED FRAMEWORKS & ASSESSMENTS	1	CWA (Total Cognitive Work Analysis)	0	0	1	1	4	3	9	36
	2	WDA (Work Domain Analysis)	0	0	0	1	1	0	2	6
	3	CAT (Contextual Activity Template)	0	0	1	0	0	0	1	6
	4	DML (Decision-Making Ladder)	0	0	0	0	1	1	2	6
	5	Strategies Analysis (StrA)	0	0	0	0	1	1	2	6
	6	SOCA (Social & Organisational Cooperation Analysis)	0	0	0	0	0	0	0	6
	7	WCA (Worker Competencies Analysis)	0	0	0	0	1	1	2	6
	8	Strategies Analysis Diagram (SAD)	0	0	0	0	1	1	2	6
	9	DoA (Degree of Automation)	0	0	0	0	1	0	1	6
	10	EAST	0	0	1	0	0	0	1	6
TIME PREDICTION	11	Timeline Analysis	0	0	1	1	0	1	3	6
	12	KLM (Keystroke Level Model)	0	0	0	1	1	1	3	6
	13	CPA (Multimodal Critical Path Analysis)	0	0	0	1	1	0	2	6
SYSTEM DESIGN	14	Task-Centred System Design	0	0	1	1	0	1	3	6
	15	Scenario Based Design	0	0	1	1	1	1	4	6
	~~16~~	~~Mission Analysis~~								
	17	Focus Groups	0	0	0	0	0	1	1	6
	18	Allocation of Function Analysis	0	0	0	1	1	1	3	6
INTERFACE DESIGN	19	Waklthrough Analysis	0	0	0	1	1	0	2	6
	20	User Trial	0	0	0	1	1	0	2	6
	21	SUS (System Usability Scale)	0	0	0	0	1	0	1	6
	22	SUMI (Software Usability Measurement Inventory)	0	0	0	0	1	0	1	6
	23	Repertory Grid Analysis	0	0	0	1	1	0	2	6
	24	QUIS (Questionnaire for User Interface Satisfaction)	0	0	0	1	1	0	2	6
	25	Layout Analysis	0	0	0	1	1	0	2	6
	26	Link Analysis	0	0	0	0	1	0	1	6
	27	Interface Survey	0	0	0	1	0	0	1	6
	28	Heuristic Analysis	0	0	0	0	1	0	1	6
	29	Checklist	0	0	0	1	0	0	1	6
TEAM ASSESSMENT	30	TTRAM (Task and Training Requirements Analysis)	0	0	1	0	0	0	1	6
	31	Team Workload Assessment	0	0	1	0	0	0	1	6
	32	TTA (Team Task Analysis)	0	0	1	0	1	1	3	6
	33	Questionnaires for Distributed Assessment of Team Mutual Awareness	0	0	1	0	0	0	1	6
	34	SNA (Social Network Analysis)	0	0	1	0	0	0	1	6
	35	TCTA (Team Cognitive Task Analysis)	0	0	0	0	1	0	1	6
	36	HTA(T) (Hierarchical Task Analysis for Teams)	0	0	1	0	1	0	2	6
	37	GTA (Groupware Task Analysis)	0	0	1	1	1	1	4	6
	38	DRX (Decision Requirements Exercise)	0	0	1	0	1	0	2	6

	39	CDA (Coordination Demands Analysis)	0	1	1	0	0	1	3	6
	40	CUD (Comms Usage Diagram)	0	0	0	0	1	0	1	6
	41	BOS (Behavioural Observation Scales)	0	1	1	1	1	1	5	6
MENTAL WORKLOAD ASSESSMENT	42	CTLA (Cognitive Task Load Analysis)	0	0	0	0	1	1	2	6
	43	ISA (Instantaneous Self-Assessment)	0	0	0	0	1	1	2	6
	44	Bedford Scales	0	0	0	0	1	1	2	6
	45	Workload Profile Technique	0	0	0	0	1	1	2	6
	46	MACE (Malvern Capacity Estimate)	0	0	0	0	1	0	1	6
	47	DRAWS (DRA Workload Scales)	0	0	0	0	1	1	2	6
	48	SWORD (Subjective Workload Dominance Technique)	0	0	0	0	1	1	2	6
	49	SWAT (Subjective Workload Assessment Technique)	0	0	0	0	1	1	2	6
	~~50~~	~~MCH (Modified Cooper Harper Scales)~~								
	51	NASA TLX (NASA Task Load Index)	0	0	0	0	1	1	2	6
	52	Physiological Mental Workload Measures	0	0	0	0	1	1	2	6
	53	Primary & Secondary Task Performance Measures	0	0	0	0	1	1	2	6
SITUATION AWARENESS ASSESSMENT	54	Propositional Networks	0	0	1	1	1	0	3	6
	55	C-SAS (Cranfield Situation Awareness Scale)	0	0	1	1	1	0	3	6
	56	CARS (Crew Awareness Rating Scale)	0	0	1	1	1	0	3	6
	57	SABARS (Situation Awareness Behavioural Rating Scale)	0	0	1	1	1	0	3	6
	58	MARS (Mission Awareness Rating Scale)	0	0	1	1	1	0	3	6
	~~59~~	~~SASHA_L and SASHA_Q~~								
	60	SPAM (Situation Present Assessment Method)	0	0	1	1	1	0	3	6
	~~61~~	~~SARS (Situation Awareness Rating Scales)~~								
	62	SACRI (Situational Awareness Control Room Inventory)	0	0	1	1	1	0	3	6
	63	SALSA	0	0	1	1	1	0	3	6
	64	SA-SWORD (Situation Awareness Subjective Workload Dominance)	0	0	1	1	1	0	3	6
	65	SART (Situation Awareness Rating Technique)	0	0	0	0	1	1	2	6
	66	SAGAT (Situation Awareness Global Assessment Technique)	0	0	1	1	1	0	3	6
	67	SA Requirements	0	0	1	1	1	0	3	6
HUMAN ERROR IDENTIFICATION	68	CREAM (Cognitive Reliability and Error Analysis Method)	0	1	1	1	1	1	5	6
	69	HEART (Human Error Assessment and Reduction Technique)	0	0	1	1	1	0	3	6
	70	SPEAR (System for Predictive Error Analysis and Reduction)	0	0	1	1	1	0	3	6
	71	HERA (Human Error and Recovery Assessment Framework)	0	0	0	0	1	1	2	6
	72	HEIST (Human Error Identification in Systems Tool)	0	0	0	1	1	0	2	6
	73	THEA (Technique for Human Error Assessment)	0	1	1	1	1	0	4	6
	74	HAZOP (Hazard and Operational Human Error Study)	0	0	1	1	1	0	3	6
	75	TAFEI (Task Analysis for Error Identification	0	0	0	1	1	0	2	6
	76	TRACEr (Technique for the Retrospective and Predictive Analysis of Cognitive Errors)	0	0	1	1	1	0	3	6
	77	HET (Human Error Template)	0	0	1	1	1	0	3	6
	78	SHERPA (Systematic Human Error Reduction and Prediction Approach	0	0	1	1	1	0	3	6
PROCESS CHARTING	79	Murphy Diagram	0	0	0	0	1	1	2	6
	80	Fault Trees	0	0	0	0	1	1	2	6
	81	DAD (Decision Action Diagram)	0	0	0	0	1	0	1	6
	82	ETA (Event Tree Analysis)	0	0	1	1	1	0	3	6
	83	OSD (Operational Sequence Diagram)	0	0	1	1	1	0	3	6
	84	Process Charting	0	0	1	1	1	0	3	6
COGNITIVE TASK ANALYSIS	85	CIT (Critical Incident Technique)	0	1	0	0	1	0	2	6
	86	CDM (Critical Decision Method)	0	1	0	0	1	0	2	6
	87	Cognitive Walkthrough	0	0	0	0	1	1	2	6
	88	ACTA (Applied Cognitive Task Analysis)	0	0	0	0	1	0	1	6
T A S	89	TTA (Tabular Task Analysis)	0	0	1	1	1	0	3	6

	90	Sub-Goal Template Method (SGT)	0	0	1	1	1	0	3	6
	91	Task Decomposition	0	0	1	1	1	0	3	6
	92	VPA (Verbal Protocol Analysis)	0	0	0	0	1	0	1	6
	93	HTA (Hierarchical Task Analysis)	0	0	1	1	1	0	3	6
SUM			0	6	42	45	79	33		
TOTAL POSSIBLE			89	89	89	89	89	89		

METHOD TYPE	METHOD		APPLICABLE INTERACTIONS BETWEEN LEVELS OF SYSTEM GRANULARITY (PHYSICAL)										SUM	TOTAL POSSIBLE
			WHOLE SYSTEM - SUB-SYSTEM 7	WHOLE SYSTEM - FUNCTIONAL UNIT 8	SUB-SYSTEM - FUNCTIONAL UNIT 9	FUNCTIONAL UNIT - SUB-ASSEMBLY 10	SUB-ASSEMBLY - COMPONENT (THEORETICAL) 11	SUB-ASSEMBLY - COMPONENT (CONTEXTUAL) 12	WHOLE SYSTEM - COMPONENT (THEORETICAL) 13	SUB-SYSTEM - COMPONENT (THEORETICAL) 14	FUNCTIONAL UNIT - COMPONENT (THEORETICAL) 15	COMPONENT (THEORETICAL) - COMPONENT (CONTEXTUAL) 16		
INTEGRATED FRAMEWORKS & ASSESSMENTS	1	CWA (Total Cognitive Work Analysis)	0	1	0	1	3	2	1	0	2	1	11	60
	2	WDA (Work Domain Analysis)	0	0	0	1	1	0	0	0	0	0	2	10
	3	CAT (Contextual Activity Template)	0	1	0	0	0	0	1	0	1	0	3	10
	4	DML (Decision-Making Ladder)	0	0	0	0	1	1	0	0	0	0	2	10
	5	Strategies Analysis (StrA)	0	0	0	0	0	0	0	0	0	0	0	10
	6	SOCA (Social & Organisational Cooperation Analysis)	0	0	0	0	0	0	0	0	1	0	1	10
	7	WCA (Worker Competencies Analysis)	0	0	0	0	1	1	0	0	0	1	3	10
	8	Strategies Analysis Diagram (SAD)	0	0	0	1	1	0	0	0	1	0	3	10
	9	DoA (Degree of Automation)	0	0	0	0	1	0	0	0	0	0	1	10
	10	EAST	0	0	0	0	0	0	0	0	1	0	1	10
TIME PREDICT ION	11	Timeline Analysis	0	0	0	1	0	1	0	0	0	0	2	10
	12	KLM (Keystroke Level Model)	0	0	0	0	1	0	0	0	0	0	1	10
	13	CPA (Multimodal Critical Path Analysis)	0	0	0	1	1	0	0	0	0	0	2	10
SYSTEM DESIGN	14	Task-Centred System Design	0	0	0	1	0	1	0	0	0	0	2	10
	15	Scenario Based Design	0	0	0	1	1	0	0	0	1	0	3	10
	~~16~~	~~Mission Analysis~~	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	17	Focus Groups	0	0	0	0	0	1	0	0	0	0	1	10
	18	Allocation of Function Analysis	0	0	0	0	0	0	0	1	1	0	2	10
INTERFACE DESIGN	19	Waklthrough Analysis	0	0	0	0	1	0	0	0	0	0	1	10
	20	User Trial	0	0	0	0	1	0	0	0	0	0	1	10
	21	SUS (System Usability Scale)	0	0	0	0	1	0	0	0	0	0	1	10
	22	SUMI (Software Usability Measurement Inventory)	0	0	0	0	1	0	0	0	0	1	2	10
	23	Repertory Grid Analysis	0	0	0	0	1	0	0	0	0	0	1	10
	24	QUIS (Questionnaire for User Interface Satisfaction)	0	0	0	0	1	0	0	0	0	1	2	10
	25	Layout Analysis	0	0	0	0	1	0	0	0	0	0	1	10
	26	Link Analysis	0	0	0	0	1	0	0	0	0	0	1	10
	27	Interface Survey	0	0	0	0	0	1	0	0	0	0	1	10
	28	Heuristic Analysis	0	0	0	0	0	0	0	0	0	0	0	10
	29	Checklist	0	0	0	0	1	0	0	0	0	0	1	10
TEAM ASSESSMENT	30	TTRAM (Task and Training Requirements Analysis)	0	0	0	0	0	0	0	0	1	1	2	10
	31	Team Workload Assessment	0	0	0	0	0	0	0	0	0	0	0	10
	32	TTA (Team Task Analysis)	0	0	0	0	1	0	0	0	1	0	2	10
	33	Questionnaires for Distributed Assessment of Team Mutual Awareness	0	0	0	0	0	0	0	0	0	0	0	10

	34	SNA (Social Network Analysis)	0	0	0	0	0	0	0	0	1	0	1	10
	35	TCTA (Team Cognitive Task Analysis)	0	0	0	0	0	0	0	0	0	1	1	10
	36	HTA(T) (Hierarchical Task Analysis for Teams)	0	0	0	0	0	0	0	0	0	0	0	10
	37	GTA (Groupware Task Analysis)	0	0	0	0	0	1	0	0	1	0	2	10
	38	DRX (Decision Requirements Exercise)	0	0	0	0	0	1	0	0	0	0	1	10
	39	CDA (Coordination Demands Analysis)	0	0	1	1	1	0	0	0	1	0	4	10
	40	CUD (Comms Usage Diagram)	0	0	0	1	1	0	0	0	1	0	3	10
	41	BOS (Behavioural Observation Scales)	0	0	1	1	0	0	0	0	1	0	3	10
MENTAL WORKLOAD ASSESSMENT	42	CTLA (Cognitive Task Load Analysis)	0	0	0	0	0	0	0	0	0	0	0	10
	43	ISA (Instantaneous Self-Assessment)	0	0	0	0	0	0	0	0	0	0	0	10
	44	Bedford Scales	0	0	0	0	0	0	0	0	0	0	0	10
	45	Workload Profile Technique	0	0	0	0	1	0	0	0	0	0	1	10
	46	MACE (Malvern Capacity Estimate)	0	0	0	0	0	0	0	0	0	0	0	10
	47	DRAWS (DRA Workload Scales)	0	0	0	0	0	0	0	0	0	0	0	10
	48	SWORD (Subjective Workload Dominance Technique)	0	0	0	0	0	0	0	0	0	0	0	10
	49	SWAT (Subjective Workload Assessment Technique)	0	0	0	0	0	0	0	0	0	0	0	10
	~~50~~	~~MCH (Modified Cooper Harper Scales)~~												
	51	NASA TLX (NASA Task Load Index)	0	0	0	0	1	0	0	0	0	0	1	10
	52	Physiological Mental Workload Measures	0	0	0	0	1	0	0	0	0	0	1	10
	53	Primary & Secondary Task Performance Measures	0	0	0	0	1	0	0	0	0	0	1	10
SITUATION AWARENESS ASSESSMENT	54	Propositional Networks	0	0	0	0	1	0	0	0	1	0	2	10
	55	C-SAS (Cranfield Situation Awareness Scale)	0	0	0	0	1	0	0	0	0	0	1	10
	56	CARS (Crew Awareness Rating Scale)	0	0	0	0	1	0	0	0	0	0	1	10
	57	SABARS (Situation Awareness Behavioural Rating Scale)	0	0	1	0	1	0	0	0	1	0	3	10
	58	MARS (Mission Awareness Rating Scale)	0	0	0	0	0	0	0	0	0	0	0	10
	~~59~~	~~SASHA_L and SASHA_Q~~												
	60	SPAM (Situation Present Assessment Method)	0	0	0	0	1	0	0	0	0	0	1	10
	~~61~~	~~SARS (Situation Awareness Rating Scales)~~												
	62	SACRI (Situational Awareness Control Room Inventory)	0	0	0	0	1	0	0	0	0	0	1	10
	63	SALSA	0	0	0	0	1	0	0	0	1	0	2	10
	64	SA-SWORD (Situation Awareness Subjective Workload Dominance)	0	0	0	0	1	0	0	0	0	0	1	10
	65	SART (Situation Awareness Rating Technique)	0	0	0	0	0	0	0	0	0	0	0	10
	66	SAGAT (Situation Awareness Global Assessment Technique)	0	0	0	0	0	0	0	0	0	0	0	10
	67	SA Requirements	0	0	0	0	0	0	0	0	0	0	0	10
HUMAN ERROR IDENTIFICATION	68	CREAM (Cognitive Reliability and Error Analysis Method)	0	0	0	0	1	0	0	1	1	1	4	10
	69	HEART (Human Error Assessment and Reduction Technique)	0	0	1	1	1	0	0	0	0	0	3	10
	70	SPEAR (System for Predictive Error Analysis and Reduction)	0	0	0	0	1	0	0	0	0	0	1	10
	71	HERA (Human Error and Recovery Assessment Framework)	0	0	0	0	1	0	0	1	1	0	3	10
	72	HEIST (Human Error Identification in Systems Tool)	0	0	0	0	1	0	0	0	0	0	1	10
	73	THEA (Technique for Human Error Assessment)	0	0	0	0	1	0	0	0	1	0	2	10
	74	HAZOP (Hazard and Operational Human Error Study)	0	0	0	0	1	0	0	0	0	0	1	10
	75	TAFEI (Task Analysis for Error Identification	0	0	0	0	1	0	0	0	0	0	1	10
	76	TRACEr (Technique for the Retrospective and Predictive Analysis of Cognitive Errors)	0	0	0	0	1	0	0	0	1	0	2	10
	77	HET (Human Error Template)	0	0	0	0	1	0	0	0	0	0	1	10
	78	SHERPA (Systematic Human Error Reduction and Prediction Approach	0	0	0	0	1	0	0	0	0	0	1	10
PROCESS	79	Murphy Diagram	0	0	0	0	1	0	0	0	0	0	1	10
	80	Fault Trees	0	0	0	0	0	0	0	0	0	0	0	10

	81	DAD (Decision Action Diagram)	0	0	0	0	1	0	0	0	0	0	1	10
	82	ETA (Event Tree Analysis)	0	0	0	0	0	0	0	0	0	0	0	10
	83	OSD (Operational Sequence Diagram)	0	0	0	1	0	0	0	0	0	0	1	10
	84	Process Charting	0	0	0	0	1	0	0	0	0	0	1	10
COGNITIVE TASK ANALYSIS	85	CIT (Critical Incident Technique)	0	0	0	0	0	0	0	0	0	0	0	10
	86	CDM (Critical Decision Method)	0	0	0	0	0	0	0	0	0	0	0	10
	87	Cognitive Walkthrough	0	0	0	0	1	1	0	0	0	0	2	10
	88	ACTA (Applied Cognitive Task Analysis)	0	0	0	0	1	0	0	0	0	0	1	10
TASK ANALYSIS	89	TTA (Tabular Task Analysis)	0	0	0	0	1	0	0	0	0	0	1	10
	90	Sub-Goal Template Method (SGT)	0	0	0	0	1	0	0	0	0	0	1	10
	91	Task Decomposition	0	0	0	0	1	0	0	0	0	0	1	10
	92	VPA (Verbal Protocol Analysis)	0	0	0	0	0	1	0	0	1	0	2	10
	93	HTA (Hierarchical Task Analysis)	0	0	0	0	1	0	0	0	0	0	1	10
SUM			0	2	4	12	55	12	2	3	23	7		
TOTAL POSSIBLE			89	89	89	89	89	89	89	89	89	89		

METHOD TYPE	METHOD		APPLICABLE LEVEL OF SYSTEM GRANULARITY (COGNITIVE)						SUM	TOTAL POSSIBLE
			1 WHOLE SYSTEM	2 SUBSYSTEM	3 FUNCTIONAL UNIT	4 SUBASSEMBLY	5 COMPONENT (THEORETICAL)	6 COMPONENT (CONTEXTUAL)		
INTEGRATED FRAMEWORKS & ASSESSMENTS	1	CWA (Total Cognitive Work Analysis)	0	1	2	0	3	3	9	36
	2	WDA (Work Domain Analysis)	0	1	1	0	0	0	2	6
	3	CAT (Contextual Activity Template)	0	0	1	0	0	0	1	6
	4	DML (Decision-Making Ladder)	0	0	0	0	1	1	2	6
	5	Strategies Analysis (StrA)	0	0	0	0	1	1	2	6
	6	SOCA (Social & Organisational Cooperation Analysis)	0	0	0	0	0	0	0	6
	7	WCA (Worker Competencies Analysis)	0	0	0	0	1	1	2	6
	8	Strategies Analysis Diagram (SAD)	0	1	1	0	1	1	4	6
	9	DoA (Degree of Automation)	0	0	0	1	1	0	2	6
	10	EAST	0	0	1	0	0	0	1	6
TIME PREDICTION	11	Timeline Analysis	0	0	0	0	0	0	0	6
	12	KLM (Keystroke Level Model)	0	0	0	0	0	0	0	6
	13	CPA (Multimodal Critical Path Analysis)	0	0	0	1	1	0	2	6
SYSTEM DESIGN	14	Task-Centred System Design	0	0	0	1	0	1	2	6
	15	Scenario Based Design	0	1	1	0	1	0	3	6
	~~16~~	~~Mission Analysis~~								
	17	Focus Groups	0	0	0	0	0	1	1	6
	18	Allocation of Function Analysis	0	0	0	1	1	1	3	6
INTERFACE DESIGN	19	Waklthrough Analysis	0	0	0	1	1	0	2	6
	20	User Trial	0	0	0	1	1	0	2	6
	21	SUS (System Usability Scale)	0	0	0	0	1	0	1	6
	22	SUMI (Software Usability Measurement Inventory)	0	0	0	0	1	0	1	6
	23	Repertory Grid Analysis	0	0	0	0	0	0	0	6
	24	QUIS (Questionnaire for User Interface Satisfaction)	0	0	0	1	1	0	2	6
	25	Layout Analysis	0	0	0	1	0	0	1	6
	26	Link Analysis	0	0	0	0	1	0	1	6
	27	Interface Survey	0	0	0	0	0	0	0	6
	28	Heuristic Analysis	0	0	0	1	0	0	1	6
	29	Checklist	0	0	0	0	0	0	0	6
TEAM ASSESSMENT	30	TTRAM (Task and Training Requirements Analysis)	0	1	0	0	0	0	1	6
	31	Team Workload Assessment	0	0	1	0	0	0	1	6
	32	TTA (Team Task Analysis)	0	0	1	0	0	0	1	6
	33	Questionnaires for Distributed Assessment of Team Mutual Awareness	0	0	1	0	0	0	1	6
	34	SNA (Social Network Analysis)	0	0	1	0	0	0	1	6
	35	TCTA (Team Cognitive Task Analysis)	0	0	0	0	1	0	1	6
	36	HTA(T) (Hierarchical Task Analysis for Teams)	0	1	1	0	1	0	3	6
	37	GTA (Groupware Task Analysis)	0	0	0	0	1	1	2	6
	38	DRX (Decision Requirements Exercise)	0	0	1	0	1	0	2	6
	39	CDA (Coordination Demands Analysis)	0	1	1	0	0	1	3	6

	40	CUD (Comms Usage Diagram)	0	0	0	0	0	0	0	6
	41	BOS (Behavioural Observation Scales)	0	1	1	1	1	1	5	6
MENTAL WORKLOAD ASSESSMENT	42	CTLA (Cognitive Task Load Analysis)	0	0	0	0	1	1	2	6
	43	ISA (Instantaneous Self-Assessment)	0	0	0	0	1	1	2	6
	44	Bedford Scales	0	0	0	0	1	1	2	6
	45	Workload Profile Technique	0	0	0	0	1	1	2	6
	46	MACE (Malvern Capacity Estimate)	0	0	0	0	1	0	1	6
	47	DRAWS (DRA Workload Scales)	0	0	0	0	1	1	2	6
	48	SWORD (Subjective Workload Dominance Technique)	0	0	0	0	1	1	2	6
	49	SWAT (Subjective Workload Assessment Technique)	0	0	0	0	1	1	2	6
	~~50~~	~~MCH (Modified Cooper Harper Scales)~~								
	51	NASA TLX (NASA Task Load Index)	0	0	0	0	1	1	2	6
	52	Physiological Mental Workload Measures	0	0	0	0	1	1	2	6
	53	Primary & Secondary Task Performance Measures	0	0	0	0	1	1	2	6
SITUATION AWARENESS ASSESSMENT	54	Propositional Networks	0	0	0	0	0	0	0	6
	55	C-SAS (Cranfield Situation Awareness Scale)	0	0	0	0	0	0	0	6
	56	CARS (Crew Awareness Rating Scale)	0	0	0	0	0	0	0	6
	57	SABARS (Situation Awareness Behavioural Rating Scale)	0	0	0	0	0	0	0	6
	58	MARS (Mission Awareness Rating Scale)	0	0	1	1	1	0	3	6
	~~59~~	~~SASHA_L and SASHA_Q~~								
	60	SPAM (Situation Present Assessment Method)	0	0	0	0	0	0	0	6
	~~61~~	~~SARS (Situation Awareness Rating Scales)~~								
	62	SACRI (Situational Awareness Control Room Inventory)	0	0	0	0	0	0	0	6
	63	SALSA	0	0	0	0	0	0	0	6
	64	SA-SWORD (Situation Awareness Subjective Workload Dominance)	0	0	0	0	0	0	0	6
	65	SART (Situation Awareness Rating Technique)	0	0	0	0	1	1	2	6
	66	SAGAT (Situation Awareness Global Assessment Technique)	0	0	0	0	1	1	2	6
	67	SA Requirements	0	0	0	0	1	0	1	6
HUMAN ERROR IDENTIFICATION	68	CREAM (Cognitive Reliability and Error Analysis Method)	0	1	1	1	0	1	4	6
	69	HEART (Human Error Assessment and Reduction Technique)	0	0	0	0	0	1	1	6
	70	SPEAR (System for Predictive Error Analysis and Reduction)	0	0	0	0	0	0	0	6
	71	HERA (Human Error and Recovery Assessment Framework)	0	0	0	0	1	1	2	6
	72	HEIST (Human Error Identification in Systems Tool)	0	0	0	0	1	0	1	6
	73	THEA (Technique for Human Error Assessment)	0	0	0	0	0	0	0	6
	74	HAZOP (Hazard and Operational Human Error Study)	0	0	0	0	0	0	0	6
	75	TAFEI (Task Analysis for Error Identification	0	0	0	0	0	0	0	6
	76	TRACEr (Technique for the Retrospective and Predictive Analysis of Cognitive Errors)	0	0	0	0	0	0	0	6
	77	HET (Human Error Template)	0	0	0	0	0	0	0	6
	78	SHERPA (Systematic Human Error Reduction and Prediction Approach	0	0	0	0	0	0	0	6
PROCESS CHARTING	79	Murphy Diagram	0	0	0	0	0	0	0	6
	80	Fault Trees	0	0	0	0	0	0	0	6
	81	DAD (Decision Action Diagram)	0	0	0	0	0	0	0	6
	82	ETA (Event Tree Analysis)	0	0	0	0	0	0	0	6
	83	OSD (Operational Sequence Diagram)	0	0	0	0	0	0	0	6
	84	Process Charting	0	0	0	0	0	0	0	6
COGNITIVE TASK ANALYSIS	85	CIT (Critical Incident Technique)	0	1	0	0	1	0	2	6
	86	CDM (Critical Decision Method)	0	1	0	0	1	0	2	6
	87	Cognitive Walkthrough	0	0	0	0	1	1	2	6
	88	ACTA (Applied Cognitive Task Analysis)	0	0	0	0	1	1	2	6
TAS K ANA	89	TTA (Tabular Task Analysis)	0	0	0	0	0	0	0	6
	90	Sub-Goal Template Method (SGT)	0	0	0	0	0	0	0	6

	91	Task Decomposition	0	0	0	0	0	0	0	6
	92	VPA (Verbal Protocol Analysis)	0	0	0	0	1	0	1	6
	93	HTA (Hierarchical Task Analysis)	0	0	0	0	0	0	0	6
SUM			0	11	17	12	44	30		
TOTAL POSSIBLE			89	89	89	89	89	89		

METHOD TYPE		METHOD	APPLICABLE INTERACTIONS BETWEEN LEVELS OF SYSTEM GRANULARITY (COGNITIVE)										SUM	TOTAL POSSIBLE
			WHOLE SYSTEM - SUB-SYSTEM 7	WHOLE SYSTEM - FUNCTIONAL UNIT 8	SUB-SYSTEM - FUNCTIONAL UNIT 9	FUNCTIONAL UNIT - SUB-ASSEMBLY 10	SUB-ASSEMBLY - COMPONENT (THEORETICAL) 11	SUB-ASSEMBLY - COMPONENT (CONTEXTUAL) 12	WHOLE SYSTEM - COMPONENT (THEORETICAL) 13	SUB-SYSTEM - COMPONENT (THEORETICAL) 14	FUNCTIONAL UNIT - COMPONENT (THEORETICAL) 15	COMPONENT (THEORETICAL) - COMPONENT (CONTEXTUAL) 16		
INTEGRATED FRAMEWORKS & ASSESSMENTS	1	CWA (Total Cognitive Work Analysis)	1	0	1	0	3	3	4	3	3	1	19	60
	2	WDA (Work Domain Analysis)	1	0	1	0	0	0	0	0	0	0	2	10
	3	CAT (Contextual Activity Template)	0	0	0	0	0	0	1	0	0	0	1	10
	4	DML (Decision-Making Ladder)	0	0	0	0	1	1	1	1	1	0	5	10
	5	Strategies Analysis (StrA)	0	0	0	0	1	1	1	1	1	0	5	10
	6	SOCA (Social & Organisational Cooperation Analysis)	0	0	0	0	0	0	0	0	0	0	0	10
	7	WCA (Worker Competencies Analysis)	0	0	0	0	1	1	1	1	1	1	6	10
	8	Strategies Analysis Diagram (SAD)	1	0	1	0	1	1	0	0	0	0	4	10
	9	DoA (Degree of Automation)	0	0	0	0	1	0	1	0	0	0	2	10
	10	EAST	0	0	0	0	0	0	0	0	1	0	1	10
TIME PREDICTION	11	Timeline Analysis	0	0	0	0	0	0	0	0	0	0	0	10
	12	KLM (Keystroke Level Model)	0	0	0	0	0	0	0	0	0	0	0	10
	13	CPA (Multimodal Critical Path Analysis)	0	0	0	1	1	0	0	0	0	0	2	10
SYSTEM DESIGN	14	Task-Centred System Design	0	0	0	1	0	1	0	0	0	0	2	10
	15	Scenario Based Design	0	0	0	1	1	0	0	0	1	0	3	10
	~~16~~	~~Mission Analysis~~												
	17	Focus Groups	0	0	0	0	1	0	0	0	0	0	1	10
	18	Allocation of Function Analysis	0	0	0	0	0	0	0	1	1	1	3	10
INTERFACE DESIGN	19	Waklthrough Analysis	0	0	0	0	1	0	0	0	0	0	1	10
	20	User Trial	0	0	0	0	1	0	0	0	0	0	1	10
	21	SUS (System Usability Scale)	0	0	0	0	1	0	0	0	0	0	1	10
	22	SUMI (Software Usability Measurement Inventory)	0	0	0	0	1	0	0	0	0	1	2	10
	23	Repertory Grid Analysis	0	0	0	0	1	0	0	0	0	0	1	10
	24	QUIS (Questionnaire for User Interface Satisfaction)	0	0	0	0	1	0	0	0	0	1	2	10
	25	Layout Analysis	0	0	0	0	1	0	0	0	0	0	1	10
	26	Link Analysis	0	0	0	0	0	0	0	0	0	0	0	10
	27	Interface Survey	0	0	0	0	0	0	0	0	0	0	0	10
	28	Heuristic Analysis	0	0	0	0	0	0	0	0	0	0	0	10
	29	Checklist	0	0	0	0	1	0	0	0	0	0	1	10
TEAM ASSESSMENT	30	TTRAM (Task and Training Requirements Analysis)	0	0	0	0	0	0	0	0	0	1	1	10
	31	Team Workload Assessment	0	0	0	0	0	0	0	0	0	0	0	10
	32	TTA (Team Task Analysis)	0	0	0	0	1	0	0	0	1	0	2	10
	33	Questionnaires for Distributed Assessment of Team Mutual Awareness	0	0	0	0	0	0	0	0	1	0	1	10

	34	SNA (Social Network Analysis)	0	0	0	0	0	0	0	0	1	0	1	10
	35	TCTA (Team Cognitive Task Analysis)	0	0	0	0	1	0	1	0	0	1	3	10
	36	HTA(T) (Hierarchical Task Analysis for Teams)	0	0	0	0	0	0	0	1	0	0	1	10
	37	GTA (Groupware Task Analysis)	0	0	0	0	0	1	0	0	1	0	2	10
	38	DRX (Decision Requirements Exercise)	0	0	0	0	0	1	0	0	0	1	2	10
	39	CDA (Coordination Demands Analysis)	0	0	1	1	1	0	0	0	1	0	4	10
	40	CUD (Comms Usage Diagram)	0	0	0	1	0	0	0	0	1	0	2	10
	41	BOS (Behavioural Observation Scales)	0	0	1	1	0	0	0	0	1	0	3	10
MENTAL WORKLOAD ASSESSMENT	42	CTLA (Cognitive Task Load Analysis)	0	0	0	0	1	0	0	0	0	0	1	10
	43	ISA (Instantaneous Self-Assessment)	0	0	0	0	1	0	0	0	0	0	1	10
	44	Bedford Scales	0	0	0	0	1	0	0	0	0	0	1	10
	45	Workload Profile Technique	0	0	0	0	1	0	0	0	0	0	1	10
	46	MACE (Malvern Capacity Estimate)	0	0	0	0	1	0	0	0	0	0	1	10
	47	DRAWS (DRA Workload Scales)	0	0	0	0	1	0	0	0	1	0	2	10
	48	SWORD (Subjective Workload Dominance Technique)	0	0	0	0	0	0	0	0	0	0	0	10
	49	SWAT (Subjective Workload Assessment Technique)	0	0	0	0	1	0	0	0	0	0	1	10
	~~50~~	~~MCH (Modified Cooper Harper Scales)~~												
	51	NASA TLX (NASA Task Load Index)	0	0	0	0	1	0	0	0	0	0	1	10
	52	Physiological Mental Workload Measures	0	0	0	0	1	0	0	0	0	0	1	10
	53	Primary & Secondary Task Performance Measures	0	0	0	0	1	0	0	0	0	0	1	10
SITUATION AWARENESS ASSESSMENT	54	Propositional Networks	0	0	0	0	1	0	0	0	1	0	2	10
	55	C-SAS (Cranfield Situation Awareness Scale)	0	0	0	0	1	0	0	0	0	0	1	10
	56	CARS (Crew Awareness Rating Scale)	0	0	0	0	1	0	0	0	0	0	1	10
	57	SABARS (Situation Awareness Behavioural Rating Scale)	0	0	1	0	1	0	0	0	1	0	3	10
	58	MARS (Mission Awareness Rating Scale)	0	0	0	0	0	0	0	0	0	0	0	10
	~~59~~	~~SASHA_L and SASHA_Q~~												
	60	SPAM (Situation Present Assessment Method)	0	0	0	0	0	0	0	0	0	0	0	10
	~~61~~	~~SARS (Situation Awareness Rating Scales)~~												
	62	SACRI (Situational Awareness Control Room Inventory)	0	0	0	0	0	0	0	0	0	0	0	10
	63	SALSA	0	0	0	0	1	0	0	0	1	0	2	10
	64	SA-SWORD (Situation Awareness Subjective Workload Dominance)	0	0	0	0	1	0	0	0	0	0	1	10
	65	SART (Situation Awareness Rating Technique)	0	0	0	0	0	0	0	0	0	0	0	10
	66	SAGAT (Situation Awareness Global Assessment Technique)	0	0	0	0	0	0	0	0	0	0	0	10
	67	SA Requirements	0	0	0	0	1	0	0	1	1	0	3	10
HUMAN ERROR IDENTIFICATION	68	CREAM (Cognitive Reliability and Error Analysis Method)	0	0	0	0	1	0	0	1	1	1	4	10
	69	HEART (Human Error Assessment and Reduction Technique)	0	0	0	0	1	0	0	0	0	0	1	10
	70	SPEAR (System for Predictive Error Analysis and Reduction)	0	0	0	0	1	0	0	0	0	0	1	10
	71	HERA (Human Error and Recovery Assessment Framework)	0	0	0	0	1	0	0	1	1	0	3	10
	72	HEIST (Human Error Identification in Systems Tool)	0	0	0	0	1	0	0	0	0	0	1	10
	73	THEA (Technique for Human Error Assessment)	0	0	0	0	0	0	0	0	0	0	0	10
	74	HAZOP (Hazard and Operational Human Error Study)	0	0	0	0	1	0	0	0	0	0	1	10
	75	TAFEI (Task Analysis for Error Identification	0	0	0	0	1	0	0	0	0	0	1	10
	76	TRACEr (Technique for the Retrospective and Predictive Analysis of Cognitive Errors)	0	0	0	0	1	0	0	0	1	0	2	10
	77	HET (Human Error Template)	0	0	0	0	1	0	0	0	0	0	1	10
	78	SHERPA (Systematic Human Error Reduction and Prediction Approach	0	0	0	0	1	0	0	1	1	0	3	10
PROCES S	79	Murphy Diagram	0	0	0	0	1	0	0	0	0	0	1	10
	80	Fault Trees	0	0	0	0	0	0	0	0	0	0	0	10

	81	DAD (Decision Action Diagram)	0	0	0	0	1	0	0	0	0	0	1	10
	82	ETA (Event Tree Analysis)	0	0	0	0	0	0	0	0	0	0	0	10
	83	OSD (Operational Sequence Diagram)	0	0	0	0	0	0	0	0	0	0	0	10
	84	Process Charting	0	0	0	0	1	0	0	0	0	0	1	10
COGNITIVE TASK ANALYSIS	85	CIT (Critical Incident Technique)	0	0	1	0	1	0	0	0	0	0	2	10
	86	CDM (Critical Decision Method)	0	0	0	0	1	0	1	0	0	0	2	10
	87	Cognitive Walkthrough	0	0	0	1	1	1	0	0	0	0	3	10
	88	ACTA (Applied Cognitive Task Analysis)	0	0	0	0	1	0	1	1	1	0	4	10
TASK ANALYSIS	89	TTA (Tabular Task Analysis)	0	0	0	0	1	0	0	0	0	0	1	10
	90	Sub-Goal Template Method (SGT)	0	0	0	0	1	0	0	0	1	0	2	10
	91	Task Decomposition	0	0	0	0	1	0	0	1	1	0	3	10
	92	VPA (Verbal Protocol Analysis)	0	0	0	0	0	0	0	0	0	0	0	10
	93	HTA (Hierarchical Task Analysis)	0	0	0	0	1	0	0	0	1	0	2	10
SUM			3	0	7	7	60	11	12	14	29	9		
TOTAL POSSIBLE			89	89	89	89	89	89	89	89	89	89		

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APPENDIX C.1:
UK 2015 Hierarchical Task Analysis for Commercial Driving (HTAoCD)

Full 74-page analysis can be viewed and downloaded at the following DOI link: https://doi.org/10.6084/m9.figshare.7881896.

APPENDIX C.2:
UK 2020 Hierarchical Task Analysis for Commercial Driving (HTAoCD)

Full 75-page analysis can be viewed and downloaded at the following DOI link: https://doi.org/10.6084/m9.figshare.7882757.

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APPENDIX C.3:
UK 2025 Hierarchical Task Analysis for Commercial Driving (HTAoCD)

Full 75-page analysis can be viewed and downloaded at the following DOI link: https://doi.org/10.6084/m9.figshare.7883249.

APPENDIX C.4:
UK 2030 Hierarchical Task Analysis for Commercial Driving (HTAoCD)

Full 75-page analysis can be viewed and downloaded at the following DOI link: https://doi.org/10.6084/m9.figshare.7883252.

APPENDIX D.1:
UK 2015 Training Needs Analysis for Commercial Driving (TNAoCD)

Full 95-page analysis can be viewed and downloaded at the following DOI link: https://doi.org/10.6084/m9.figshare.7883255.

APPENDIX D.2:
UK 2020 Training Needs Analysis for Commercial Driving (TNAoCD)

Full 98-page analysis can be viewed and downloaded at the following DOI link: https://doi.org/10.6084/m9.figshare.7883258.

APPENDIX D.3:
UK 2025 Training Needs Analysis for Commercial Driving (TNAoCD)

Full 100-page analysis can be viewed and downloaded at the following DOI link: https://doi.org/10.6084/m9.figshare.7883267.

APPENDIX D.4:
UK 2030 Training Needs Analysis for Commercial Driving (TNAoCD)

Full 100-page analysis can be viewed and downloaded at the following DOI link: https://doi.org/10.6084/m9.figshare.7883270.

APPENDIX E:
Cognitive Work Analysis (CWA) Prompts

Prompts from **Jenkins, D. P., Stanton, N. A., Salmon, P. M., & Walker, G. H. (2009).** ***Cognitive Work Analysis: Coping with Complexity*****. Barnham: Ashgate.**

	Prompts		Keywords
Functional Purpose(s)	Purposes	• For what reasons does the work system exist?	Reasons, goals, objectives, aims, intentions, mission, ambitions, plans, services, products, roles, targets, aspirations, desires, motives, values, beliefs, views, rationale, philosophy, policies, norms, conventions, attitudes, conventions, attitudes, customs, ethics, morals, principles
		• What are the highest-level objectives or ultimate purposes of the work system?	
		• What services does the work system provide to the environment?	
		• What needs of the environment does the work system satisfy?	
		• What role does the work system play in the environment?	
		• What has the work system been designed to achieve?	
		• What are the values of the people in the work system?	
	External constraints	• What kinds of constraints does the environment impose on the work system?	Laws, regulations, guidance, standards, directives, requirements, rules, limits, public opinion, policies, values, beliefs, views, rationale, philosophy, norms, conventions, attitudes, customs, ethics, morals, principles
		• What values does the environment impose on the work system?	
		• What laws and regulations does the environment impose on the work system?	
		• What societal laws and conventions does the environment impose on the work system?	
Values & Priority Measures		• What criteria can be used to judge whether the work system is achieving its purposes?	Criteria, measures, benchmarks, tests, assessments, appraisals, calculations, evaluations, estimations, judgements, scales, yardsticks, budgets, schedules, outcomes, results, targets, figures, limits Measures of: effectiveness, efficiency, reliability, risk, resources, time, quality, quantity, probability, economy, consistency, frequency, success Values: laws, regulations, guidance, standards, directives, requirements, rules, limits, public opinion, policies, values, beliefs, views, rationale, philosophy, norms, conventions, attitudes, customs, ethics, morals, principles
		• What criteria can be used to judge whether the work system is satisfying its external constraints?	
		• What criteria can be used to compare the results or effects of the purpose-related functions on the functional purposes? What are the performance requirements of various functions in the work system? How is the performance of various functions in the work system measured or evaluated and compared?	
		• What criteria can be used to assign priorities to the purpose-related functions? What are the priorities of the work system? How are priorities assigned to the various functions in the work system?	
		• What criteria can be used to allocate resources (e.g. material, energy, information, people, money) to the purpose-related functions? What resources are allocated to the various functions of the work system? How are resources allocated to the various functions of the work system?	

Purpose-Related Functions		• What functions are required to achieve the purposes of the work system?	Functions, roles, responsibilities, purposes, tasks, jobs, duties, occupations, positions, activities, operations
		• What functions are required to satisfy the external constraints on the work system?	
		• What functions are performed in the work system?	
		• What are the functions of individuals, teams, and departments in the work system?	
		• What functions are performed with the physical resources in the work system?	
		• What functions coordinate the use of the physical resources in the work system?	
Object-Related Processes		• What can the physical objects in the work system do or afford?	Processes, functions, purposes, utility, role, uses, applications, functionality, characteristics, capabilities, limitations, capacity, physical processes, mechanical processes, electrical processes, chemical processes
		• What processes are the physical objects in the work system used for?	
		• What are the functional capabilities and limitations of physical objects in the work system?	
		• What physical, mechanical, electrical, or chemical processes are afforded by the physical objects in the work system?	
		• What functionality is required in the work system to enable the purpose-related functions?	
Physical Objects		• What are the physical objects or physical resources in the work system – both man-made and natural?	Man-made and natural objects: tools, equipment, devices, apparatus, machinery, items, instruments, accessories, appliances, implements, technology, supplies, kit, gear, buildings, facilities, premises, infrastructure, fixtures, fittings, assets, resources, staff, people, personnel, terrain, land, meteorological features
		• What physical objects or physical resources are necessary to enable the processes and functions of the work system?	
		• What is the inventory (e.g. names, number, types) of physical objects or physical resources in the work system?	Inventory: names of physical objects, number, quantities, brands, models, types
		• What are the material characteristics (e.g. external form including shape, dimensions, colour; internal configuration; material composition) of physical objects or physical resources in the work system?	Material characteristics: appearance, shape, dimensions, colour, attributes, configuration, arrangement, layout, structure, construction, make up, design
		• What is the topography or organisation (e.g. layout or location of physical objects in relation to each other) of physical objects or physical resources in the work system?	Topography: organisation, location, layout, spacing, placing, positions, orientations, ordering, arrangement

APPENDIX F:
NodeXL Results, 2015 – 2030

Betweenness Centrality for 2015 Truck-Driver System Abstraction Hierarchy	
Node	*Betweenness Centrality*
Accelerator pedal	0.000
Acts as supporting infrastructure for communication	441.217
Adhesive/staple	0.000
Adjusts seat	274.988
Airbags	16.266
Airline pressure display	0.000
Alarm (cab area)	0.000
Alarm (cargo area)	0.000
Alarm (doors)	0.000
Alarm (ignition)	0.000
Alarm (seatbelt reminder)	0.000
Alarm for reversal	0.000
Alarm/display (other)	0.000
Alerts to brake pad wear	649.155
Alerts to lack of seatbelt use	479.432
Alerts to low tyre pressure	649.155
Alerts to presence of smoke	447.124
Alerts to status of cab area hazards	516.220
Alerts to status of cab doors	479.432
Attaches ID tag/label to goods	217.000
Battery	0.000
Brake pedal	0.000
Brake system hardware	0.000
Break area	0.000
Breathalyser	0.000
Bumper	0.000
Cab (including windows/windscreen)	144.083
Cab heating & cooling systems	0.000
Cargo chain hooks/clips/fasteners	0.000
Cargo paperwork/ID tags	0.000
Cargo/goods	0.000
Central locking system	0.000
Clock	0.000
Clutch	0.000
Communicate/collaborate with other drivers/transport dispatcher	1765.104
Connect trailer to vehicle/ enable delivery to site	3304.967
Connects airlines	447.475
Connects braking system	447.475
Connects power/electricity	447.475
Controls vehicle trajectory	217.000
Coolant display	0.000
Crane	8.029
Current fuel consumption display	0.000
Deploys airbag	273.822
Digital tachograph	4.765
Display (oil level warning)	0.000
Display (vehicle & trailer weight)	0.000
Drawbar/kingpin	0.000
Drive vehicle (basic, operational, & tactical tasks)	10263.423
Driver	891.316
Driver tachograph card	0.000
Electricity fuses/connectors	0.000
Enables change in vehicle speed	1412.787
Enables communication pathway/passage of info	749.124
Enables driver feedback receptors (vision, hearing, and/or	1789.890
Enables driver rest/recharge	666.619

Enables locomotion	534.890
Enables trailer locomotion	275.607
Enables vehicle start-up	849.994
Enables worker to get into position	426.038
Engine (mechanical)	0.000
Engine Control Unit/computer	2740.788
Ensure occupational health/comfort of worker	1726.979
Ensure operation within existing law	1233.779
Ensure provision of goods to customer	621.320
Ensure security of vehicle	529.192
Ensures vehicle and cab are functional/fit for purpose	758.501
External lights	45.600
Facilitates refuelling point	217.000
Facilitates work environment	1509.057
Food/drink	0.000
Front grill/bull bar	0.000
Fuel	0.000
Fuel level display	0.000
Fuel station	0.000
Fuel tank	0.000
Fuel/refuel	447.918
Fulfills customer order	217.000
Gear box	0.000
Gear stick	0.000
Generator	0.000
GPS system	4.235
GPS-enabled order software	9.442
Hand rails	42.824
Hazard lights	0.000
High vis vest etc.	0.000
Horn	0.000
Identify and relay service issues	2619.125
Identify vehicle/system is not fit for purpose	156.672
Ignition	0.000
Indicators	0.000
Ink	0.000
Internal lights	0.000
Keys	37.847
Land-based comms tower	0.000
Laptop	0.000
Laptop mount	0.000
Lifts/adjusts cargo to/from trailer	45.662
Maintains temperature/climate	454.200
Map	0.000
Maximise "forebearing, gentle driving style"	95.580
Maximise efficiency/miles driven 'loaded'	226.079
Maximise flexibility in routine	37.225
Maximise safety	1756.810
Maximise user/worker health/comfort	162.689
Maximise vehicle/system reliability	146.563
Mill/processing site	0.000
Minimise financial cost/loss of time	6249.659
Minimise noise	21.200
Mirrors	0.000
Mobile phone	62.139
Oil pressure display	0.000
Orange traffic triangle	0.000
Other mechanical display warnings (sub-system comms not	0.000
Other mechanical display warnings (sub-system not functional)	0.000
Other mechanical display warnings (sub-system on/off indicator)	0.000
Paper	0.000
Pen/pencil	0.000
Personal belongings	0.000

Physically connects trailer to vehicle	217.000
Pick up/load vehicle with goods	1852.186
Plan schedule/pickups/route/rest periods	3041.093
Presents info on coolant level	447.124
Presents info on vehicle sub-system fitness	648.000
Prevents build-up of dirt/water/ice	276.798
Printer	0.000
Prioritises/selects next driving steps	788.683
Protect vehicle from being damaged	1004.494
Protect/ensure immediate safety of worker	1564.139
Protects worker's hands	217.000
Provide goods to customer	318.789
Provides fuel/power	648.000
Provides info on airline pressure	510.853
Provides info on cargo area	1105.473
Provides info on current day/driver drive times	48.329
Provides info on current ignition setting	516.220
Provides info on current time	232.265
Provides info on fuel consumption	217.000
Provides info on fuel level	217.000
Provides info on location	117.253
Provides info on oil level	447.124
Provides info on oil pressure	539.313
Provides info on other system/vehicle characteristics	607.771
Provides info on RPMs	217.000
Provides info on speed	217.000
Provides info on temperature	649.155
Provides info on vehicle & trailer weight	1803.176
Provides traction	101.890
Provides traffic info	377.510
Provides visual or auditory alerts others to presence	2250.947
Radio/media	0.000
Ridged floor mats	0.000
Road navigation signs	0.000
Roadside clearing/loading points (for timber)	0.000
Roadway/path	0.000
RPM display	0.000
Satellite	0.000
Seat controls	0.000
Seatbelt	0.000
Secures vehicle	256.853
Sensor (oil level)	0.000
Sensor (oil pressure)	0.000
Sensors (airline pressure)	0.000
Sensors (brake pads)	0.000
Sensors (cab area e.g. front grill)	0.000
Sensors (cargo area)	0.000
Sensors (coolant)	0.000
Sensors (doors)	0.000
Sensors (ignition)	0.000
Sensors (other)	11.926
Sensors (seat/seatbelts)	0.000
Sensors (smoke)	0.000
Sensors (temperature)	0.000
Sensors (vehicle & trailer weight)	0.000
Smoke alarm	0.000
Speed display	0.000
Stabilises human	307.822
Stabilises/protects tools	217.000
Stabilises/protects vehicle body	648.000
Stabilises/secures cargo	1089.475
Stabilises/secures trailer	231.475
Steering wheel	0.000

Steps	0.000
Stores cargo	231.475
Stores cargo description & location	550.253
Stores fuel/power	433.000
Stores info on cargo characteristics	217.000
Stores info on driver's hours/rest periods	489.879
Stores navigation info	657.003
Stores vehicle/system info	276.247
Temperature controls	0.000
Temperature display	0.000
Trailer ABS hook-up inputs	0.000
Trailer ABS hook-ups	0.000
Trailer air hook-up inputs	0.000
Trailer air hook-ups	0.000
Trailer body	0.000
Trailer cargo chains/steel wires/straps	0.000
Trailer electricity hook-ups	0.000
Trailer light hook-ups	0.000
Trailer parking brake	0.000
Trailer sheeting	0.000
Trailer side barrier	0.000
Trailer steel wire adjusting button	0.000
Trailer suspension	0.000
Tyre pressure monitoring display	0.000
Tyre pressure monitoring sensors/system	0.000
Tyres	59.887
Unload goods	1602.163
Vehicle parking brake	0.000
Vehicle seats	0.000
Vehicle suspension	0.000
Vehicle user manual	0.000
Warning display (brake pads)	0.000
White smoke limiter button	0.000
Window adjusters	0.000
Windscreen defogger	0.000
Windscreen wipers	0.000
Work gloves	0.000

Betweenness Centrality for 2020 Truck-Driver System Abstraction Hierarchy

Node	*Betweenness Centrality*
Accelerator pedal	0.000
Acts as supporting infrastructure for communication	405.815
ADAS feedback system with collision avoidance warnings	2618.274
Adhesive/staple	0.000
Adjusts seat	182.304
Aerodynamic fittings	0.000
Airbags	9.755
Alarm for reversal	0.000
Alerts to brake pad wear	325.209
Alerts to lack of seatbelt use	296.341
Alerts to low tyre pressure	460.284
Alerts to presence of smoke	212.245
Alerts to status of cab area hazards	286.202
Alerts to status of cab doors	296.341
Attaches ID tag/label to goods	202.000
Automated emergency braking	12.955
Battery	0.000
Brake pedal	0.000
Brake system hardware	0.000
Break area	0.000
Breathalyser	0.000
Bumper	0.000
Cab (including windows/windscreen)	120.201
Cab heating & cooling systems	0.000
Cargo chain hooks/clips/fasteners	0.000
Cargo paperwork/ID tags	0.000
Cargo/goods	0.000
Central locking system	0.000
Clutch	0.000
Communicate/collaborate with other drivers/transport dispatcher	1496.040
Connect trailer to vehicle/ enable delivery to site	2989.101
Connects airlines	417.975
Connects braking system	417.975
Connects power/electricity	417.975
Controls vehicle trajectory	202.000
Crane	7.058
Deploys airbag	217.134
Drawbar/kingpin	0.000
Drive vehicle (basic, operational, & tactical tasks)	7960.457
Driver	432.108
Electricity fuses/connectors	0.000
Electrification of hotel loads	0.000
Enables change in vehicle speed	1481.123
Enables communication pathway/passage of info	657.439
Enables driver feedback receptors (vision, hearing, and/or	1876.458
Enables driver rest/recharge	615.480
Enables locomotion	497.510
Enables trailer locomotion	256.204
Enables vehicle start-up	793.908
Enables worker to get into position	391.198
Engine (mechanical)	0.000
Engine Control Unit/computer	1072.382
Ensure occupational health/comfort of worker	1339.010
Ensure operation within existing law	896.714
Ensure provision of goods to customer	516.311
Ensure security of vehicle	465.035
Ensures vehicle and cab are functional/fit for purpose	677.711
External lights	51.881
Facilitates refuelling point	202.000
Facilitates work environment	1360.901

Food/drink	0.000
Front grill/bull bar	0.000
Fuel	0.000
Fuel station	0.000
Fuel tank	0.000
Fuel/refuel	423.212
Fulfills customer order	202.000
Gear box	0.000
Gear stick	0.000
Generator	0.000
GPS system with real-time traffic data	3.041
GPS-enabled order software	18.970
Hand rails	35.331
Haptic interfaces	11.218
Hazard lights	0.000
Heat management technology	9.143
High vis vest etc.	0.000
Horn	0.000
Identify and relay service issues	856.099
Identify vehicle/system is not fit for purpose	28.483
Ignition	0.000
Indicators	0.000
Ink	0.000
Internal lights	0.000
Keys	34.270
Land-based comms tower	0.000
Laptop	0.000
Laptop mount	0.000
Lifts/adjusts cargo to/from trailer	40.907
Maintains temperature/climate	289.090
Maximise "forebearing, gentle driving style"	76.164
Maximise efficiency/miles driven 'loaded'	142.256
Maximise flexibility in routine	20.376
Maximise safety	1371.149
Maximise user/worker health/comfort	115.175
Maximise vehicle/system reliability	83.498
Mild hybrid stop/start system	49.011
Mill/processing site	0.000
Minimise emissions/environmental impact	929.303
Minimise financial cost/loss of time	4033.392
Minimise fossil fuel use	612.157
Minimise noise	47.669
Mirrors	0.000
Mobile phone	84.740
Next-gen digital tachographs	2.546
On-board cameras	0.000
Orange traffic triangle	0.000
Paper	0.000
Pen/pencil	0.000
Personal belongings	0.000
Physically connects trailer to vehicle	202.000
Pick up/load vehicle with goods	1801.608
Plan schedule/pickups/route/rest periods	1684.963
Presents info on coolant level	212.245
Presents info on vehicle sub-system fitness	3.697
Prevents build-up of dirt/water/ice	245.995
Printer	0.000
Prioritises/selects next driving steps	1018.397
Protect vehicle from being damaged	939.870
Protect/ensure immediate safety of worker	1298.362
Protects worker's hands	202.000
Provide goods to customer	281.352
Provides fuel/power	942.205

Provides info on airline pressure	323.980
Provides info on cargo area	986.938
Provides info on current day/driver drive times	135.256
Provides info on current ignition setting	286.202
Provides info on current time	74.484
Provides info on fuel consumption	47.940
Provides info on fuel level	30.931
Provides info on location	70.233
Provides info on oil level	212.245
Provides info on oil pressure	276.403
Provides info on other system/vehicle characteristics	294.455
Provides info on RPMs	47.940
Provides info on speed	47.940
Provides info on temperature	325.209
Provides info on vehicle & trailer weight	922.842
Provides traction	94.510
Provides traffic info	436.249
Provides visual or auditory alerts others to presence	1943.390
Radio/media	0.000
Reduces drag	261.608
Ridged floor mats	0.000
Road navigation signs	0.000
Roadside clearing/loading points (for timber)	0.000
Roadway/path	0.000
Satellite	0.000
Seatbelt	0.000
Secures vehicle	234.363
Sensor (oil level)	0.000
Sensor (oil pressure)	0.000
Sensors (airline pressure)	0.000
Sensors (brake pads)	0.000
Sensors (cab area e.g. front grill)	0.000
Sensors (cargo area)	0.000
Sensors (coolant)	0.000
Sensors (doors)	0.000
Sensors (ignition)	0.000
Sensors (other)	9.790
Sensors (seat/seatbelts)	0.000
Sensors (smoke)	0.000
Sensors (temperature)	0.000
Sensors (vehicle & trailer weight)	0.000
Stabilises human	290.476
Stabilises/protects tools	202.000
Stabilises/protects vehicle body	603.000
Stabilises/secures cargo	1019.881
Stabilises/secures trailer	216.975
Steering wheel	0.000
Steps	0.000
Stores cargo	216.975
Stores cargo description & location	473.233
Stores fuel/power	491.884
Stores info on cargo characteristics	202.000
Stores info on driver's hours/rest periods	148.031
Stores navigation info	605.529
Stores vehicle/system info	229.568
Topographical ACC	118.338
Trailer ABS hook-up inputs	0.000
Trailer ABS hook-ups	0.000
Trailer air hook-up inputs	0.000
Trailer air hook-ups	0.000
Trailer body	0.000
Trailer cargo chains/steel wires/straps	0.000
Trailer electricity hook-ups	0.000

Trailer light hook-ups	0.000
Trailer parking brake	0.000
Trailer sheeting	76.248
Trailer side barrier	0.000
Trailer steel wire adjusting button	0.000
Trailer suspension	0.000
Tyre pressure monitoring sensors/system	0.000
Tyres	55.724
Unload goods	1317.324
Vehicle parking brake	0.000
Vehicle seats	0.000
Vehicle suspension	0.000
Vehicle user manual	0.000
White smoke limiter button	0.000
Window adjusters	0.000
Windscreen defogger	0.000
Windscreen wipers	0.000
Work gloves	0.000

Betweenness Centrality for 2025 Truck-Driver System Abstraction Hierarchy

Node	*Betweenness Centrality*
Accelerator pedal	0.000
Active collision avoidance system	53.624
Active dolly for double trailers	99.516
Acts as supporting infrastructure for communication	427.858
ADAS feedback system via head-up display with collision avoidance warnings	2887.644
Adhesive/staple	0.000
Adjusts seat	185.177
Aerodynamic fittings	0.000
Airbags	9.954
Alarm (cargo area)	0.000
Alarm for reversal	0.000
Alerts to brake pad wear	344.821
Alerts to lack of seatbelt use	309.095
Alerts to low tyre pressure	344.821
Alerts to presence of smoke	224.069
Alerts to status of cab area hazards	302.627
Alerts to status of cab doors	309.095
Attaches ID tag/label to goods	213.000
Automated emergency braking	11.176
Battery	0.000
Brake pedal	0.000
Brake system hardware	0.000
Break area	0.000
Breathalyser	0.000
Bumper	0.000
Cab (including windows/windscreen) with integrated aerodynamic design and lightweighting	212.066
Cab heating & cooling systems	0.000
Cargo chain hooks/clips/fasteners	0.000
Cargo paperwork/ID tags	0.000
Cargo/goods	0.000
Central locking system	0.000
Clutch	0.000
Communicate with infrastructure	154.862
Communicate with surrounding vehicles	268.640
Communicate/collaborate with other drivers/transport dispatcher	1583.156
Connect trailer to vehicle/ enable delivery to site	3250.735
Connects airlines	437.925
Connects braking system	437.925
Connects power/electricity	437.925
Contactless induction charging	0.000
Controls vehicle trajectory	416.569
Crane	8.364
Deploys airbag	226.045
Drawbar/kingpin	0.000
Drive vehicle (basic, operational, & tactical tasks)	8633.940
Driver	452.805
DSRC technology for V2V and V2I applications	0.000
Electric hybrid propulsion technology	0.000
Electricity fuses/connectors	0.000
Electrification of hotel loads	0.000
Enables change in vehicle speed	1625.399
Enables communication pathway/passage of info	948.595
Enables driver feedback receptors (vision, hearing, and/or	2165.526
Enables driver rest/recharge	651.153
Enables locomotion	718.205
Enables trailer locomotion	296.585
Enables vehicle start-up	835.304
Enables worker to get into position	412.198

Engine (mechanical)	0.000
Engine Control Unit/computer	1126.025
Ensure occupational health/comfort of worker	1399.020
Ensure operation within existing law	1107.631
Ensure provision of goods to customer	552.540
Ensure security of vehicle	491.297
Ensures vehicle and cab are functional/fit for purpose	715.514
External lights	55.519
Facilitates refuelling point	213.000
Facilitates work environment	1441.769
Food/drink	0.000
Front grill/bull bar	0.000
Fuel	0.000
Fuel station	0.000
Fuel tank	0.000
Fuel/refuel	449.026
Fulfills customer order	213.000
Gear box	0.000
Gear stick	0.000
Generator	0.000
GPS-enabled order software	21.569
Hand rails	35.724
Haptic interfaces	11.228
Hazard lights	0.000
Heat management technology	10.952
High vis vest etc.	0.000
Horn	0.000
Identify and relay service issues	885.435
Identify vehicle/system is not fit for purpose	29.661
Ignition	0.000
Indicators	0.000
Ink	0.000
Integrated digital tachograph & connected telematic data collection	15.410
Internal lights	0.000
Keys	33.554
Land-based comms tower	0.000
Laptop	0.000
Laptop mount	0.000
Lifts/adjusts cargo to/from trailer	39.729
Low rolling resistance tyres	73.705
Maintains temperature/climate	314.691
Maximise "forebearing, gentle driving style"	117.398
Maximise efficiency/miles driven 'loaded'	36.217
Maximise flexibility in routine	26.165
Maximise safety	1591.349
Maximise user/worker health/comfort	120.761
Maximise vehicle/system reliability	81.521
Mild hybrid stop/start system	47.742
Mill/processing site	0.000
Minimise emissions/environmental impact	775.562
Minimise financial cost/loss of time	4672.011
Minimise fossil fuel use	1063.219
Minimise noise	55.530
Mirrors with optimised design	0.000
Mobile phone	102.176
On-board cameras	0.000
Orange traffic triangle	0.000
Paper	0.000
Pen/pencil	0.000
Personal belongings	0.000
Physically connects trailer to vehicle	233.836
Pick up/load vehicle with goods	1520.446

Plan schedule/pickups/route/rest periods	1656.885
Presents info on coolant level	224.069
Presents info on vehicle sub-system fitness	4.103
Prevents build-up of dirt/water/ice	253.905
Printer	0.000
Prioritises/selects next driving steps	1165.642
Protect vehicle from being damaged	992.408
Protect/ensure immediate safety of worker	1369.982
Protects worker's hands	213.000
Provide goods to customer	285.856
Provide info on vehicle dynamics & emissions	47.455
Provides fuel/power	1201.871
Provides info on airline pressure	349.806
Provides info on cargo area	1254.704
Provides info on current day/driver drive times	120.016
Provides info on current ignition setting	302.627
Provides info on current time	78.473
Provides info on fuel consumption	51.381
Provides info on fuel level	33.911
Provides info on location	226.571
Provides info on oil level	224.069
Provides info on oil pressure	300.182
Provides info on other system/vehicle characteristics	313.204
Provides info on RPMs	51.381
Provides info on speed	51.381
Provides info on temperature	344.821
Provides info on vehicle & trailer weight	967.407
Provides optimal traction	153.284
Provides traffic info	432.813
Provides visual or auditory alerts others to presence	2071.113
Radio/media	0.000
Reduces drag	364.752
Ridged floor mats	0.000
Road navigation signs	0.000
Roadside clearing/loading points (for timber)	0.000
Roadway/path	0.000
Satellite	0.000
Seatbelt	0.000
Secures vehicle	247.250
Sensor (oil level)	0.000
Sensor (oil pressure)	0.000
Sensors (airline pressure)	0.000
Sensors (brake pads)	0.000
Sensors (cab area e.g. front grill)	0.000
Sensors (cargo area)	0.000
Sensors (coolant)	0.000
Sensors (doors)	0.000
Sensors (ignition)	0.000
Sensors (other)	10.097
Sensors (seat/seatbelts)	0.000
Sensors (smoke)	0.000
Sensors (temperature)	0.000
Sensors (vehicle & trailer weight)	0.000
Sophisticated sat nav (vehicle-specific, with real-time traffic data)	13.035
Stabilises human	307.066
Stabilises/protects tools	213.000
Stabilises/protects vehicle body	636.000
Stabilises/secures cargo	1028.652
Stabilises/secures trailer	295.764
Steering wheel	0.000
Steps	0.000
Stores cargo	225.925
Stores cargo description & location	494.573

Stores fuel/power	513.942
Stores info on cargo characteristics	213.000
Stores info on driver's hours/rest periods	116.691
Stores info on vehicle dynamics & emissions	205.339
Stores navigation info	617.840
Stores vehicle/system info	242.364
Telematic data collection device	13.020
Topographical ACC	117.549
Trailer ABS hook-up inputs	0.000
Trailer ABS hook-ups	0.000
Trailer air hook-up inputs	0.000
Trailer air hook-ups	0.000
Trailer body	0.000
Trailer cargo chains/steel wires/straps	0.000
Trailer electricity hook-ups	0.000
Trailer light hook-ups	0.000
Trailer parking brake	0.000
Trailer sheeting	74.048
Trailer side barrier	0.000
Trailer steel wire adjusting button	0.000
Trailer suspension	0.000
Tyre pressure monitoring sensors/system	0.000
Unload goods	1520.446
Vehicle parking brake	0.000
Vehicle seats	0.000
Vehicle suspension	0.000
Vehicle user manual	0.000
White smoke limiter button	0.000
Window adjusters	0.000
Windscreen defogger	0.000
Windscreen wipers	0.000
Work gloves	0.000

Betweenness Centrality for 2030 Truck-Driver System Abstraction Hierarchy	
Node	*Betweenness Centrality*
Accelerator pedal	0.000
Active collision avoidance system	50.483
Active dolly for double trailers	165.588
Acts as supporting infrastructure for communication	441.747
ADAS feedback system via head-up display with collision avoidance warnings	3107.932
Adhesive/staple	0.000
Adjusts seat	180.989
Aerodynamic fittings	0.000
Airbags	8.989
Alarm (cargo area)	0.000
Alarm for reversal	0.000
Alerts and wakes driver	523.309
Alerts to brake pad wear	357.914
Alerts to lack of seatbelt use	296.942
Alerts to low tyre pressure	357.914
Alerts to presence of smoke	231.084
Alerts to status of cab area hazards	313.897
Alerts to status of cab doors	296.942
Attaches ID tag/label to goods	220.000
Automated emergency braking	18.743
Automated low-speed maneuvering	50.483
Battery	0.000
Battery electric propulsion	0.000
Brake pedal	0.000
Brake system hardware	0.000
Break area	0.000
Breathalyser	0.000
Bumper	0.000
Cab (including windows/windscreen) with integrated aerodynamic design and lightweighting	223.285
Cab heating & cooling systems	0.000
Cargo chain hooks/clips/fasteners	0.000
Cargo paperwork/ID tags	0.000
Cargo/goods	0.000
Central locking system	0.000
Clutch	0.000
Communicate with infrastructure	157.456
Communicate with surrounding vehicles	262.838
Communicate/collaborate with other drivers/transport dispatcher	1590.640
Connect trailer to vehicle/ enable delivery to site	3301.580
Connects airlines	452.664
Connects braking system	452.664
Connects power/electricity	452.664
Contactless induction charging	0.000
Controls vehicle trajectory	510.958
Crane	8.910
Deploys airbag	222.599
Detect driver fatigue/sleep	309.443
Diesel-mix fuel	0.000
Drawbar/kingpin	0.000
Drive vehicle (basic, operational, & tactical tasks)	9764.281
Driver	469.571
DSRC technology for V2V and V2I applications	0.000
Electric hybrid propulsion technology	0.000
Electricity fuses/connectors	0.000
Electrification of hotel loads	0.000
Enables change in vehicle speed	1561.474
Enables communication pathway/passage of info	977.769

Enables driver feedback receptors (vision, hearing, and/or proprioception)	2249.559
Enables driver rest/recharge	673.297
Enables locomotion	834.727
Enables trailer locomotion	310.778
Enables vehicle start-up	866.582
Enables worker to get into position	426.327
Engine (mechanical)	0.000
Engine Control Unit/computer	1138.882
Ensure occupational health/comfort of worker	1390.542
Ensure operation within existing law	1279.401
Ensure provision of goods to customer	592.012
Ensure security of vehicle	499.399
Ensures vehicle and cab are functional/fit for purpose	721.085
External lights	54.716
Facilitates refuelling point	220.000
Facilitates work environment	1507.841
Fatigue detection system	0.711
Food/drink	0.000
Front grill/bull bar	0.000
Fuel	0.000
Fuel station	0.000
Fuel tank	0.000
Fuel/refuel	461.621
Fulfills customer order	220.000
Gear box	0.000
Gear stick	0.000
Generator	0.000
GPS-enabled order software	21.895
Hand rails	34.156
Haptic interfaces	9.922
Hazard lights	0.000
Heat management technology	13.879
High vis vest etc.	0.000
Horn	0.000
Identify and relay service issues	876.136
Identify vehicle/system is not fit for purpose	29.383
Ignition	0.000
Indicators	0.000
Ink	0.000
Integrated digital tachograph & connected telematic data collection	15.063
Internal lights	0.000
Keys	35.755
Land-based comms tower	0.000
Laptop	0.000
Laptop mount	0.000
Lifts/adjusts cargo to/from trailer	40.241
Low rolling resistance tyres	0.000
Maintains temperature/climate	321.425
Maximise "forebearing, gentle driving style"	110.247
Maximise efficiency/miles driven 'loaded'	204.479
Maximise flexibility in routine	25.428
Maximise safety	1546.544
Maximise user/worker health/comfort	98.848
Maximise vehicle/system reliability	78.427
Mild hybrid stop/start system	52.355
Mill/processing site	0.000
Minimise emissions/environmental impact	810.928
Minimise financial cost/loss of time	4642.413
Minimise fossil fuel use	1137.623
Minimise noise	55.772
Mirrors with optimised design	0.000

Mobile phone	103.503
On-board cameras	0.000
Orange traffic triangle	0.000
Paper	0.000
Pen/pencil	0.000
Personal belongings	0.000
Physically connects trailer to vehicle	239.423
Pick up/load vehicle with goods	1706.149
Plan schedule/pickups/route/rest periods	1700.299
Presents info on coolant level	231.084
Presents info on vehicle sub-system fitness	4.135
Prevents build-up of dirt/water/ice	255.474
Printer	0.000
Prioritises/selects next driving steps	1356.917
Protect vehicle from being damaged	1097.346
Protect/ensure immediate safety of worker	1341.604
Protects worker's hands	220.000
Provide goods to customer	267.342
Provide info on vehicle dynamics & emissions	51.136
Provides fuel/power	1668.555
Provides info on airline pressure	349.120
Provides info on cargo area	1295.040
Provides info on current day/driver drive times	121.067
Provides info on current ignition setting	313.897
Provides info on current time	81.239
Provides info on fuel consumption	53.271
Provides info on fuel level	34.368
Provides info on location	226.683
Provides info on oil level	231.084
Provides info on oil pressure	299.071
Provides info on other system/vehicle characteristics	328.763
Provides info on RPMs	53.271
Provides info on speed	53.271
Provides info on temperature	357.914
Provides info on vehicle & trailer weight	945.099
Provides optimal traction	249.659
Provides traffic info	446.027
Provides visual or auditory alerts others to presence	2134.141
Radio/media	0.000
Reduces drag	377.798
Ridged floor mats	0.000
Road navigation signs	0.000
Roadside clearing/loading points (for timber)	0.000
Roadway/path	0.000
Satellite	0.000
Seatbelt	0.000
Secures vehicle	253.173
Sensor (oil level)	0.000
Sensor (oil pressure)	0.000
Sensors (airline pressure)	0.000
Sensors (brake pads)	0.000
Sensors (cab area e.g. front grill)	0.000
Sensors (cargo area)	0.000
Sensors (coolant)	0.000
Sensors (doors)	0.000
Sensors (ignition)	0.000
Sensors (other)	10.303
Sensors (seat/seatbelts)	0.000
Sensors (smoke)	0.000
Sensors (temperature)	0.000
Sensors (vehicle & trailer weight)	0.000
Sophisticated sat nav (vehicle-specific, with real-time traffic data)	13.117
Stabilises human	315.236

Stabilises/protects tools	220.000
Stabilises/protects vehicle body	657.000
Stabilises/secures cargo	1137.508
Stabilises/secures trailer	233.664
Steering wheel	0.000
Steps	0.000
Stores cargo	233.664
Stores cargo description & location	509.057
Stores fuel/power	530.982
Stores info on cargo characteristics	220.000
Stores info on driver's hours/rest periods	121.650
Stores info on vehicle dynamics & emissions	218.742
Stores navigation info	641.929
Stores vehicle/system info	249.655
Telematic data collection device	13.412
Topographical ACC	125.909
Trailer ABS hook-up inputs	0.000
Trailer ABS hook-ups	0.000
Trailer air hook-up inputs	0.000
Trailer air hook-ups	0.000
Trailer body with expanded dimensions	0.000
Trailer cargo chains/steel wires/straps	0.000
Trailer electricity hook-ups	0.000
Trailer light hook-ups	0.000
Trailer parking brake	0.000
Trailer sheeting	79.690
Trailer side barrier	0.000
Trailer steel wire adjusting button	0.000
Trailer suspension	0.000
Tyre pressure monitoring sensors/system	0.000
Unload goods	1491.325
Vehicle parking brake	0.000
Vehicle seats	0.000
Vehicle suspension	0.000
Vehicle user manual	0.000
White smoke limiter button	0.000
Window adjusters	0.000
Windscreen defogger	0.000
Windscreen wipers	0.000
Work gloves	0.000