Transition co-design for purposive United Kingdom road freight decarbonisation

Philip Daniel Churchman

Submitted in accordance with the requirements for the degree of:

Doctor of Philosophy in Transport Studies

The University of Leeds Institute for Transport Studies

Submitted for examination in March 2025

Intellectual Property and Publication Statements

Authorship

I confirm that the work submitted is my own, except where work which has formed part of jointly authored publications has been included. My contribution and the other authors to this work has been explicitly indicated below. I confirm that appropriate credit has been given within the thesis where reference has been made to the work of others.

This thesis is presented in the alternative format and is comprised of an introduction; six papers; a closing discussion and conclusions; and three appendices. At the time of submission, three of the papers are published, two have been invited for revisions and revised versions are under review, and one is submitted. The alternative format was chosen because, due to the interdisciplinary approach adopted and the novelty of some of the methods used, it was felt that it would be beneficial to gain early reviewer feedback. In addition, I hope that publication will provide an opportunity for greater research impact.

The papers, with authors and publication status at the time of submission, are listed in table 1.

I was first author in all papers and:

- Identified research gaps and questions
- Conducted systematic and non-systematic literature reviews
- Conceived data gathering and analysis approaches
- Recruited research participants and conducted research
- Developed software, analysis and facilitation tools
- Prepared interview and workshop materials
- Conducted analysis and synthesised findings
- Drafted papers
- Made revisions based on reviewer feedback

My supervisors Professor Thijs Dekker, Professor Kate Pangbourne and Professor Jillian Anable participated on papers for which they were co-authors as follows:

- Provided advice on research framing and methods selection
- Critically assessed outputs
- Provided guidance on findings synthesis and presentation
- Reviewed and edited draft papers

Professor Vasco Sanchez Rodrigues of Cardiff Business School collaborated as an additional co-author on papers 5 and 6 and:

- Provided guidance on findings presentation
- Reviewed and edited draft papers

Professor Kate Pangbourne provided editing advice for the resubmitted version of paper 1 following reviewer feedback. Dr David Golightly provided editing advice on paper 4.

The thesis introduction, closing discussion and conclusions, and appendices were written by me, and I conducted the supporting literature reviews and industry analysis. Professor Thijs Dekker and Professor Kate Pangbourne reviewed and provided editing advice on these elements. Professor Kate Pangbourne in addition provided guidance for the consideration of research approaches included in the thesis introduction and appendix B.

Table 1: Papers, authors and status

Paper (authors)	**Status**
1. Decarbonising road freight by operationalising transition theory: A systematic literature review (Phil Churchman, Thijs Dekker, Jillian Anable)	Revisions submitted in December 2024: European Transport Research Review
2. Transition codesign for purposive road freight decarbonization (Phil Churchman, Thijs Dekker, Kate Pangbourne)	Published: Transportation Research Part D – Transport and Environment https://doi.org/10.1016/j.trd.2023.103980
3. Decision pathways for road freight decarbonization (Phil Churchman, Thijs Dekker, Kate Pangbourne)	Published: Transportation Research Part D – Transport and Environment https://doi.org/10.1016/j.trd.2025.104831
4. Pathplotter: A software tool for codesigning transition decision pathways (Phil Churchman, Thijs Dekker, Kate Pangbourne)	Submitted in March 2025: The Design Journal
5. Purposive transition governance for road freight decarbonization (Phil Churchman, Kate Pangbourne, Thijs Dekker, Vasco Sanchez Rodrigues)	Revisions submitted in May 2025: Transport Policy
6. Hydrogen for long-haul road freight: A realist retroductive assessment (Phil Churchman, Thijs Dekker, Kate Pangbourne, Vasco Sanchez Rodrigues)	Published: Renewable and Sustainable Energy Reviews https://doi.org/10.1016/j.rser.2025.115898

Acknowledgements

I would like to thank all the participants who generously gave their time to participate in interviews and workshops. In addition, I am very grateful to Carolina Buneder and Cameron Cox of Transport for London, and Professor Vasco Sanchez Rodrigues of Cardiff Business School for co-hosting workshops; Clare Linton, Rupert Oldfield and Dr Tony Whiteing for being willing test subjects for workshop pilots; and Dr David Golightly for his editing advice on paper 4.

Doing a PhD can be a challenging experience, and I cannot express my gratitude enough for the friendship and encouragement of University of Leeds staff and fellow PhD students in the Institute for Transport Studies; the Social and Political Sciences research group; the Social and Political Dimensions of Sustainability research group; and the Priestley Centre for Climate Futures.

I would have never started the PhD without the encouragement and guidance of Dr Noel Longhurst, Dr Rosalind Bark and Dr Michael Brock of the University of East Anglia. I am deeply grateful to them. I am also very grateful for the scholarship provided by the University of Leeds.

One of the reasons for choosing the alternative format thesis option was the opportunity to gain earlier feedback from reviewers. Some of this has been gentle and some less so, but all has given me valuable guidance and challenge, for which I am very appreciative.

My final thanks go to my supervisors Professor Thijs Dekker, Professor Kate Pangbourne and Professor Jillian Anable. My determination not to be constrained by disciplinary boundaries or tried and tested paths of investigation has made their job even more difficult than it would otherwise have been. There have been many hours of robust discussion but, thanks to their wisdom and commitment to helping me succeed, this has led to stronger research and triggered new avenues of investigation. They have helped me see the gaps in my thinking, and have guided me to address these, while at the same time supporting my ideas and giving me the freedom to pursue my research choices.

Use of generative AI and proof-reading services

No generative AI was used in the production of this thesis or included papers; or to generate any research inputs or outputs. The sole use of ChatGPT was as a lookup reference for the Python, JavaScript and HTML code used for streamlining repetitive analysis tasks and for developing the bespoke application “Pathplotter”.

No third-party proof-reading services have been used.

Use of previous work

This thesis builds on and references work conducted for my previous MSc dissertation. However, all of the research and analysis presented, unless explicitly stated otherwise, is new.

Abstract

This thesis addresses the problem that, despite rapid and radical decarbonisation being identified as necessary to avert the most severe climate change scenarios, the decarbonisation of road freight in the United Kingdom (UK) and other countries remains slow and incremental. It was found in my previous MSc research that, while most research into road freight decarbonisation is techno-economic, many of the barriers to this transition are political and socio-technical. Furthermore, as a result of system complexity and dependencies, it was concluded that rapid and radical decarbonisation can only be affected via purposive intent and coordinated action. Consequently, the two overarching research questions addressed by the thesis are: "What are the requirements for rapid and radical road freight decarbonisation recognising political and socio-technical as well as techno-economic dimensions?" and "How can these requirements be purposively fulfilled?".

The thesis is in the alternative format and includes six papers that investigate different aspects of the research questions:

1. Decarbonising road freight by operationalising transition theory: A systematic literature review
2. Transition codesign for purposive road freight decarbonisation
3. Decision pathways for road freight decarbonization
4. Pathplotter: A software tool for codesigning transition decision pathways
5. Purposive transition governance for road freight decarbonization
6. Hydrogen for long-haul road freight: A realist retroductive assessment

In addition to key findings regarding the two research questions, the thesis makes the following novel theoretical and methodological contributions: a conceptual transition attributes framework; a process and tool for decision pathway codesign; a purposive transition governance framework; a realist retroductive approach for transition option assessment; and a "purposivist" approach for interdisciplinary transitions research. Collectively, the research findings and contributions provide specific transition insights and a toolkit for policymakers, industry participants and researchers seeking to purposively enact road freight decarbonisation in the UK.

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Ethics approval

Please see Thesis appendix A for confirmation of ethics approval from the University of Leeds Faculty Research Ethics Committee for Business, Environment, Social Sciences.

Abbreviations

3PL	Third Party Logistics Provider	ALICE	Alliance for Logistics Innovation through Collaboration in Europe
AM	Adaptive Management	AMOC	Atlantic Meridional Overturning Current
API	Application Programming Interface	AV	Automated Vehicle
BEIS	(UK) Department for Business, Energy and Industrial Strategy	BEV	Battery Electric Vehicle
CAD	Canadian Dollar	CBG	Compressed Biogas
CCC	(UK) Climate Change Committee	CCS	Carbon, Capture and Storage
CCUS	Carbon Capture, Utilisation and Storage	CILT	(UK) Chartered Institute of Logistics and Transport
CNG	Compressed Natural Gas	CO_2	Carbon Dioxide
COP	Conference of the Parties (to the United Nations Framework Convention on Climate Change)	CSRF	Centre for Sustainable Road Freight
CSS	Cascading Style Sheet	CSV	Comma Separated Values (file format)
DAC	Direct Air Capture	DC	Distribution Centre
DfS	Design for Sustainability	DfT	(UK) Department for Transport
DMDU	Decision-Making under Deep Uncertainty	DNO	Distribution Network Operator
DUKFT	Decarbonising UK Freight Transport	ERS	Electric Road System
ERSS	Energy Research and Social Science	ESG	Earth System Governance <u>or</u> Environment, Social and Governance
ETC	European Transport Conference	EU	European Union
EV	Electric Vehicle	FCEV	(Hydrogen) Fuel Cell Electric Vehicle
FMCG	Fast Moving Consumer Goods	FQP	Freight Quality Partnership
GB	Great Britain	GHG	Greenhouse Gas
GWL	Global Warming Level	GWP	Global Warming Potential
HGV	Heavy Goods Vehicle	HTML	Hypertext Markup Language
HVO	Hydrogenated Vegetable Oil	ICCT	International Council on Clean Transportation
ICE	Internal Combustion Engine	IPCC	Intergovernmental Panel on Climate Change
ITF	International Transport Forum	JSON	JavaScript Object Notation (data file format)

LBG	Liquid Biogas	LCV	Light Commercial Vehicle
LGV	Light Goods Vehicle	LNG	Liquid Natural Gas
LRN	Logistics Research Network	MLP	Multi-Level Perspective
MSF	Multiple Streams Framework	NECTAR	Network on European Communications and Transport Activities Research
NGO	Non-Governmental Organisation	NIC	(UK) National Infrastructure Commission
OEM	Original Equipment (Vehicle) Manufacturer	ONS	(UK) Office for National Statistics
PERT	Program Evaluation Review Technique (chart)	PD	Participatory Design
PDF	Portable Document Format (file format)	PM	Particulate Matter
PNG	Portable Network Graphics (image file format)	PRSM	The Participatory System Mapper
RDM	Robust Decision Making	RGS	(UK) Royal Geographical Society
RHA	(UK) Road Haulage Association	ROSES	RepOrting standards for Systematic Evidence Syntheses in environmental research
RROA	Realist Retroductive Option Assessment	SALSA	Search, AppraisaL, Synthesis and Analysis
SD	System Dynamics	SIC	Standard Industrial Classification
SLR	Sea Level Rise	SME	Small and Medium-Sized Enterprise
STS	Science and Technology Studies	TA	Transition Arena
TCO	Total Cost of Ownership / Operation	TM	Transition Management
TPM	Transport Practitioners Meeting	ST	Systems Thinking
SVG	Scalable Vector Graphics	UK	United Kingdom
ULEZ	(London) Ultra Low Emissions Zone	URL	Uniform Resource Locator (web address)
US	United States	USD	US Dollar
UTSG	University Transport Studies Group	VECTO	Vehicle Energy Consumption Calculation Tool
VHS	Video Home System (video tape format)	WEF	World Economic Forum
WG	Welsh Government	ZEHID	(UK) Zero Emission Heavy Goods Vehicles and Infrastructure Demonstration
ZERFD	(UK) Zero Emission Road Freight Demonstration (previous name for ZEHID)	ZEV	Zero Emission Vehicle

Introduction

1. Thesis overview

This thesis is presented in the alternative format and is comprised of this introduction, six papers, a conclusion and three appendices. At the time of submission, three of the papers are published, two have been invited for revisions and revised versions are under review, and one is submitted.

The thesis takes an interdisciplinary approach to addressing the problem that, despite rapid and radical decarbonisation being identified as necessary to avert the most severe climate change scenarios, the decarbonisation of road freight in the United Kingdom (UK) and other countries remains slow and incremental. The research considers the requirements for rapid and radical road freight decarbonisation in the UK and how these requirements can be purposively fulfilled by road freight actors and policymakers.

It was found in my previous MSc research that, while most research into road freight decarbonisation is techno-economic, many of the barriers to this transition are political and socio-technical. Furthermore, as a result of system complexity and dependencies, it was concluded that rapid and radical decarbonisation can only be affected via purposive intent and coordinated action. Consequently, the two overarching research questions addressed by the thesis are: "What are the requirements for rapid and radical road freight decarbonisation recognising political and socio-technical as well as techno-economic dimensions?" and "How can these requirements be purposively fulfilled?". A critical realist ontology is adopted as this explicitly permits the epistemologically flexible scrutiny required to investigate all three transition perspectives and emphasises the importance of understanding system mechanisms and causal relationships.

The remainder of this introduction chapter is organised as follows: section 2 lays out the road freight decarbonisation problem that the thesis addresses; section 3 considers key road freight sector characteristics and road freight decarbonisation status in the UK and other countries; section 4 presents foundational propositions, research gaps and research questions; section 5 summarises the research conducted and the narrative running through the six papers; section 6 positions the thesis within relevant literature; and section 7 presents the critical realist research approach and research methods applied.

The six papers are:

1. Decarbonising road freight by operationalising transition theory: A systematic literature review
2. Transition codesign for purposive road freight decarbonisation
3. Decision pathways for road freight decarbonisation
4. Pathplotter: A software tool for codesigning transition decision pathways
5. Purposive transition governance for road freight decarbonisation
6. Hydrogen for long-haul road freight: A realist retroductive assessment

Key findings regarding the two research questions are presented in Closing discussion and conclusions section 2. In addition to these, the thesis makes the following novel theoretical and methodological contributions: a conceptual transition attributes framework; a process and tool for decision pathway codesign; a purposive transition governance framework; a realist retroductive approach for transition option assessment; and a "purposivist" approach for interdisciplinary transitions research. A description of these contributions is provided in Closing discussion and conclusions section 3.

Collectively, the research findings and contributions provide specific transition insights and a toolkit for policymakers, industry participants and researchers seeking to purposively enact road freight decarbonisation in the UK. Some of the approaches and tools developed may also be applicable to other transitions in which system dependencies mean that key transition decisions and pathways need to be codesigned by system actors.

2. The problem addressed

2.1. Rapid and radical decarbonisation is necessary

The evidence for human-induced climate change is now unequivocal (IPCC, 2023). Median projections for implemented climate change mitigation policies show greenhouse gas (GHG) emissions stabilising but not decreasing, resulting in a projected global warming level (GWL) in 2100 of 3.2°C above pre-industrial levels (IPCC, 2023). This GWL far exceeds the Paris Agreement objective to hold "the increase in the global average temperature to well below 2°C above pre-industrial levels"; and pursue efforts "to limit the temperature increase to 1.5°C above pre-industrial levels" (UNFCCC, 2015). The projected impacts of global warming on natural and human systems are already very substantial at a 1.5°C GWL and these impacts increase rapidly with further GWL increases (IPCC, 2018). Annual hottest day temperatures are projected to increase by 1.5 - 2 times the GWL in several global regions and annual wettest day rainfall is expected to increase in almost all regions. Sea level rise (SLR) by 2100 is anticipated to be between 50 and 100cm compared to a 1986-2005 baseline, and SLR estimates for high emissions scenarios for 2300 range from 2m to more than 15m. Risks to all identified land and ocean based natural systems are judged as either high or very high at a GWL of 3.2°C. Running counter to the general warming trend, the climate in northern Europe will become substantially colder if the Atlantic Meridional Overturning Current (AMOC), also known as the Gulf Stream, is disrupted (Jackson et al., 2015). Some climate scientists believe that the risk of AMOC collapse this century has been underestimated (Multiple signatories, 2024). Impact on humans through heat and humidity stress, loss of food production capacity and sea encroachment is also expected to be severe, with a disproportionate impact on poorer countries and communities. Negative economic impact is likewise expected to be very material, with Swiss Re Institute (2021) estimating that the global economy may lose 10-18% of its total value by 2050 due to climate change. It is no longer necessary to rely on scientific projections for evidence of climate change or its impacts. 2024 was the hottest year on record, with an estimated average global temperature of 1.47°C above the mid-19th century average (NASA, 2025). There are frequent news stories regarding reducing sea ice, retreating glaciers, unprecedented flooding, extreme heat, wildfires[1] (The Guardian, 2025), and severe winds. The World Meteorological Organisation (2023) describes extreme weather as the new norm.

Despite this evidence, we are failing to achieve overall emissions reduction. Global emissions, following a slight dip during the COVID-19 pandemic, have returned to pre-pandemic levels (Global Carbon Project, 2022), with reductions in the United States and Europe being more than offset by increases in China and India - a shift in part driven by the large-scale offshoring of US and European manufacturing. Sustainability competes for prioritisation with other major societal and geopolitical challenges including the cost of living crisis, economic and military confrontation, erosion of social cohesion and societal polarisation, cyber risks and large scale involuntary migration (WEF, 2023). Fossil fuel interests are seen by some as too strongly represented in the annual COP (Conference of the Parties to the United Nations Framework Convention on Climate Change) process (Union of Concerned Scientists, 2023). The United Nations' Secretary General's plea that *"Fossil fuel industry transition plans must be transformation plans, that chart a company's move to clean energy – and away from a product incompatible with human survival"* (António Guterres, June 2023) can be contrasted with record levels of fossil fuel extraction and the ongoing heavy subsidisation of fossil fuels, exacerbated by the energy crisis following Russia's invasion of Ukraine (IEA, 2023).

It could be argued that, given the enormous political, social and economic obstacles to reducing emissions, we would be better advised to focus on adapting to climate change. Adaptation is

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[1] Major wildfires in Los Angeles in January 2025, precipitated by drought conditions resulting from climate change, resulted in losses estimated to be over $200 billion, making it the costliest wildfire event in history (The Guardian, 2025).

essential, as climate change is here and will worsen irrespective of the success or failure of future emissions reduction. However, there are at least four arguments why reducing emphasis on climate change mitigation via emissions reduction is, in my opinion, morally unsupportable:

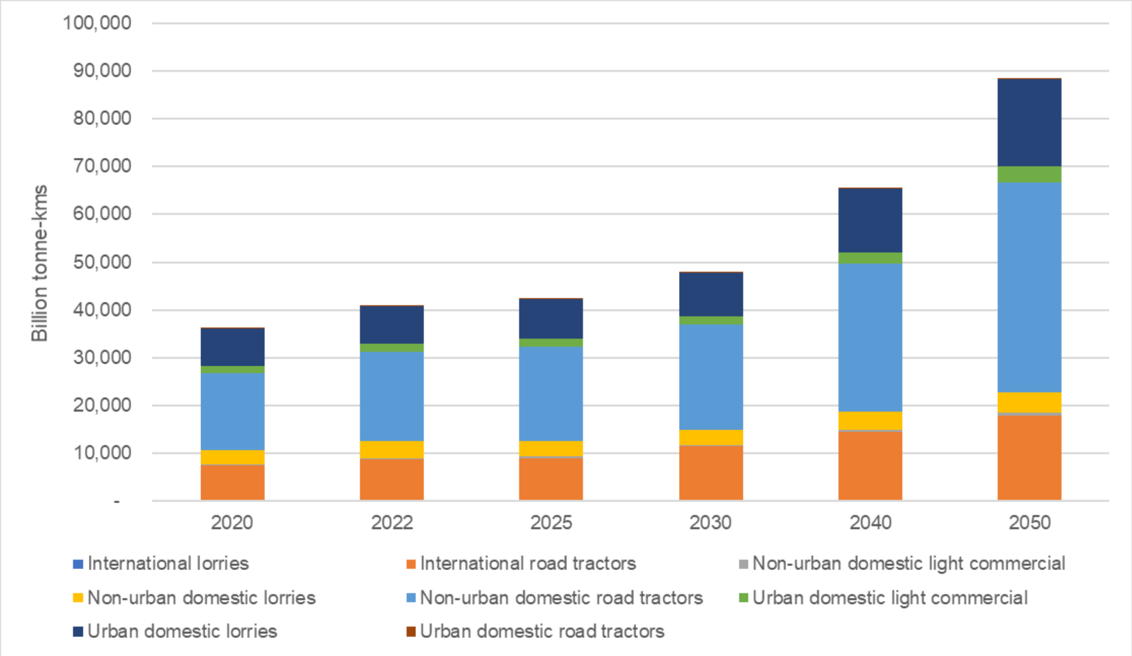
- The consequences of the decisions being made in the economic and political interests of those in power today will be felt most by today's youth and future generations.
- The unmitigated and often irreversible destruction of natural environments and non-human species, as well as being a dereliction of our custodial duty to the planet, will have profound foreseen and unforeseen negative human impacts. Environmental tipping points such as the destruction of coral reefs and the melting of sea ice and ice sheets are already being crossed, with other tipping points almost certain to follow.
- Reliance on future mitigation of current and past emissions using technologies such as direct air capture (DAC) or geo-engineering using atmospheric aerosols is highly speculative and dependent on the establishment of enormous new industrial infrastructure. These solutions are not technically demonstrated at the required scale and DAC is also extremely energy intensive. Furthermore, an assumption that the capital and operating cost of deploying such solutions can or should be borne by future generations is a further dereliction of our collective current responsibility.
- While developed economies such as the United Kingdom (UK), United States (US) and European Union (EU) generate by far the most emissions per capita, it is the world's poor who will suffer the most. Discussions regarding loss and damage funds to enable developing countries to adequately adapt to the effects of climate change are mired in debates regarding social and climate justice; and reparations for historic colonial exploitation and for the harm done by past and continuing emissions. It seems unlikely that these debates will be resolved soon.

Continuing with efforts for energy consumption reduction and the transition to non-fossil fuel energy sources therefore remains essential for ensuring an acceptable future for humankind, other species and the planet.

2.2. Road freight cannot be excluded from decarbonisation

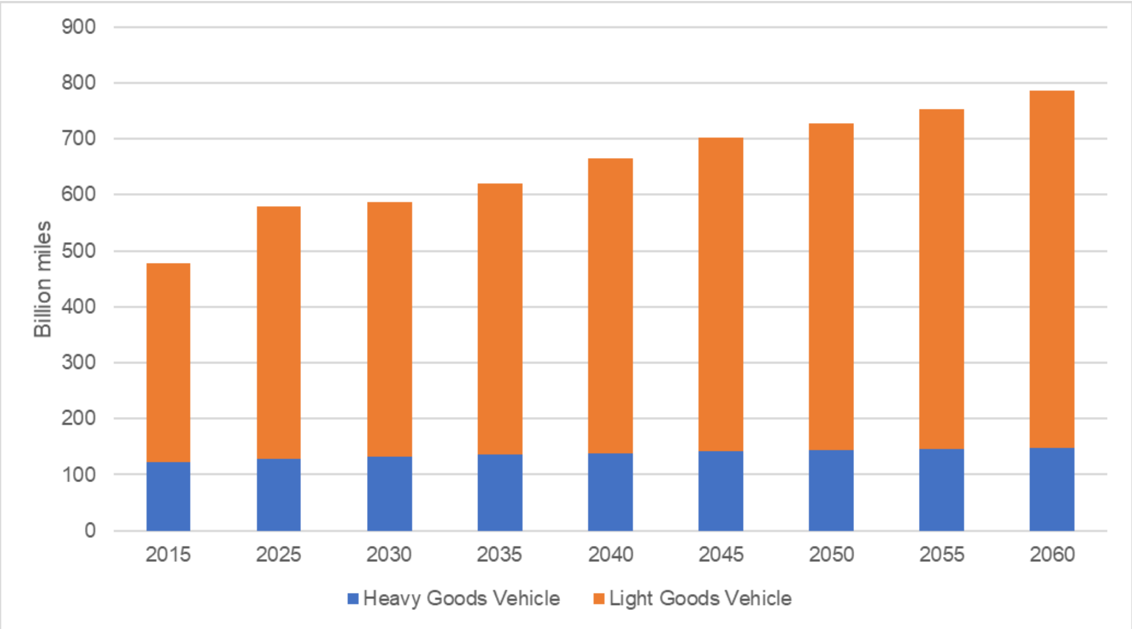
Heavy duty road freight is widely considered to be a hard to abate sector (Sharmina et al., 2021; McKinsey & Company / WEF, 2022). However, globally, trucks and vans emitted 2.63 Gt or 7.0% of a total 37.5 Gt of CO_2 from all sectors in 2022, of which heavy rigid and articulated trucks represented 80% (Global Carbon Project, 2022; ITF, 2023b). The ITF (2023b) projects that the global demand for road freight will more than double to 88.6 trillion tonne-kilometres by 2050 under a "current ambition" scenario (figure In-1).

Figure In-1: Projected global road freight demand – Current ambition scenario
(source: ITF (2023b))



Total 2020 UK heavy truck and light van CO_2 equivalent GHG emissions were 35 million tonnes or 8.6% of a total 406 million tonnes GHG emissions from all sectors (DfT, 2022c). UK freight miles are projected to increase by approximately 35% from 2025 to 2060 (DfT, 2022b) (figure In-2).

Figure In-2: Projected United Kingdom road freight demand
(source: DfT (2022b))



There may be opportunities to incrementally reduce road freight demand through measures such as supply chain reconfiguration, improved vehicle utilisation and changing consumption behaviours (Brand et al., 2021). However, even in a “high ambition” climate change mitigation scenario, global road freight demand is projected to almost double to 81.4 trillion tonne-kilometres by 2050 (ITF, 2023b).

Considering commodities transported, food products, mining, waste, agricultural products, glass, cement and wood products account for 56% of domestic freight movements in Great Britain registered vehicles (table In-1). While greater use of home and next day deliveries receives substantial attention in sustainability research, mail and parcels only account for 2% of total road freight tonne-kilometres. It is necessary to pursue all feasible opportunities for energy demand reduction. However, it is hard to imagine a non-catastrophic scenario where road freight demand reduction could on its own have a radical emissions abatement impact. It is therefore also essential to decarbonise road freight movements themselves.

Table In-1: 2022 Great Britian (GB) Domestic Road Freight of GB registered Heavy Goods Vehicles
(source: DfT (2022a)) (million tonne-kilometres)

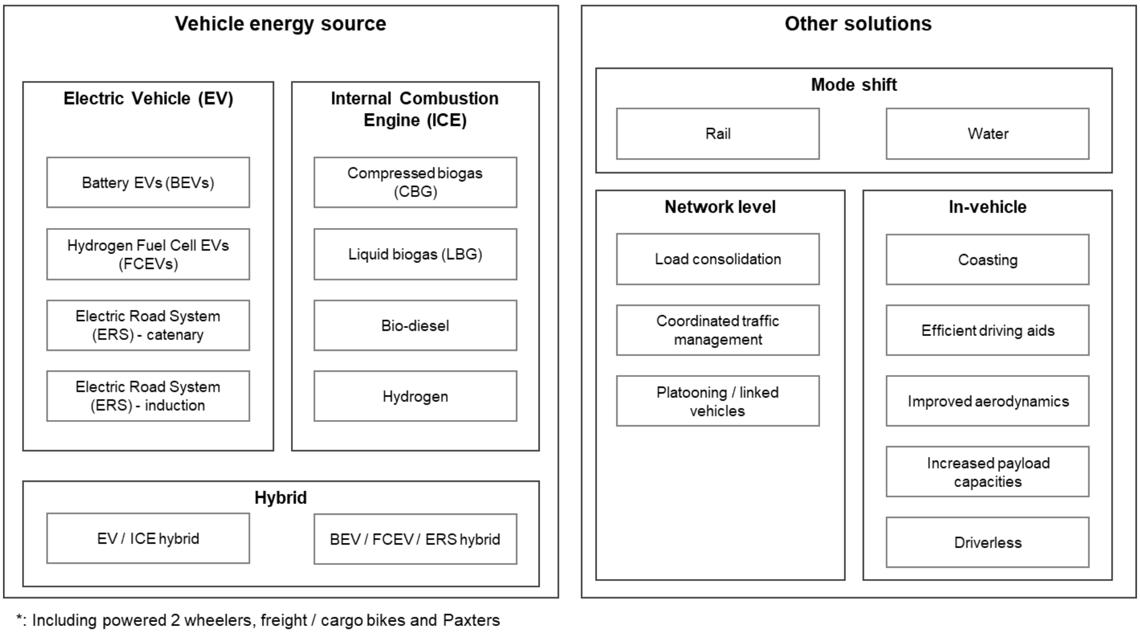
Commodity	**2022**
Groupage	46,528
Food products, including beverages and tobacco	30,600
Metal ore and other mining and quarrying	17,453
Waste related products	12,374
Empty containers, pallets and other packaging	11,718
Agricultural products	11,552
Glass, cement and other non-metallic mineral products	8,682
Wood products	5,932
Chemical products	5,291
Coke and refined petroleum products	5,290
Mail and parcels	3,400
Transport equipment	3,306
Metal products	3,169
Unidentifiable goods	2,761
Household and office removals and other non-market goods	2,192
Machinery and equipment	2,124
Textiles and textiles products, leather and leather products	1,193
Furniture and other manufactured goods	1,113
Coal and lignite	449
Other goods not elsewhere classified	6
Total (million tonne-kilometres)	**175,133**

2.3. The current rate of road freight decarbonisation is insufficient

There are multiple road freight decarbonisation solutions available (figure In-3). A principal solution category is to change from internal combustion engines (ICEs) burning fossil fuels to lower-carbon vehicle energy sources. Electric vehicles could be powered by a battery, hydrogen fuel cell or an electric road system that supplies electricity to the vehicle via an overhead catenary or an induction system embedded in the road. ICEs could be powered by biogas, bio-diesel or hydrogen produced from renewable sources. Hybrid solutions could combine multiple motive technologies in a single vehicle.

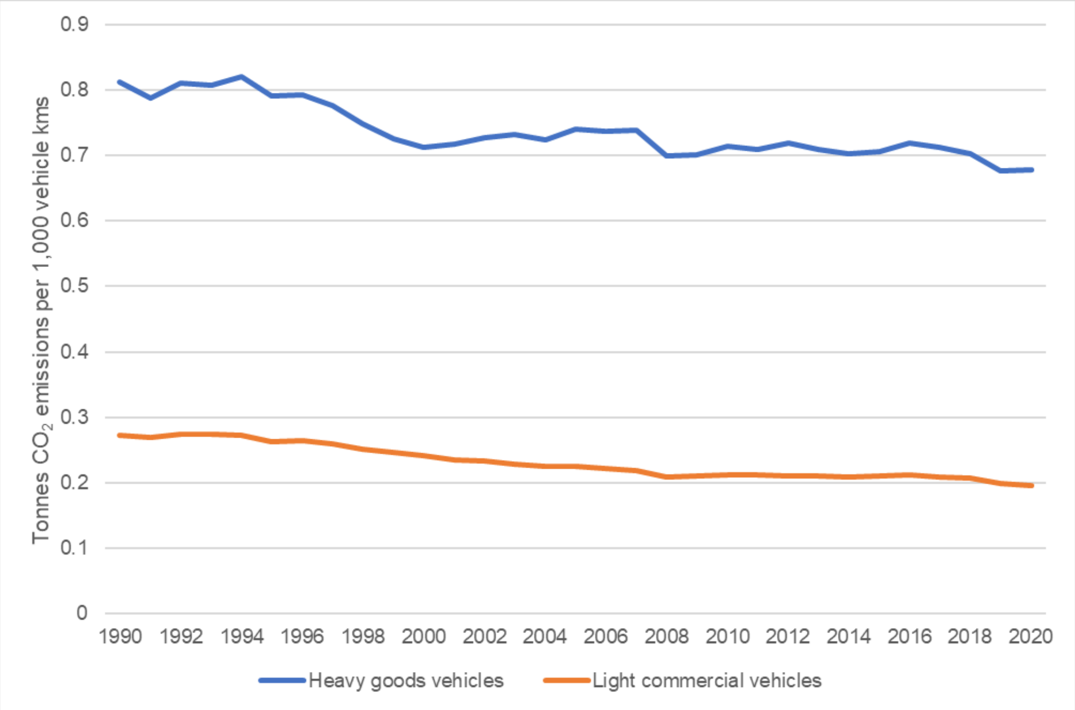
There are also other decarbonisation opportunities. Mode shift moves freight from road to lower-carbon transport modes such as rail or water. Network-level solutions deliver improved total efficiency by coordinating freight operations across multiple vehicles and operators. In-vehicle solutions increase the operational efficiency of individual vehicles.

Figure In-3: Potential solutions for decarbonisation of road freight movements – not exhaustive (source: adapted from Churchman and Longhurst (2022, p.2))



In the UK, between 1990 and 2020, there was a reduction of CO_2 emissions per 1,000 kilometres driven of approximately 16% for heavy goods vehicles (HGVs) and 28% for light commercial vehicles (LCVs) (figure In-4). If it is assumed that the average load size has not reduced, this is a substantial achievement, particularly as 99.7% of HGVs and 99.5% of LCVs registered in the UK were still fully diesel or petrol at the end of 2020 (DfT, 2023b).

Figure In-4: UK tonnes of CO2 emitted per 1,000 vehicle kilometres
(sources: (DfT, 2022c, 2023a))



However, this rate of progress, equivalent to a 0.5-1% reduction per year on a 1990 base, is not compatible achieving net zero by 2050, and may not even be sufficient to offset projected freight demand increases. More rapid and radical decarbonisation is necessary to materially contribute to mitigating climate change.

2.4. There is no clear pathway to deliver road freight decarbonisation

A pathway is defined in this thesis as a timeline of decisions and actions with associated accountabilities to deliver specific desired outcomes. Google searches using the terms "Road freight decarboni(s/z)ation" and ("pathway" or "blueprint" or "roadmap"), with localisation set as United Kingdom, United States, France and India (China and European Union are not localisation options in Google) were conducted. The same search was also run without localisation but including the term "European". These searches identified twelve relevant reports, listed in Table In-2, either authored or endorsed by government departments or inter-governmental agencies. To assess the extent to which they also provide clarity of direction and responsibility, the reports were qualitatively assessed against five factors:

1. A comparative assessment of decarbonisation opportunities is provided;
2. Specific policy and action choices are selected, and others are ruled out;
3. Responsibilities for decision-making and implementation are defined;
4. Critical enablers including infrastructure, financing, regulation, institutional capabilities and vehicle supply are considered; and
5. The pathway is specifically endorsed by government(s).

As no examples of such an assessment were found in literature, these factors were developed as part of the thesis to distinguish credible transition plans from directional provocations or broad statements of intent. The reports were reviewed and subjectively assessed as strong, medium or weak according to the extent they fulfilled each factor (table In-2). Reports assessed as weak against these factors can still provide important road freight decarbonisation framing, but do not specify a clear pathway in the sense considered in this thesis.

Table In-2: Subjective assessment of extent to which reports define a clear pathway for road freight decarbonisation

Title	**Reference and scope**	**Extent to which factors addressed***				
		1	**2**	**3**	**4**	**5**
Towards Road Freight Decarbonisation Trends, Measures and Policies	(ITF, 2018) International	Strong	Weak	Weak	Med	Weak
A framework and process for the development of a roadmap towards zero emissions logistics 2050	(ALICE, 2019) Europe	Strong	Weak	Strong	Weak	Weak
Decarbonising Road Freight	(Greening et al., 2019) UK	Med	Weak	Weak	Med	Med
The U.S. National Blueprint for Transportation Decarbonisation	(Department of Energy, 2023) US	Med	Weak	Weak	Weak	TBC**
Decarbonising UK Transport	(Mott MacDonald, 2021) UK	Weak	Weak	Weak	Med	Med
Road freight global pathways report	(McKinsey & Company / WEF, 2022) International	Med	Weak	Weak	Med	Weak
Roadmap for India's Energy Transition in the Transport Sector	(The Energy Resources Institute, 2023) India	Med	Weak	Weak	Weak	Weak
How governments can bring low-emission trucks to our roads – and fast	(ITF, 2023a) International	Strong	Med	Med	Med	Weak

Title	Reference and scope	Extent to which factors addressed*				
		1	2	3	4	5
HGV Decarbonisation Pathway for Scotland	(Transport Scotland, 2024) Scotland	Med	Med	Weak	Med	Med
Delivery Roadmap for Net Zero Transport in the UK	(Zemo Partnership, 2024) UK	Med	Med	Weak	Med	Weak
National Zero-Emission Freight Corridor Strategy	(Joint Office of Energy and Transportation, 2024) US	Strong	Med	Strong	Med	TBC**
Efficient Transportation: An action plan for Energy and Emissions Innovation	(Department of Energy, 2024) US	Med	Med	Weak	Weak	TBC**

*: 1) A comparative assessment of decarbonisation opportunities is provided; 2) Specific policy and action choices are selected, and others are ruled out; 3) Responsibilities for decision-making and implementation are defined; 4) Critical enablers including infrastructure, financing, regulation, institutional capabilities and vehicle supply are considered; 5) The pathway is specifically endorsed by government(s)

**: Reports published by US government departments are assessed as "to be confirmed" (TBC) on factor 5 due to, at the time of writing, the recent change of administration and strongly negative rhetoric regarding climate change mitigation action.

Regarding factor 1, most of the identified reports propose solution options for road freight decarbonisation and offer some level of comparative assessment of these. Regarding factor 2, the degree to which reports published prior to 2023 recommend specific solutions or policies is limited. However, more recent reports are bolder in this respect. Regarding factor 3, most reports are weak in identifying responsibilities for decision-making and implementation, with the notable exceptions of ALICE (2019), ITF (2023a) and Joint Office of Energy and Transportation (2024). Regarding factor 4, while no reports are judged to be strong, the eight reports assessed as medium consider key decarbonisation enablers including infrastructure and finance at a high level. Regarding factor 5, reports published by government departments or on government websites were judged to have medium government support, with the exception of US reports which were assessed as "to be confirmed" due to the uncertainty at the time of writing resulting from the recent change of administration and a strongly negative rhetoric from the new administration regarding climate change mitigation action.

The overall picture suggested by this assessment is a good understanding of potential decarbonisation solutions (factor 1), but variable clarity on the other factors assessed, with factors 2 and 3 potentially representing the biggest gaps.

3. Sector characteristics and decarbonisation status

3.1. Road freight sector characteristics

3.1.1. United Kingdom (UK)

Road freight in the UK, as in many other countries, is highly fragmented, competitive and runs on low margins. The UK road freight sector had a revenue of £33.5 billion in 2023 and a total of 60,515 businesses, of which the largest individual company, DHL, had 6.1% revenue share (IBISWorld, 2023a). In April 2024, there were 80,596 UK companies with a Standard Industrial Classification (SIC) of "Freight Transport by Road" (FAME, 2024). This number is larger as it includes companies whose primary activity is not road transport. Of the latter companies, 43,588 had ten or fewer employees.

In September 2023, there were 529,000 heavy good vehicles (HGVs – goods vehicles over 3.5 tonnes) registered in Great Britain (DfT, 2023b). Approximately 40,200 new HGVs were registered for the first time in 2022, giving a mean vehicle life of circa 13 years. Noting that HGVs are often subsequently exported to developing countries, their total life can be longer. Road freight accounted for 81% of all domestic tonne-kilometres moved in Great Britain in 2022 compared to 71% in 2012 (DfT, 2022a, 2022d). The tonne-kilometres moved by rail or water has decreased by circa 25% since 2012 (DfT, 2022d).

Industry bodies such the Road Haulage Association and Logistics UK recognise that reducing emissions is a priority, and that current commitments are not sufficient. However, the sector faces substantial challenges in addition to the requirement to reduce carbon emissions including acute driver shortages (RHA, 2021); longer term skills shortages and an aging workforce (Logistics UK, 2020a); additional customs administration and border restrictions following EU exit (RHA, 2020a); urban congestion and traffic restrictions (Logistics UK, 2020b); and non-CO_2 emission restrictions and vehicle design regulations which can result in increased vehicle resale value depreciation (RHA, 2019, 2020b).

While industry associations and many freight operators express a will to decarbonise, industry fragmentation and competition, customer service requirements, supply chain configurations, available infrastructure, skills shortages and other economic and regulatory challenges constrain the ability of many individual operators to take radical road freight decarbonisation action on their own (Churchman and Longhurst, 2022).

3.1.2. European Union (EU)

EU road freight movements in 2022 were 1,920 billion tonne-kms, growing from 1,764 billion tonne-kms in 2018 (Eurostat, 2023). The road freight transport market size was €443 billion in 2023, with 548,536 enterprises employing 3,698,721 people. This suggests a high degree of fragmentation, although somewhat lower than the UK.

3.1.3. United States (US) and Canada

In the US, trucks move 72.6% of freight and 95.8% of carriers operate ten or fewer trucks. There were 13.86 million trucks registered in 2021 and 3.54 million truck drivers employed in 2022 (American Trucking Associations, 2024). These statistics confirm that road freight in the US and Canada is, as in the UK and EU, fragmented, competitive and generally low margin.

Table In-3 provides a summary of US and Canada road freight statistics.

Table In-3: US and Canada road freight statistics
(source: IBISWorld (2023b))

	Turnover (billion)	**Currency**	**Profit margin**	**Enter-prises**	**Largest company share**
US long haul freight	280	USD	4.1%	616,000	5.5%
US local trucking	94	USD	6.3%	374,000	9.9%
Canada long haul freight	30	CAD	12.1%	76,933	2.9%
Canada local trucking	13.4	CAD	13.7%	39,549	4.5%

3.2. Road freight decarbonisation status

3.2.1. UK

The UK government has committed to achieving net-zero carbon by 2050 (HM Government, 2019). However, in September 2023 there were only 4,020 plug in electric or hybrid HGVs in Great Britain[2] representing 0.75% of total licensed HGVs (DfT, 2023b). Zero emission vehicles were just 1 in 119 of new HGV sales and 1 in 20 of new van sales in 2023 (Fleet News, 2023). This needs to accelerate dramatically to meet planned end of sale dates for diesel vehicles of 2035 for vans and 2040 for HGVs.

[2] Great Britain includes the UK countries England, Scotland and Wales, but not Northern Ireland. Some transport statistics such as those provided here are not available for Northern Ireland.

A key activity at the time of writing is “Zero Emission Heavy Goods Vehicles and Infrastructure Demonstrations” (ZEHIDs) that have been funded by the government to conduct real-world pilots of battery electric and hydrogen trucks and infrastructure (GOV.UK, 2023a). In addition, the Department of Transport has established a Freight Energy Forum to “*bring together senior representatives from the freight and energy sectors and other government departments to support the freight sector’s transition to net zero by 2050”* (GOV.UK, 2022). Transport Scotland (2024) has established a Zero Emission Truck Taskforce that has identified four key requirements for road freight decarbonisation:

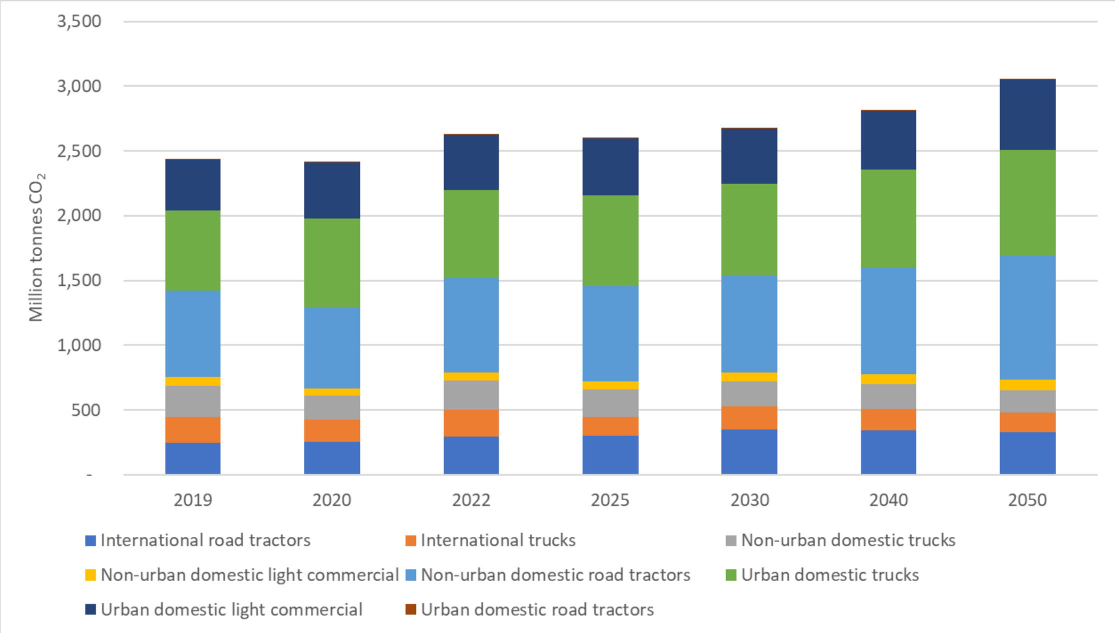
- Access to energy infrastructure
- New financial models supporting decarbonisation
- Confidence in new technologies and business models among first movers and small operators
- Workforce skills to procure and operate zero emission HGVs and their energy infrastructure

While these initiatives were at too early a stage to incorporate into research for this thesis, their ongoing development will be central to the effort to decarbonise long-haul road freight in the UK.

3.2.2. Global

The ITF (2023b) reports that global CO_2 emissions from road freight are growing, and they project that this trend will continue under a current ambition scenario (figure In-5). Contributors to this overall growth are the projected doubling of total road freight activity presented in figure In-1 and an increase in urban freight emissions as cities grow in emerging economies. An alternative high ambition scenario is also presented. However, even the current ambition scenario incorporates arguably bold assumptions including a large increase in the use of cargo bikes and other low-carbon last mile solutions, increased use of high-capacity vehicles, increased use of intermodal freight and the meeting of all existing zero emission vehicle sales targets. The ability to achieve these goals is yet to be demonstrated, and road freight carbon emissions at the time of writing remain closely linked to increasing road freight demand.

Figure In-5: Global road freight transport CO2 emissions by activity type, 2019-50; Current ambition scenario
(source: ITF (2023b))



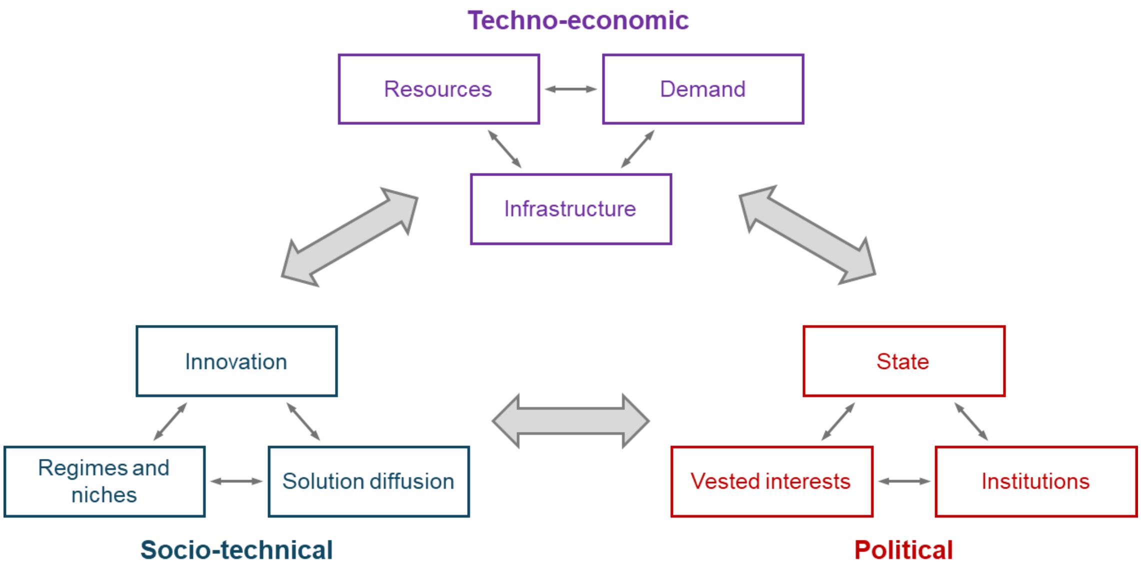
4. Foundational propositions, research gaps and research questions

4.1. Foundational propositions

4.1.1. Barriers are socio-technical and political as well as techno-economic

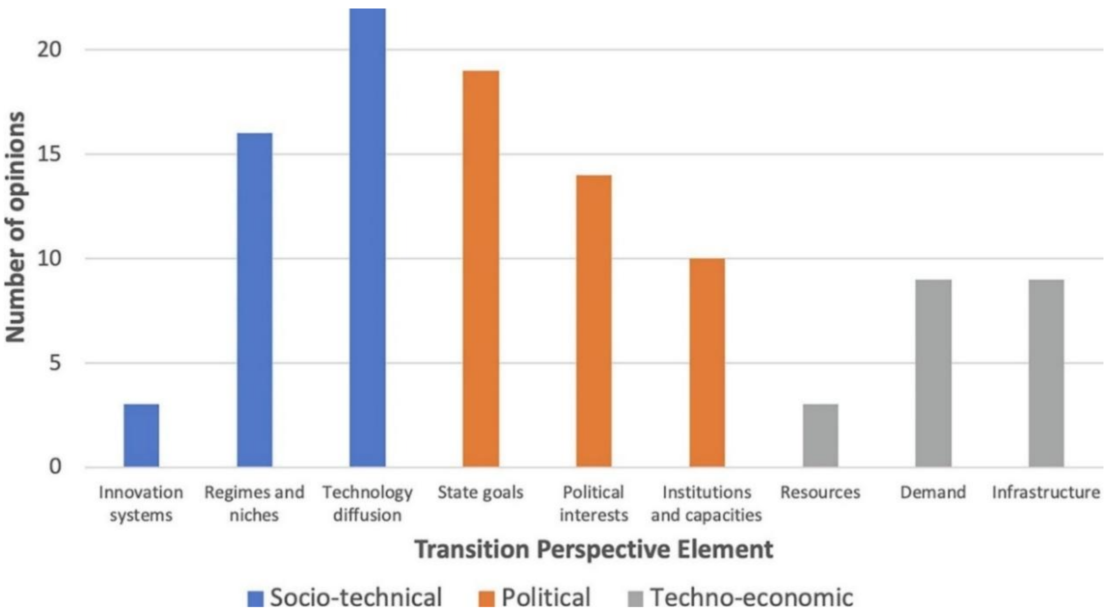
One of the principal inspirations for this thesis was Cherp et al. (2018)'s paper, "*Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework*". In this, considering national energy transitions, they identify techno-economic, socio-technical and political perspectives as individually insufficient to explain the success or failure of transitions. However, by combining these into a meta-theoretical framework (figure In-6), they argue that it is possible to explain differences between national energy transitions in Germany and Japan. The ***techno-economic perspective*** considers the technical and economic benefits, limitations, and costs of different technology solutions. The ***socio-technical perspective*** considers how innovations emerge and ultimately displace incumbent socio-technical systems (Kivimaa and Kern, 2016; Loorbach et al., 2017). The ***political perspective*** considers how policy processes (Rogge and Reichardt, 2016), networks (Markard et al., 2016; Normann, 2017), vested interests (Downie, 2017) and the state (Johnstone and Newell, 2018) interact to enable or hinder sustainability transitions.

Figure In-6: Meta-theoretical transitions framework
(source: Cherp et al. (2018, p.186))



In my MSc thesis, published as Churchman and Longhurst (2022), I applied this framework to the decarbonisation of road freight. In interviews with 15 industry participants and experts, socio-technical and political factors were identified more frequently than techno-economic ones as key barriers to road freight decarbonisation (figure In-7). Additionally, an extensive bibliographic analysis by Meyer (2020) (see section 6.1) confirms that most of the literature studying road freight decarbonisation is techno-economic. While there has been some increase in research considering socio-technical aspects of road freight decarbonisation since these analyses were conducted, e.g. Paddeu et al. (2024), work considering socio-technical and political aspects remains scarce compared to that considering techno-economic aspects.

Figure In-7: Count of opinions per transition perspective element
(source: Churchman and Longhurst (2022, p.8))



4.1.2. The road freight system is complex and interconnected

Road freight exists within complex and interconnected operational, commercial, technical, political, social and regulatory systems. It must meet the needs of freight customers across a huge variety of goods and supply chains. Exacting service requirements must be fulfilled despite just-in-time demand, congested road networks and chronic driver shortages. For intermodal freight, road operations connect with marine and rail networks, which are also subject to disruption. Regulatory requirements vary between authorities, with different restrictions on EURO emission standards, driver visibility, clean air zones and permitted loading and unloading times and locations. Road freight has historically been treated as secondary to passenger transport by planning authorities and suffers from a negative public perception, despite it being a necessary service to society (Ballantyne et al., 2013). It is highly dependent on road, energy and vehicle maintenance infrastructures and is regulated by multiple government bodies.

The above illustrates the complexity of the multiple systems within which road freight operates. These systems have evolved over the last century based on the characteristics, capabilities and economics of fossil fuel engines and infrastructure. Unpicking these, and differentiating between constraints that are unavoidable consequences of meeting society's needs versus a feature of the legacy system that needs to change, is complex but essential.

4.1.3. Actors are individually constrained

Besides road freight being a highly unconcentrated sector, it is also highly competitive. This means there is little opportunity for operators to experiment with novel solutions if doing so risks increasing cost or reducing operational flexibility, as either of these will make operators uncompetitive against their peers. While some conservatism amongst operators may be down to lack of understanding or unwillingness to adapt, it is also true that few incumbent business owners will willingly make choices that risk rendering their businesses unviable unless doing so is a regulatory requirement or there is a clear upside opportunity.

Service requirements are set by freight customers who themselves operate in complex supply chains over which they have only partial influence. The principles of lean manufacturing and supply chain synchronisation to customer demand have resulted in just-in-time supply chains, minimum workable stock levels, regional consolidation of distribution and global consolidation of manufacturing. While this has generated dramatic cost savings and improvements in product quality and customer service, it has also made supply chains more vulnerable to disruption and typically unable to accommodate reduced freight transport service levels or longer transport times without increasing costs or reducing service levels to end customers (Choi et al., 2023). Operators are in addition restricted by available infrastructure, energy supply and vehicle supply.

4.1.4. Road freight decarbonisation needs to be purposively codesigned

An implication of the observation that individual actors are often heavily constrained is that coordinated action by multiple actors is necessary to achieve more than incremental decarbonisation. One way in which coordination could be achieved is for key decisions to be made by central government. However, the UK government has so far been hesitant to impose decisions such as fuel selection on industry. Instead, it is engaging with industry representatives via the Freight Energy Forum and by funding the ZEHID trials mentioned in section 3.2 (GOV.UK, 2023b). The extent to which this strategy provides direction on necessary transition decisions remains to be seen. However, the process being followed could be seen as a form of codesign by industry actors and policymakers. Such a codesign approach offers the only apparent alternative to centralised decision-making for the enablement of rapid and radical road freight decarbonisation.

Within a constructionist paradigm, "codesign" is used similarly to "coproduction" and "cocreation" to refer to the engagement of societal groups or "publics" to develop shared future visions. Emphasis is often more on the value of participative democratic engagement than on the achievement of defined common objectives, with the belief that this form of engagement will naturally lead to better societal outcomes than top-down, expert-led or technocratic forms of governance.

The definition of codesign that is instead adopted in this thesis is the one proposed by Hyysalo et al. (2019b) of *"better connecting the relevant actors that are needed for bringing about societal change in liberal democracies: decision makers, experts, civil servants, citizens, NGOs, and business leaders (to name but a few)"*. Hyysalo et al. identify that, while end designs may to a degree be necessarily fluid, a key purpose of codesign is to create more concrete intermediate designs that can inform and guide action, and that such intermediate designs have a key role in transition governance. Although Hyysalo et al. do not mention critical realism (or any other research philosophy), their vision of codesign appears well aligned to the critical realist view that governance of socio-technical transitions needs to recognise material interests and power (Sorrell, 2018) and be based on an understanding of system interactions and causation (Mingers, 2015). Lukkarinen et al. (2023) identify that even decentralised citizen energy initiatives need to be coordinated by carefully designed and interlinked policies to connect these to the wider energy system.

4.2. Research gaps

4.2.1. Political and socio-technical aspects of road freight decarbonisation

While political and socio-technical factors are identified as important for road freight decarbonisation by road freight actors (Churchman and Longhurst, 2022), most of the research into this transition is techno-economic (Meyer, 2020). This possibly reflects an assumption that, as most road freight actors are businesses, they will implement low carbon solutions once these are operationally and economically feasible compared to existing solutions. This view does not take account of the substantial system dependencies that limit the ability of individual actors to take major decarbonisation action on their own. It also neglects the role of beliefs, values, knowledge, power and vested interests in the decisions that companies take individually and collectively.

4.2.2. Purposively codesigned transitions

Socio-technical transitions research highlights the importance of technology innovation and diffusion in sustainability transitions. Most often it considers the success or failure of past transitions as opposed to considering how future transitions can be purposively brought about. Transition Management (TM) theory, a subset of socio-technical transitions theory, provides a framework for purposive execution of transitions. However, with the exception of Hyysalo et al. (2019b), there are few examples in literature of TM being applied ex-ante to purposively enact transitions.

Within the fields of business and management studies, "Change Management" is a term that is commonly used to represent the bringing about of desired change by effectively identifying and engaging with change actors and stakeholders. Typically, a change management programme is orchestrated by an organisation or group of organisations with a defined common goal. It will often include the engagement of actors and stakeholders both within and outside these organisations. In almost all cases, change management is associated with a specific project and the desired goal is the delivery of that project and associated benefits. However, there are no identified examples of change management being applied at a system level to a national or international sustainability transition.

"Systems Thinking" (ST) is helpful in that it recognises that change occurs within systems and that these systems need to be quantitatively and qualitatively understood to bring about desired change. It advocates a holistic and inclusive approach and provides a diverse basket of tools and methods for investigating and modelling systems. A challenge with ST is its inclusivity, which rules little in or out. The onus is therefore on the researcher to select from the tools and methods available, and to define the boundaries of the system that will be studied.

Each of the above frameworks provides helpful insights for purposive transition delivery, but no literature has been found that describes their application to purposively deliver a large-scale sustainability transition. A framework is required that can be used by actors and policymakers to do this. In the absence of such a framework, we are reliant on existing political, social and economic mechanisms, which have so far proved insufficient to deliver material road freight decarbonisation.

4.3. Research questions

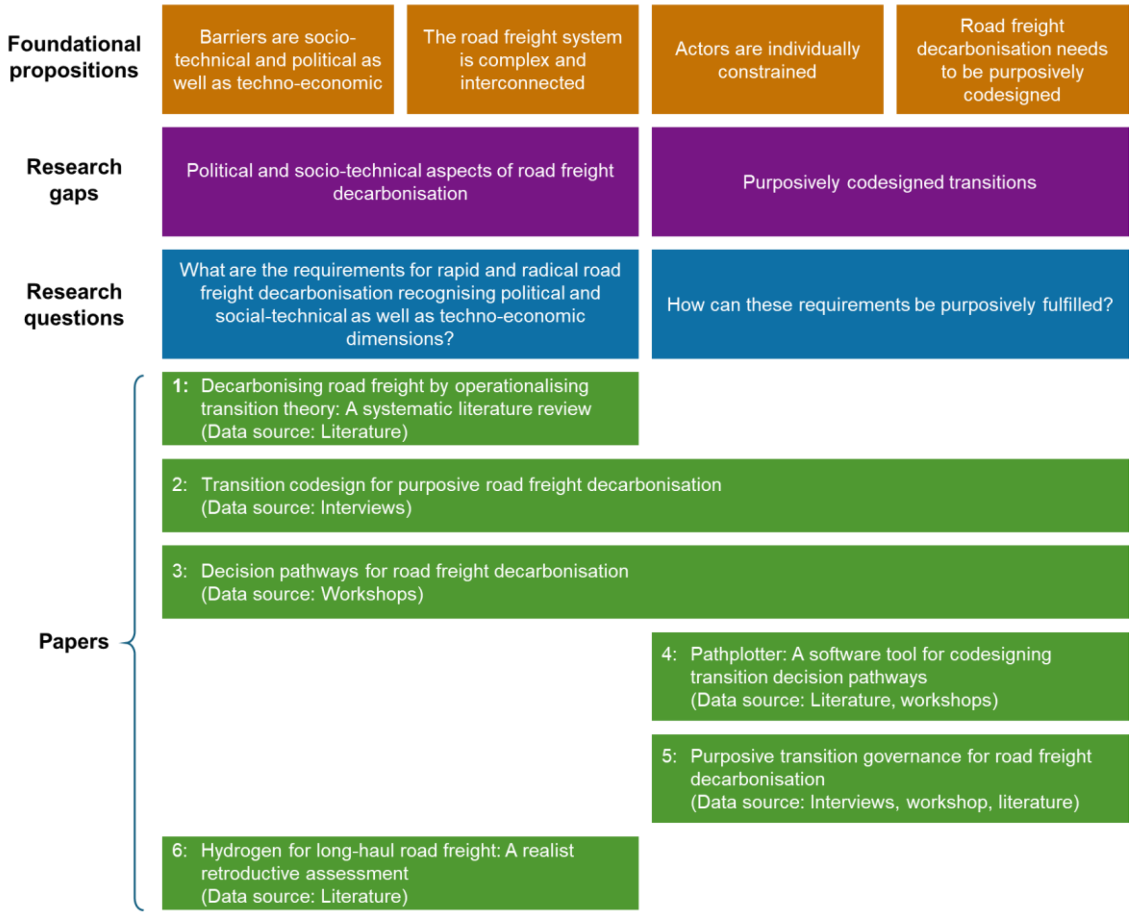
Two overarching research questions are considered within the thesis to address the above-identified research gaps:

- What are the requirements for rapid and radical road freight decarbonisation recognising political and social-technical as well as techno-economic dimensions?
- How can these requirements be purposively fulfilled?

5. Research overview

Figure In-8 shows the alignment of the six papers written for this thesis with the foundational propositions, research gaps and research questions presented in section 4.

Figure In-8: Alignment of papers to foundational propositions, research gaps and research questions
(Principal data sources for papers in brackets)



The sequence of the papers reflects both the order in which work was conducted (papers 3 and 4 having been developed in parallel) and the evolution of the research from exploratory analysis and transitions theory to practical enablement of policy and decision-making. Figure In-9 presents how findings and contributions from earlier papers informed research in subsequent papers.

Conducting research that considers techno-economic, socio-technical and political transition dimensions and that bridges transitions theory and practice has necessitated an interdisciplinary approach spanning participative codesign, transition studies, technical and economic feasibility assessment, logistics and supply chain management, and design studies. The fact that these disciplines encompass a full spectrum of subjectivist social science to objectivist business studies, engineering and economics has raised philosophical and research design challenges which are discussed in more depth in Closing discussion and conclusions section 5. While an easier path may have been to adopt a single disciplinary focus, it was concluded early in the thesis that restricting the research in this way would substantially reduce its ability to engage with the multi-dimensional challenges of rapid and radical road freight decarbonisation.

Although principally qualitative, the research is founded on a viewpoint that climate change and the measures required to mitigate it are objectively real and grounded in scientific fact. At the same time, it recognises that the systems that must be transitioned are social and political as well as technical and economic, and that the analysis of these must therefore bridge objectivist and subjectivist epistemologies. Addressing this challenge resulted in the development of "purposivism", a new research approach that combines critical realist ontology; systems thinking; and abductive and retroductive research methods. Purposivism, and the philosophical rationale behind it, are presented in section 7.1 and in more depth in Thesis Appendix B.

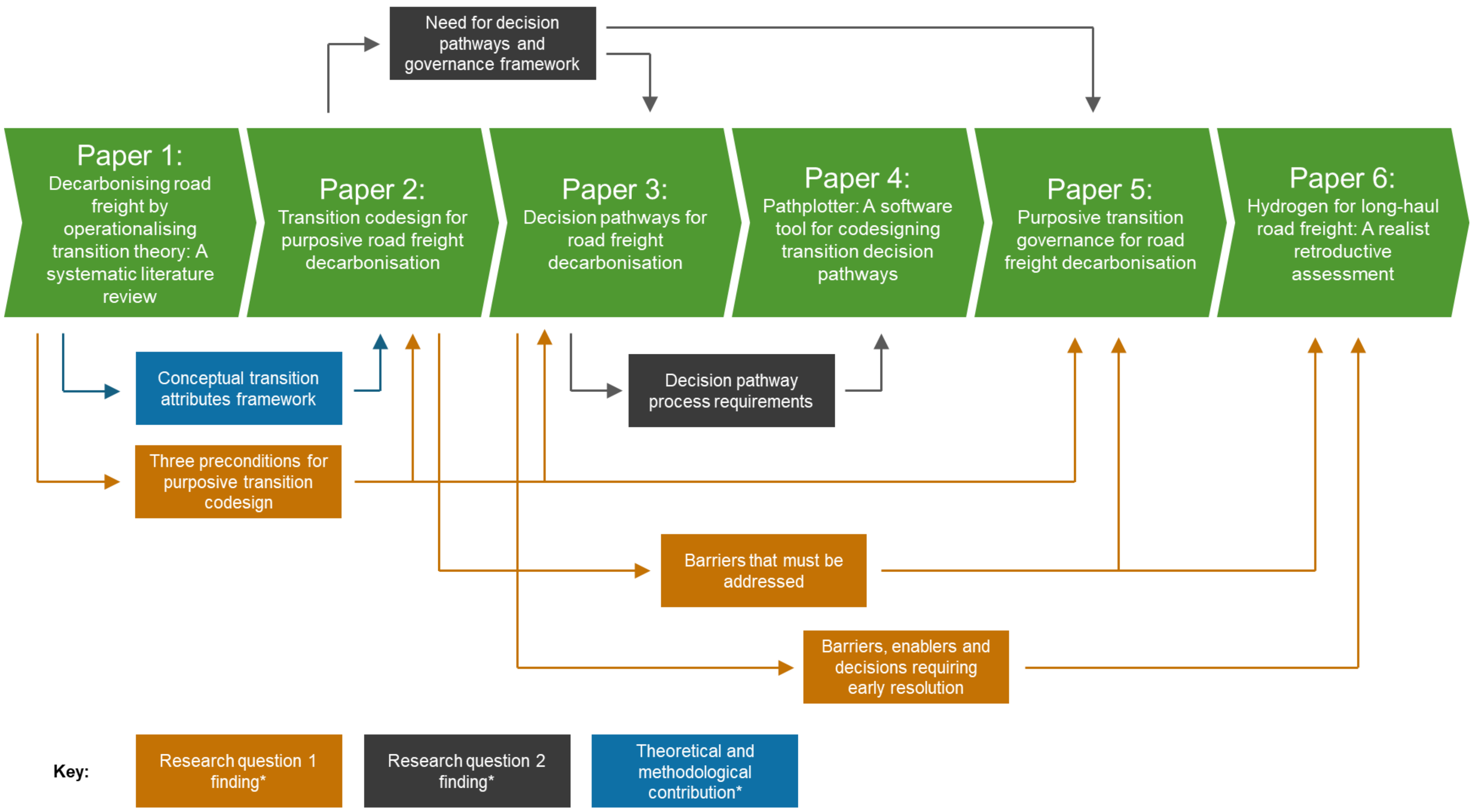
The interdisciplinary and purposivist research approach is a principal theoretical contribution of the thesis. Further theoretical and methodological contributions are:

- Paper 1: A new conceptual socio-technical and political transition attributes framework synthesised from literature
- Papers 3 and 4: A novel process and bespoke tool for decision pathway codesign
- Paper 5: A new framework for purposive transition governance
- Paper 6: A realist retroductive approach for transition option assessment

These contributions are summarised in Closing discussion and conclusions section 3.

The remainder of this section summarises the research conducted for each paper and the linkages between the papers. A more detailed summary of findings related to the two research questions is presented in Closing discussion and conclusions section 2.

Figure In-9: How papers informed research in subsequent papers



*: Only includes findings and contributions that informed subsequent papers - for full findings and contributions see Closing discussion and conclusions figure C-1

5.1. Paper 1: Decarbonising road freight by operationalising transition theory: A systematic literature review

This systematic literature review identifies practical insights from socio-technical and political transitions literature that can aid purposive road freight decarbonisation. Papers are selected with specific relevance to road freight decarbonisation that provide forward-looking guidance to actors seeking to purposively enact this transition. It is found that, of 7,065 deduplicated papers identified from Scopus, Web of Science and Google Scholar searches, only 18 meet the selection criteria, confirming the scarcity of literature with this focus. The 18 papers are qualitatively coded and 16 socio-technical and political attributes that may be required for purposive transitions are identified using grounded theory methods. These are organised into a conceptual framework under five headings: Actors, Arenas, Design, Policy and Politics, and important feedback loops are identified. The findings reinforce the need for transition codesign. The application of the conceptual framework to the case of United Kingdom road freight highlights three specific codesign preconditions for purposive decarbonisation:

1) techno-economically feasible options able to deliver rapid and radical decarbonisation need to exist;
2) a shared understanding of the design choices that need to be codesigned is required; and
3) a politically and socio-technically feasible codesign framework to make these design choices must be established.

5.2. Paper 2: Transition codesign for purposive road freight decarbonisation

Published in Transportation Research Part D: Transport and Environment
DOI: 10.1016/j.trd.2023.103980

Focusing on the case of food deliveries to supermarkets and supermarket distribution centres in Great Britain, this paper tests the three preconditions identified in paper 1 via 32 semi-structured interviews with 37 road freight industry participants, policymakers and experts. Considering the third precondition, the conceptual framework developed in paper 1 is used to investigate requirements for a politically and socio-technically feasible codesign framework. Interview data is analysed using qualitative coding and quantitative descriptive statistical analysis, and several important transition barriers are identified. There is broad consensus that the preconditions are necessary, but differences in views on what would fulfil these. Certain of these views reveal underlying differences in normative beliefs regarding the role of government and the extent to which system change can or should be centrally architected. Geographic and sectoral dimensions are also identified as important, but with differences in views on the level at which decision-making should be conducted. It is concluded that system and path dependencies mean decision pathways and effective transition governance are needed, the latter incorporating defined attributes and conflict resolution mechanisms.

5.3. Paper 3: Decision pathways for road freight decarbonisation

This paper focuses on the second precondition identified in paper 1 that a shared understanding of the design choices that need to be codesigned is required; and the finding from paper 2 that decision pathways are needed. The results of five pathway development workshops with mixed groups of industry actors, policymakers and experts are presented. Each workshop considers a different road freight decarbonisation goal selected by participants. Barriers, enablers and decisions (collectively termed "nodes") relevant to the selected goal are identified and dependencies between nodes are specified. A new software tool called "Pathplotter", presented in more detail in paper 4, is used to represent nodes and dependencies as decision networks; identify circular loops of dependencies requiring resolution; determine decision sequences; and present these as Gantt charts. Workshop commentary is transcribed and coded using NVivo.

The ability of mixed actor groups to codesign decision pathways is demonstrated and key requirements for this approach to be operationalised are identified. Pivotal nodes that need to occur early in the decision pathway and strongly dependent nodes that may need to occur later are highlighted. Most pivotal nodes are found to be socio-technical, political or related to decision governance. This reinforces the need for more research into these understudied transition aspects. Further qualitative transition insights are also captured from transcribed workshop commentary. Key learnings for operationalising decision codesign are 1) the approach needs to work for both intuitive and process thinkers; 2) sufficient time for reflection and iteration is required; and 3) the process and outputs must align to decision-maker needs.

5.4. Paper 4: Pathplotter – A software tool for codesigning transition decision pathways

This paper begins with a systematic literature review of research that considers a design approach to sustainability transitions. Fifteen papers from Design for Sustainability (DfS), Transition Management (TM) and Participatory Design (PD) literature are selected based on relevance to sustainability transition codesign by mixed actor groups. The papers are qualitatively coded to identify key codesign themes and requirements. These themes are consolidated with learnings from pilot workshops to specify requirements for a tool to aid the definition of transition decision pathways.

The paper then presents the design specifications and features of Pathplotter, a software tool developed to fulfil these requirements. Pathplotter includes tools to aid node and dependency definition; facilities for chicken and egg loop identification and management; automated node sequencing; interactive graphical network layouts; configurable Gantt charts; and a suite of data analysis, input and output facilities. The benefits of Pathplotter for decision pathway design are discussed and opportunities for further development are considered. While the focus of this thesis is on road freight decarbonisation, Pathplotter could also be applied to other system transitions that require coordinated decision-making by actors and policymakers.

5.5. Paper 5: Purposive transition governance for road freight decarbonisation

This paper focuses specifically on the third precondition identified in paper 1 that a politically and socio-technically feasible codesign framework to make design choices must be established; and the finding from paper 2 that effective transition governance is needed. A systematic review of transitions governance literature is conducted and a new governance framework based on the three pillars of governance processes, effectiveness and legitimacy is abductively developed. This framework is then retroductively validated and further developed via 13 semi-structured interviews and a workshop with transport authorities and road freight industry associations. As a result of this, a fourth pillar "governance enablers" is added. Conclusions are drawn regarding maintaining system functions and managing asymmetric power relations during transitions; key practical and political governance enablers; and the importance of achieving input, throughput and output legitimacy. Governance tensions and connections are also identified, and the implications of these are discussed.

5.6. Paper 6: Hydrogen for long-haul road freight: A realist retroductive assessment

An important transition enabler identified in paper 3 is reduction of technology uncertainty for vehicle purchasers, vehicle manufacturers, infrastructure providers and energy suppliers. The potential use of hydrogen for long-haul freight is highlighted as a key contributor to technology uncertainty, with strong advocates and political vested interests both for and against. This uncertainty underpins the frequently cited "VHS / Betamax" dilemma that inhibits vehicle purchasers and energy, infrastructure and vehicle providers from committing to a low-carbon technology pathway. These observations lead to the identification of the two linked research questions: "What systemic conditions would need to be true for hydrogen to be feasible for general-purpose long-haul road freight?" and "How likely is it that these conditions will be met within the lifespan of vehicles being bought today?". Vehicle lifespan is considered as only options that become feasible within the lifespan of a vehicle should affect the operational competitiveness of the vehicle and therefore, if a rational market is assumed, the vehicle resale value.

A realist retroductive approach for analysis is developed and ten conditions that would need to be true are identified. An evidence-based consideration of each condition for hydrogen concludes that it is very unlikely that all will be satisfied within the lifespan of vehicles bought today. As a result, it is inferred that hydrogen can be disregarded by organisations seeking to purchase new vehicles for general-purpose long-haul freight at this time. A higher-level assessment of battery electric, electric road systems, biomethane and hydrogenated vegetable oil (HVO) against the same criteria concludes that, while none of these are feasible for all long-haul freight, there are circumstances under which each could be feasible. Immediate policy and decision focus should therefore be on maximising the deployment of decarbonisation solutions other than hydrogen where these fulfil feasibility conditions, and on developing the energy, infrastructure and vehicle supply to support this.

6. Positioning in literature

Table In-4: Mapping of introduction and thesis papers to referenced literatures

Literatures: → Thesis papers: ↓	Techno-economic aspects of road freight decarbonisation	Socio-technical transitions, systems thinking and design for sustainability	Political transition dynamics and policy feedbacks	Transition codesign and governance	Grey literature
Introduction	○	●	○	○	●
1: Decarbonising road freight by operationalising transition theory: A systematic literature review	○	●	●	○	●
2: Transition codesign for purposive road freight decarbonisation	●	○	○		○
3: Decision pathways for road freight decarbonisation	●	●	○	○	●
4: Pathplotter: A software tool for codesigning transition decision pathways		●	○	○	○
5: Purposive transition governance for road freight decarbonisation		○	○	●	●
6: Hydrogen for long-haul road freight: A realist retroductive assessment	●	○	○		●

Key: Core focus: ● Secondary focus: ○

Because of the multi-perspective approach adopted, the thesis builds on literatures from several different disciplines. These are summarised in this section under five headings:

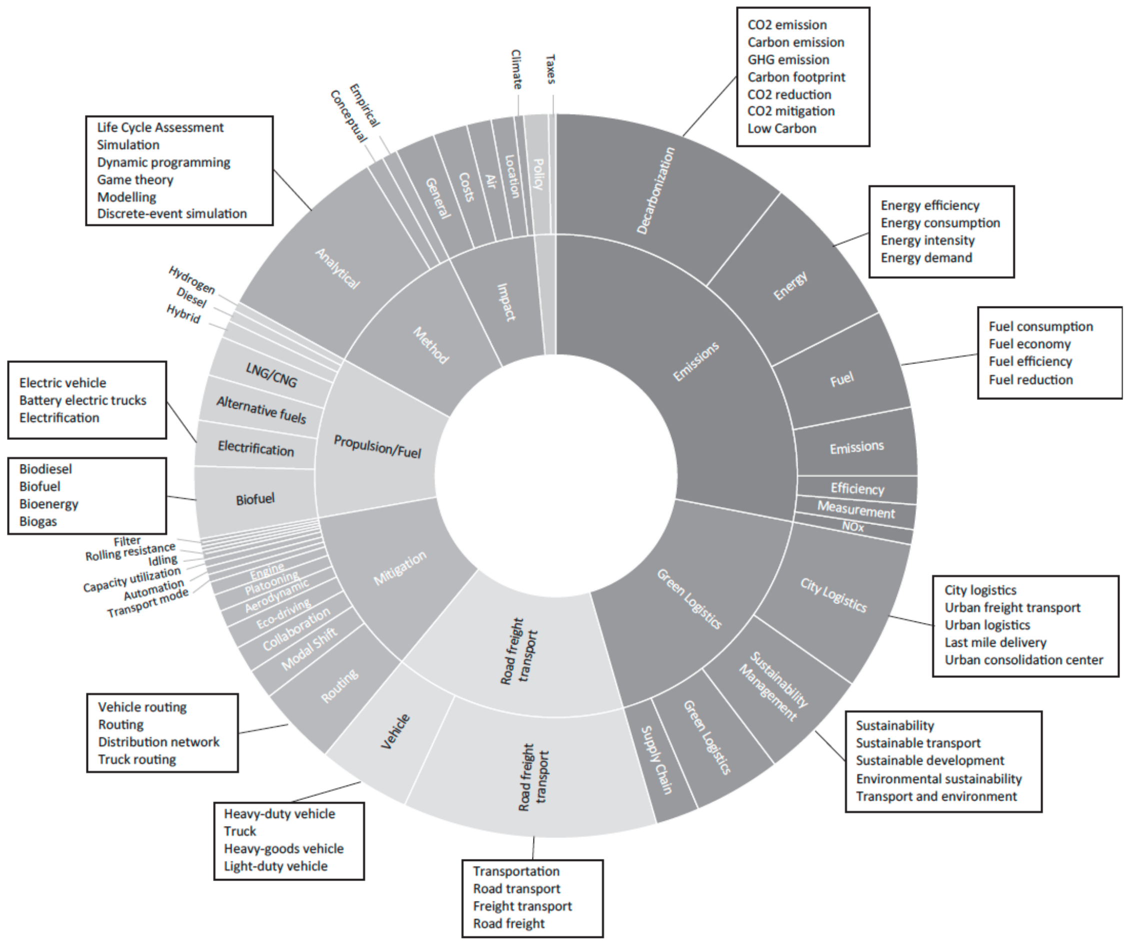
1. Techno-economic aspects of road freight decarbonisation
2. Socio-technical transitions, systems thinking and design for sustainability
3. Political transition dynamics and policy feedbacks
4. Transition codesign and governance
5. Grey literature

Table In-4 provides an overview of the alignment of this introduction chapter and the six thesis papers to these literatures. The remainder of this section summarises the literature consulted within each literature category.

6.1. Techno-economic aspects of road freight decarbonisation

An extensive bibliographic keyword analysis by Meyer (2020) finds that most papers considering road-freight decarbonisation focus on techno-economic factors (figure In-10).

Figure In-10: Road freight transition study bibliographic keyword analysis
(source: Meyer (2020, p.7))



Only a small minority of papers reviewed are found to consider socio-technical or political factors. Based on this observation, the decision was made in this thesis to prioritise consideration of socio-technical and political system dimensions. However, techno-economic system understanding remains essential as, without this, politically and socially desirable solutions could be identified that are technically or economically infeasible, or could not be implemented without deconstructing essential existing systems with major negative human and social consequences.

The techno-economic literature consulted falls into four overlapping categories:

- Identification of energy and transport decarbonisation solutions and challenges
- Assessment of technological and economic feasibility and effectiveness of solutions
- Consideration of infrastructure and resource requirements
- Analysis of the connection between market forces, systems functioning and decarbonisation

6.2. Socio-technical transitions, systems thinking and design for sustainability

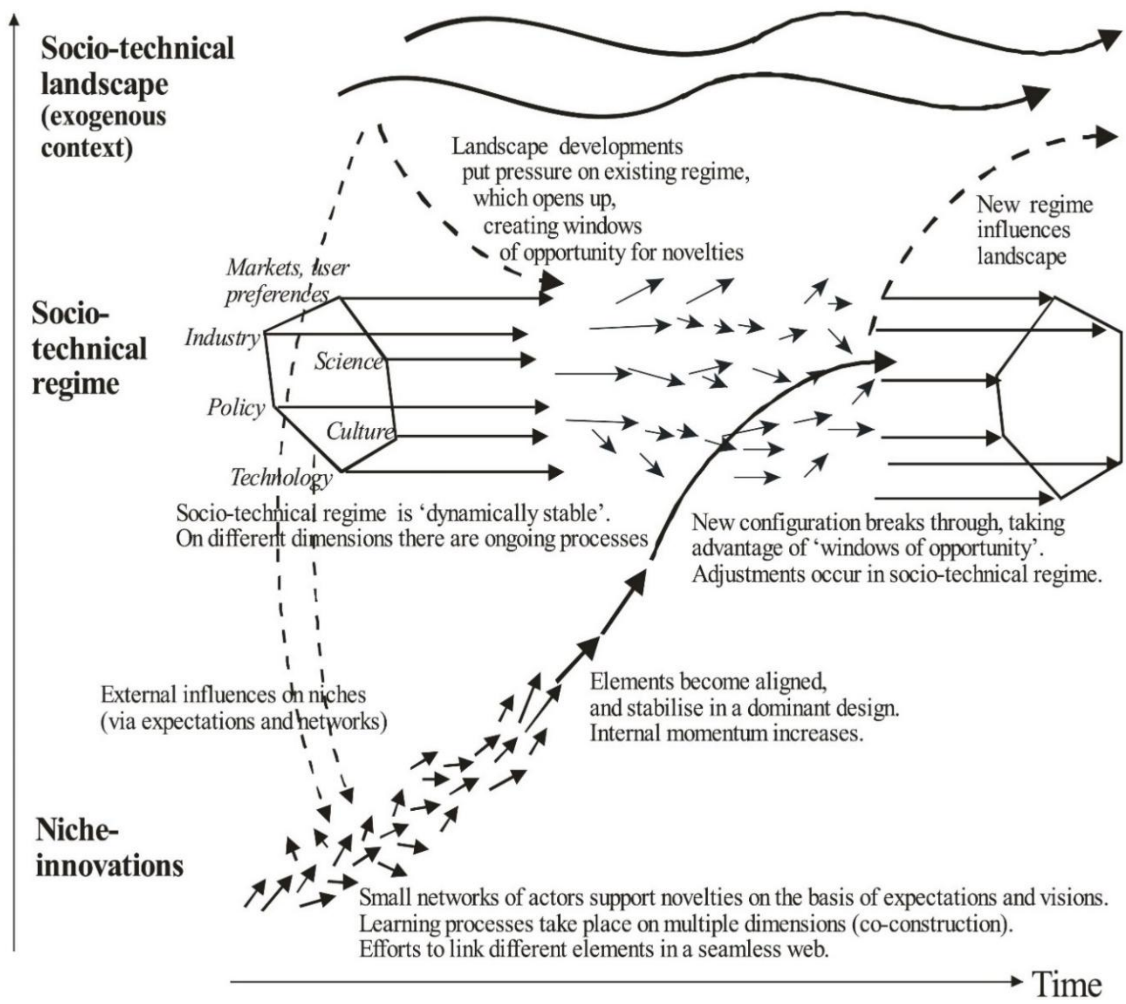
6.2.1. Socio-technical transitions

Socio-technical transitions theory considers the dynamics of how innovations develop, destabilise and ultimately displace incumbent systems. The most prominent socio-technical transitions model is the “Multi-Level Perspective” (MLP) developed by Geels (2002). MLP has been widely applied to case-study analyses of historic transitions, and frames what many social scientists understand socio-technical transitions to be. MLP describes socio-technical systems in terms of “landscape”, “regimes” and “niches” (figure In-11). “Landscape” embodies the material context including cities, roads and infrastructure, and socio-economic context including energy prices, macro-economic conditions, geo-political conflict, migration, political coalitions, cultural and normative values and environmental problems. “Regimes” are the established routines and norms related to the application of current technologies. “Niches” are protected spaces within which technological innovation can happen without being exposed to the full competitive force of the established regime.

MLP is a helpful heuristic for articulating the need for new innovations to have the space to develop in niches and for incumbent regimes to be destabilised to create the opportunity for these to be displaced. MLP is rooted in the study of innovation and technology diffusion, and these concepts are central in its framing. Other innovation-centred frameworks include Technology Innovation Systems (Bergek et al., 2008) and Strategic Niche Management (van der Laak et al., 2007; Schot and Geels, 2008) which, like MLP, come from the “Dutch school” of socio-technical transitions theory (Li et al., 2015).

However, MLP is critiqued as being less helpful for envisioning purposive enactment of transitions, or for explaining why some transitions occur and others do not. Svensson and Nikoleris (2018) propose that this is largely a result of it seeing structure and agency as inseparable. They instead suggest a critical realist framing in which structure, rather than being inseparable from agency, represents inherent system connections, and that a transition occurs when there is a qualitative structural change to these connections. This, they argue, contrasts with MLP's presentation of transitions as a quantitative shift in regime dominance.

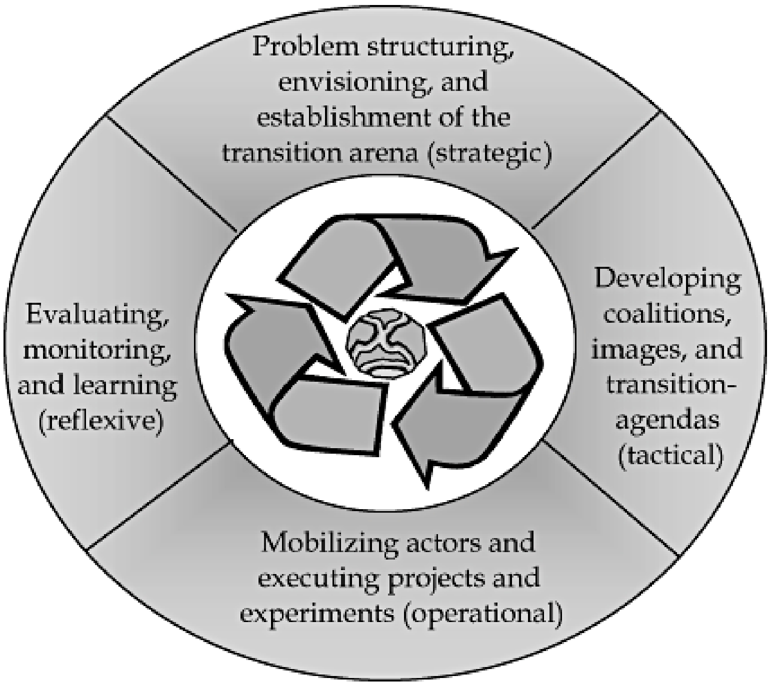
Figure In-11: Multi-level perspective
(source: Geels and Schot (2007, p.401))



Also stemming from the Dutch school is Transitions Management (TM), which adopts an explicitly governance perspective in considering how socio-technical transitions can be purposively brought about (Loorbach, 2010). TM considers four different components of a transition management cycle: strategic, tactical, operational and reflexive (figure In-12). TM also introduces the concept of transition arenas (TAs) in which transition frontrunners gather to develop visions in the strategic stage of the transition cycle (Loorbach, 2010).

Hyysalo et al. (2019a) extend the strategic visioning role of TAs to include mid-range planning and pilot a workshop toolkit for developing mid-range pathways for specific sustainability transitions in Finland. This is the most concrete example found in literature of a TM framework being applied for real-world transition planning. Other literature explores the democratic legitimacy of transition management and the political challenges of reflexive governance.

Figure In-12: Transition management cycle
(source: Loorbach (2010, p.173))



6.2.2. Systems thinking

Mingers (2015) argues that research that seeks to have a positive impact on the world, in addition to adopting critical realist principles, needs to be systemic, transdisciplinary, multimethodological, critical and committed. They propose that a key characteristic of real-world problems is that they are complex, interconnected and multidisciplinary in nature, and that in engaging with this, research needs to become problem rather than theory or data driven. Mingers advocates Systems Thinking (ST) on the basis that it adopts a trans-disciplinary and holistic approach.

Regarding the multimethodological aspect of ST, Mingers proposes that systems have multiple dimensions that are physical, social, conceptual and cognitive that, as well as being ontologically different, require a variety of “hard” and “soft” methods to be adequately explored. ST contains a broad spectrum of practical methods that include, at the hard end, mathematical modelling and system dynamics and, at the soft end, soft systems methodology and cognitive mapping. Accepting the validity and relevance of this full spectrum of system dimensions and research methods requires both the flexible epistemological positioning offered by critical realism, and recognition of the need for both quantitative and qualitative research.

The ST literature referenced:

- Reviews ST tools and methods
- Considers system resilience
- Discusses wider energy system dependencies and barriers to system change

6.2.3. Design for sustainability

Design for sustainability (DfS) literature lies within the design studies discipline and considers how design can deliver more sustainable products, services and systems. A subset of DfS literature referenced in this thesis sits at the intersection of DfS and TM, and considers how transitions can be codesigned, as exemplified by the work of researchers including Sampsa Hyysalo, İdil Gaziulusoy, Fabrizio Ceschin, Satu Lähteenoja and Chris Ryan.

6.3. Political transition dynamics and policy feedbacks

In techno-economic and socio-technical transition studies, political system elements are often treated as part of the exogenous system landscape rather than endogenous aspects of the system that needs to be transitioned. It is proposed in this thesis that a purposive system transition approach requires relevant political system elements to be treated as endogenous and to be subject to the same codesign principles as techno-economic and socio-technical elements.

While political transitions literature is sparce compared to techno-economic and socio-technical transitions literature, it provides important relevant insights. Literature has been consulted that considers the following political aspects of system transitions:

- Advocacy coalitions
- System - policy feedbacks
- Multiple streams theory and policy entrepreneurs

Considering each of these in turn:

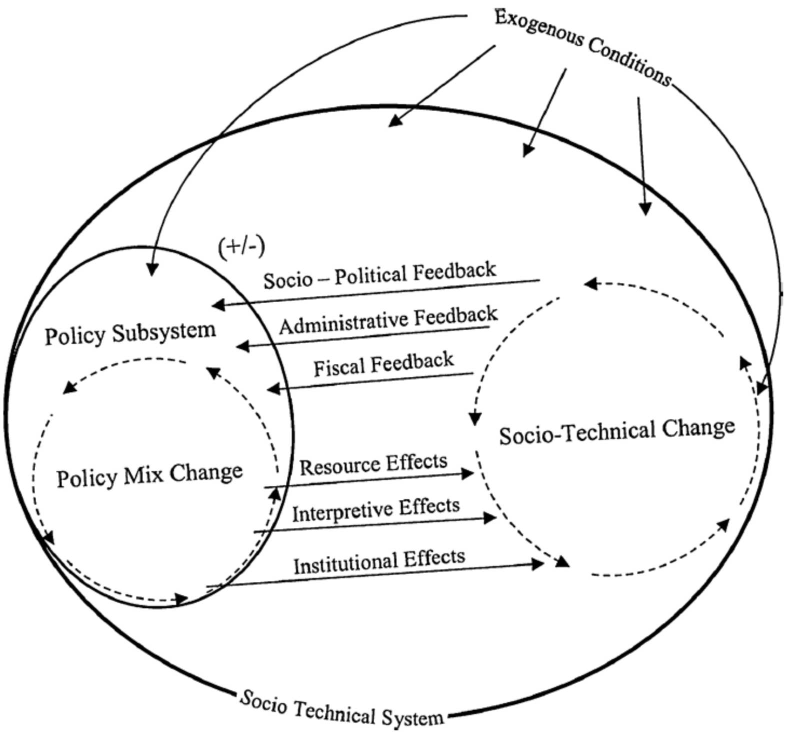
6.3.1. Advocacy networks

The concept of advocacy networks is developed by Normann (2017) to contrast case examples of securing state funding for offshore wind farms and carbon capture and storage (CCS) projects in Norway. They demonstrate how different network structures facilitated different access to the policymaking process which secured very different levels of government support in each case. Markard et al. (2016) apply a related concept of advocacy coalitions to map the beliefs of influencing groups in Swiss energy policy.

6.3.2. System - policy feedbacks

This literature considers the co-evolution of policy mixes and socio-technical systems, and the feedback mechanisms linking these (figure In-13). The effects of policy mix on socio-technical change are considered and socio-political, fiscal and administrative feedback mechanisms that influence policy are identified. These mechanisms provide a helpful basis to consider how policy must both drive and respond to socio-technical change.

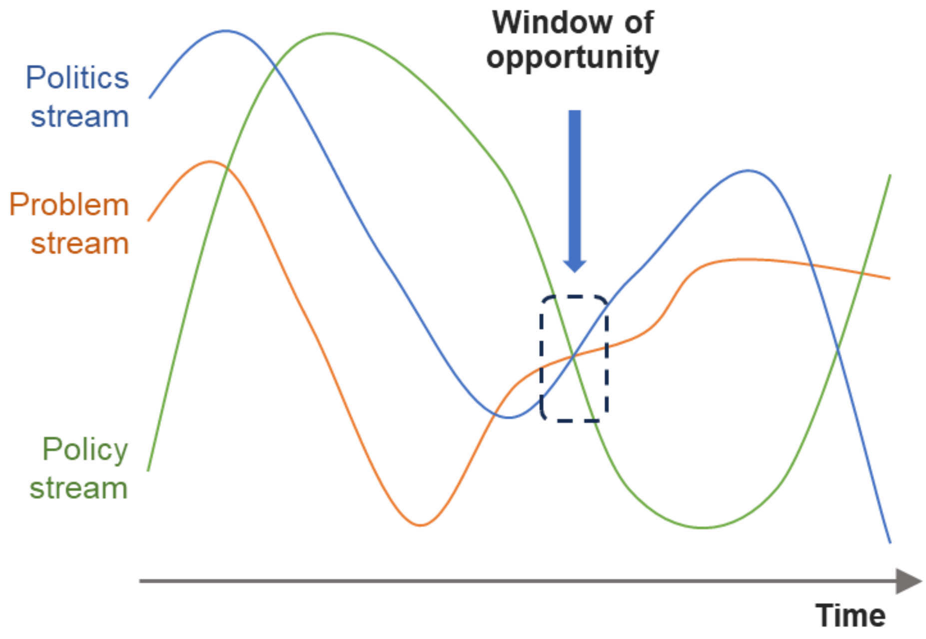
Figure In-13: Interface of policy and socio-technical change
(source: Edmondson et al. (2019, p.5))



6.3.3. Multiple streams framework and policy entrepreneurs

A leading political theory of policy formation is the Multiple Streams Framework (MSF) (figure In-14). This proposes that major change happens when political, policy and problem streams align, creating windows of opportunity for new solutions to be adopted (Kingdon, 1984). Knaggård (2015) suggests that "problem brokers" can help navigate political and social systems to align problems and solutions. Using different language to describe a similar concept, the positive and negative roles that "policy entrepreneurs" can play by exploiting MSF windows of opportunity are explored by Salas Gironés et al. (2020). These ideas are helpful as they consider the specific mechanics of how certain policies gain political support and are consequently implemented and others do not.

Figure In-14: Multiple streams framework
(source: Adapted from Cooper-Searle et al. (2018, p.54))



6.4. Transition codesign and governance

The definition of transition codesign used in this thesis is that provided by Hyysalo et al. (2019b) of "better connecting the relevant actors that are needed for bringing about societal change in liberal democracies: decision makers, experts, civil servants, citizens, NGOs, and business leaders (to name but a few)". More specifically, codesign is used to mean collaborative and collective decision-making by policymakers and road freight actors. The transition governance literature consulted considers in a codesign context:

- The qualities of effective governance
- The outcomes of effective governance
- The requirements of governance to achieve social and political legitimacy

Transition management, discussed above in section 6.2, is presented as a potential framing for transitions governance. Other frameworks identified are Earth Systems Governance (ESG) (Biermann et al., 2010) and Adaptive Management (AM) (Olsson et al., 2004). Patterson et al. (2017) discuss three overarching transition governance challenges: the deeply political nature of transitions; the challenges of thinking about transformations ex-ante; and the tensions between steering change and recognizing its open-ended and emergent nature.

A systematic literature review was conducted for paper 5 to inform the development of a transition codesign governance framework. Particularly helpful work was identified by authors including Voß and Bornemann (2011), Avelino and Grin (2017), Termeer et al. (2017), Dentoni et al. (2018), Keating and Katina (2019) and de Geus et al. (2022).

6.5. Grey literature

McKinnon (2023) identifies that grey literature provides an important source of quantitative and qualitative information on the current state of road freight decarbonisation, transport policy, and industry and expert opinion regarding challenges and opportunities. Referenced grey literature comes from five principal sources:

- Government agencies
- Non-governmental organisations focused on sustainable economic development, transportation and energy
- Lobby groups and private sector stakeholders
- Road freight media and industry bodies
- Non-peer reviewed academic research reports

7. Research approach and methods

As discussed in section 5, conducting research that considers techno-economic, socio-technical and political transition dimensions and that bridges transitions theory and practice has necessitated an interdisciplinary approach spanning participative codesign, transition studies, technical and economic feasibility assessment, logistics and supply chain management, and design studies. Reconciling the philosophical and methodological differences between these disciplines has led to a substantive review of established research approaches and the development of "purposivism". Purposivism is summarised briefly in section 7.1 and expanded on more fully in Thesis Appendix B. Section 7.2 presents the research methods used within a purposivist framing for the six thesis papers.

7.1. Purposivist research approach

The research approach applied in this thesis adopts a critical realist ontology. Critical realism considers truth and reality to be independent of context and the norms, values and beliefs of humans; but also complex, stratified and emergent and therefore potentially never fully knowable. Critical realists argue that causal mechanisms and structures are more fundamentally "real" than phenomena events, which are the observed behaviours of systems. They reject the "epistemic fallacy" of only considering a single mode of knowledge creation (epistemology) as valid (Bhaskar, 2013). They argue instead that broad critical enquiry is necessary to gain the fullest possible understanding complex systems (Fleetwood, 2004; Sayer, 2004).

Positivism, which is aligned to objectivist epistemology, is principally logically deductive and tests predefined theories through repeated experimentation and observation. Interpretivism, which is aligned to subjectivist and constructionist epistemologies, is principally logically inductive and develops theories from observations. By contrast, critical realist research approaches can be described as a combination of “abductive” in which probable theories regarding causal mechanisms are developed from incomplete information and “retroductive” in which the researcher considers the contextual conditions under which causal mechanisms would take effect and observed empirical trends would occur (Meyer and Lunnay, 2013; Fletcher, 2017). Aligned with these arguments, this thesis adopts a pluralist epistemology and applies abductive and retroductive methods.

Building on the theme of causality within systems, Systems Thinking (ST), summarised in section 6.2, is a commonly used umbrella term for research approaches and methods that consider the implications of causal relationships for system analysis and design. Systems Thinking is identified as well aligned to critical realism (Mingers, 2015). Heuristics that have been found to be helpful in envisioning system transitions within a Systems Thinking framing are the Multiple Streams Framework (Kingdon, 1984), Multi-Level Perspective (Geels and Schot, 2007), Transition Management (Loorbach, 2010), Advocacy Networks (Normann, 2017) and Policy Mix Feedback Loops (Edmondson et al., 2019). These heuristics are summarised in sections 6.2 and 6.3.

The term “purposivism” is adopted to describe the research approach used in this thesis that encompasses critical realist ontology, pluralist epistemology, abductive and retroductive methods, Systems Thinking, and the pragmatic use of relevant heuristics. It is proposed as a more helpful alternative for the study of purposive system transitions than positivism, which is typically applied in techno-economic transitions research; and interpretivism, which is typically applied in socio-technical and political transitions research. Please see Thesis Appendix B for a more in-depth consideration of the theoretical and methodological bases of purposivism.

7.2. Research methods

Table In-5 maps the six thesis papers to the specific research methods used within the purposivist research approach described in section 7.1. The remainder of this sub-section summarises how each method was applied in the thesis.

Table In-5: Mapping of thesis papers to methods used

Methods: → Thesis papers: ↓	Systematic literature review*	Semi-structured interviews	Mixed actor workshops	Network analysis	Descriptive statistical analysis	Qualitative coding and analysis	Abductive theory building / grounded theory	Retroductive “ what needs to be true” analysis
1: Decarbonising road freight by operationalising transition theory: A systematic literature review	●					●	●	
2: Transition codesign for purposive road freight decarbonisation		●			●	●		●
3: Decision pathways for road freight decarbonisation			●	●	●	●		
4: Pathplotter: A software tool for codesigning transition decision pathways	●			●		●	●	
5: Purposive transition governance for road freight decarbonisation	●	●				●	●	●
6: Hydrogen for long-haul road freight: A realist retroductive assessment								●

*: All papers include a literature review component. For the ones highlighted, a systematic approach was adopted.

7.2.1. Systematic literature review

Systematic literature reviews (SLRs) are defined as: “a way of synthesising scientific evidence to answer a particular research question in a way that is transparent and reproducible, while seeking to include all published evidence on the topic and appraising the quality of this evidence” (Lame, 2019). Grant and Booth (2009) assess different literature review approaches on the basis of Search, AppraisaL, Synthesis and Analysis (SALSA). Systematic reviews are summarised as:

- Search: Aims for exhaustive, comprehensive searching
- Appraisal: Quality assessment may determine inclusion/exclusion
- Synthesis: Typically narrative with tabular accompaniment
- Analysis: What is known: recommendations for practice; and what remains unknown: uncertainty around findings and recommendations for future research

The SLRs conducted in this thesis meet these requirements by:

- Search:
    - Clearly defining the search databases, terms and selection filters used
- Appraisal:
    - Specifying the quality and relevance criteria applied
    - Progressively reviewing and deselecting papers based on review of titles, then abstracts, then full paper content, maintaining an audit trial in Microsoft Excel of which papers were deselected at which stage based on which criteria
- Synthesis:
    - Qualitatively coding full paper content of the remaining papers using NVivo and synthesising relevant findings and insights based on this
- Analysis:
    - Conducting abductive theory building based on synthesised findings.

For paper 1, the ROSES framework for systematic evidence synthesis in environmental research (ROSES, 2024) was applied.

7.2.2. Semi-structured interviews

Semi-structured interviews were used as the primary data-gathering method for papers 2 and 5. In these, a topic list of interview questions was defined in advance of interviews. Most meetings were conducted online using Microsoft Teams, and were recorded and auto-transcribed with the participants' consent. The small number of interviews conducted in person were also recorded and the same data capture and analysis approach was followed.

Transcriptions captured by Teams were downloaded as Word documents and timings for each interview question were entered in a lookup table with reference to the recorded video. Code was written in Python to split responses into individual questions using transcript timestamps, and then to further auto-process the text to delete repeated and hesitation words and replace colloquialisms (e.g. "gonna" with "going to"). The resulting text split by question was then manually reviewed and corrected with reference to recordings in preparation for qualitative analysis.

For paper 2, in addition to unstructured data captured from interview transcriptions, structured data was captured using a JISC Online Surveys questionnaire that was shared on screen with the participant.

7.2.3. Mixed actor workshops

Mixed actor workshops were conducted as the primary data gathering method for paper 3. The custom-developed Pathplotter tool used to facilitate the workshops is documented in paper 4. The workshop approach was initially piloted with a logistics expert and two local authority representatives, and it was on the basis of these pilots that the decision was made to develop Pathplotter. A refined approach and the Pathplotter tool were then used in five 2.5 - 3 hour workshops.

Each workshop had between five and nine participants representing a combination of public authorities, freight operators, infrastructure providers and industry associations. One workshop was co-hosted with Transport for London and another with Cardiff Business School. Three workshops were conducted in person and two online. Each workshop focused on a different specific road freight decarbonisation goal defined by participants and followed a pre-defined process to identify transition decisions, barriers and enablers (collectively termed "nodes") and dependencies between these. Nodes were brainstormed and then clustered using Miro for online workshops and Post-Its for in-person workshops. Dependencies were captured using Pathplotter. A refinement was implemented for workshops 4 and 5 to provide the facility for participants to enter dependencies directly using a Jisc Online Survey that was automatically created using Python code based on the nodes defined in the first part of the workshop.

7.2.4. Network analysis

Network analysis was conducted on decision nodes and dependencies defined in the mixed actor workshops using the custom developed Pathplotter tool. The purpose of the analysis was to identify decision pathways that determine the sequence of decisions that would best enable decarbonisation goals to be achieved. Key elements of the network analysis are:

- Use of automated algorithms to:
    - Graphically lay out nodes and dependencies as network diagrams
    - Identify "chicken and egg loops" of dependencies
    - Identify nodes with a path to the end goal
    - Find node sequences that minimise the number of dependencies completed out of order
    - Identify the number of other nodes directly or indirectly required for, or dependent on each node

- Graphical presentation of:
    - Node and dependency networks
    - Sequences as Gantt charts, with or without node durations
    - Node dependency bar charts
- Use of Pathplotter tools to:
    - Manage and resolve chicken and egg loops
    - Harmonise nodes across workshops to allow consolidation and cross-comparison
- Creation of a library of standard nodes and dependencies to enable an aggregate pathway to be defined and to facilitate future decision pathway development

7.2.5. Descriptive statistical analysis

Descriptive statistical analysis was conducted on structured data outputs from semi-structured interviews in paper 2 and on both structured and unstructured data outputs from decision pathway workshops in paper 3:

For paper 2, structured data from questionnaire responses was analysed and presented using code written in Python. Response data was downloaded as an Excel spreadsheet from Jisc Online Surveys and imported as a Pandas Dataframe. Comparative counts or percentages were calculated for all respondents and per respondent group. These analyses were presented using the Python library Matplotlib. A benefit of this approach compared to conducting the analysis and producing output graphs in Microsoft Excel was that, once the code had been written, updated outputs could be generated following each interview on the press of a button. It was also possible to tailor the graphical outputs to a greater degree than would have been the case in Excel.

For paper 3, in addition to individual workshop outputs enabling the creation of a preliminary decision pathways for the specific road freight decarbonisation goals considered, harmonisation of code descriptions enabled nodes identified in multiple workshops to be identified, forming the basis of an aggregate road freight decarbonisation decision pathway. Based on this, pivotal nodes and strongly dependent nodes that are applicable to multiple road freight goals were highlighted. Qualitative coding of transcribed commentary from workshops also enabled the number of workshops in which insights were raised to be identified.

7.2.6. Qualitative coding and analysis

Qualitative coding was applied using NVivo for two purposes: the coding of paper content during the synthesis phase of systematic literature reviews, and the coding of unstructured question responses and commentary from interview and workshop transcriptions. A consistent approach of open, axial and selective coding was applied in each case (Williams and Moser, 2019) with phases defined as:

- Open: identifies distinct concepts and themes for categorisation
- Axial: further refines, aligns, and categorises the themes
- Selective: selects and integrates categories of organised data from axial coding in cohesive and meaning-filled expressions

7.2.7. Abductive theory building / grounded theory

Abduction, together with retroduction which is described below, are methodological alternatives to the deductive methods typically used in positivist and quantitative research and the inductive methods typically used in interpretivist and qualitative research. Abduction is where probable theories regarding causal mechanisms are developed from incomplete information (Meyer and Lunnay, 2013; Fletcher, 2017). A detective forming theories based on evidence from a crime scene is a form of abduction.

Grounded theory was originally proposed by Glaser and Strauss (1967) to provide methodological rigour to qualitative research and to democratise social science theory generation. Emergence is identified as an essential part of grounded theory (Charmaz, 2008). While the nature of emergence is debated, it embodies the ideas that the past shapes the present and future, but does not make these entirely predictable; and that subjects being studied are subject to movement and change. *"Grounded theory starts with an inductive logic but moves into abductive reasoning as the researcher seeks to understand emergent empirical findings. Abductive reasoning aims to account for surprises, anomalies, or puzzles in the collected data."* (Charmaz, 2008, p.157). Reichertz (2009) likewise proposes that abduction is central to grounded theory.

The combination of abductive analysis and grounded theory has been used throughout this thesis and, together with retroduction, is central to the purposivist research approach proposed in section 7.1. Theories have been built using abduction and grounded theory from primary research data and literature reviews in papers 1, 4 and 5.

7.2.8. Retroductive "what needs to be true" analysis

Retroduction is a research approach in which the researcher considers the contextual conditions under which theorised causal mechanisms would take effect and observed empirical trends would occur (Meyer and Lunnay, 2013; Fletcher, 2017). It builds well on abduction, in which theories regarding causal mechanisms are proposed (Land, 2024). The "retro" in retroduction implies a form of backcasting in which the conditions that would need to be true for a theory to be proven valid are assessed. Retroduction allows an ontologically realist view of the future to be taken while at the same time recognising that complex and emergent causal mechanisms of systems are very hard to "prove" deductively using traditional positivist methods (Bhaskar, 2013).

Retroduction is applied for testing and refining abductively developed theories in papers 2 and 5, and for considering the likelihood of hydrogen becoming feasible for long-haul road freight within the lifespan of a vehicle bought today in paper 6.

8. Remainder of thesis

The remainder of the thesis is comprised of the six papers introduced in section 5 followed by a closing discussion and conclusions chapter, and three appendices.

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Paper 1: Decarbonising road freight by operationalising transition theory: A systematic literature review

Phil Churchman, Thijs Dekker, Jillian Anable

Abstract

Background, context and purpose: Rapid and radical road freight decarbonisation is necessary to achieve climate change mitigation goals, and yet to date it remains slow and incremental. While techno-economic perspectives are well studied for this specific transition, socio-technical and political perspectives are less so. However, socio-technical and political transitions research may provide helpful reflection on transition challenges and complexities. Motivated by these observations, this systematic literature review considers the research question: "What practical insights are provided by socio-technical and political transitions research that can aid purposive road freight decarbonisation?".

Methods: Scopus, Web of Science and Google Scholar searches were conducted that identified a deduplicated total of 5,743 research articles and review papers. Screening rules and terms were developed and applied to remove papers that did not meet relevance, forward-looking, design framing or stakeholder focus criteria, resulting in a shortlist of 57 papers. Further qualitative screening of abstracts and full paper text reduced the number of selected papers to 18. 1,599 citing and referenced papers of these 18 papers were also screened, and no additional papers met the selection criteria. The 18 papers were qualitatively coded and synthesised using NVivo to identify key socio-technical and political transition insights and themes.

Results: Sixteen specific insights into how socio-technical and political requirements of road freight decarbonisation can be purposively fulfilled are identified. These insights are grouped under the five themes of Actors, Arenas, Design, Policy and Politics. A further consideration of these insights applied to the specific case of UK road freight decarbonisation identifies three preconditions for a purposive transition approach to the adopted: 1) techno-economically feasible options able to deliver rapid and radical decarbonisation need to exist; 2) a shared understanding of the design choices that need to be codesigned is required; and 3) a politically and socio-technically feasible codesign framework to make these design choices must be established.

Conclusions: The new conceptual model formed by the five themes provides a framework that can be applied by transition actors, policymakers and researchers considering how this transition can be purposively brought about. In addition, specific policy, management and research implications are proposed. While this study has focused on road freight decarbonisation within

a European or comparable political and socio-technical context, some findings may have wider applicability.

Keywords: Socio-technical, Political, Techno-economic, Codesign, Purposive

1 Introduction

Rapid and radical decarbonisation is necessary to achieve climate change mitigation goals (IPCC, 2022). Considering the case of the United Kingdom (UK), goods vehicles over 3.5 tonnes represented 21 million tonnes or 5% of a total 426 million tonnes of CO_2 emissions in 2022 (DfT, 2023). The global picture is similar, with heavy and medium duty road freight transport accounting for 1,830 million tonnes (IEA, 2024), or 5% of a total 36,800 million tonnes (IEA, 2023) of CO_2 emissions. Global road freight demand is forecast to substantially increase to 2050 in both “current ambition” and “high ambition” decarbonisation scenarios (ITF, 2023).

Road freight emissions must therefore be dramatically reduced to materially mitigate climate change. This can either be achieved through demand reduction or by decarbonising road freight movements. The focus of this paper is on the decarbonisation of road freight movements. In all likely future scenarios, there will remain a substantial volume of inland freight, most of which is currently moved by road, meaning that demand reduction and mode-shift alone cannot be relied upon to deliver rapid and radical decarbonisation.

Li and Strachan (2019) argue that deliberate, planned, and explicit transition choices are required to overcome path dependencies within the freight system that cause lock-ins to fossil fuel technologies. This means that decarbonising road freight movements requires purposive action by actors and policymakers. Cherp et al. (2018) put forward that successful energy transitions require combining socio-technical, political, and techno-economic perspectives. The ***techno-economic perspective*** considers the technical and economic benefits, limitations, and costs of different technology solutions. The ***socio-technical perspective*** considers how innovations emerge and ultimately displace incumbent socio-technical systems (Kivimaa and Kern, 2016; Loorbach et al., 2017). The ***political perspective*** considers how policy processes (Rogge and Reichardt, 2016), networks (Markard et al., 2016; Normann, 2017), vested interests (Downie, 2017) and the state (Johnstone and Newell, 2018) interact to enable or hinder sustainability transitions.

A bibliographic analysis by Meyer (2020) confirms that most literature studying road freight decarbonisation is techno-economic. However, actors observe that the challenges of purposive road freight decarbonisation are political and socio-technical as well as techno-economic (Churchman and Longhurst, 2022). Furthermore, while political and socio-technical transitions research identifies transition challenges and complexities, it often does not consider how transitions can be purposively achieved (Sorrell, 2018; Svensson and Nikoleris, 2018). Building on these observations, this paper considers the research question "What practical insights are provided by socio-technical and political transitions research that can aid purposive road freight decarbonisation?". Given substantially different socio-technical and political contexts in different countries, research was selected that considers transitions principally within a European or comparable socio-technical and political context.

The remainder of the paper is structured as follows: Section 2 describes the literature search, screening and synthesis methods that were applied; Section 3 presents synthesised transition attributes and a new conceptual transition framework based on findings from eighteen selected papers; Section 4 discusses linkages and feedbacks between identified transition attributes; Section 5 considers the specific case of UK road freight decarbonisation and identifies three preconditions for purposive transition; and Section 6 reflects on original contributions, limitations and opportunities for further research.

2 Methods

The review was completed according to the ROSES framework for systematic evidence synthesis in environmental research (ROSES, 2024). The ROSES checklist is provided in supplementary material.

2.1 Search

Scopus, Web of Science and Google Scholar searches were conducted on 23 Nov 2024 for papers in the date range 2000-2025. For a paper to be returned, one or more terms in each of the columns in Table 1-1 needed to be present in the title, abstract or keywords (for Scopus and Web of Science) or full article text (for Google Scholar).

Table 1-1: Search terms

Socio-technical and political transition perspectives	Relevant transition type
• Socio-technical / sociotechnical • Politic* • Technology adoption • Technology diffusion • Technology adaptation • Stakeholder*	• Freight • Logistics • Transport • Vehicle(s)

Due to the large number of papers returned from Scopus and Web of Science searches, results were limited to source titles including the words “transport*”, “sustain*” or “energ*”. After a preliminary review it was confirmed that papers from source titles that also contain the words “technolog*” or “econ*” were almost always techno-economic rather than socio-technical or political in focus, so these source titles were excluded.

In addition to the source titles meeting the above conditions, the following additional source titles containing previously identified relevant papers were specifically included in the Scopus search: “Technological Forecasting and Social Change”, “Cities”, “Journal of Cleaner Production”, “Research in Transportation Economics” and “Environmental Innovation and Societal Transitions”.

Results were limited to articles and reviews in English language; and the relevant topic areas of Energy, Social Sciences, Environment, and Business (for Scopus) and Environmental Sciences, Environmental Studies, Transportation, and Business (for Web of Science). See appendix A for the full Scopus and Web of Science search expressions. These resulted in a de-deduplicated total of 5,506 papers from 251 journals being identified.

Four Google Scholar searches were required to cover the same combination of search terms. The first hundred results from each of these searches were captured, with no constraint placed on source title. Once the search results were combined and deduplicated, 299 results remained. These were then deduplicated against Scopus and Web of Science results, and results with no DOI reference were removed. After this, 237 results remained, making a total of 5,743 papers.

2.2 Scopus and Web of Science results screening

Screening of Scopus and Web of Science results was carried out in four steps:

2.2.1 Rules-based relevance screening

Six relevance categories were considered: research method, geographic context, transition type, social objective, transition perspective and document purpose. For each category, if a term was identified in a title or abstract that suggested it was unlikely that the paper would provide political or socio-technical transition insights relevant to road freight decarbonisation within a European context, documents were filtered for that term in Excel. If a review of filtered document titles and (if required) abstracts confirmed that none were relevant, the term was added to the exclusion list. This list was progressively developed until it contained 288 terms (see Appendix B). Python code was used to flag papers that contained a term in the exclusion list, highlighting the exclusion term and category in each case. This approach means that there is a full audit trail of the specific terms that have resulted in papers being excluded.

2.2.2 Rules-based purposive screening

While socio-technical and political transitions research can provide important insights, it is often retrospective and reflective rather than forward-looking and purposive in focus. This means that insights, while theoretically interesting, may not provide ex-ante guidance to actors seeking to purposively enact transitions. A distillation of literature by authors including Paddeu and Aditjandra (2020), Lebeau et al. (2018) and Churchman and Longhurst (2022) suggests that literature is more likely to provide ex-ante guidance if it has three features: 1) a forward looking perspective; 2) a design framing; and 3) an actor / stakeholder focus. To systematise and provide auditability of the screening based on these criteria, a rules-based framework was developed based on terms contained in abstracts. The screening terms and conditions were iteratively developed until it was found that a good screening ratio was achieved without excluding any papers that had previously been identified as helpful or were likely to be so based on paper titles. The screening removed papers that did not contain in the abstract:

- *Forward looking perspective:* Two or more of: future, decision, plan, change, implement*, improv*, rapid, path*, effective
- *Design framing:* One or more of: strateg*, specific, design, factor, criteria, blueprint, solution, measures, scenario, combination, select*, co-creat*, feedback
- *Actor / stakeholder focus:* One or more of: actor, stakeholder, entrepreneur, institution, enterprise

2.2.3 Qualitative abstract screening

The abstracts of remaining papers were reviewed and, if a paper was considered as unlikely to be relevant or helpful to the research question, it was deselected and the rationale for deselection was recorded.

2.2.4 Qualitative full text screening

As for abstract screening but based on full text review

2.3 Google Scholar results screening

Downloaded Google Scholar search results did not include paper abstracts, which meant that the rules-based screening used for Scopus and Web of Science results could not be applied. Instead, deduplicated papers were qualitatively screened based on source title and then on title. Abstracts were individually retrieved for the remaining papers and these papers were qualitatively screened on abstract. After this process, no papers remained that had not been identified in the Scopus or Web of Science searches. As the Google Scholar searches were not restricted on source title or topic area, this provides a validation of the source title and topic area restrictions applied in the Scopus and Web of Science searches.

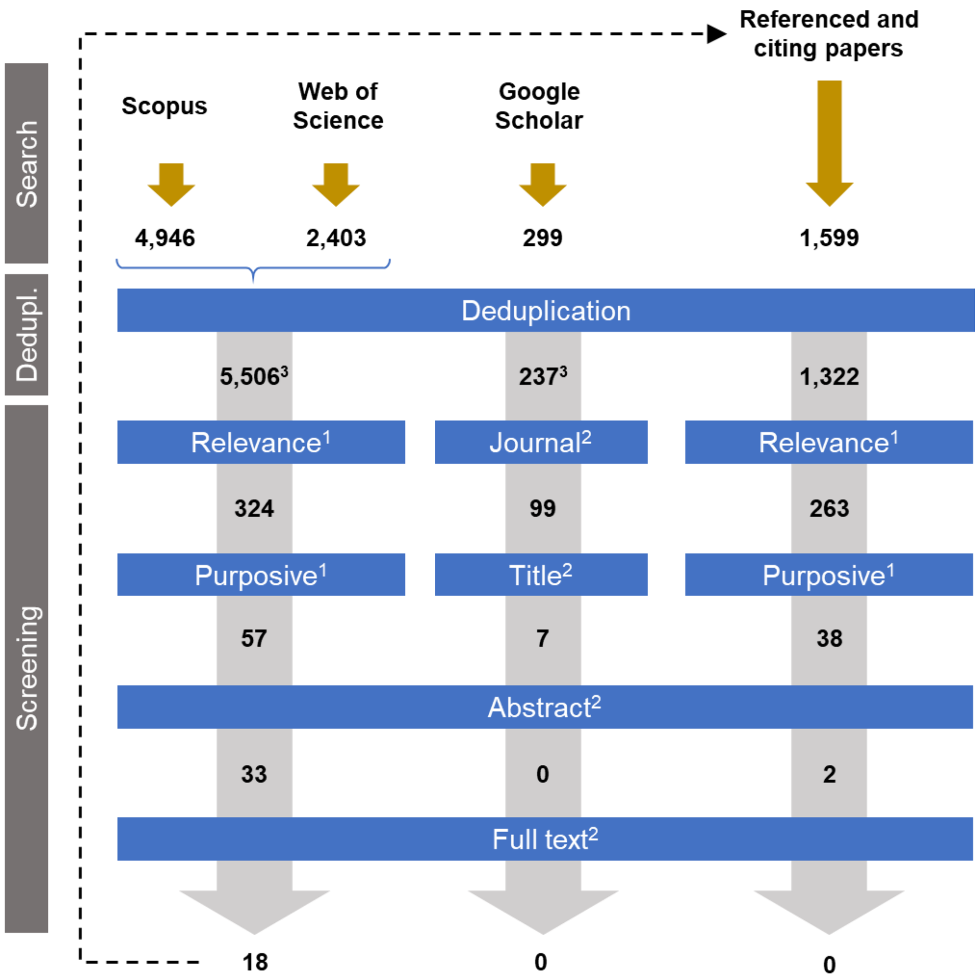
2.4 Referenced and citing papers

The screening of papers from Scopus, Web of Science and Google Scholar searches resulted in eighteen papers remaining selected. As a final step, all papers that were referenced by or that cited one of these eighteen papers were identified using Scopus and Web of Science. Any papers that had already been captured in the original search were deduplicated. The four screening steps in section 2.2 were then applied to the remaining papers. No additional papers remained selected following this process, providing further validation of the search parameters used in the original Scopus and Web of Science searches.

2.5 Results

The search and screening results are summarised in figure 1-1 and the selected papers are included in Appendix C.

Figure 1-1: Paper selection and screening results



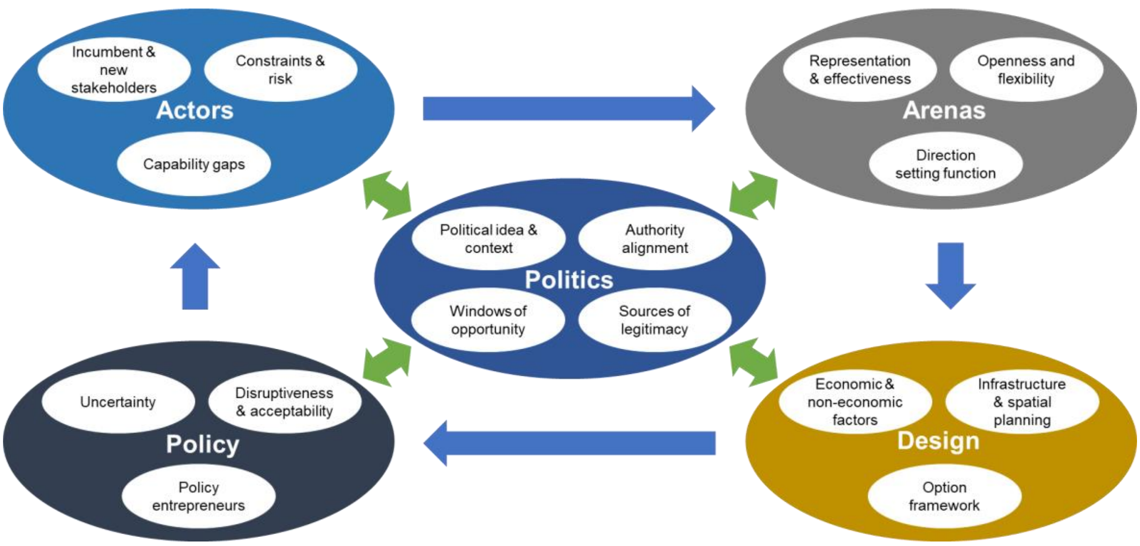
1: Rules-based screening; 2: Qualitative screening;
3: Deduplicated total from Scopus, Web of Science and Google Scholar searches: 5,743

3 Synthesised findings

Full paper content from the eighteen selected papers was coded using NVivo software, applying principles from grounded theory (Charmaz, 2006; Braun and Clarke, 2019). An iterative process of open, axial and selective coding (Williams and Moser, 2019) was applied. Open coding is unconstrained and typically generates a long list of codes. Axial coding synthesises and clusters codes according to key overarching themes. Selective coding refines codes and themes to communicate identified insights and relationships more effectively. Sixteen socio-technical and political transition attributes were identified clustered under the five themes of "Actors", "Arenas", "Design", "Policy" and "Politics". Figure 1-2 presents these attributes and themes as a new conceptual socio-technical and political transitions framework. The arrows in Figure 1-2 represent linkages between the five transition themes. These are discussed further in section 4.

Qualitative coding using NVivo was used as the analysis method as the purpose of the review was to identify and synthesise qualitative transition insights. Qualitative coding is extensively used in social science research to extract insights from unstructured textual data from interviews, workshops, focus groups and other sources (Braun and Clarke, 2019), and we have found it to be equally effective applied to literature. Bibliometric and narrative reviews that are more commonly used in systematic literature reviews are helpful for establishing the landscape of existing literature and identifying gaps, but we believe are less effective for the extraction and synthesis of diverse qualitative insights or for qualitative theory building.

Figure 1-2: Conceptual socio-technical and political transition framework for purposive road freight decarbonisation



In the remainder of this section, we will focus on the sixteen socio-technical and political transition attributes in more detail. Attributes classified under **"Actors"** provide guidance on the motivators, constraints and strategies of road freight incumbents and new entrants[1]. The **"Arenas"** grouping comes from the concept of transition arenas (TAs), which is central to Transition Management (TM) theory. Loorbach (2010) presents TM as the governance of the transition of complex systems. Within the TM framework, TAs are where *"groups of stakeholders envision and build transition visions, goals and pathways of change, and suggest immediate actions to be taken"* (Hyysalo et al., 2019). The concept of **"Design"** recognises that, if a transition is to be purposively enacted in a complex system, multiple coordinated actions are required that form a pathway to a defined target outcome. **"Policy"** includes measures used by government at all levels to affect the transition. The complexity of systems and the need to balance disruption with acceptability requires policy mixes that may span local, regional and national scales (Thaller et al., 2021). **"Politics"** encompasses the institutional and political environment that, while not necessarily specific to the transition, has a strong bearing on it.

3.1 Actors

3.1.1 Actor constraints and risk must be considered

Actors include operators; shippers; infrastructure, energy, and vehicle providers; authorities; and, in a local context, residents and local businesses (Marcucci et al., 2017; Paddeu et al., 2024). A prerequisite for all actors is that they understand how the transition will serve their own objectives (Macharis and Kin, 2017). Green innovations may come with disadvantages compared to conventional technologies and may therefore be associated with greater operational and financial risk (Denstadli and Julsrud, 2019). In situations where cost and risk are certain but benefits and the ability to capture these are uncertain, there will be significant reluctance on the part of operators to support the transition (Nordtømme et al., 2015). Existing operations also tend to be highly optimised around existing technologies and operating models (Nordtømme et al., 2015).

In the context of bus decarbonisation, Mohamed et al. (2018) highlight that bus operators require a technology that will be stable for the 12-16 year lifespan of a bus. They conclude as a result that the additional cost and risk of switching Canadian buses to electric vehicles exceeds the financial capacity of operators and that risk may need to be transferred to authorities. Churchman et al. (2023) similarly identify the importance of asset lifecycles for road freight

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[1] Incumbents are actors who already exist and play a substantial role in the road freight system. New entrants do not currently play a substantial role but may be required in the future system. For example, new entrant actors for road freight decarbonisation could be charging infrastructure providers and electrical grid operators.

operators. Nordtømme et al. (2015) propose that ways need to be found to alleviate risk for private actors who take a lead in decarbonisation.

3.1.2 Incumbent and new stakeholders need to be engaged

Radical decarbonisation requires engagement with new stakeholders that are not part of the established socio-technical regime, for example renewable electricity and charging infrastructure providers. In addition, existing stakeholders may need to take on new functions, for example the involvement of local government in charging (Aldenius et al., 2022). Edmondson et al. (2019) argue that policy mixes need to create incentives for incumbents as well as emerging niche actors and that, without these, the regime may mount significant opposition. Xu and Su (2016) make an additional point that, in the early stages of a transition, it is rarely possible to pick with certainty which actors will be the eventual winners and losers, and therefore to know who to protect and who to destabilise.

Taefi et al. (2016) and Ballantyne et al. (2013) find that transport planners have historically been more concerned about passenger than freight transport. Set against this is the key role of authorities in communicating responsibilities for road freight decarbonisation and requirements for individual and collective action (Paddeu et al., 2024).

3.1.3 Actor capability gaps should be addressed

Ballantyne et al. (2013) find that local authorities have not historically focused on freight transport and lack key freight planning knowledge and skills. In the context of bus decarbonisation, lack of required skill sets in bus operators is identified as a substantial transition barrier (Mohamed et al., 2018). Bus electrification in the United Kingdom and Sweden has also resulted in local authorities taking on additional responsibilities, thereby requiring new skills and capabilities to be developed (Aldenius et al., 2022). Learning from the experience of bus decarbonisation, it seems reasonable to assume that freight decarbonisation will also require authorities and operators to develop new capabilities.

3.2 Arenas

3.2.1 Representation and effectiveness must be reconciled

There is consensus in the identified literature that stakeholder engagement in transition planning is necessary. The road freight sector is highly fragmented (Churchman and Longhurst, 2022). However, a maximum number of approximately 25 participants is suggested for an arena to remain an effective negotiation and decision-making body (Lindholm and Browne, 2013). If all stakeholders are to be represented with this number of participants, certain groups will need to be represented by trusted bodies such as industry associations (Marcucci et al., 2017). The selection of arena participants must therefore be carefully considered to enable effective stakeholder representation while ensuring the arena remains effective as a negotiation and decision-making body.

3.2.2 Barriers to collaboration need to be overcome

It is observed that, in the context of collaborative initiatives, stakeholders with competing interests are required to trust each other and the collaborative initiative itself (Paddeu et al., 2024). A lack of willingness to share information and resources with competitors is identified as a manifestation of lack of trust and/or lack on alignment of individual interests with the initiative. Paddeu and Aditjandra (2020) find in the case example they consider that operational factors including an urban consolidation centre's location and special delivery requirements prevented implementation of a freight partnership's proposals.

Cooperation between political entities is also identified as necessary, with this being highlighted as a primary determinant of transport futures in Mexico City (Steurer and Bonilla, 2016). It is proposed that it may be possible to accommodate different stakeholder priorities in different ways, for example through flexibility in implementation details or by expanding policy scope to encompass an issue that is important for a subset of stakeholders (Sørensen et al., 2014).

3.2.3 A direction setting and coordination function is required

Salas Gironés et al. (2020) argue the need for a direction-setting function in transformative change processes which favours societally desirable changes over others. Hausknost and Haas (2019) suggest that, in some cases, the role of institutions is to define the attributes of transformation success, while in others it is necessary for them to "pick winners". Conversely, the lack of clear guidance from authorities is identified as a significant transition inhibitor (Mohamed et al., 2018). In a case study, Marcucci et al. (2017) found the local chamber of commerce was able to provide a "compensation room" between public and private interests.

3.3 Design

3.3.1 A framework for option identification, evaluation and selection is required

Several of the identified papers highlight the need for a framework for option identification, evaluation, and selection. One dimension of this is the framing of different concepts for decarbonisation, for example the "four A's of sustainable city distribution" of Awareness; Avoidance; Act and shift; and Anticipation of new technologies (Macharis and Kin, 2017). A second dimension is framing how options are identified and assessed, for example via Multi Actor, Multi Criteria Analysis (MAMCA) (Lebeau et al., 2018).

The assessment of different options necessarily requires some form of foresight or prediction of option impacts. Auvinen et al. (2015) propose a combination of participatory definition of futures by stakeholders, policy impact assessment and simulation modelling as potential ways that an action-oriented approach can be adopted for socio-technical transitions.

Differences are found between stakeholders in the degree of desired arena formality. In the UK case they considered, Lindholm and Browne (2013) find that freight industry participants typically seek a greater degree of formality, whereas local authorities prefer greater flexibility. Churchman et al. (2023) also find polarised views between stakeholders who would prefer clear direction from government versus those who believe operators should be free to choose solutions that work for them.

3.3.2 Infrastructure provision and spatial planning are critical

Thaller et al. (2021) find that the importance of infrastructure provision is the most cited requirement by transport transition stakeholders. Anderhofstadt and Spinler (2019), Denstadli and Julsrud (2019) and Xu and Su (2016) observe that the switch to alternative fuel heavy duty vehicles, e-vans and passenger vehicles requires a comprehensive charging or fuelling infrastructure. Taefi et al. (2016) conclude that to enable this, local authorities will need to redistribute scarce and expensive public space. However, Ballantyne et al. (2013) find that land use was rarely considered in freight planning by local authorities.

3.3.3 Economic and non-economic factors are important

Anderhofstadt and Spinler (2019) identify that a truck's reliability, an available fuelling/charging infrastructure and the possibility to enter low-emission zones are key factors when purchasing alternative fuel powered heavy-duty vehicles. Taefi et al. (2016) similarly conclude that the market uptake of electric vehicles for urban freight cannot be explained by financial incentives alone and that the effectiveness of legal measures such as privileged loading zones is underestimated by policymakers.

Considering mode shift, Gomez and Vassallo (2020) find that there is not strong evidence that this has either influenced road freight volume or promoted the shift of freight to alternative modes. They propose that mode shift also requires improving efficiency, quality and availability of competing modes. Lam and Mercure (2021) argue that conventional welfare economics, which recommends the comprehensive pricing of carbon emissions, may not be the most effective approach for transport systems, as this does not account for the dynamics of technology diffusion. Denstadli and Julsrud (2019) elaborate on such dynamics in relation to the adoption of e-vans:

- "Institutional isomorphism" where the managerial behaviour of companies in sectors can become homogenous through learning and information sharing or via imitation of successful competitors;

- The strong influence of small and medium-sized enterprise owners' norms and attitudes on company practices;
- The role of customer pressure and signalling of a green company image.

3.4 Policy

3.4.1 Policymaking should address uncertainty

The selected papers identify three dimensions of transition uncertainty that should be reflected in policymaking:

1. Anderhofstadt and Spinler (2019) argue that a key aspect of transport transitions is the progressive reduction of user uncertainty, and that information gathering about reliability and operating costs is an important determinant of the rate of adoption of low-emission heavy-duty vehicles.
2. Ballantyne et al. (2013) and Axsen and Wolinetz (2021) consider uncertainty in relation to the response of vehicle users and freight stakeholders to policy instruments.
3. Taefi et al. (2016) discuss uncertainty in the speed with which local authority measures can be implemented, with freight EV users being more pessimistic than policymakers.

Transition design and policy needs to progressively reduce user uncertainty and be resilient to multiple outcomes on each uncertainty dimension. Approaches such as Dynamic Adaptive Planning (Axsen and Wolinetz, 2021) or Anticipatory Governance (Muiderman et al., 2022) may be appropriate ways to achieve this.

3.4.2 Policy entrepreneurs can aid but also mis-direct policy

Related to the above finding regarding business actor influencing strategies, Denstadli and Julsrud (2019) discuss the importance of innovation champions who promote the adoption of a specific technology. Salas Gironés et al. (2020) however take a partially contrary view. In a case study of automated vehicle (AV) policy in the Netherlands in the period 2010-2019, they conclude that policy was strongly influenced by policy entrepreneurs with access to policy venues. They observe that policymakers were influenced by think tanks, NGOs, industry representatives, businesspeople and other policymakers "selling" their solutions. During the agenda setting phase, policy entrepreneurs were able to present AVs as a solution to societal problems such as congestion, without any specific commitments to deliver policy outcomes. After experimentation over a multi-year period, the programme was discontinued with limited tangible result.

3.4.3 Policy mix needs to balance disruptiveness and acceptability

Thaller et al. (2021) consider the balance of disruptiveness and acceptability in policy mixes for passenger transport. They find that “a well-balanced combination of diverse policy instruments is required to adequately address both dimensions”. Sørensen et al. (2014) observe that in all three road charging cases they studied, measures that were expected to encounter resistance were combined with more popular measures. Creating transparency on how revenues raised will be returned to the public is also identified as a key success factor.

3.5 Politics

3.5.1 Authorities and departments within authorities need to align

Nordtømme et al. (2015) identify institutional barriers resulting from challenges of coordination between different authoritative bodies and levels. In the case of an urban consolidation centre trial in Oslo, differing priorities between the Agency for Urban Environment, the city procurement office and the local police authorities contributed to the failure of the trial to proceed. Ballantyne et al. (2013) note that while freight is recognised as necessary for the urban economy, it is often not prioritised in transport plans, meaning the local plans may not align with regional or national road freight objectives.

3.5.2 Political windows of opportunity may need to be considered

Multiple Streams theory hypothesises that effective policymaking occurs when problem, solution and political streams come together (Kingdon and Stano, 1984; Salas Gironés et al., 2020). The convergence of the three streams is termed a policy window. Edmondson et al. (2019) identify that, over the course of a transition, windows of opportunity can allow actors to obtain favourable policy outcomes. However, changing conditions can cause these windows to close and the beliefs of actors can also change over time (Markard et al., 2014; Normann, 2015). Sørensen et al. (2014) highlight that as well as predictable windows associated, for example, with election cycles, unforeseen windows of opportunity can open suddenly. They argue it is therefore necessary to continually map the need for initiatives and prepare status reports at the political level to keep issues on the agenda.

3.5.3 Connecting to a political idea and the political context may be necessary

Sørensen et al. (2014) observe that the successful implementation of congestion charging in London was aided by the clear mandate that mayor Ken Livingston had for its implementation, and that the authorities responsible for its delivery reported ultimately to him. Salas Gironés et al. (2020) conclude that addressing societal transition challenges requires coupling of problems and solutions, and that this coupling is dependent on the political environment and the ideologies and beliefs of those in charge of making decisions. Conversely, Axsen and Wolinetz

(2021) identify that lack of political acceptability is the largest barrier to the implementation of road pricing. Kern and Howlett (2009) find that in the Dutch energy process, potentially incoherent, inconsistent or incongruent policy mixes emerged, and that local political inertia and resistance to change counteracted the TM-inspired governance mechanisms.

Salas Gironés et al. (2020) observe that theoretical transition processes often focus on societal engagement as a principal driver of direction-setting and that this, despite being desirable, neglects the fact that transformative innovation is inherently political in nature, with contestation, conflict, winners and losers. Steurer and Bonilla (2016) find that effective negotiation with private sector participants is a critical determinant of transport futures.

3.5.4 Sources of legitimacy other than decarbonisation itself may be required

Klenert et al. (2018) observe that substantial carbon prices only exist in countries where there is high government trust. They also propose that perceived fairness and political acceptability can be enhanced with careful design of exemptions and usage of revenues. They note however that implementing exceptions in freight transport may be more challenging than with personal transport. Churchman and Longhurst (2022) likewise find that freight operators did not always believe that government either understood or were interested in their challenges and were not confident that disconnected policymaking across authorities would deliver policy that worked for them.

Hausknost and Haas (2019) recognise the challenge of political institutions imposing transition choices and emphasise the need for legitimacy when centralised choices are required. Hyysalo et al. (2019) propose that more practical sources of legitimacy than the normative justification of sustainability are required. In the context of the portfolio of Finnish energy transition goals that they considered, this was derived from referencing existing energy and climate governance structures, broad consultation and an emphasis on experimentation and trials. Sørensen et al. (2014), Anderhofstadt and Spinler (2019) and Thaller et al. (2021) find that trials are an effective way to create legitimacy.

4 Linkages and feedback

4.1 “Collaboration” feedback loop

The blue arrows in figure 1-2 highlight that:

- Actors will only participate in arenas if they choose to do so.
- Arenas are only of value if they enable effective negotiation and decision-making.
- The design defined in arenas should inform transition policy.
- Policy should have a pro-transition influence on actor behaviour.

The fact that these linkages form a closed sequence suggests the existence of a feedback loop, and this indeed is intuitively the case. If actor participation in arenas is voluntary, they will only participate if they perceive the collaboration process and the design and policy outcomes of that process to be more aligned to their interests than would have been the case without their participation.

4.2 "Political" feedback loops

The green double-ended arrows in Figure 1-2 highlight the multiple influences of politics on the transition process and vice versa. At a high level, it is unlikely that the purposive transition process will be successful without a broadly supportive political environment. The four attributes within the politics theme provide an indication of what "supportive" might mean in relation to purposive transition delivery: political idea and context; windows of opportunity; authority alignment; and legitimacy. The transition process and outcomes need ideally to reinforce, and as a minimum to not undermine, these political foundations. For example, if the arena delivers a transition design that requires an ongoing financial subsidy that is not politically or financially realistic, political support for the purposive transition process is likely to rapidly diminish.

4.3 "Pervasive" attributes

Certain attributes, while aligned within the framework to a single theme, have impacts across other themes. "Policymaking should address uncertainty" for example is aligned to the policy theme but has substantial implications for "Actor constraints and risk must be considered" within Actors; "Barriers to collaboration need to be overcome" within Arenas; "Infrastructure provision and spatial planning are critical" within Design; and "Authorities and departments within authorities need to align" within Politics.

4.4 Summary

Many of the challenges of road freight decarbonisation could be articulated in terms of failing to effectively manage the described linkages and feedbacks. They are conceptually complex and it may not be possible to map and manage them fully. However, we propose that an awareness of the most significant linkages and feedbacks will be helpful in constructing a transition framework that has a greater chance of delivering desired transition outcomes.

5 Application to the case of road freight decarbonisation in the UK

This review is a part of a project focusing on road freight decarbonisation in the UK. This section reflects on the implications of the identified insights in this specific context. These reflections may also be applicable to other countries with comparable socio-technical and political contexts, but this would need to be confirmed.

An implication of the conceptual purposive transition model is that actors need to be willing and able to work in arenas to make collective design choices. Although many UK road freight operators and shippers publicly support decarbonisation, collective decision making and commitment to specific bold decarbonisation action requires a level of confidence in the ability to deliver decarbonisation while maintaining a successful business which is not yet present for many operators (Paddeu et al., 2024). This challenge is exacerbated by the fact that the UK road freight market is highly fragmented, with only one operator, DHL, having a market share of over 5%. The sector is as a result characterised by high competition and low barriers to entry (IBISWorld, 2022). This means that operators that are operationally or financially disadvantaged by implementing decarbonised solutions risk losing business to operators who have not taken such action. This leads to the first of the transition preconditions: ***techno-economically feasible options able to deliver rapid and radical decarbonisation need to exist.***

The UK government has set a target of banning the sale of diesel light good vehicles (LGVs) by 2030, heavy goods vehicles (HGVs) under 26 tonnes by 2035 and HGVs over 26 tonnes by 2040 (DfT, 2021). There is broad consensus that battery electric is the most suitable zero emission motive technology for lighter and shorter distance applications (Noll et al., 2022). For heavy duty and long haul applications, the government is funding Zero Emission Road Freight Demonstrations (ZERFDs) to demonstrate hydrogen fuel cell, battery electric and electric road system technologies (GOV.UK, 2021; Innovate UK, 2022). In addition, the government advocates transition from road to rail, cargo-bikes and inland waterways (DfT, 2022). Other measures that have the potential to reduce carbon emissions include supply chain reconfiguration; logistics coordination at a network level; increased individual vehicle capacity, utilisation and fuel efficiency; and freight demand reduction (European Environment Agency, 2022).

The existence of technically feasible solutions on its own is, however, insufficient. System dependencies mean that operator action needs to be supported by that of other actors. To reduce uncertainty and aid alignment, the road freight industry has called for a clear transition roadmap (RHA, 2020) and for a frank discussion on the cost of decarbonisation (Freight Zero Carbon, 2022). New technologies will have major implications for vehicle and road taxation, vehicle and driver licencing, and vehicle maintenance and safety standards, which are currently overseen by different government authorities.

Because of the major interdependencies between operators, infrastructure providers and vehicle manufacturers in relation to motive technology choices, motive technology selection appears to be a clear candidate for codesign. Large-scale mode shift and coordinated load and route scheduling across operators also requires substantial investment in shared physical and technology infrastructure and alignment of operating procedures. The planning and funding of infrastructure requires coordination between national, regional, and local planning authorities and private sector infrastructure providers.

While not all decisions can or should be made collectively, the above factors reinforce that certain decisions, if not mandated by government, need to be codesigned by actors. Given the significant challenge of collaborative decision-making, it will be necessary to be highly targeted in the design choices that will be codesigned. This leads to the second codesign precondition: ***A shared understanding of the design choices that need to be codesigned is required.***

Considering each of the purposive transition themes identified in the conceptual model in section 3:

5.1.1 Actors

Key road freight decarbonisation actors include freight operators, freight customers / shippers, vehicle manufacturers, infrastructure providers, energy providers and local, regional and national authorities (Briand et al., 2024; Paddeu et al., 2024). Different combinations of these are likely to be required to participate in different design choices. Each actor group has goals in addition to decarbonisation. For freight operators, COVID, Brexit and the war in Ukraine have added major new stresses to the pre-existing challenges of an aging workforce, poor driver facilities, low margins, just-in-time supply chains and devolved regulation (House of Commons Transport Committee, 2022; IBISWorld, 2022). In developing decarbonisation plans, each actor must inevitably consider the risk that decarbonisation action creates for other goals.

Freight operators consistently highlight the importance of asset lifecycles, total cost of ownership and confidence in resale values in new vehicle purchase decisions. Recent experience of the implementation of EURO vehicle standards, Direct Vision and Clean Air Zones by local authorities has made operators sceptical that new regulations are sufficiently thought through or that unintended consequences have been considered (Churchman and Longhurst, 2022).

Because of the large number of road freight operators, industry associations such as Logistics UK and the Road Haulage Association will play a key role in representing these actors in codesign arenas.

5.1.2 Arenas

Transition arenas are important for road freight decarbonisation for several reasons. Firstly, the diverse actor goals and constraints mentioned above need to be understood and factored into the transition design. Secondly, arenas provide a forum to increase actor understanding of potential solutions. Thirdly, they enable a view to be taken across national, regional and local levels (Marsden and Docherty, 2019). Finally, and perhaps most importantly, they provide a foundation of participation and legitimacy for transition codesign. One of the key challenges of a TA will be to allow participation of diverse actor groups while not permitting any one group to dominate decision making or block progress.

Freight Quality Partnerships (FQPs) have been established in the UK and other countries to aid collaboration between road freight stakeholders. FQPs are partnerships between local government, local businesses, the freight industry and other parties with a common interest in freight deliveries in a region or city (Lindholm and Browne, 2013; Marcucci et al., 2017). It is possible that the FQP concept could be combined with that of TAs to provide direction setting and mid-range planning for road-freight decarbonisation. The success of FQPs is however mixed (Allen et al., 2010; Browne and Lindholm, 2014), and lessons would need to be learned from past experience of these.

5.1.3 Design

There is consensus in the selected papers that road freight technology adoption and investment decisions must consider non-economic as well as economic factors (Nordtømme et al., 2015; Mohamed et al., 2018; Anderhofstadt and Spinler, 2019; Denstadli and Julsrud, 2019). A transition design developed by an arena must therefore also consider non-economic factors including infrastructure availability, legal and regulatory incentives, and differing actor motives for seeking to decarbonise.

A further transition consideration is maintaining capacity stability (Barazza and Strachan, 2020). Experience of the Brexit transition and Covid pandemic combined with chronic driver shortages has confirmed the vulnerability of road freight to supply disruption (BBC News, 2021; Piecyk and Allen, 2021). The design needs to take account of these factors while still effectively driving decarbonisation.

5.1.4 Policy

Policy uncertainty is cited by UK freight operators as a significant inhibitor to new technology adoption (Churchman and Longhurst, 2022). Other important aspects of uncertainty include the reliability, performance and cost of new technologies, roll out of supporting infrastructure and availability of skilled staff able to operate and maintain vehicles. Policy should aim to reduce these uncertainties, especially at the early stages of the transition.

The selected papers highlight the need for policy mixes that balance disruptiveness and acceptability. Increasing tax on diesel would be an example of a disruptive road freight incentive that on its own may be unwelcome to operators. However, if this was phased in according to a clearly defined schedule that aligned to vehicle replacement cycles and was accompanied by measures giving privileged access for low emission vehicles to city loading areas, this may make the policy package more acceptable. This example illustrates the importance of coordinating national policy (e.g., setting of fuel duty) with local policies (e.g., allocation of city loading spaces).

5.1.5 Politics

Sørensen et al. (2014) use the successful implementation of congestion charging in London as an example of where politics worked effectively to deliver what could have been a highly challenging transition. UK road freight operators on the other hand cite devolution of transport policy to national, regional and local authorities as a significant barrier (Churchman and Longhurst, 2022).

Hausknost and Haas (2019) argue that political decisions determine the transition option space. In the case of road freight decarbonisation, the option space is the suite of feasible technologies and transition pathways. At this point, all main technology options remain on the table in the UK (Greening et al., 2019). While this can be presented as maximising the option space, radical decarbonisation options involving motive technology or mode shift depend on the provision of major new infrastructure which requires a clear decision on the technologies to be developed. Political leadership needs to strike a balance between leaving options open and providing required technology and pathway clarity.

Taken together, these observations lead to the third codesign precondition: ***A politically and socio-technically feasible codesign framework to make these design choices must be established.***

6 Conclusions

6.1 Contribution

The research presented in this review paper is motivated by the urgent need to decarbonise road freight movements and the importance of socio-technical and political factors to this transition. A systematic literature review was conducted to address the research question: “What practical insights are provided by socio-technical and political transitions research that can aid purposive road freight decarbonisation?”. The eighteen papers that meet these criteria were coded using grounded theory methods and sixteen socio-technical and political transition attributes were identified. These were organised under five themes: Actors, Arenas, Design, Policy and Politics, and a new conceptual model for transition codesign was proposed.

A reflection on road freight decarbonisation in the UK based on the five transition themes was presented. This led to the identification of three preconditions for road freight decarbonisation. Although based on a specific consideration of the UK, we believe that the preconditions are sufficiently generally applicable to also be relevant in other national contexts.

To our knowledge, this is the first time that socio-technical and political transition attributes have been systematically identified from literature and synthesised into a framework for purposive transition delivery. We also believe that it is the first time the three identified preconditions for rapid and radical road freight decarbonisation have been explicitly articulated.

From a methodology perspective, we have not found other examples of the use of qualitative coding and grounded theory methods for the synthesis of transition insights from literature. This approach has proved effective in this study, and we propose that it there is potential for it to be used more widely.

6.2 Limitations

The principal limitations of the review are:

- Socio-technical and political transitions focus: Techno-economic transition considerations and a comparison of different technical solutions have not as a result been considered.
- Consideration of European and other comparable political and socio-technical contexts: Research that focuses on substantially different socio-technical and political contexts such as in developing countries or centrally planned economies has as result not been considered.
- Selection of insights specifically relevant to road freight decarbonisation: Insights that are not relevant to this transition but may be relevant to personal transport decarbonisation or other sustainability and societal transitions have not been captured.
- Project resource constraints: While every effort has been made to ensure that the review is systematic and repeatable based on the ROSES framework, resources were not available to allow a full independent validation of the review.

6.3 Further research opportunities

Opportunities for further research that emerge from the review include:

6.3.1 Testing and developing transition attributes with road freight actors

While the identified findings from literature make a strong case for a purposive transition approach and the three identified transition preconditions, these must be tested and developed with road freight actors.

6.3.2 Investigating multi-scalar transition design and governance

Policymakers operate within local, regional, and national authorities. Road freight operations similarly run at local, regional, national, and international levels. There are multiple road freight segments with different actors, opportunities, and constraints. Some design choices may need to be made at an international or national level whereas others may be better made at a local level or for individual freight subsegments. Further research is required to better understand these multi-scalar transition dimensions and implications for transition design and governance.

6.3.3 Applying purposive transition framework to other business-centred transitions

Subject to further validation, the purposive transition framework presented in section 3 may be applicable with adaptation to other sustainability transitions in which principal actors are public authorities and businesses, and where there are systemic interdependencies between actors necessitating coordinated action.

6.3.4 Wider application of qualitative coding and grounded theory to synthesise transition insights from literature

While qualitative coding and grounded theory methods are not widely used in literature reviews, they are extensively used in qualitative social science research. This review has demonstrated how they can be equally effective for extracting and synthesising insights from literature. There is an opportunity to use this approach for other transitions to identify insights that are not only helpful to researchers, but also to actors and policymakers seeking to affect transitions.

6.4 Final reflections

A possible conclusion from this work is that purposively codesigning the road freight decarbonisation transition is too complex to be practicable. The UK government, as an example, could be considered to have implicitly adopted this view. It has committed to achieving net-zero emissions by 2050 and is targeting the banning of sales of diesel freight vehicles. However, it remains agnostic on alternative decarbonisation technologies and pathways, instead asserting that market forces will lead operators and shippers to select from and implement these.

Our view based on the work conducted is that, in the absence of a purposive transition approach, rapid and radical road freight decarbonisation compatible with achieving climate change mitigation goals is unlikely to occur. The proposed conceptual framework and the three identified preconditions provide a helpful high-level framing for purposive transition. It is possible that slower non-radical decarbonisation could be achieved without a purposive approach being adopted. A key question for government and the freight transport industry is whether this would be considered a success or failure, given that it would fall short of achieving net zero or materially mitigating climate change.

Appendix A: Search expressions

6.5 Scopus search

(TITLE-ABS-KEY (socio-technical) OR TITLE-ABS-KEY (sociotechnical) OR TITLE-ABS-KEY ("politic*") OR TITLE-ABS-KEY ("technology adoption") OR TITLE-ABS-KEY ("technology diffusion") OR TITLE-ABS-KEY ("technology acceptance") OR TITLE-ABS-KEY ("stakeholder*")) AND (TITLE-ABS-KEY (freight) OR TITLE-ABS-KEY (logistics) OR TITLE-ABS-KEY (transport) OR TITLE-ABS-KEY (vehicle*)) AND PUBYEAR > 1999 AND PUBYEAR < 2026 AND (SRCTITLE (energ*) OR SRCTITLE (cities) OR SRCTITLE ("research policy") OR SRCTITLE (sustain*) OR SRCTITLE ("technological forecasting and social change") OR SRCTITLE ("Environmental Innovation and Societal Transitions") OR SRCTITLE ("Journal of Cleaner Production") OR SRCTITLE (transport*)) AND NOT (SRCTITLE (econ*) AND NOT SRCTITLE ("Research in Transportation Economics")) AND NOT SRCTITLE (technology) AND NOT SRCTITLE (technologies) AND (LIMIT-TO (SRCTYPE , "j")) AND (LIMIT-TO (PUBSTAGE , "final")) AND (LIMIT-TO (SUBJAREA , "SOCI") OR LIMIT-TO (SUBJAREA , "ENER") OR LIMIT-TO (SUBJAREA , "ENVI") OR LIMIT-TO (SUBJAREA , "BUSI")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "re")) AND (LIMIT-TO (LANGUAGE , "English"))

6.6 Web of Science search

(TS=socio-technical OR TS=sociotechnical OR TS="politic*" OR TS="technology adoption" OR TS="technology diffusion" OR TS="technology acceptance" OR TS="stakeholder*") AND (TS=freight OR TS=logistics OR TS=transport OR TS=vehicle*) NOT (SO=technology OR SO=technologies OR SO=econ*) AND (SO=energ* OR SO=cities OR SO="research policy" OR SO=sustain* OR SO="technological forecasting and social change" OR SO=transport*)

Filters applied to Web of Science results:

- Year range 2000 – 2025
- English language
- Articles and reviews
- Categories: Environmental Sciences, Environmental Studies, Transportation, Business
- Papers without DOI excluded

Appendix B: Relevance exclusion terms applied to titles and abstracts

Table 1-2: Relevance exclusion terms applied to titles and abstracts

Category	Exclusion key
Research method	agent-based, anova, appraisal, backcasting, big data, boundary, cognitive, community task force, contingent, decomposition, deconstructing, demographic, descriptive analysis, discourse, discrete choice, econometric, fuzzy, game, Hamiltonian, heuristic, holistic, imaginar, language, linear, lingu, long-term visions, machine learning, modelling sustainability risk, neo-Gramscian, niche, normal distribution, performance meansurement frameworks, phonetic, policy learning, policy transfer, principal components analysis, rank correlation, revealed preferences, rhetoric, stochastic, street experiments, system dynamics, typology, urban living labs, visioning, willingness to pay
Transition type	_port, _river, agri, aircraft, airplane, airport, artificial, automated mobilities, automobil, automobile, automotive, autonomous, aviation, bicycle, bike, biking, bioeconomy, buildings, bus rapid transit, car sharing, carsharing, cement, chemical, circular, climate target-setting, cluster, coastal, communism, community-based, congestion charging, cook, crypto, cycle, cycling, cyclist, decentralized energy system, digital supply chain, driverless, drones, ecolog, electric mobility, electricity sector, electromobility, e-mobility, expressway, extraction, flood, food, function-oriented, glass, health, heat, industry 4.0, land use, maas, maintenance, manufacturing, maritime, medical, medicine, megaproject, metro_, micromobility, mobility service, national park, oil refining, plastic, PM emissions, police, policing, pollution, positive energy districts, prosumer, public procurement, pulp, rail, real-time, recycl, residential, reverse logistics, ride-hailing, rideshar, road investments, ropeway, safety, scooter, SDG, security, shared mobility, shared vehicles, shipping, signal priority, smart city, steel, student, sustainable dev, taxi, touris, trip-planning apps, trolleybus, universit, urban congestion, urban travel management, vehicle automation, walk, waste, water
Geographic context	africa, amazon, bahrain, bangladesh, belt and road, china, chinese, developing count, emerging markets, ethiopia, ghana, global south, hong kong, india, kazakhstan, kenya, korea, mongolia, namibia, nepal, nigeria, pakistan, papua new guinea, rwanda, saudi, taiwan, tanzania, tokyo
Social issues addressed	aborig, accessibility, asylum, border, christian, civic, collective action, consumption, covid, crime, cultur, degrowth, democ, disabl, empower, equality, ethn, fair, femin, grassroot, household, human factor, humanitarian, ideol, inclusion, inclusive, indigen, islam, just, liberal, literacy, marketing, media, migrant, migration, modern, museum, muslim, population, populist, poverty, protest, relig, school, social media, sociology, terror, violence, voter, voting, war_, wealth, women, youth
Transition perspective	5G, access management, audit, biomass, blockchain, bond, budget, charges, codes and standards, comput, crowd, cyber, design procedure, distribution methodologies, dynamic wireless charging, engineer, financing, FLM, freight data, fuel economy, fuel technology, generation, geo-, grid, highways, hydrogen technol, index, intelligent, iptv, key performance indicator, materials, mobile, NFT, optimal, optimi, optimum, photovoltaic, physics, ppis, PV, safe system, storage, strategic misrepresentation, supply chain technolog, tendering, trade, trading, transportation models, warehous
Document purpose	congress, response to critics, workshop 4 report, workshop 6 report

Appendix C: Selected papers from systematic literature review

Table 1-3: Selected papers from systematic literature review

Author (Year)	**DOI link**
Road freight transitions	
Anderhofstadt and Spinler (2019)	https://doi.org/10.1016/j.trd.2019.06.003
Ballantyne et al. (2013)	https://doi.org/10.1016/j.jtrangeo.2013.08.013
Denstadli and Julsrud (2019)	https://doi.org/10.3390/su11143878
Nordtømme et al. (2015)	https://doi.org/10.1016/j.tranpol.2015.08.005
Taefi et al. (2016)	https://doi.org/10.1016/j.tra.2016.06.003
Paddeu et al. (2024)	https://doi.org/10.1016/j.retrec.2024.101424
Paddeu and Aditjandra (2020)	https://doi.org/10.3390/SU12010441
Lebeau et al. (2018)	https://doi.org/10.1016/j.cstp.2018.07.003
Lindholm and Browne (2013)	https://doi.org/10.18757/ejtir.2013.13.1.2986
Macharis and Kin (2017)	https://doi.org/10.1080/15568318.2016.1196404
Marcucci et al. (2017)	https://doi.org/10.1016/j.retrec.2017.09.001
Passenger and general transport transitions	
Axsen and Wolinetz (2021)	https://doi.org/10.1016/j.enpol.2021.112457
Mohamed et al. (2018)	https://doi.org/10.1016/j.trd.2017.09.019
Salas Gironés et al. (2020)	https://doi.org/10.1016/j.techfore.2020.120243
Steurer and Bonilla (2016)	https://doi.org/10.1016/j.tranpol.2016.06.002
Thaller et al. (2021)	https://doi.org/10.1016/j.trd.2021.102714
Aldenius et al. (2022)	https://doi.org/10.1016/j.trd.2022.103204
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Paper 2: Transition codesign for purposive road freight decarbonization

Phil Churchman, Thijs Dekker, Kate Pangbourne

Abstract

Three potential preconditions are identified for rapid and radical road freight decarbonization: 1) techno-economically feasible solutions; 2) a shared understanding of design choices that need to be codesigned; and 3) a politically, socially and organizationally feasible codesign framework for making these design choices. Focusing on the case of food deliveries to supermarkets and supermarket distribution centers in Great Britain, this study tests these preconditions via qualitative coding and quantitative descriptive statistical analysis of data from 32 semi-structured interviews with road freight actors, policymakers and experts. There is broad consensus that the preconditions are necessary, but differences in views on what would fulfil these. Several transition challenges are identified. System and path dependencies mean that decision pathway(s) and a codesign framework are needed, the latter incorporating defined attributes and conflict resolution mechanisms. Geographic and sectoral dimensions are also identified as important for framework design.

Keywords: Road freight, Decarbonization, Socio-technical, Political, Techno-economic, Codesign

1 Introduction

Trucks and vans represent c. 8.5% of United Kingdom (UK) carbon emissions (DfT, 2017; BEIS, 2021). Road freight is responsible for approximately two-thirds of these emissions (GOV.UK, 2021) and is considered to be a hard-to-abate sector. However, it must be abated to achieve net zero carbon by 2050 or sooner. Road freight decarbonization progress to-date in the UK and other countries is nevertheless limited, despite a range of potential decarbonization solutions.

Churchman et al. (2023) propose three preconditions for rapid and radical road freight decarbonization:

1. *Techno-economically feasible solutions need to be available:* There is a consensus in literature that solutions must be techno-economically feasible (Cebon, 2020; Meyer, 2020; ICCT, 2022). However, there is substantial debate on which solutions fulfil this criterion.
2. *A shared understanding of the design choices that need to be codesigned is required:* Literature identifies the need for certain design choices to be codesigned by

policymakers and road freight actors (Ballantyne et al., 2013; Taefi et al., 2016). However, codesign is difficult (Hyysalo et al., 2019a; Macedo et al., 2020) and so should be targeted only at the choices that need it. The term "codesign" is used in literature to represent a wide range of collaborative processes, not all of which are relevant for road freight decarbonization. The broad definition of codesign used in this study is that provided by Hyysalo et al. (2019b) of *"better connecting the relevant actors that are needed for bringing about societal change in liberal democracies: decision makers, experts, civil servants, citizens, NGOs, and business leaders (to name but a few)"*. More specifically for purposive transition design, it is used to mean collaborative and collective decision making by policymakers and road freight actors. For this to be effective, there must be agreement on the design choices that will be codesigned.

3. *A politically, socially and organizationally feasible codesign framework to make these design choices needs to be put in place:* Studies identify several factors that are important for successful codesign including synthesizing information for decision support (Förster et al., 2015; Cerreta et al., 2021), "alliance network" configurations (Ali and Hawryszkiewycz, 2020); focusing on mid-range pathways (Hyysalo et al., 2019a), defining the "cocreation lifecycle" (DeLosRíos-White et al., 2020) and having a framework for evaluating decision alternatives (Cerreta et al., 2021). Studies also identify that transport and energy transitions are subject to strong political, social and organizational challenges (Steurer and Bonilla, 2016; Downie, 2017; Normann, 2017; Edmondson et al., 2019; Salas Gironés et al., 2020). Given these challenges, it is proposed that a robust codesign framework is required that defines decision processes, roles, tools and governance. This framework must itself be designed to be practically effective and provide necessary legitimacy within the political, social and organizational context.

The objective of this study is to obtain actor perspectives on these preconditions via semi-structured interviews with road freight actors, policymakers and experts and, applying qualitative and quantitative analysis, consider the implications of these for purposive road freight decarbonization, with purposive defined as deliberate, planned, structured and organized. The specific case of food deliveries to supermarkets and supermarket distribution centers (DCs) in Great Britain (GB) is selected because of the relatively small number of easily identifiable freight customers and operators, which increases both the ability to access research participants and the feasibility of a codesign approach. Other factors favoring this choice are that it is the largest single road freight segment (excluding groupage) representing 30.6 billion of a total 175.1 billion tonne-kilometers of UK movements of GB registered heavy goods vehicles (HGVs) (GOV.UK, 2022); is comprised of both local and long-haul movements; includes time-critical deliveries of short shelf life product; is politically and socially prominent; and is an existing focal point for increasing sustainability. GB excluding Northern Ireland (NI) is considered so as not to introduce post-Brexit considerations for freight movements to and from NI.

The novelty of this study is twofold: the consideration of political, social and organizational as well as technical and economic factors in road freight decarbonization; and the assessment of requirements to achieve purposive transition delivery. Elements of these are incorporated in studies considering other transitions, for example a multi-actor perspective (e.g. Lode et al. (2021)), a multi-disciplinary perspective (e.g. Cherp et al. (2018)) and purposive codesign (e.g. Hyysalo et al. (2019b)). No identified study however considers all of these elements with a focus on purposive delivery of road freight decarbonization.

The paper proceeds as follows: section 2 provides a review of literature relevant to interview design; section 3 describes the data gathering and analysis methods used; section 4 summarizes interview design; section 5 presents the findings of the research; section 6 discusses the implications of findings for road freight decarbonization codesign; section 7 draws key conclusions; and section 8 identifies principal study limitations.

2 Literature review

This section summarizes the literature that formed the basis of interview questions and response options (see section 4 and appendix) for each of the three proposed road freight decarbonization preconditions.

2.1 Techno-economically feasible solutions need to be available

This study does not attempt to answer the question "what are the techno-economically right solutions?" but instead "what do participants think the right solutions are and what are the implications for decarbonization codesign?". The following literature formed the basis of the solution options provided to participants, from which they could select those they considered most promising.

One solution category is the transition from internal combustion engines (ICEs) burning fossil fuels to low or zero emission motive technologies. Some of these, such as battery electric (Liimatainen et al., 2019), hydrogen fuel cell (Çabukoglu et al., 2019) and electric road systems (Schulte and Ny, 2018), result in zero carbon emissions from the vehicle itself, although total carbon reductions depend on the how the electricity or hydrogen is produced (Howarth and Jacobson, 2021) and energy losses in the chain from energy production to consumption in the vehicle (Lux and Pfluger, 2020). These solutions have the additional benefit of reducing non-carbon emissions including particulates and nitrogen oxide (NOx) (Breuer et al., 2020). Biofuels such as biomethane made from food and agricultural waste (Prussi et al., 2021) and hydrogenated vegetable oil (HVO) (Aatola et al., 2009) compensate for carbon emissions from the vehicle with carbon capture when the biomass is grown. Alternative fossil fuels such as compressed natural gas (CNG) and liquid natural gas (LNG) provide marginal rather than radical decarbonization and were not included in the options provided to participants.

A second category is the transition of road freight to less carbon-intensive rail and water modes (Bai et al., 2016; Kaack et al., 2018). There are clear carbon reduction benefits where this is an available option, but also challenges in terms of increased logistics and planning complexity, increased journey times and the need for investment to increase rail and water freight capacity and develop intermodal facilities (Islam et al., 2016).

A third category is to improve individual vehicle efficiency and/or load capacity. A number of means of doing this are proposed including increasing weight, length and height limits for vehicles (Sanchez Rodrigues et al., 2015), improving vehicle aerodynamics (Hariram et al., 2019), using double deck trailers and other means of increasing vehicle capacity (Galos et al., 2015; Palmer et al., 2018) and efficient driving measures including coasting (Henriksson et al., 2018).

A fourth category is driverless vehicles, which have the potential to remove the need for charging stops to be combined with driver rest periods (Hariram et al., 2019; Monios and Bergqvist, 2019). Significant practical and public perception issues however remain with the adoption of driverless technology (Hudson et al., 2019). Another form of automation is platooning, where trucks drive closely behind each other in convoy to increase fuel efficiency by reducing aerodynamic drag (Alam et al., 2015). This requires vehicles to be connected via an appropriate information system and fuel savings are dependent on operational factors (McAuliffe et al., 2018; Paddeu and Denby, 2022).

A fifth category is to improve load and schedule optimization across multiple operators to reduce empty load space (WEF, 2023) and optimize vehicle deliveries and routings (McAuliffe et al., 2018).

A sixth category is the redesign of supply chains to reduce total carbon emissions, for example via localization of manufacturing (Kalmykova et al., 2018). Sustainable supply chain design needs to consider complex trade-offs between transport and manufacturing emissions, and other key factors such as supply chain resilience and supply security (Rothwell et al., 2016).

The final category identified is consumer behavior change and consumption reduction, leading to reduced volumes of freight needing to be transported (Polinori et al., 2018; Russo and Comi, 2020).

2.2 A shared understanding of the design choices that need to be codesigned is required

Literature reinforces the view that it is only by codesigning key road freight decarbonization choices that the deep lock-in of fossil fuel technologies can be overcome. Complex path and system dependencies such as those between infrastructure demand, planning, financing and development; and the interaction of freight shippers, operators and receivers; are highlighted (Sternberg et al., 2013; Driscoll, 2014). Market forces driving individual organization action are seen as being unlikely on their own to achieve radical decarbonization (Kluschke et al., 2019) as, without coordinated decision making, the actions of individual organizations are heavily constrained (Churchman and Longhurst, 2022). Transitioning complex systems is identified as requiring a systems approach to avoid unforeseen consequences (Ghisolfi et al., 2022). The UK and some other governments do not see a centralized command and control approach to road freight decarbonization as either politically feasible or desirable (Aditjandra, 2018; Monios, 2019). This leaves codesign by actors as the only apparent option to make the pathway dependent design choices that are necessary to rapidly and radically decarbonize road freight (Colicchia et al., 2017).[1]

Which actors need to be involved in which decisions will be influenced by the geographic and sectoral levels at which decisions need to be made. Some decisions may be appropriately made at a national level for all road freight. Others might need to be made for individual road freight segments and/or for individual cities or regions. To define an effective codesign framework, it will be necessary to specify the geographic and sectoral decision-making levels. In the UK, this needs to recognize the devolution of transport policymaking to national and sub-national authorities (Butcher, 2017). While these multi-scalar factors add complexity to decision making, devolved national and subnational bodies are also identified as helpful for collaboration (Cowell et al., 2017).

Five categories of decision potentially requiring codesign were identified:

- *Decarbonization speed and scale:* Decarbonization targets and timelines per road freight use case[2]
- *Technology / solution selection:* Selection of the technologies and solutions identified in section 2.1 that will be implemented per road freight use case
- *Infrastructure:* Specification and funding of required infrastructure

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[1] While this was the case in the UK at the time of writing, this may not be true in other jurisdictions and, for a given jurisdiction, this could change over time.

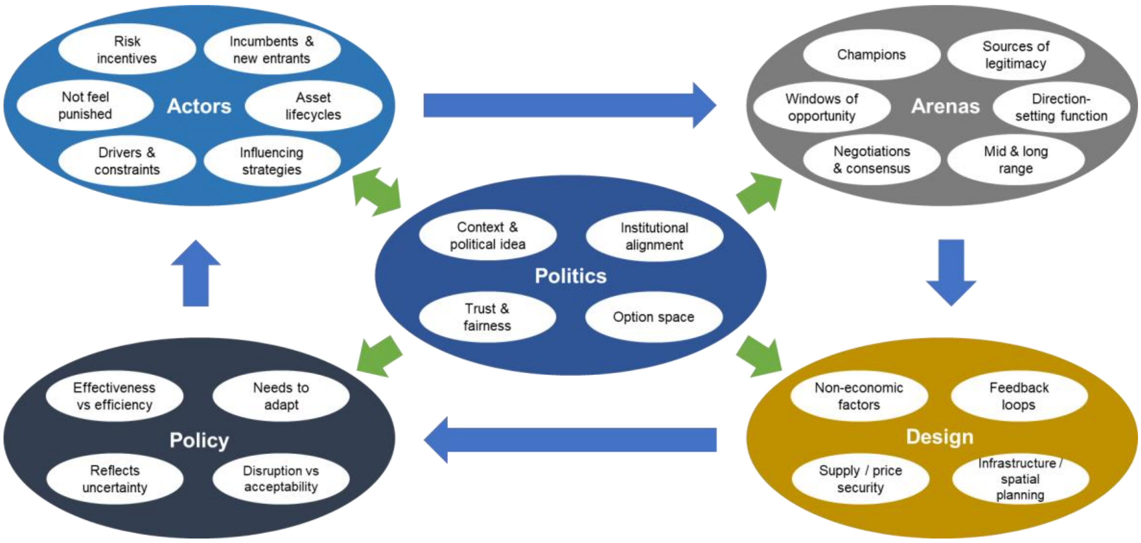
[2] "Use case" is a road freight segment or sub-segment with defined physical handling and logistics requirements, for example urban delivery of goods to supermarkets in roll cages.

- *Transition incentives:* Specification and funding of economic and non-economic incentives to accelerate the transition
- *Institutional capacity:* Specification and funding of public and private sector capabilities required to implement decarbonized solutions

2.3 A politically, socially and organizationally feasible codesign framework to make these design choices needs to be put in place

Based on a systematic literature review, Churchman et al. (2023) used qualitative methods to develop the conceptual model in figure 2-1 which groups 24 codesign attributes under five headings: Actors, Arenas, Design, Policy and Politics (see appendix for full attribute statements). Within this framework, "Actors" are road freight actors and policymakers who work together in "Arenas" to codesign key design choices. The resulting "Design" influences "Policy" which in turn influences the priorities and actions of "Actors." "Politics" affects each of these stages and can also be affected by "Actors" through lobbying and other activities.

Figure 2-1: Conceptual model of socio-technical and political transition attributes for purposive road freight decarbonization
(source: (Churchman et al., 2023))[3]



[3] The conceptual model used in this paper is an earlier version than that presented in the referenced paper, and there are some differences in the included attributes.

3 Methods

3.1 Data gathering

Due to the qualitative as well as quantitative insights sought, interviews and workshops were considered as potential data gathering methods rather than a remote survey. Interviews were selected as it was considered these would be more effective at capturing the full diversity of participant opinion, whereas workshops would risk being dominated by more vocal participants. To effectively investigate the three preconditions identified in section 1 within an interview of acceptable duration, and to ensure a sufficient degree of comparability between participant responses, it was decided that a semi-structured interview combining open and closed questions would be most effective – see section 4 and appendix for interview structure and questions aligned to the three transition preconditions. To facilitate interview navigation, the topic list that is typical for semi-structured social science interviews was augmented with a questionnaire built in Jisc Online Surveys that was shared on-screen with participants and completed by the interviewer in discussion with participants during the interviews.

Participants were encouraged to expand on their responses to both open and closed questions, so that additional unstructured insights could be captured. The combination of structured and unstructured data obtained via this approach provided rich insight, while keeping the interviews in most cases under 90 minutes in duration. Interviews were recorded and transcribed. Twenty eight of 32 interviews had a single participant; the remaining four interviews had two or, in one case, three participants jointly representing a single organization. When this was the case, one set of structured responses was captured per interview, but transcriptions were captured for each individual participant.

3.2 Participant recruitment

Three target participant groups were identified: 1) freight operators and shippers; 2) government and transport authorities; and 3) industry associations and experts. Within group 1, target sub-groups were supermarkets, third party logistics providers (3PLs) and food manufacturers. Within group 2, target sub-groups were national authorities (UK-wide and individual UK countries), regional / combined authorities, and local / city authorities. Group 3 included industry associations and experts specializing in road freight. To provide sufficient representation of all groups and subgroups, a target of 30 participants was set. Ultimately, 37 participants were engaged in 32 interviews (see table 2-1).

A purposive snowballing approach was adopted to participant recruitment. Six of the participants were previously known to the interviewer, 10 were introduced by other participants and contacts, and the remaining 21 were “cold” contacts reached via a combination of email, telephone, LinkedIn and at conferences.

An unavoidable limitation in the sample selection is that people were more likely to respond and agree to participate if they already had an interest in road freight decarbonization. This means that the results cannot be considered as representative of the total population of the target groups. The positive response rate was however good, with 45%, 64% and 75% respectively of freight operator/shipper, government/transport authority and industry association/expert organizations contacted participating in the study.

Table 2-1: Participants and interviews per target group

Group	Participants	Interviews
Freight operators and shippers	***17***	***15***
Supermarkets	8	7
Third party logistics providers	6	5
Food manufacturers	3	3
Government and transport authorities	***13***	***10***
National (including devolved country authorities)	4	2
Regional and combined authorities	7	6
Local and city	2	2
Industry associations and experts	***7***	***7***
TOTAL	**37**	**32**

Three interviews were conducted face to face and 29 were online. In all cases, the interviews were recorded and auto-transcribed in Microsoft Teams, with the structured responses captured in Jisc Online Surveys. The same data processing and analysis was applied for in-person and online interviews.

3.3 Applicability of findings to other road freight segments

While most operator/shipper participants worked within the selected road freight segment, other participants had a broader road freight remit, and their responses encompassed but were not always limited to this segment. This was considered legitimate in the context of the objective to test the three preconditions for purposive road freight decarbonization. It means however that it is not always possible to say with certainty if a finding is specific to the selected freight segment or broader. Although in many cases wider applicability seems likely, further work would be required to confirm this.

3.4 Data analysis

3.4.1 Structured data

Structured data was downloaded as an Excel spreadsheet from Jisc Online Surveys and imported into Python using Pandas. Imported data was then processed and presented graphically using Matplotlib (e.g., figures 2-2 and 2-3) showing results as counts of total responses and percentages of responses per participant group.

3.4.2 Unstructured data

For each interview, an initial auto-transcription was downloaded as a Word file from Microsoft Teams. This file included timestamps which were used to identify the start time for each question response. Start times were entered into an Excel table for each interview and Python was used to split the auto-transcribed text into question responses, removing the embedded timestamps in the process. Additional automated cleaning was applied in Python to remove duplicate and filler words and redundant punctuation, spaces and line returns. The transcriptions for each question response were then manually reviewed and corrected, referring to interview recordings where meaning was not clear from the captured text. Once this was completed, Python was used again to create well-spaced and formatted PDF files. The PDF files were imported into NVivo and qualitatively coded, applying principles from grounded theory (Charmaz, 2006) through an iterative process of open, axial and selective coding (Williams and Moser, 2019). Codes were defined to represent participant opinions, enabling the number of participants expressing each opinion to be identified. Where multiple participants in an interview expressed the same opinion, this is only counted once in the presented results.

4 Interview design

Please see appendix for full interview questions and response options.

The interviews were organized as follows:

1. Open questions on decarbonization opportunities and barriers:

The purpose of these questions was to elicit un-prompted participant views prior to asking the subsequent closed questions. Transcribed responses were captured as unstructured data.

2. Closed questions and commentary on three preconditions:

The purpose of these questions was to capture participant opinion regarding each of the three preconditions and identify specific areas of consensus and potential conflict. Structured data was captured based on the response options selected. Unstructured data was captured from transcribed commentary to the responses.

Techno-economically feasible solutions need to be available:
Participants were first asked to select from a pre-defined list of decarbonization solution categories those that they considered to provide the greatest opportunity for rapid and radical decarbonization. For each category selected, they were then asked to select the specific solutions within the category that they considered most promising. In each case, there was the option to select "Other" and specify additional solutions.

A shared understanding of the design choices that need to be codesigned is required:
For each of five categories of design choice identified from literature, participants were first asked to select to what extent they thought it was important that design choices were coordinated across multiple actors. They were then asked to select the geographic and freight segment levels at which design choices should be made.

A politically, socially and organizationally feasible codesign framework to make these design choices needs to be put in place:
Section 2.3 summarizes the framework developed by Churchman et al. (2023) that identifies 24 potential socio-technical and political codesign attributes for purposive road freight decarbonization. To test the importance of these attributes, participants were asked to what extent they agreed or disagreed with each attribute statement. If they agreed or somewhat agreed, they were then asked if they believed that it would be a significant barrier to decarbonization if the attribute was not true.

5 Findings

The headline findings from the study are:

Techno-economically feasible solutions able to deliver rapid and radical decarbonization need to be available:

- There was broad agreement that motive technology transition is necessary, however motive technology preferences for long-haul HGVs varied substantially.
- Containerized rail was seen as representing a significant opportunity in 41% of interviews and improved load and schedule optimization across multiple operators in 38% of interviews.
- Improved individual vehicle efficiency, driverless and platooning, supply chain redesign and consumer behavior change were seen in most interviews as providing only marginal decarbonization opportunity.

A shared understanding of the design choices that need to be codesigned is required:

- There was broad agreement that codesign is necessary in the five identified decision categories, with the strongest consensus for decarbonization speed and scale and technology / solution selection.
- Most participants considered that design choices need to be made at a national level, although other geographic levels were also seen as important by some participants.
- Most participants considered "all road freight" and "freight operation type" as the most important freight segment levels for design choices to be made.
- Notable differences of opinion emerged in the extent to which decarbonization speed and scale, and technology / solution selection should be government or market driven, appropriate incentives, and whether it is possible or desirable to create a level playing field for smaller operators.

A politically, socially and organizationally feasible codesign framework to make these design choices needs to be put in place:

- There was broad agreement on the importance of nine of the 24 identified codesign attributes, suggesting that these should be reflected in the codesign framework.
- There were strongly differing views on four of the codesign attributes, suggesting potential sources of conflict in whether additional sources of legitimacy are required; incumbents should feel punished; road freight decarbonization planning should consider political windows of opportunity; and if it is necessary to connect to a clear political idea and the political context.

Key challenges, each identified in at least ten interviews, are technology uncertainty and immaturity, lack of a clear direction or plan, lack of strategic infrastructure planning or funding, infrastructure chicken and egg, inconsistent incentives and policy, first mover disadvantage and up-front cost, and collaboration barriers.

While there was less discussion regarding enablers than challenges, enablers that were mentioned include Zero Emission Road Freight Demonstrations (ZERFDs), existing collaboration and consultation forums, third party logistics providers and combined authorities.

The remainder of this section presents these findings in more detail:

5.1 Techno-economically feasible solutions need to be available

Participants in 29 of 32 interviews saw motive technology transition as a key decarbonization solution, and in 26 interviews battery electric was seen as promising for local and urban freight. Significant barriers were however identified for the transition to battery electric, including grid capacity and access, vehicle availability, support for early movers, resource sharing and resolution of concerns regarding battery durability and sustainability.

Motive technology preferences for long-haul HGVs and views regarding other decarbonization opportunities varied substantially.

There were widely differing views on the feasibility of hydrogen, biofuels and mode shift to rail (table 2-2):

Hydrogen: *"Whether it's fuel cell or direct drive hydrogen, for me it's the future for the longer distances."* (Operator/shipper #3) ***vs.*** *"Hydrogen is more promising for, for example, aeroplanes where you have a whole system with big quantities, but not road necessarily … It's a very expensive technology to use in road."* (Government/transport authority #6)

Biofuels: *"That's why things like biodiesel, particularly HVO, is so powerful, because with HVO you haven't got to touch the vehicle or the refueling mechanism."* (Operator/shipper #2) ***vs.*** *"For biodiesel and biomethane, there are options that we've looked at, for example, HVO. We walked away from HVO because it's more expensive and there's a challenge around how that fuel is manufactured."* (Operator/shipper #11)

Mode shift to rail: *"The way we're tackling it, mode shift is our biggest opportunity in the long term. We've already made decisions about the position of the new DC."* (Operator/shipper #10) ***vs.*** *"I'd never build my business on the idea that it was going to get somewhere by rail. You only have to look at what's going on at the moment."* (Operator/shipper #8)

More participants saw electric road systems as not feasible than feasible (10 non-supportive vs. 5 supportive views), primarily due to the large up-front infrastructure investment required and concerns regarding the practicality of catenaries over motorways and trunk routes. Fourteen supportive views regarding improved load and schedule optimization at a network level were expressed, but substantial collaboration challenges were also raised. Improving individual vehicle efficiency via improved aerodynamics, longer / taller / double-deck trailers, efficient driving aids and coasting was identified by freight operators and shippers, but not by participants in other groups. By contrast, supply chain redesign opportunities were primarily selected by industry associations and experts, and collaborative network opportunities were more likely to be selected by government and transport authority participants. The principal consumer behavior change opportunity, identified in 8 of 32 interviews, was reduced use of rapid / next day delivery, which was provided as an option, although was not strictly applicable to the defined road freight segment. There was little support for driverless and platooning across all participant groups.

Table 2-2: Which solutions provide the greatest potential for rapid and radical decarbonization? – Summary of structured and unstructured response data

Solution		Selected in structured responses (of 32 total)	Unstructured responses (of 32 total)*		
			Supportive	Non-supportive**	Neutral or no comment
Motive technology shift	Biodiesel / biomethane	11	8	9	15
	Hydrogen fuel cell	16	10	8	14
	Battery electric	26	16	3	13
	Electric road system	8	5	10	17
Mode shift	Rail	14	11	10	11
	Water	6	2	12	18
Individual vehicle efficiency / load capacity		7	5	6	21
Driving automation / platooning		2	1	13	18
Improve load and schedule optimization at a network level		12	14	4	14
Reduce total supply chain carbon emissions		11	6	4	22
Consumer behavior change	Reduced rapid / next day delivery	8	11	0	21
	Consumption reduction	0	0	11	20
	Other	8	1		

*: When more than one participant in an interview raised aligned views, these are counted one time only

**: Includes comments expressing opposition and those where benefits are seen as marginal

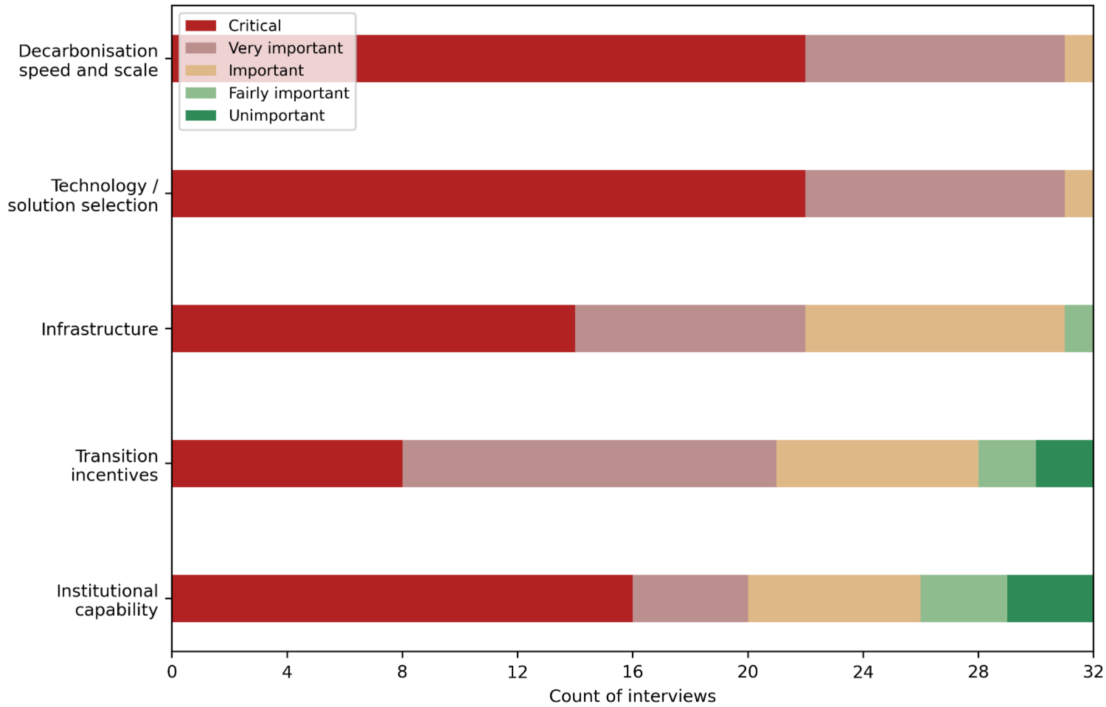
5.2 A shared understanding of the design choices that need to be codesigned is required

5.2.1 Decisions requiring codesign

Design coordination was identified as "critical" or "very important" in between 62% and 96% of interviews for the five pre-identified decision categories, with "decarbonization speed and scale" and "technology / solution selection" seen as most critical (see figure 2-2).

Regarding speed and scale, there was consensus that clear decarbonization targets had been helpful and had galvanized action. Uncertainty in the strength of future government commitment to decarbonization and risk of back-tracking was however seen as unhelpful. With respect to technology and solution selection, the availability of more than one potential motive technology winner for long-haul and heavy-duty applications was considered problematic, with the "VHS / Betamax" dilemma being frequently cited. Uncertainty regarding infrastructure availability and the chicken and egg dynamic between infrastructure provision and new technology adoption were seen as major transition hindrances. A mixture of publicly and privately funded infrastructure was seen as likely to be necessary, but coordinating infrastructure planning across multiple authorities was identified as a challenge. There was broad consensus that incentives were necessary to neutralize some of the cost penalty of new technologies and to reduce risk for first movers, but differing views on what form incentives should take. Geographic alignment of incentives was seen as important, while recognizing that local incentives and funding can also play a role. Key institutional capability gaps were identified by both freight operators / shippers and government / transport authorities in areas including strategic planning, vehicle and driver licensing, vehicle standards, maintenance and safety, and land and infrastructure planning.

Figure 2-2: How important is it that the identified aspects of transition codesign are coordinated?



In addition to the decision categories that were identified prior to the interviews, alignment of policy across devolved authorities was seen as necessary by most operators / shippers and industry associations / experts who expressed a view. Education and training on decarbonization solutions, requirements and planning were also identified by some participants as important.

5.2.2 The role of government

Unstructured responses reveal underlying differences of opinion in the extent to which it is possible or desirable for the government to drive or guide the transition via incentives or decision making. These differences are illustrated by the following contrasting quotes:

Speed and scale: *"I firmly believe that in order to decarbonize, you've got to try and be the best you can at the point in time you're at."* (Operator/shipper #7) ***vs.*** "*It's critical that we know what speed we're going at and how much we have to achieve. There has to be that policy direction that everybody can follow."* (Industry association/expert #3)

Technology / solution selection: "*The market should be allowed to evolve, to innovate, and sometimes it just needs that freedom. I would suggest, with developing technologies, coordination smacks of a command-and-control situation."* (Industry association/expert #6) ***vs.*** *"And then having a real industry alignment, at least at the European level, that this is the route we're going down for HGV. It's mandated that either it's electric, it's hydrogen or it's some form of other fuel that reduces carbon."* (Operator/shipper #1)

Incentives: *"Incentivizing the transition is largely going to be driven by the sector themselves when they have confidence in the technology having been demonstrated to be effective for their needs."* (Government/transport authority #1) ***vs.*** *"Although the business case can be positive with alternative fuels, your capital cost is higher … and therefore you need more funding in order to make it happen."* (Operator/shipper #5)

Policy: *"Ultimately, big operators will manage this transition quite well. Others might not make it at all, and I think government has a question, does it care? As harsh as it sounds."* (Government/transport authority #2) ***vs.*** *"Given the scale of the costs involved that only big business can afford … only the government can make sure this level playing field emerges [for smaller operators]."* (Industry association/expert #6)

The tension between these opposing views, each being expressed in some form in at least three interviews, is a key finding. While some participants felt that it was necessary for government to make key design choices, others saw this as highly undesirable. This raises important questions regarding the appropriate codesign framework and how road freight decarbonization should be governed.

5.2.3 Geographic and freight segment levels

Understanding the geographic and freight segment levels at which decisions need to be made is important for arena specification and will influence who participates in arenas. In the case of geographic level, four options were provided: "international", "national", "regional" and "local/city." For the five pre-defined decision categories, participants in between 24 and 31 of the 32 interviews said that national coordination is required, with international coordination also seen as important by just over half of participants for “decarbonization speed and scale” and “technology / solution selection”. Regional or local coordination were seen as important in between 25% and 50% interviews per decision category.

A difference observed between responses from different participant groups is that approximately double the proportion of government / transport authority participants identified regional or local/city levels as important compared to operator / shipper and industry association / expert participants Regarding the freight segment level at which coordination is required, five options were provided: “all freight”, “freight operation type”, “freight demand segment”, “freight operator” and “freight customer / shipper”. “Freight operation type” is determined by logistics and physical handling characteristics, for example urban delivery of ambient product. “Freight demand segment” is defined by the shipper category, for example urban supermarket chains. While there is some correspondence between these two segmentations, the first could also deliver clothes and office supplies, which would not fall into the second. Likewise, the second could include chilled and frozen product, which would not fall into the first. The last two segmentations align to individual actors, with coordination being most critical either for a single operator in one case or for a single shipper in the other. In the UK, it is common for supermarkets to have dedicated fulfilment operations, whereas other segments such as container freight often have single operations serving multiple shippers.

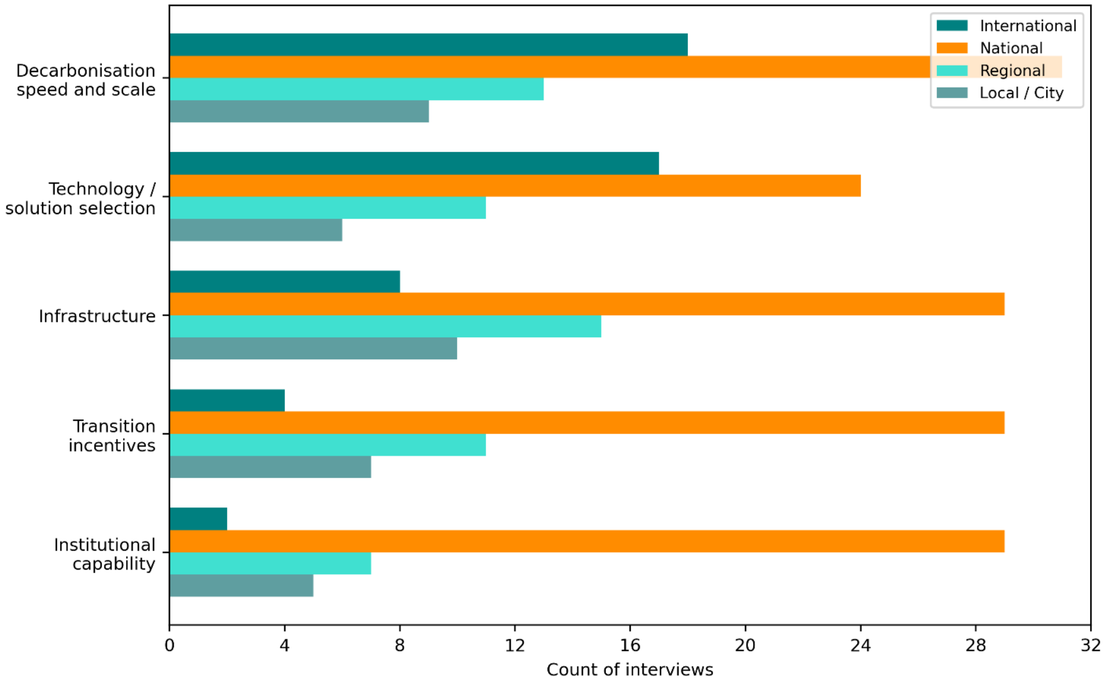
This complexity illustrates both the importance and challenge of ensuring that codesign arenas are aligned to appropriately defined freight segments. Further segmentation possibilities exist, including combinations of the above segmentations. However, to keep complexity manageable for the interviews, these further options were not included.

Participants in between 16 and 28 of interviews thought coordination was required either across all road freight or per freight operation type in each decision category (see figure 2-3), suggesting that these are the primary freight segment levels at which codesign arenas need to be created. However, participants in between 7 and 10 interviews also thought freight demand segment was important for decarbonization speed and scale, technology / solution selection and infrastructure design choices; and freight operator and freight customer / shipper were also selected in some interviews.

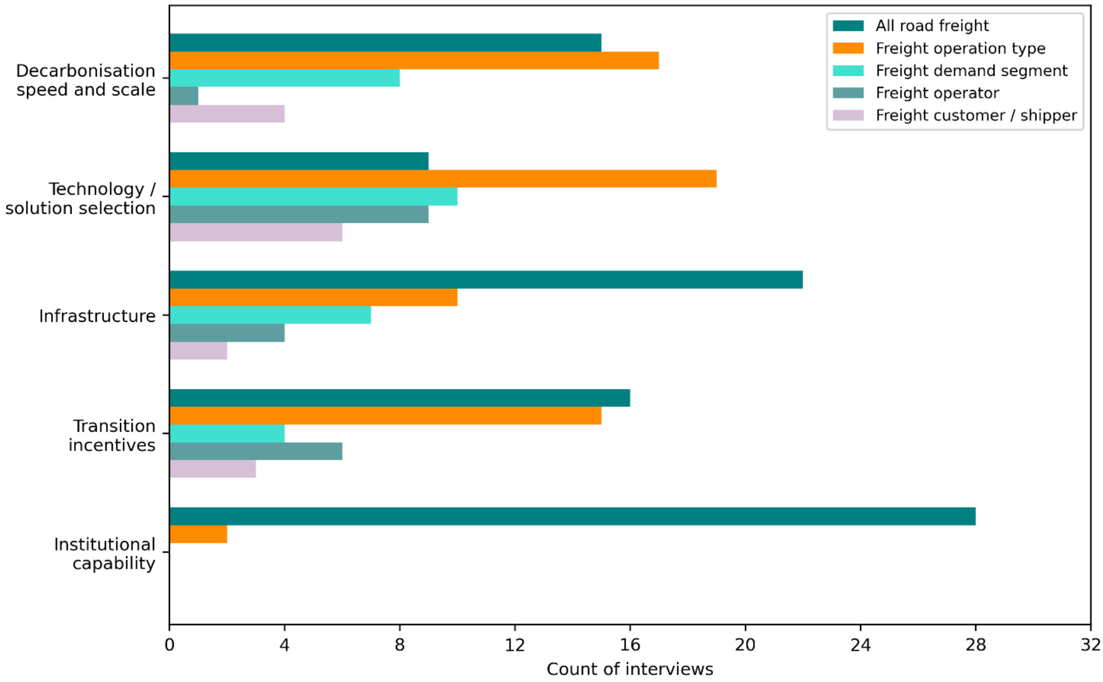
Overall, these findings reinforce the need for careful consideration of geographic and freight segment levels in specifying codesign arenas.

Figure 2-3: At what levels do design decisions need to be made?

Geographic



Freight segment



5.3 A politically, socially and organizationally feasible codesign framework to make these design choices needs to be put in place

i. *Potential priority codesign attributes:* Where, in at least 75% of interviews, participants agreed or somewhat agreed with the attribute statement and believed it would be a significant barrier if not true. The nine attributes falling into this category are:

- Actors require incentives to take on additional risk
- Incumbents and new entrants should both have incentives to innovate and support the transition
- Asset and contract lifecycles must be considered
- Business risk and dependencies must be understood to identify feasible options
- Collaborative mid-range planning is required in addition to long-range visioning
- Infrastructure provision and spatial planning must be prioritized
- Need to consider supply security and price stability as well as transition effectiveness
- Policy needs to reduce uncertainty
- Authorities and departments within authorities need to align

In addition to meeting the above quantitative criterion, these attributes are qualitatively identified in unstructured commentary as important for rapid and radical decarbonization. It is therefore proposed that these are considered as core requirements for the codesign framework.

ii. *Potential sources of conflict:* Where, in over 25% of interviews, participants did not agree or somewhat agree with the attribute statement. The four attributes falling into this category are:

- Incumbents should not feel punished
- Sources of legitimacy other than decarbonization itself are required
- It is important to consider political windows of opportunity
- Need to connect to a clear political idea and the political context

Further illustrating the potential conflicts from unstructured question responses:

Incumbents should not feel punished: *"Completely disagree. They need to be made to feel like pariahs. It's the only way they're going to do anything about it."* (Industry association/expert #7) ***vs***. *"If you're going to punish people for not having made the change and create an artificially favorable environment for people who have got the new technology, then there's quite a risk to the whole market because there will be organizations that have already made enormous investments in what they currently do."* (Operator/shipper #8)

Sources of legitimacy other than decarbonization itself are required: *"You shouldn't need to bring in anything else. There's more than enough to say: 'get off your backside and do something'."* (Industry association/expert #3) ***vs.*** "*You do need a broader focus than decarbonization. It also needs to be articulated in terms of green growth or levelling up or other social aspects. There needs to be an economic and the social dimension."* (Operator/shipper #13)

It is important to consider political windows of opportunity: *"If we're serious about decarbonization, political windows of opportunity don't come into it."* (Industry association/expert #6) ***vs.*** *"You do need to be aware of the cycle of political opportunity. Certain decisions are easier to take earlier in a political term than others."* (Government/transport authority #2)

Need to connect to a clear political idea and the political context: *"I don't see it in any way as being essential because it's such a hideously difficult thing to do."* (Operator/shipper #13) ***vs.*** "*In the sense that everything is politics, it's impossible to divorce these kinds of decisions from the political context. So, without a clear political direction, then yes, these things tend not to get off the ground."* (Government/transport authority #2)

For other attributes (see appendix), while most participants agreed with the statements, there was a not a strong consensus that they would be a significant barrier if not true. For this reason, it is proposed that these are considered as lower priority for the codesign framework.

5.4 Key challenges

Challenges were captured from responses both to the specific open question on decarbonization challenges and from commentary on closed question responses. Aspects of technology uncertainty and immaturity were identified as a challenge in 28 interviews. Uncertainty regarding technology performance, reliability over time and what would be the winning technology for different road freight use cases was a particular concern. Technology, particularly for long haul applications, was seen as either undemonstrated or "not there yet." The risk of picking the wrong technology and being left with stranded assets (the "VHS / Betamax" problem) was seen as significant. The need for international technical standards was identified as important, with a shared view that truck manufacturers, most of which are not based in the UK, would be unlikely to produce trucks with bespoke specifications for the UK market. Views were split however on whether government should make technology choices or whether all technology options should be developed so the market could decide which to adopt.

Lack of a clear direction or plan was identified in 24 interviews. While the legally binding commitment to net zero and the planned banning of diesel vehicle sales were seen as very helpful motivators, some participants perceived the government to be back-tracking on decarbonization commitments. There was also seen to be a large gap between a strong decarbonization ambition and the absence of clear plans or policies to deliver this. Some participants felt that we should spend less time talking about more challenging use cases, such as long-haul freight, and focus on developing robust plans to accelerate the decarbonization of shorter distance back-to-base use cases where battery electric technology is increasingly demonstrated and mature. It was noted that, while the national target for net zero carbon was 2050, some local authorities were targeting 2038 and others as early as 2028, creating further ambiguity in decarbonization objectives. Coordinated planning between government, infrastructure providers, vehicle manufacturers and operators was seen as very important, noting that most vehicle manufacturers are not UK based.

A specific planning challenge that was raised in 23 interviews was the lack of strategic infrastructure planning and funding. For local and back-to-base operations, lack of high-capacity grid connectivity and high connection costs were seen as a barrier. For longer haul operations, a public or shared charging and fueling infrastructure was seen as essential. A significant shift to rail would require a large investment in rail intermodal facilities and increased rail freight capacity. How new shared infrastructure would be funded was seen as a key unaddressed question, with national government seeing it as being provided by the private sector, while most operator / shipper participants saw public funding as being necessary. At a practical level, it was pointed out that the charging infrastructure focus for cities such as London has been on passenger vehicles, and that neither the parking spaces nor the charging capacities being installed were suitable for freight vehicles.

Related to infrastructure planning, the chicken and egg dilemma between infrastructure provision and demand for infrastructure was mentioned in 12 interviews. In the absence of public funding, private investors would not fund infrastructure development until they were confident that demand would be there for that infrastructure. Likewise, operators would not invest in new technology vehicles until they knew that necessary fueling/charging, maintenance and information technology infrastructure was available to support those technologies. This dilemma is exacerbated by technology selection uncertainty.

Inconsistent incentives and policy were identified in 23 interviews as a significant challenge. Different implementations of clean air zones and EURO vehicle standards in different UK countries and cities were cited by operators and shippers as examples of how not to regulate an industry that runs national and international services. In general, operators and shippers saw little benefit in regulations being set at a regional or local level, while government and transport authority participants typically saw this as necessary and helpful if it gave access to local funding sources or incentives. Another dimension of inconsistency that was raised was between different regulatory bodies, with several participants mentioning the example of the vehicle weight derogation for vans to allow for the additional weight of batteries not being matched by increased driver license weight limits.

The problem of first-mover disadvantage was raised in 20 interviews, whereby early adopters make decisions under greater uncertainty, potentially incurring higher costs and greater risk of stranded assets, while other operators wait to the last moment to switch, thereby gaining maximum benefit from the experience of others. High up-front costs for battery electric and hydrogen fuel cell vehicles were also seen as a major issue. Hydrogen was perceived as currently having both high up-front costs and high running costs, and therefore not providing a viable business case over any time horizon. Battery EVs were seen as approaching cost neutrality for some use cases on a total cost of ownership basis but requiring higher up-front investment than diesel vehicles. One participant mentioned that lease providers were factoring a full battery replacement into seven-year vehicle leases, significantly weakening business cases for operators who lease rather than purchase vehicles. Larger operators were seen as being in a better position to take first-mover risk and fund higher up-front costs, but in general most operators were seen as being risk averse and approaching decarbonization on an incremental basis because of these factors.

Collaboration barriers were raised in 11 interviews as a substantial challenge. Resource and data sharing between operators was seen as an important enabler of decarbonization, but achieving this was considered very challenging when operators are also competitors and data is proprietary. Legal constraints to joint planning and data sharing were also seen as a barrier. Lack of collaboration between freight customers and operators was likewise seen as a challenge, with procurement processes prioritizing cost and operational service levels over other factors including decarbonization. Several participants said that the best incentive to decarbonize would be if freight customers required it in tenders. It was also identified that the adoption of low or zero carbon technologies would have operational and supply chain consequences for freight customers, which would need to be recognized and factored into supply chain planning and design.

Other challenges raised were lack of incentive funding, barriers for smaller operators, lack of vehicle availability, rail network limitations, and insufficient grid capacity / connectivity.

6 Discussion

6.1 The need for codesign

The challenges of centrally managing the transition are recognized by participants, with a full spectrum of views on whether this would be the right or wrong thing to do. The UK government has said that it will not make top-down decisions on technology selection, and consistently reinforces that it is industry that should make choices on how to decarbonize. Set against this, the fact that most participants felt collaborative decision making was “critical” or “very important” across decision categories indicates an underlying belief that market forces influencing individual organization action are insufficient to make decarbonization happen at the required pace.

If both centralized planning and individual organization action are eliminated as mechanisms for decarbonization delivery, the only apparent remaining option is codesign of key decisions by actors with the required collective knowledge of the freight transport system and the ability to execute the decisions made. As described above, “codesign” is used in this study to mean collaborative and collective decision making by policymakers and road freight actors for purposive transition design.

6.2 Codesign tensions

If it is agreed that codesign of certain key design choices is necessary, the existence of trade-offs and potential sources of conflict must be considered. This study has identified the following tensions:

- Techno-economically feasible solutions:
  - Opposing positions regarding hydrogen, biofuels and mode shift to rail
  - The benefit of keeping emerging technology options open versus proceeding rapidly with solutions that are already proven at scale
  - Whether incremental decarbonization options should be considered as valid alternatives to options capable of achieving radical decarbonization
- A shared understanding of design choices that need to be codesigned:
  - Top-down versus market-led approach to defining decarbonization speed and scale per use case, technology selection and infrastructure provision
  - The use of direct incentives to freight operators versus demand incentives driven by freight customer requirements
  - Whether a level playing field for smaller operators is required and feasible
  - Centralized versus devolved policymaking
- A politically, socially and organizationally feasible codesign framework to make these design choices:
  - Whether additional sources of legitimacy are required
  - Whether incumbents should feel punished
  - Whether road freight decarbonization planning should consider political windows of opportunity
  - Whether it is necessary to connect to a clear political idea and the political context

6.3 Codesign pathways

If it is accepted that a) codesign between policymakers and road freight actors is necessary for rapid and radical road freight decarbonization and b) system and path dependencies mean that individual design choices cannot be considered in isolation, a codesign pathway is needed that defines the sequence and timing of design decisions. Such a pathway would need to be specified based on a clear understanding of system dependencies and have the support of a critical mass of road freight actors and policymakers. For both reasons, as Hyysalo et al. (2019a) find, it is necessary that the pathway is itself codesigned by relevant actors with the required system understanding and ability to represent and make commitments on behalf of their respective organizations. These actors are likely to include, in addition to policymakers, operators and shippers, industry associations, vehicle manufacturers, infrastructure providers and finance providers.

6.4 Codesign framework

Assuming that it is possible to define a codesign pathway, the codesign approach needs to enable decisions to be made in a way that achieves sufficient collective buy-in and is robust to scrutiny and challenge, particularly as there are likely to be winners and losers from each decision. Defined decision processes, roles, tools and governance are necessary components of a framework that enables effective codesign. This study concludes that the codesign framework will also need to embed the priority codesign attributes identified in section 5.3 and have mechanisms to manage the codesign tensions summarized in section 6.2. Pedersen (2020) identifies the gap in research of studies that consider the connection between designers and stakeholders, and explores an approach that incorporates negotiation between actors in a codesign framework. However, no work has been found that specifically considers codesign for road freight decarbonization or, with the exception of Hyysalo et al. (2019b), extends the concept of codesign to system-wide sustainability transitions. Further work is therefore required to define such a framework if a codesign approach to road freight decarbonization is to be feasible.

6.5 Government and key actor support

While many road freight actors and policymakers may agree in principle to a collaborative approach to road freight decarbonization, translating this into a collective commitment to a shared codesign pathway and framework presents a formidable challenge. Road freight actors work in highly competitive environments with tight margins and finely honed supply chains. There will be winners and losers from codesign decisions, and it would be naive to assume that potential losers will not do all they can to resist these. National, regional and local authorities are also key actors, and each of these has priorities and policies that are not always aligned either to each other or with the goal of rapid and radical road freight decarbonization. A codesign approach will therefore need the backing of relevant government authorities and key road freight actors to provide necessary legitimacy and authority. The feasibility of codesign will to a large extent be dependent on whether this condition can be met.

6.6 Applicability of codesign to other road freight segments

GB food deliveries to supermarkets and supermarket DCs was selected for this study primarily because of the volume of road freight that it represents and the concentration of large road freight operators and shippers that may make a codesign approach more feasible. Other industry sectors representing a large volume of road freight that have a high concentration of participants are metal ore, mining and quarrying; coke and refined petroleum products; non-metallic mineral products including glass and cement; and chemical products, which together represent 37 billion of the total 173 billion tonne-kilometers of product moved in GB registered HGV vehicles (GOV.UK, 2022; ONS, 2022). Each of these sectors would need to be considered individually to understand specific road freight decarbonization opportunities and barriers, and the feasibility of a codesign approach.

In sectors with a greater number of smaller participants, it is possible that industry associations would need to act as a proxy for the hundreds or thousands of freight operators and shippers. Codesign could also be centered on freight nodes such as ports or industrial clusters. Further work focused on these segments is required to determine if such an approach could generate feasible decarbonization pathways compatible with net zero goals.

6.7 Use cases and network dependencies

One of the clearest areas of consensus across participants was that different road freight use cases will require different decarbonization solutions. For example, while battery electric may be suitable for local back-to-base operations, it is not yet suitable for long haul applications. Alternatively, while trucks exclusively serving an industrial cluster that has a ready hydrogen supply may be well-suited to run on hydrogen, this may not be true for other use cases without access to sufficiently low cost or plentiful hydrogen.

Taken alone, this would suggest that every road freight requirement should be considered on its own merits to identify the most appropriate decarbonization solution. A challenge to this appealingly simple view is that any use case that is dependent on shared infrastructure will be subject to infrastructure economies of scale and the requirement for a minimum viable infrastructure network. Also, the greater the number of different vehicle variants that are required, the lower the efficiencies in vehicle sourcing, resale, maintenance and regulation. This makes it likely that some standardization of technology and solution selection across use cases will be required, further indicating a requirement for codesign.

6.8 Acceleration of back-to-base battery electric deployment

Battery electric is an increasingly mature and tested solution and, in the case of local back-to-base operations, is not dependent on public charging infrastructure. There is an argument, echoed by several study participants, that we should focus on accelerating the transition of suitable use cases to battery electric rather than expending effort debating use cases where the best technology choice is not yet clear. The fact that the take-up of battery electric has not been more rapid reinforces that there are barriers other than technology selection, and these are indeed raised by participants: high vehicle cost, poor availability and prohibitive cost of the required high capacity grid connections, open questions on battery material supply and recycling, vulnerability to power outages, poor vehicle availability and the fact that many operators work from leased depots and cannot justify the cost of installing charging infrastructure in locations where they may only be for a few years. If we are to accelerate the transition to battery electric for local back-to-base operations, these challenges need to be systematically addressed via codesign, as not all can be overcome by simple regulation or a financial incentive.

7 Conclusions

This study started with the findings from Churchman et al. (2023) that there are three potential preconditions for rapid and radical road freight decarbonization: 1) techno-economically feasible solutions able to deliver rapid and radical decarbonization; 2) a shared understanding of design choices that need to be codesigned; and 3) a politically, socially and organizationally feasible codesign framework to make these design choices. An interview approach was defined that draws on techno-economic, socio-technical and political perspectives to test these preconditions for the case of food deliveries to supermarkets and supermarket distribution centers in Great Britain.

To this end, 32 semi-structured interviews were conducted with 37 freight operators and shippers; government and transport authority representatives; and industry associations and experts. Structured and unstructured outputs were analyzed, and findings drawn that confirm the need for certain design choices to be codesigned by actors. Areas of agreement and of potential codesign conflict were also identified. To achieve rapid and radical decarbonization, it was concluded that for this road freight segment, codesign pathways are required that are based on a robust understanding of path and system dependencies. In addition, the need for a codesign framework that incorporates identified codesign attributes and provides mechanisms for managing codesign conflict is reinforced.

While codesign provides the only apparent alternative to centralized transition design by government, there are open questions on the feasibility of a codesign approach including whether is possible to define and agree the necessary codesign pathways and framework. In addition, further work is required to consider if a codesign approach is appropriate and feasible for other road freight segments. Planned next steps focus on these open questions and will further explore with actors and experts the specification of codesign pathways and frameworks that could enable rapid and radical decarbonization of food deliveries to supermarkets and supermarket distribution centers, and other road freight segments.

8 Study limitations

This study has focused on the specific case of rapid and radical decarbonization of road freight deliveries to supermarkets and supermarket distribution centers in Great Britain. While it seems likely that some findings may also be applicable to other road freight segments and potentially to wider sustainability transitions, further work would be required to confirm this.

A second limitation is that road freight actors, policymakers and experts were more likely to agree to participate if they were broadly supportive of the goal to decarbonize road freight. This means that views expressed cannot be considered as representative of the whole population of the targeted actor groups. As a result, the areas of conflict identified should be considered as a best-case scenario that potentially understates the conflict that would occur in an actual transition.

Appendix: Interview questions and response options

Table 2-3: Interview questions and response options

Questions	Response options
1: Respondent information:	
1.1: Your name	Free text
1.2: Your position / organization	Free text
1.3: How would you describe yourself? (select all that apply)	Freight operator; Freight customer / shipper; Local authority representative; Regional / national government representative; Transport authority representative; Consultant / academic; Sector / policy expert; Other (please specify)
1.4: Please confirm you have read the participant information sheet and have signed the participant consent form	Checkbox
2: Decarbonization opportunities and challenges:	
2.1: What do you see as principal road freight decarbonization opportunities?	Open question, response transcribed
2.2: What do you see as principal challenges?	Open question, response transcribed
3: Decarbonization options:	
3.1: What are the most important levers for rapid and radical decarbonization of road freight (check all that apply)?	Motive technology transition; Mode shift to rail or water; Improving individual vehicle efficiency / load capacity; Driving automation including platooning; Improving load and schedule optimization at a network level; Supply chain redesign; Consumer behavior change / consumption reduction; Other (please specify)
3.2*: [Conditional on selection in 3.1]* Please select the most promising motive technologies (check all that apply)	Biodiesel / biomethane; Hydrogen fuel cell; Battery electric; Electric road system (e.g. overhead catenary); Other (please specify)
3.3: *[Conditional on selection in 3.1]* Please select most promising mode shift opportunities (check all that apply)	Bulk rail; Containerized rail; Inland water; Coastal water; Other (please specify)
3.4: *[Conditional on selection in 3.1]* Please select the most promising individual vehicle efficiency / load capacity opportunities (check all that apply)?	Improved aerodynamics; Longer / heavier / taller vehicles; Use of space over cab and between wheels; Efficient driving aids / coasting; Other (please specify)

Questions	Response options
3.5: *[Conditional on selection in 3.1]* Please select the most promising driving automation opportunities (check all that apply)	Platooning; Full driverless; Other (please specify)
3.6: *[Conditional on selection in 3.1]* Please select the most promising opportunities to improve load and schedule optimization at a network level (check all that apply)	Optimize vehicle utilization and backloads on defined routes; Collaborative freight management at a city or regional level; Network scheduling and traffic flow optimization; Shared logistics / consolidation hubs; Other (please specify)
3.7: *[Conditional on selection in 3.1]* Please select the most promising opportunities to reduce total supply chain carbon emissions (check all that apply)	Smaller / more frequent shipments; Larger / less frequent shipments; Centralized manufacturing and distribution; Localized manufacturing and distribution; Supply chains optimized for rail and water modes; Slower freight transit times; Other (please specify)
3.8: *[Conditional on selection in 3.1]* Please select the most promising consumer behavior change / consumption reduction opportunities	Consumption reduction / degrowth; Buying locally; Waste reduction; Reduced use of rapid / next day delivery; Increased reuse, upcycling and remanufacturing; Other (please specify)
3.9: Any further comments	Open question, response transcribed

4: Design choices

The following questions were asked for each of the following categories of design choices:

1. Decarbonization speed and scale
2. Technology / solution selection
3. Infrastructure
4. Transition incentives
5. Institutional capabilities

4.1: How important is it that this aspect of transition design is coordinated?	Critical; Very important; Important; Fairly important; Unimportant
4.2: Are there any specific elements you would highlight as more important?	Open question, response transcribed
4.3: At what geographic level(s) do choices need to be made? (check all that apply)	International; National; Regional; Local / City
4.4: At what segment level(s) do choices need to be made? (check all that apply)	All road freight; Freight operation type; Freight demand segment; Freight operator; Freight customer / shipper
4.5: Any further comments	Open question, response transcribed

Questions	Response options
5: Feasibility attributes	

The below questions were asked for each of the following potential feasibility attributes identified from literature by Churchman et al. (2023):

Actors:

1. Actors require incentives to take on additional risk.
2. Incumbents should not feel punished.
3. Incumbents and new entrants should both have incentives to innovate and support the transition.
4. Asset and contract lifecycles must be considered.
5. The influence of business actors on policy and politics must be understood and leveraged.
6. Business risk and dependencies must be understood to identify feasible options.

Arenas:

7. Champions of specific solutions must not dominate option selection and policy.
8. Sources of legitimacy other than decarbonization itself are required.
9. A direction-setting function prioritizing societal benefit is necessary.
10. Collaborative mid-range planning is required in addition to long-range visioning.
11. Negotiation and consensus-building are necessary.
12. It is important to consider political windows of opportunity.

Design:

13. Technology selection and investment decisions should be based on both economic and non-economic factors.
14. Infrastructure provision and spatial planning must be prioritized.
15. Need to foster pro-transition and minimize anti-transition feedback loops.
16. Need to consider supply security and price stability as well as transition effectiveness.

Policy:

17. Policy should adapt through the transition.
18. Policy mix needs to balance disruptiveness and acceptability.
19. Policy needs to reduce uncertainty.
20. Policy cost-efficiency may need to be compromised for policy effectiveness.

Politics:

21. Need to connect to a clear political idea and the political context.
22. Authorities and departments within authorities need to align.
23. Trust of government and perceived fairness are necessary.
24. Authorities and departments within authorities need to align.

5.1: To what extent do you agree / disagree with the statement?	Agree; Somewhat agree; Neither agree nor disagree; Somewhat disagree; Disagree
5.2: *[Conditional on selecting "Agree" or "Somewhat agree" in 5.1]* Would the absence of this factor be a significant barrier to the decarbonization of road freight in this segment?	Yes; No

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Paper 3: Decision pathways for road freight decarbonization

Phil Churchman, Thijs Dekker, Kate Pangbourne

Abstract

The road freight system is complex, with many system dependencies. These dependencies mean that individual actors are often unable to take radical decarbonization action alone, and system-level decisions are required. Decision dependencies mean decision pathways are needed specifying key decisions and decision sequencing.

Five decision pathway workshops were held with mixed groups of industry actors, policymakers and experts. Decarbonization barriers, enablers and decisions were identified and dependencies between these specified. A new software tool "Pathplotter" was used to facilitate pathway definition and analysis, and workshop commentary was qualitatively analyzed using NVivo.

It is found that it is possible for mixed actor groups to define decision pathways, and requirements to operationalize this approach are identified. While techno-economic factors remain important, most barriers, enablers and required decisions are found to be socio-technical, political or related to decision governance. This reinforces the need for more research into these understudied transition aspects.

Keywords: Pathways, Systems Thinking, Governance, Transition Management, Critical Realism, Road Freight Decarbonization

1 Introduction

Road freight is often cited as a hard-to-abate sector (Shell / Deloitte, 2021). The European Environment Agency (2021) observes that freight transport emissions continue to grow and are closely linked to economic activity. Their analysis concludes that improvements in energy efficiency and the use of biofuels have been offset by demand growth and modal shift of freight to road. However, as trucks and vans represent c.7% of global carbon emissions (Global Carbon Project, 2022; ITF, 2023), they must be decarbonized to achieve net zero[1] (United Nations, 2025).

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[1] The United Nations (2025) defines net zero as "cutting carbon emissions to a small amount of residual emissions that can be absorbed and durably stored by nature and other carbon dioxide removal measures".

Whilst technological constraints are real, these are easing, and the rapid development of battery electric technology means that it is becoming possible to transition an increasing proportion of road freight (Link and Plötz, 2022). However, the availability of technologically feasible vehicle solutions is not sufficient, as the adoption of battery electric or other low carbon solutions has major implications for charging / fueling infrastructure (Taefi et al., 2016; Al-Hanahi et al., 2021); vehicle supply (WEF, 2023); road systems (Hospodka et al., 2024); supply chain design and logistics practices (Gillström et al., 2024); planning and regulation (Lindholm, 2010); and the wider energy system (Borlaug et al., 2021).

These systemic dependencies mean that the ability of individual freight operators to take radical action alone is often limited (Churchman and Longhurst, 2022). System-level design decisions are needed which address transition barriers and establish enablers (Bryson et al., 2020; Pineda et al., 2024). Reflecting the dependencies in the system to be transitioned, these design decisions, barriers and enablers are also interdependent. This means a decision pathway is required that specifies the decisions needed and the sequence in which these should be made. Because of the diverse system knowledge required to define decision pathways, these should be codesigned by industry actors and policymakers (Churchman et al., 2023b).

While extensive research has been conducted on potential road freight decarbonization solutions (Meyer, 2020), little work has considered decision pathways or system-level processes for implementing solutions (Marsden and Reardon, 2017; Churchman et al., 2025a). This study addresses this gap by considering two research questions:

1. How can mixed actor groups codesign decision pathways for road freight decarbonization?
2. What learnings can be drawn regarding critical pathway requirements for this transition?

Answering these questions is necessary if decision pathways for road freight decarbonization are to be defined, which are in turn needed for transition barriers to be overcome and enablers established.

The paper is organized as follows: section 2 reviews relevant literature; section 3 describes the research approach and methods used; section 4 presents findings related to the two research questions; and section 5 reflects on implications for decision pathway definition, study limitations and original research contributions.

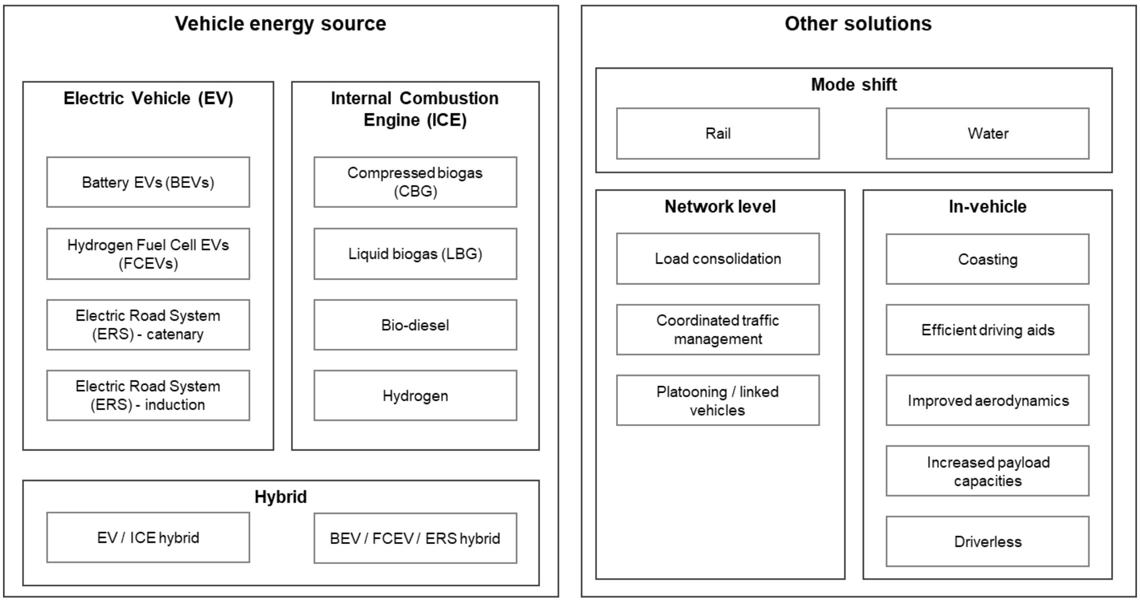
2 Literature review

Churchman and Longhurst (2022) identify that road freight decarbonization is subject to techno-economic, socio-technical and political drivers; and that many of the barriers to decarbonization are socio-technical and political. Building on this, Churchman et al. (2025a) conclude that a coordinated approach to road freight decarbonization must consider social-technical and political as well as techno-economic system dimensions. Section 2.1 summarizes techno-economic literature considering road freight decarbonization. Given the limited socio-technical and political transitions literature considering this specific transition, literature considering these aspects of wider transport and energy transitions is drawn upon in section 2.2.

2.1 Techno-economic perspective

Several technical opportunities are available for road freight decarbonization (Zhang et al., 2022). Operational interventions include increasing vehicle capacity and utilization, journey optimization and changing driving behavior to improve fuel efficiency; and technical interventions include enhancing aerodynamics, reducing rolling resistance, using alternative fuels and transitioning to new vehicle energy sources such as battery electric, hydrogen fuel cells or electric road systems (ERSs) (Greening et al., 2019). Further opportunities are vehicle automation and platooning, the latter being where trucks drive closely in convoy to reduce total aerodynamic resistance; however Paddeu and Denby (2022) conclude that the emissions saving potential from platooning is limited. Mode shift to lower carbon rail or water modes is also possible where these modes are available, although Gomez and Vassallo (2020) find that heavy vehicle tolling in Europe has done little to encourage the transition of road freight to rail. Figure 3-1 summarizes some of the principal available decarbonization opportunities.

Figure 3-1: Technical decarbonization opportunities – not exhaustive
(source: adapted from Churchman and Longhurst (2022, p.2))



*: Including powered 2 wheelers, freight / cargo bikes and Paxters

If it is assumed that in all likely future scenarios there will remain a substantial volume of road freight, new vehicle energy sources are required to deliver radical decarbonization compatible with net zero. Jahangir Samet et al. (2023) analyze the greenhouse gas emission reduction potential for battery electric trucks in Finland and Switzerland and find that the longer-term potential is 60% and 93% in these countries respectively. Deshpande et al. (2023) conduct a breakeven analysis of ERS infrastructure investments and conclude that the proportion of road freight for which a 20 year or shorter payback could be achieved in England, France, India and South Africa is 30%, 50-70%, 38% and 50-60% respectively. However, operators remain concerned about additional tangible and intangible costs of new technology vehicles (Aryanpur and Rogan, 2024).

While cutting the carbon content of energy used by logistics has greater carbon reduction potential than other interventions, this is dependent on the green transition of the energy system and is rate-limited by the development of new infrastructure and operators' fleet replacement cycles (McKinnon, 2023). Aligned with this, DUKFT (2023) finds that for road freight decarbonization, a circa £20 billion fleet and infrastructure investment is required in the UK, the nature of which will depend on whether the dominant solution is electric or hydrogen-based. The study observes that in the UK to-date, investments have been limited to pilot and demonstration projects and that, until a clear direction is defined, private investment in charging or fueling infrastructure will remain low.

Principal factors affecting operator purchase decisions of alternative powered trucks are vehicle reliability; an available fueling/charging infrastructure; the possibility to enter low-emission zones; and current and future fuel costs (Anderhofstadt and Spinler, 2019). Vehicle range for battery electric trucks, vehicle availability and model variety, and the large capital cost of vehicles are further reasons for the limited adoption of zero emission trucks in Europe (ICCT, 2022). The WEF (2021) proposes that, as well as lack of infrastructure for zero emission fleets, gaps in vehicle and infrastructure financing are an important factor.

2.2 Social-technical and political perspectives

While techno-economic research is essential to identify potentially viable decarbonization solutions, it often neglects social, political and organizational dimensions. Socio-technical transitions research seeks to address this gap by considering the dynamics of how new technologies destabilize and ultimately displace incumbent technologies within societal systems (Geels, 2012) and how innovation systems can enable transitions (Sovacool et al., 2024). Political transitions research considers further important factors including how policy mixes influence transition outcomes (Xu and Su, 2016), political / policy feedback loops (Edmondson et al., 2019), the role of political lobbying (Downie, 2014), negotiation and cooperation between institutions (Steurer and Bonilla, 2016), and how incumbent actor vested interests play a critical role in enabling and hindering transitions (Ertelt and Kask, 2024; Urban et al., 2024).

Studies considering socio-technical perspectives for road freight decarbonization have been scarce, although recent work is increasingly highlighting its importance (Neagoe et al., 2024). Wider socio-technical transitions literature offers valuable theoretical perspectives but can be limited in its ability to aid purposive transition design and delivery (Genus and Coles, 2008; Svensson and Nikoleris, 2018). Socio-technical research can also neglect the role of politics and vested interests in transitions (Meadowcroft, 2009). To address this, it is important to consider "micro" drivers for individual organizations as well as "macro" system-level drivers (Upham et al., 2020).

Amongst socio-technical theoretical frameworks, Transition Management (TM) perhaps offers the most tangible basis for purposive transition governance. Loorbach (2010) proposes four TM governance levels: strategic, tactical, operational and reflexive, and suggests that it is by linking these that descriptive and prescriptive views of transitions can be connected. Loorbach and Wijsman (2013) further explore how TM can be used by businesses to engage with transitions. The concept of Transition Arenas (TAs), where actors come together to collaboratively govern transitions, is central to TM (Hyysalo et al., 2019).

Considering the political perspective, Marsden and Reardon (2017) identify that only 13% of papers reviewed from two leading transport policy journals consider specific aspects of the policy cycle, and fewer than 10% engage with debates regarding policy aims. In wider policy literature, the Multiple Streams Framework (MSF) proposes that major change happens when political, policy and problem streams align, creating windows of opportunity for new solutions to be adopted (Kingdon, 1984). Knaggård (2015) suggests that "problem brokers" within the MSF framework can help navigate political and social systems to align problems and solutions. Using different language to describe a similar concept, the positive and negative roles that "policy entrepreneurs" can play by exploiting MSF windows of opportunity are explored by Salas Gironés et al. (2020). The importance of advocacy coalitions and policy networks in affecting major transitions is considered (Markard et al., 2014; Normann, 2017). The need is also highlighted, when considering decision making under deep uncertainty, to embed context, organize stakeholders, consider the decision space at an organizational (micro) level and recognize the role of decision-maker non-rationality and individual preferences (Stanton and Roelich, 2021).

3 Approach and methods

3.1 Purposivist research approach

The literature summarized in section 2 provides valuable insight, but little research was found that considers how to purposively bring about the transition of complex systems that span techno-economic, socio-technical and political dimensions. Churchman et al. (2024) conclude that this may be a consequence of limitations in the positivist and interpretivist research approaches that respectively underpin most techno-economic and socio-technical / political transitions research. They propose the critical realist approach “purposivism” as a more appropriate basis for research that seeks to aid system actors to purposively enact system transitions. This approach is applied in this study.

Purposive transition requires actors to make predictive judgements regarding the impact over time of alternative decisions and actions. Prediction requires an assumption of a reality that is independent of the human observer. Unlike interpretivism, critical realism makes this assumption. However, unlike positivism, it asserts that reality is stratified and emergent, and therefore may never be fully understood (Bhaskar, 2013). This is intuitively the case for complex systems that include techno-economic, socio-technical and political dimensions, and even more so when considering scenarios for which there is no precedent such as radical road freight decarbonization. A consequence of this is that attempting to prove transition theories via repeated experiments and statistical tests, as positivist research does, is often neither helpful nor practically possible.

Critical realism instead proposes broad critical scrutiny that focuses on understanding system structures and causal mechanisms. It is epistemologically flexible, meaning that any research approach that provides helpful insight into system structures and mechanisms is permissible. Methodologically, purposivism adopts a combination of “abduction” in which probable theories regarding causal mechanisms are developed from incomplete information and “retroduction” in which the researcher considers the contextual conditions under which the causal mechanisms would take effect (Meyer and Lunnay, 2013; Fletcher, 2017).

3.2 Methods

This section describes the abductive and retroductive methods adopted to address the two research questions.

3.2.1 How can mixed actor groups codesign decision pathways for road freight decarbonization?

Hyysalo et al. (2019) and Paddeu et al. (2024) find mixed actor workshops to be effective for codesigning sustainability transition pathways, and these were adopted as the data gathering method for this study. The workshop approach and Pathplotter, a custom software tool for decision pathway codesign, were developed based on Systems Thinking (ST) principles and learnings from pilot workshops conducted with two transport authority representatives and a freight logistics expert. These learnings include:

- It is necessary to map transition barriers, enablers and decisions (collectively called “nodes”) and dependencies between these to derive decision pathways.

- The above is very difficult to do in a spreadsheet format, and an interactive graphical tool is required.
- Existing graphical tools do not provide the features and automation needed to make developing pathways in a group context possible, meaning a new tool had to be developed.
- While dependency loops appear similar to System Dynamics (SD) feedback loops (Ghisolfi et al., 2022), their time-dependent nature means they represent decision sequencing dilemmas rather than reinforcing and regulating mechanisms as is the case in SD models.
- Pathfinding methods adapted from physical and information system network navigation (Javaid, 2013) can be applied to derive decision pathways from node and dependency networks.

An overview of Pathplotter is provided in Appendix A and a full description of Pathplotter's design principles and functionality is provided by Churchman et al. (2025b). At the time of writing, Pathplotter is available as freeware at www.pathplotter.net.

The ability to use the developed approach and Pathplotter to define decision pathways for road freight decarbonization was tested via five mixed actor workshops with participants that included policymakers, industry actors and road freight experts. A purposive snowballing approach was used for workshop participant recruitment, and a total of 29 workshop participants were recruited. Some of these were already known to the lead researcher and others were introduced or contacted via email, LinkedIn and at conferences. Potential participants were either invited to join a workshop individually or to co-host a workshop in which they recruited other participants. Three individually recruited workshops and two co-hosted workshops were held. While both in-person and online workshops were conducted, it was decided not to run hybrid workshops due to the practical challenges of hybrid brainstorming and group facilitation.

For each workshop, four to five potential road freight decarbonization goals were suggested to participants and/or co-hosts covering a range of road freight segments from last mile to long-haul freight. The purpose of this was to encourage participants and co-hosts to think broadly about possible goal options, rather than to steer them towards a specific goal. In each case, participants collectively defined a goal that was either new or a refinement of one of the options provided. We took this approach because we considered the specific goal assessed in each workshop to be less important to this research question than having a goal aligned to the knowledge and interests of the participants. Table 3-1 summarizes the selected decarbonization goal, format and participants per workshop.

Table 3-1: Workshop summary

	Road freight decarbonization goal*	**Recruitment approach (Format)**	**Participants**
1:	Invest in public sector fleets to help catalyze rest of industry and kickstart manufacturers	Individually recruited (Online – MS Teams)	3 operator / shippers 1 public authority 1 expert / academic
2:	HGV** over 100km / > 12tonne decarbonized motive power	Individually recruited (Online – MS Teams)	1 operator / shippers 2 public authorities 1 expert / academic
3:	Last mile parcel delivery decarbonization in Wales	Co-hosted with Prof. Vasco Sanchez Rodrigues, Cardiff Business School (In person)	In addition to co-host: 4 expert / academics 1 public authority
4:	Decarbonizing urban HGV movements	Co-hosted with Carolina Buneder and Cameron Cox, Transport for London (In person)	In addition to co-hosts: 2 public authorities 2 industry associations 2 energy / infrastructure providers 1 expert / academic
5:	Decarbonizing long distance HGV movements of palletized goods	Individually recruited (In person)	1 operator / shipper 1 infrastructure provider 1 public authority 2 expert / academics

*: All goals were considered within the context of road freight in the United Kingdom

**: Heavy Goods Vehicle

Workshops were recorded with the permission of participants and commentary was transcribed for coding and grounded theory analysis using NVivo. This research question was assessed based on:

- Whether nodes and dependencies were defined that allowed a decision pathway to be produced
- Qualitative feedback from participants regarding the workshop process and outputs
- Researcher observations regarding what worked well and less well during the process

Findings for this research question are summarized in section 4.1.

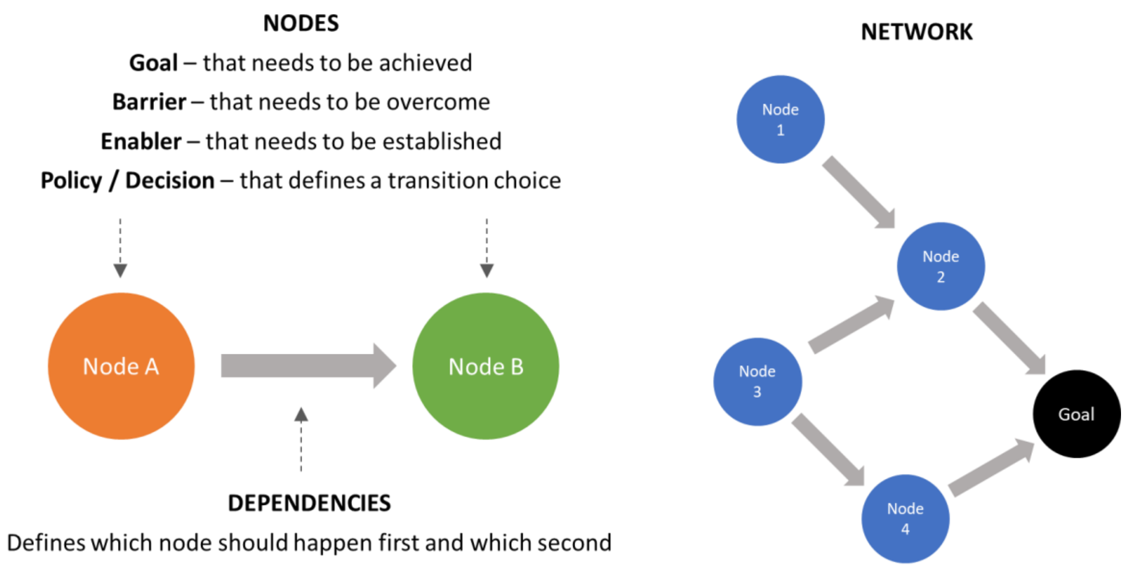
3.2.2 What learnings can be drawn regarding critical pathway requirements for this transition?

In addition to using the five workshops to assess how pathways could be codesigned by mixed actor groups, they were also structured to provide learnings regarding the transition pathways themselves. In the first part of each workshop, barriers, enablers and decisions (collectively termed “nodes”) were identified using flip charts and post-its for in-person workshops and Miro for online workshops. Five decision categories defined by Churchman et al. (2023) covering key techno-economic, socio-technical and political system dimensions were provided to participants:

1. *Speed and scale:* Decisions that determine what proportion of road freight will be decarbonized, and how quickly
2. *Technology selection:* Decisions regarding the choice of decarbonization solution or technology that will be adopted
3. *Infrastructure:* Decisions regarding the deployment of necessary infrastructure including but not limited to energy supply, fueling / charging, vehicle supply and maintenance
4. *Incentives, cost and risk:* Decisions regarding the incentives that will be applied to encourage the transition and other actions that influence transition cost and risk for operators and shippers
5. *Institutional capabilities:* Decisions regarding the establishment of required private and public sector capabilities that either do not exist today or exist but with insufficient capacity

In the second part, dependencies between nodes were identified using Pathplotter. Combining nodes and dependencies resulted in the development of decision networks (figure 3-2).

Figure 3-2: Decision pathway nodes, dependencies and network



In the final part of the workshops, the pathway and chicken and egg loops identified by Pathplotter based on the defined nodes and dependencies were discussed and the implications of these reviewed to the extent possible in the available time. Observations regarding the workshop outputs and process were also captured, and potential next steps considered.

Two types of output data were captured from each workshop:

1. Structured node and dependency data
2. Unstructured data transcribed from workshop recordings.

The data analysis methods used for each type of data are summarized below.

Structured node and dependency data

Node and dependency analysis of workshop outputs was carried out in seven steps:

Step 1: Node descriptions were coded and aligned across workshops to enable cross-comparison of outputs and to cluster nodes with similar or identical meaning.

Step 2: For nodes identified in workshops with no path to the end goal, a dependency to the end goal was added to ensure the node appeared in outputs.

Step 3: Due to workshop time constraints and the complexity of the task, some participants said they thought there may be incorrect dependencies. Dependencies that appeared incorrect or likely to be in the wrong sense, for example "Charging / fueling capacity / coverage" being required for "Shared / aggregate data", were removed.

Step 4: Also due to workshop time constraints, it is unlikely that all valid dependencies were identified in each workshop. Dependencies defined in each workshop were reviewed and, if they were identified as likely to be independent of the specific decarbonization goal being considered, they were flagged as "generally true", and were added to other workshop outputs in which both the from and to nodes were present if that dependency was not already identified. In this way, aggregated dependency insights across the five workshops were drawn upon to fill dependency gaps in individual workshops.

Step 5: Pathplotter was used to identify circular "chicken and egg" loops of dependencies. Each of these was reviewed and the dependency judged to be the weakest was removed to resolve the loop.

Step 6: For each node, two values were determined using Pathplotter: the number of other nodes that are directly or indirectly required by that node (to identify "strongly dependent" nodes); and the number of other nodes that are directly or indirectly dependent on that node (to identify "pivotal" nodes).

Step 7: Pathplotter was used to generate an optimal node sequence using pathfinding algorithms.

In addition to conducting node and dependency analysis for each workshop, an aggregate pathway was created based on nodes that were identified in two or more workshops, and "generally true" dependencies connecting any pair of these nodes. This pathway provides a consolidated view across workshops and triangulation by eliminating nodes that were only identified in one workshop. This aggregate pathway is presented in section 4.2.1.

Unstructured data transcribed from workshop recordings

Workshop recordings were auto-transcribed using Microsoft Teams, and manually corrected with reference to recordings. Open, axial and selective coding (Williams and Moser, 2019) was conducted and, where appropriate, code descriptions were aligned with standardized node descriptions. Coded commentary was then synthesized under two headings:

- Points that were raised in two or more workshops, and therefore may be applicable to multiple road freight decarbonization goals
- Points qualitatively judged to be important but specific to a single road freight decarbonization goal

These findings are presented in sections 4.2.2 and 4.2.3.

4 Findings

4.1 How can mixed actor groups codesign decision pathways for road freight decarbonization?

Within the scope of the road freight decarbonization goals considered, it is confirmed that it is possible for mixed groups of actors to codesign decision pathways. In each of the five workshops, transition decisions, barriers and enablers relevant to the selected road freight decarbonization goal were identified and dependencies between these defined. Based on these outputs, it was possible, using Pathplotter during and following workshops to:

- Identify and resolve chicken and egg dependency loops
- Specify a decision sequence that allows dependencies to be respected
- Identify nodes that are highly dependent, meaning that several other nodes need to be completed before these nodes
- Identify nodes that are pivotal, meaning that several other nodes can only be completed after these nodes

Positive feedback comments from participants include:

- *"It's a really insightful piece of work, and just gathering everyone's comments together, you've got a really good cross section of people on the call, and I completely agree it's only by that method [that it can be done]. I don't propose to know everything, and it's only by that collective effort that you get to the root cause and some real logical plans that say how they're all dependent on each other."* (Shipper / Operator)
- *"This will have very wide applicability, because it won't just work in transport to help decision making, it works across any industry that is looking at decarbonization or any large change process, to map all the different nuances of things you need to think about. It has really wide application."* (Transport planner)
- *"Using Pathplotter made it remotely tangible, whereas trying to squeeze that into some linear framework in a 2D matrix or something, you can do something, but you miss out on so many of the connections."* (Road freight expert)
- *"It helps you think through those interdependencies and, just thinking about our own work looking to develop road strategy, it helps you to think through what that route looks like."* (Transport planner)
- *"This process is very helpful when you're right at the start of something. I've just started with this piece of work, so everything that I've done up to now has been a brain dump. And then you filter it through and then you find out what's important."* (Transport planner)
- *"It shows that it's a system that needs reviewing and to get it purposeful it needs to be really thought about it a very deep way."* (Logistics expert)

There was in addition strong agreement amongst participants regarding the value of mixed participant groups representing different actors. There are however also learnings that need to be considered if pathway codesign is to be operationalized for real-world decision making:

4.1.1 The approach needs to work for both intuitive and process thinkers

While most participants were able to engage effectively with the tasks of brainstorming nodes and then defining dependencies, the degree of ease and comfort in doing this varied. The participant who voiced the greatest level of discomfort with the workshop process said, *"I'm not the person for that network stuff because I'm struggling to hold all those thoughts … it's incredibly important that you guys continue to do this stuff … it's just it's not where my brain sits."* (Policy expert)

At the other end of the spectrum, there were participants who felt that adding more structure and weighting to nodes and dependencies would allow different pathway options to be objectively compared: *"You could do an interpretive structural model matrix for barriers and enablers, and then see the connections and if they have a strong connection and medium connection or no connection."* (Logistics expert)

The contrast between these positions illustrates the need for the process to accommodate diverse participants, from those who prefer less structure and more qualitative debate, to those comfortable with detailed structural mapping and quantitative modelling.

4.1.2 Sufficient time for reflection and iteration is required

Each pathway was developed in a single 2.5-to-3-hour workshop, limiting the impact on participants' time. It was anticipated that this would be challenging, and this indeed proved to be the case. Participant comments that reflect this include:

- *"The interconnections need to be thought about. In some ways it attempts to unlock it, but in attempting to unlock it missed some bits. It is dependent on individual thought processes. And those individual thought processes are different and not perhaps connected."* (Logistics expert)
- *"You will never get more than a brain dump in an hour or two, just picking a problem out of thin air, even if you've got a set of Einsteins in the room."* (Transport planner)
- *"I appreciate we had limited time for the workshop but there is a reliance on short node descriptions and there will always be limits on the time available to complete the process. The description may not mean the same thing to everyone, so wording and understanding is critical."* (Policy expert)

If this process is operationalized, more than a single workshop will be required to develop and reflect on pathways. The process needs to accommodate iterative development of nodes and dependencies based on reflection during and between workshops. Furthermore, as with all large transitions, the pathway will need to be periodically revisited and updated during the course of the transition as new information emerges.

4.1.3 The process and outputs must align to decision-maker needs

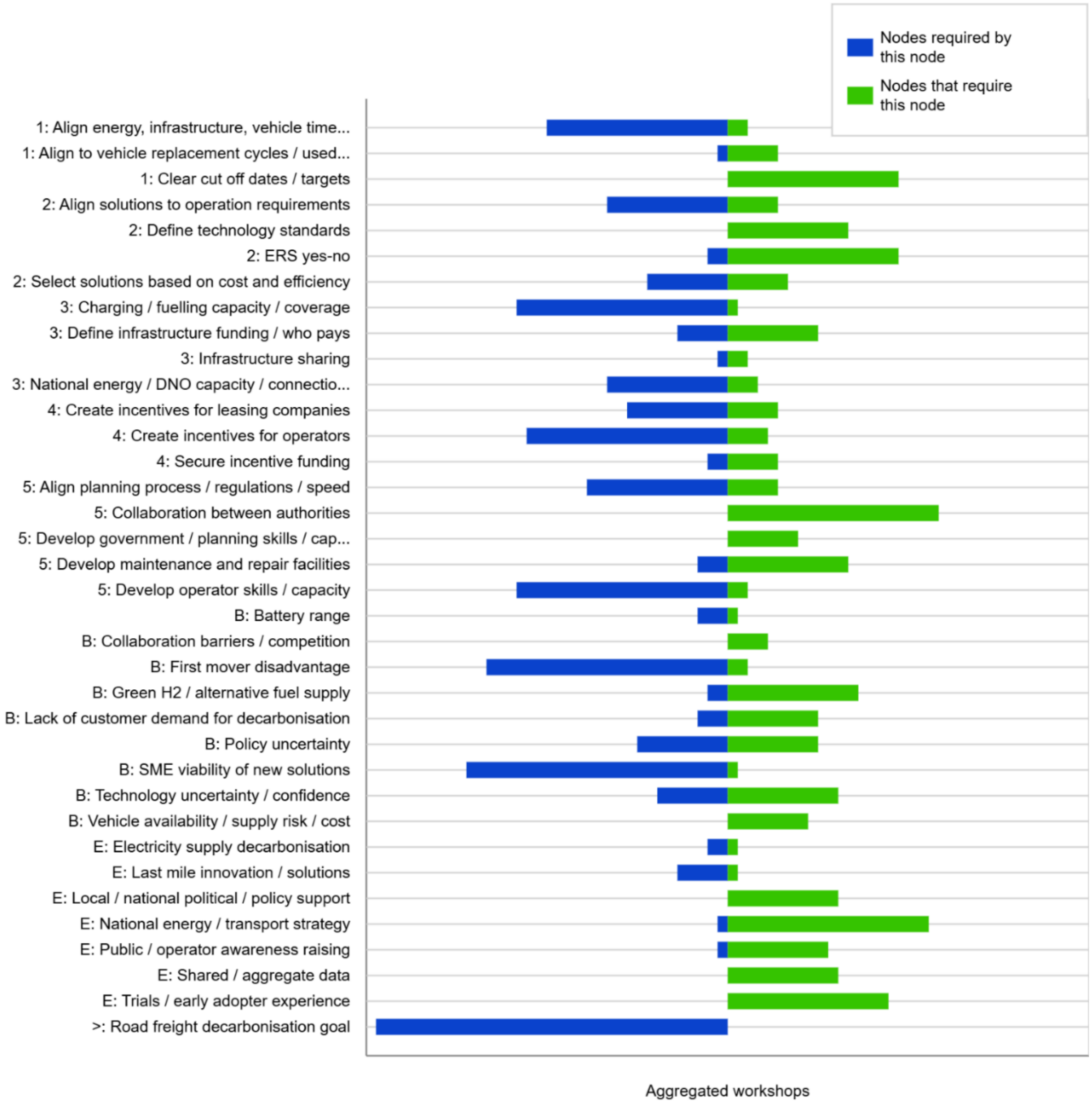
Some participants identified that one of the biggest challenges they face is engaging decision-makers, which include politicians and senior business managers. Public and private sector organizations were seen as often having bold decarbonization ambitions without the strategies or identified actions to back these up. In the context of road freight decarbonization, this was seen by participants as being in part due to a lack of understanding of the choices that need to be made and the financial and non-financial implications of those choices. This means that decision pathways need to be presented in a form that makes these choices and implications clear to decision-makers and focuses their attention on critical path decisions and quick wins.

4.2 What learnings can be drawn regarding critical pathway requirements for this transition?

4.2.1 Node and dependency analysis

To provide triangulation of findings across workshops, an aggregate pathway was created based on nodes identified in two or more workshops and dependencies judged to be "generally true" irrespective of specific road freight decarbonization goal. The resulting node and dependency network view, which is also referred to as a PERT (Program Evaluation Review Technique) chart, is shown in Appendix B.

Figure 3-3: Aggregate node analysis – nodes identified in two or more workshops



Key: 1: Speed and scale; 2: Technology selection; 3: Infrastructure; 4: Incentives, cost and risk; 5: Institutional capability; B: Barriers; E: Enablers; >: Goal

Figure 3-3 presents a node analysis for this pathway. In this figure, a long blue (left-hand) bar indicates the node is “strongly dependent”, meaning there are several nodes that need to be completed before this node. A long green (right-hand) bar indicates it is “pivotal”, meaning that several other nodes require this node to be completed first. The last node is the road freight decarbonization goal. As may be expected, this requires all other nodes and is required for no other nodes.

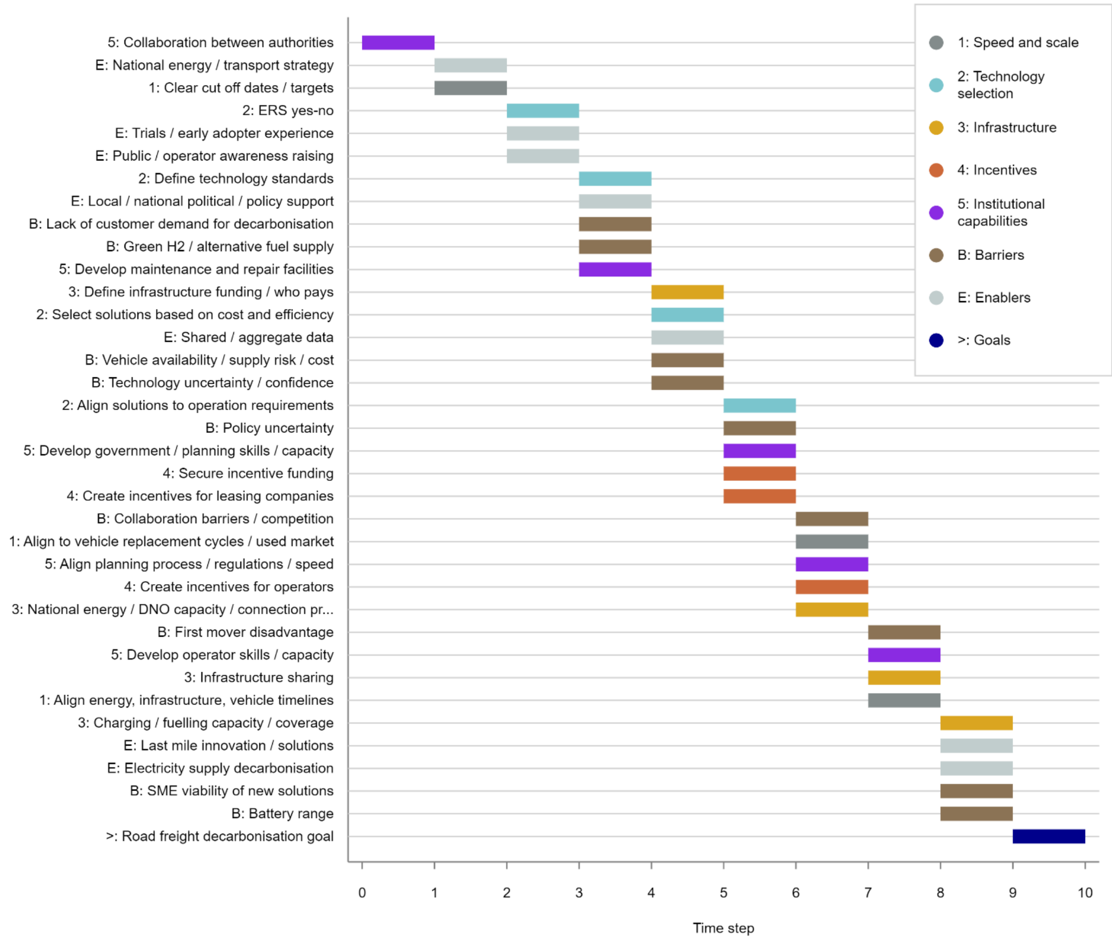
This analysis is informative as it indicates the pivotal nodes that are likely to need to be completed early in the decision pathway, and strongly dependent nodes that may need to be completed later. Table 3-2 provides information on the number of dependent nodes and the workshops in which nodes were identified for the most strongly pivotal nodes.

Table 3-2: Pivotal nodes with seven or more dependent nodes

Pivotal node	**Number of other nodes depending on this**	**Workshops in which node identified**
Decisions required		
Collaboration between authorities	20	1, 2
Clear cut off dates / targets	15	2, 3, 4
ERS yes-no	15	2, 5
Define technology standards	11	1, 5
Develop maintenance and repair facilities	11	1, 2
Define infrastructure funding / who pays	8	2, 4, 5
Barriers to be addressed		
Green H2 / Alternative fuel supply	12	1, 2, 5
Technology uncertainty / confidence	10	1, 2, 4
Lack of customer demand for decarbonization	9	1, 2, 3
Policy uncertainty	8	1, 2, 4
Vehicle availability / supply risk / cost	7	1, 2, 3, 5
Enablers to be established		
National energy / transport strategy	19	2, 5
Trials / early adopter experience	15	1, 2
Public / operator awareness raising	10	1, 2, 3
Shared aggregate data	10	1, 4
Local / national political / policy support	10	2, 5

Figure 3-4 presents a Gantt chart that shows the latest position of nodes in a sequence that allows all dependencies between nodes to be respected. As would be expected, the pivotal nodes from table 3-2 fall within the earlier steps in this sequence. While there is the facility in Pathplotter to define node durations so the Gantt shows a critical path timeline, there was not time to complete this step in the workshops. This means that each node occupies a single timestep and the Gantt chart shows a step sequence rather than timeline.

Figure 3-4: Aggregate node sequence



4.2.2 Unstructured commentary shared across multiple workshops

Table 3-3 summarizes points captured from transcribed commentary that were raised independently in two or more workshops, suggesting these points may be applicable to wider road freight decarbonization goals. The fact that the points were raised in at least two workshops also means they are not solely the opinion of a single participant or the product of a single workshop discussion.

Table 3-3: Findings from unstructured commentary identified in two or more workshops

Finding	**Workshops in which identified**
Speed and scale	
Clear targets and cutoff dates are necessary to provide policy confidence and for aligning energy, infrastructure and vehicle timelines.	2, 3, 4
Technology selection	
Hydrogen is less mature than other solutions and/or is unlikely to be feasible for national road freight due to insufficient supply and high cost of green hydrogen.	1, 2, 5
Electric road systems (ERSs) are an enormous infrastructure decision that would require strong political support.	2, 5
Charging standards need to be defined to avoid a VHS / Betamax problem.	1, 5
Technology trials are helpful for informing technology choices but can also be a way of deferring difficult decisions for political rather than technical reasons.	1, 2, 4
Infrastructure	
Private charging / fueling infrastructure sharing is needed, although this may naturally develop rather than needing to be planned.	1, 4, 5
Charging capacity is electrical supply capacity, capacity for new connections and the number and location of appropriately sized charging bays.	1, 2, 5
Incentives, cost and risk	
Some participants felt that the additional risk undertaken by first movers needed to be shared or underwritten. Others considered that if vehicle productivity and total cost of ownership (TCO) provide an adequate business case, further incentives were not necessary.	1, 2, 5
Road freight customers are not in general asking for decarbonization or willing to pay more to achieve it.	1, 2, 3, 5
Vehicle and battery supply is a risk.	1, 2
Institutional capabilities	
Public authorities need to develop capabilities to support the transition including freight transport strategy; space and infrastructure planning; and specialist areas including legal and wayleaves.	1, 2, 3, 4, 5
Battery electric vehicles are often dependent on vehicle original equipment manufacturers (OEMs) for maintenance services. Access to in-house and/or third-party repair and maintenance services would increase operator confidence.	1, 2

Finding	Workshops in which identified
Politics and decision making	
There were differing views on government versus market-led decision making, with operators and shippers more often favoring the latter and infrastructure providers the former.	1, 2, 4

4.2.3 Unstructured commentary specific to individual road freight decarbonization goals

This subsection summarizes points raised during workshops that were specific to the UK road freight decarbonization goal being considered. While some of these views may be transferable to other road freight decarbonization goals and/or national contexts, further work would be required to confirm this.

Workshop 1

This workshop considered the goal to invest in public sector fleets to help catalyze the rest of industry and kickstart manufacturers. While the focus was on road freight, relevant experience with other public service vehicles including buses was drawn upon. It was proposed that public sector fleets often do not have the range and weight requirements of other road freight segments, and so may be more suitable for battery electric vehicles.

Matching hydrogen supply to demand for hydrogen buses was identified as having proved difficult, with suppliers needing commitments to larger volumes than individual authorities could provide. It was also mentioned that private sector vehicle operators had not been willing to take on the risk of purchasing new technology vehicles, meaning the authority had had to do this and lease these to operators. It was noted that assuring vehicle supply from manufacturers would require larger forward-commitments to vehicle purchases than a single authority could make. Collaborative purchasing by multiple authorities was seen as a way of addressing this. Such a collaborative approach would require fleet replacement cycles across authorities to be considered. Vehicle retrofitting was also suggested as a possible option.

Recognizing the lack of necessary technical and maintenance capabilities in authorities, new vehicle delivery models in which OEMs provide these services were considered as potentially beneficial.

Workshop 2

This workshop considered the goal of decarbonized motive power for HGVs over 100 km or 12 tonnes. For this segment, the importance of a clear vision of what the desired future will look like in 20 years was highlighted, because otherwise each operator will reach different conclusions and the resulting lack of alignment will make rapid progress unlikely.

A decision on whether electric road systems (ERSs) would be developed was identified as particularly needed, as this decision has major implications for grid capacity and connections, infrastructure development, and the size of batteries that will be required in vehicles. Although there was some doubt expressed regarding the feasibility of building a nationwide ERS network, it was observed that anything that reduced the size of batteries would be helpful. While recent developments exploring the use of hydrogen as a combustion fuel were noted, hydrogen was seen as “pretty much non-existent” compared to battery electric. Having said this, it was identified that battery electric range was still an issue for long-haul freight, and that there was not a clear path and viable business case for HGVs as there was for light commercial vehicles.

It was proposed that clear targets need to be set, so OEMs and operators can make decisions on how these would be met. The adoption of VECTO emissions reporting within the European Union (European Commission, 2018) was seen as helpful as this requires manufacturers to reduce emissions from vehicles sold, creating an incentive to develop decarbonized solutions that work for operators.

Workshop 3

This workshop considered the goal of last mile parcel delivery decarbonization in Wales and was co-hosted with Cardiff Business School. This goal was identified as a particular priority due to the increased number of delivery vans since the COVID pandemic, and it was suggested that policy in this area was comparatively immature. Taxation on eCommerce was mentioned as a way of influencing consumer purchasing behavior, but it was noted that the UK government was reluctant to introduce additional taxes of this kind.

Last mile innovation was identified as being required. It was highlighted however that there is a large rural population in Wales which may require different solutions to urban last mile delivery. Delivery lockers were discussed as a solution that could be effective in both urban and rural locations. It was observed that lockers are used extensively in China for both posting and receiving parcels. In the case of China, customers are charged additional fees if they do not collect parcels within a defined period, encouraging efficient use of lockers.

Workshop 4

This workshop considered the goal of decarbonizing urban HGV movements. It was decided to specifically consider freight coming into London from the surrounding area, which includes delivery of goods to shops in London from regional distribution centers. Challenging fringe cases such as the delivery of fresh shellfish from the north of Scotland were as a result not considered.

The importance of a stable and supportive political context was discussed, and the question posed whether London’s transport policy success was in part due to the transport policy environment being more stable than at the national level. Recent experience with the business and public backlash against the extension of the Ultra Low Emissions Zone (ULEZ) was however highlighted as needing to be considered by London authorities.

Freight industry representatives argued that operators should not be forced into an electric solution and that, while recognizing that technology decisions were required, it was too early to make these decisions. Infrastructure provider representatives expressed a counterview that network-level decisions needed to be made, and that delaying these decisions would incur additional costs. The tension between these views is a key finding from this workshop.

A specific opportunity identified within the urban context was the sharing of charging / fueling infrastructure with buses.

Workshop 5

This workshop considered the goal of decarbonizing long distance HGV movements of palletized goods.

Regarding technology selection, the provision of both battery charging and hydrogen fueling across the national freight network was seen as being unlikely to be feasible. While hydrogen was considered as potentially appropriate for specific freight operations with dedicated vehicles and access to an economic source of green hydrogen, it was not viewed as a viable solution for most palletized freight. Range constraints and loss of vehicle capacity were also identified as limitations for battery electric trucks. The jury was seen as being out on the feasibility of swappable batteries, which it was noted are in use in China. A decision was therefore considered to be needed on whether to roll out electric trucks using existing battery technology, or to wait for the introduction of new battery technologies, potentially including battery swapping.

Another key identified requirement for the large-scale adoption of electric HGVs is the availability of enough charging capacity and spaces, with these needing to be as far as possible at locations where the vehicle would be stopping anyway. It was reported that instances where trucks had been forced to use car charging spaces had demonstrated the impracticality of this and the negative publicity that this generates. Dedicated bookable truck charging spaces were therefore seen as essential. It was considered that, if hydrogen was excluded as a solution for the national network, action to increase the capacity of the national grid and DNOs would be swifter.

Bio-CNG/LNG was proposed as a promising interim solution which, while not providing full decarbonization, is a substantial improvement over diesel. Hydrogenated Vegetable Oil (HVO) was not considered viable, partly as it is too expensive and partly because it is very difficult to assure that it is coming from sustainable sources.

Operator / shippers were considered more likely to pilot new technology vehicles if this provides a marketing benefit and enables them to participate in and influence the transition.

Third party operators were on the other hand seen to be less likely to do this unless they were meeting customer requirements. It was noted that the palletized sector is dominated by SME operators, meaning solution feasibility for SMEs is important.

5 Discussion

5.1 Implications for decision pathway definition

The workshops and analysis conducted within a purposivist framing have generated findings regarding the two research questions that provide helpful guidance for decision pathway definition. Considering each research question:

5.1.1 How can mixed actor groups codesign decision pathways for road freight decarbonization?

The study concludes that mixed actor groups can codesign decision pathways by applying the methods and tools used in the workshops, with the following qualifications:

- The approach needs to work for both intuitive and process thinkers
- Sufficient time for reflection and iteration is required
- The process and outputs must align to decision-maker needs

The creation of the UK Freight Energy Forum (GOV.UK, 2022) and the Scottish Zero Emission Truck Task Force (Transport Scotland, 2022) recognizes the need to engage road freight actors in strategy development for road freight decarbonization. If it is accepted that system dependencies mean that decision pathways are required, then strategy development must include the definition of these pathways. Differing knowledge, beliefs, priorities and vested interests across actors mean that reaching consensus will be far from easy. We propose that the chances of this being achieved are significantly increased if a structured pathway definition process such as the one used in this study is applied.

This study has focused on decision pathway definition for road freight decarbonization in a UK context. Within an individualistic and economically liberal society such as the UK's, there is resistance to decisions being imposed by government that take choice away from individuals and businesses, unless there is a substantial and tangible common benefit (Martin and Islar, 2021). This increases the challenge to governments of enacting major transitions if the benefits are not rapidly and directly experienced by all of society, as is the case with climate change mitigation. This means that collective actor engagement in pathway definition is not only needed to bring necessary system knowledge to bear, but also to give the resulting pathway required legitimacy (Sareen and Haarstad, 2020). Countries with a more directive political system, a less individualistic society or a less liberalized economy may not require the legitimacy provided by codesigning pathways to the same degree. However, the need remains to develop pathways that reflect socio-technical and political as well as techno-economic system elements. It is hard to imagine how this could be done effectively without engaging a representative cross-section of system actors.

5.1.2 What learnings can be drawn regarding critical pathway requirements for this transition?

Combining outputs across the five workshops as an aggregate pathway enabled conclusions to be drawn regarding priority nodes and node sequencing. In particular, the pivotal nodes identified in table 2 are highlighted as those that potentially need most urgent attention, as it is on these that the largest number of other nodes depend. A bibliometric analysis of literature by Meyer (2020) confirms that, prior to the date of their study, most research considering road freight decarbonization focused on techno-economic rather than socio-technical or political transition aspects. Notable exceptions to this include work by Macharis et al. (2016), Lebeau et al. (2018) and more recently Paddeu et al. (2024). However, these studies remain a small proportion of research on road freight decarbonization. Set against this, reviewing the pivotal nodes in table 2 reveals most of these to be socio-technical (e.g. trials / early adopter experience, develop maintenance and repair facilities, public / operator awareness raising, lack of customer demand for decarbonization, technology uncertainty / confidence); political (e.g. clear cut off dates / targets, collaboration between authorities, policy uncertainty, local / national political / policy support); or related to decision-making governance (e.g. ERS yes / no, define technology standards, define infrastructure funding / who pays). Some of these points are considered in grey literature, e.g. Basma and Rodríguez (2023), ITF (2022) and McKinsey & Company / WEF (2022). However, their limited consideration in peer reviewed literature is, we would argue, a substantial gap.

Relevant insights are also provided from unstructured commentary. One point raised in all five workshops is the need for public authorities to develop capabilities to support the transition. The lack of sufficient depth of expertise and enough staff with key required skills was identified as a particular issue.

A further point was that, in general, while some freight customers were seen as expressing interest in decarbonization, road freight procurement was seen as most often being determined by price and operational performance rather than environmental factors. The provision of transition incentives to operators was considered as helpful, but ultimately of marginal impact if road freight customers were not also driving the transition.

Targets and cutoff dates were identified as being important to creating an environment where effective collaboration and sufficiently rapid action can happen. Maintaining targets and cutoff dates through political transitions and electoral cycles is a key challenge. It was seen as unfortunate that in the UK the precedent has been set that targets can be rolled back if this is deemed politically expedient[2].

Discussions in three workshops identified hydrogen as being less mature than battery electric and higher cost due to large energy losses and an insufficient supply of green hydrogen. Another point that emerged from three of the workshops was differing views on whether key decisions such as technology selection should be made centrally by government or whether individual operators and shippers should be free to make their own choices. It is our view that, in a UK context, managing the tension between these two positions is one of the greatest challenges that needs addressing if rapid and radical decarbonization is to be achieved.

Several of the observations made that were specific to the individual road freight decarbonization goals considered in the workshops were also socio-technical or political in nature, for example: collaborative purchasing and new vehicle delivery models (workshop 1); the importance of a long term vision and VECTO emissions reporting (workshop 2); the tensions between infrastructure provider and freight operator viewpoints (workshop 4); and the contrast in motivators between operator / shippers (e.g. supermarkets with their own truck fleets) and third party freight operators (workshop 5).

These findings reinforce the importance of stakeholder engagement and codesign for road freight decarbonization as advocated by Macharis (2005) and Paddeu et al. (2024). In addition, while techno-economic factors remain important, we propose that the findings from this study make a strong case for more work considering socio-technical, political and decision governance factors.

5.2 Study limitations

A principal limitation of the study is that the workshops were conducted within a UK context and considered specific UK road freight decarbonization goals. We believe that the need for decision pathways is independent of national context. However, the approach to developing pathways and the need to demonstrate legitimacy in this process may vary by national context. Likewise, while we believe that at least some of the conclusions regarding decision pathways are likely to be transferable to other national contexts, further work would be required to confirm this.

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[2] On 18 November 2020, UK Prime Minister Boris Johnson announced that new petrol and diesel car sales would be banned from 2030. However, on 21 September 2023, Prime Minister Rishi Sunak announced that this would be delayed to 2035.

The constraints of the project timeframe and available resources meant that workshops were limited in number and duration, and there was not an opportunity to refine and iterate pathways over multiple workshops for each road freight decarbonization goal. This means that the individual pathways developed can only be considered as preliminary. However, we believe that the creation of the aggregate pathway allows reliable general conclusions to be drawn regarding critical nodes and dependencies. In addition, the workshops together included 29 expert participants representing transport authorities, freight operators, industry associations, infrastructure providers and research organizations. This valuable collective insight is captured in both node and dependency analysis and unstructured commentary.

The time constraints of the workshops also meant that the workshop process needed active facilitation and clear structure. For node brainstorming, the node categories listed in section 3.2 were provided to participants to encourage a broad consideration of relevant nodes. The provided node categories will have inevitably influenced workshop outputs. However, care was taken in workshops to as far as possible not lead discussion beyond this, and all structured and unstructured workshop outputs are included in the presented analysis, irrespective of whether they align with the researchers' own views. In this way, despite the qualitative nature of the research, every effort has been made to minimize the influence of researcher bias. Notwithstanding this, if this approach is to be further developed and operationalized for real-world pathway codesign, it would be important for workshops to be run by a mix of facilitators as well as engaging a wider range of actor participants.

5.3 Original contribution

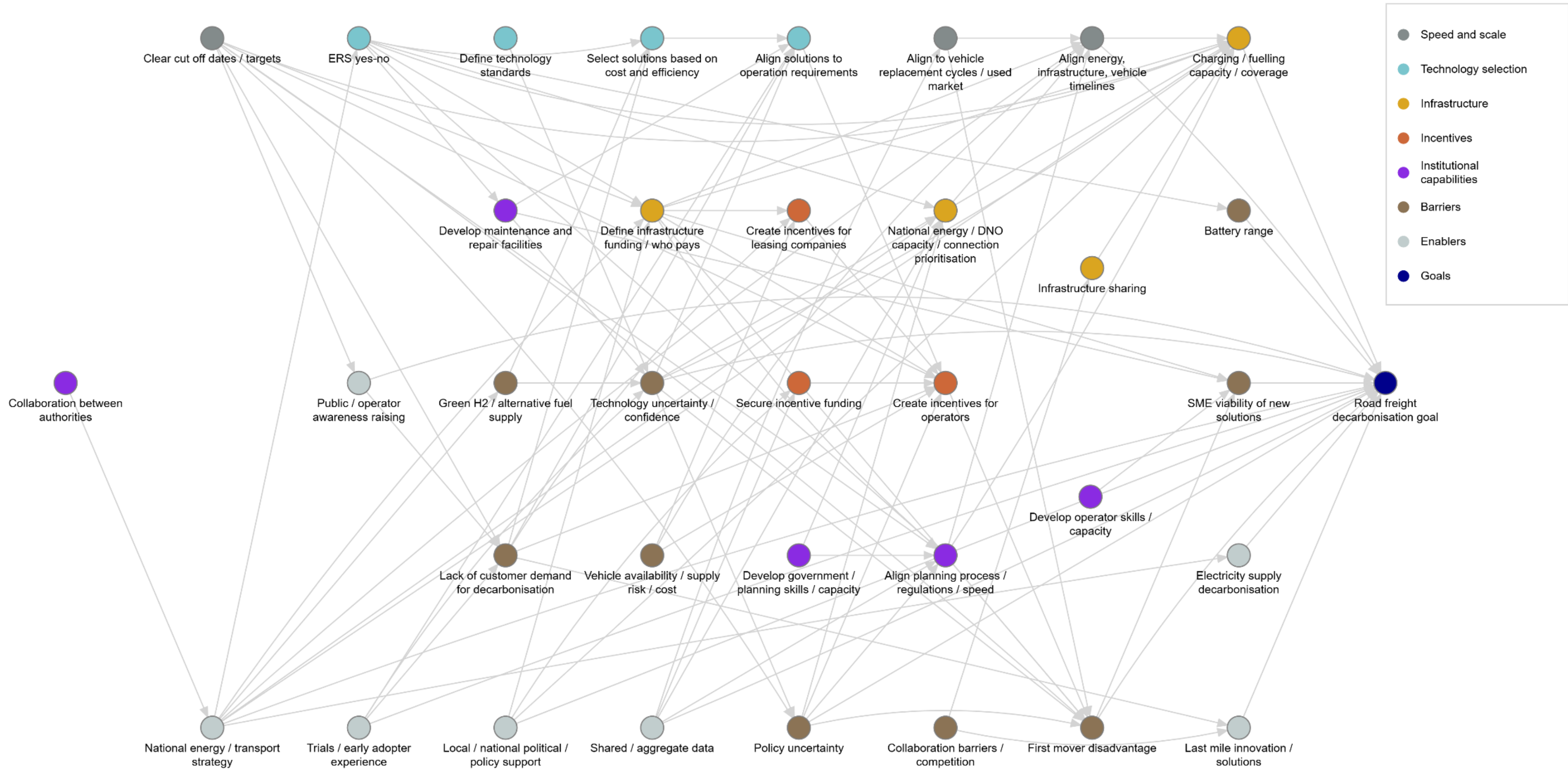
The work makes an original contribution as, to our knowledge, no other studies have considered the specific role of decision pathways for purposive road freight decarbonization. In terms of methodology, we also believe the use of mixed actor workshops, system mapping and pathfinding to develop decision pathways is new. A principal novelty is the application of a systems approach, not only to the system to be transitioned, but also to the network of decisions, barriers and enablers that need to be considered to purposively enact the transition. In addition to road freight decarbonization, the decision pathway approach could be applied to the purposive transition of other complex systems in which actors are individually constrained because of system dependencies, meaning codesign is necessary.

Appendix A: Pathplotter overview

Removed in thesis to avoid duplication - Please see Paper 4.

Appendix B: Aggregate workshop network / PERT view

Figure 3-5: Aggregate network / PERT view



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Paper 4: Pathplotter: A software tool for codesigning transition decision pathways

Phil Churchman, Thijs Dekker, Kate Pangbourne

Abstract

This paper presents "Pathplotter", a new software tool for the codesign of decision pathways for sustainability transitions. Pathplotter has been applied in five mixed actor workshops considering road freight decarbonization. It could also be applied to other transitions for which it is necessary to coordinate actor design choices. Pathplotter's design draws on Design for Sustainability (DfS), Transition Management (TM) and Participatory Design (PD) principles. It addresses two specific needs: 1) the facilitation of decision node and dependency definition by mixed groups of transition actors and 2) the efficient generation of decision maps, pathways and analyses based on these nodes and dependencies. To our knowledge, no other tool provides the combination of features required to meet these needs. This paper presents a review of relevant DfS, TM and PD literature; tool requirements; key Pathplotter features; learnings from the workshops and analysis conducted; and opportunities for further development.

Keywords:
Decision Pathways, Design for Sustainability, Transition Management, Participatory Design, PERT, Systems Thinking

1. Introduction

The need for the tool that was subsequently named Pathplotter emerged during a project considering how United Kingdom (UK) road freight decarbonization could be purposively codesigned and delivered by road freight actors and policymakers. The road freight system is highly complex, with dependencies that span transport, energy and vehicle systems; and the supply chains that road freight serves (Shell / Deloitte, 2021). These dependencies mean that road freight decarbonization requires coordination between policymakers and actors from these multiple systems and supply chains. Smith et al. (2005) propose that transitions need to be purposive when a high degree of coordination is required amongst actors, and some actors are external to the incumbent socio-technical regime, meaning design choices need to be negotiated outside of established relationships and mechanisms. Radical road freight decarbonization actions such as switching to low carbon vehicle energy sources or shifting to rail or water modes satisfy both these conditions. This reinforces the view that deliberate, planned, and explicit transition choices are required to overcome freight's deeply-rooted lock-in to fossil fuel technologies (Li and Strachan, 2019).

Mirroring interdependencies within the road freight system, systemic transition decisions are also interdependent. Decisions regarding technology, infrastructure, incentives, capability development, and transition goals and targets cannot be made in isolation of each other. Dependencies between decisions need to be understood to enable a decision pathway to be defined that specifies the sequence and timing of decisions so that dependencies between decisions are, to the extent possible, respected. The definition of a decision pathway is necessary (although not on its own sufficient) for the effective codesign of systemic transition decisions by actors and policymakers (Churchman et al., 2025a).

Based on this, it was decided to run workshops with mixed actor groups to define decision pathways for specific road freight decarbonization goals. In preparation for this, two pilot workshops were conducted with a logistics expert and two local authority representatives. In these, decision nodes and dependencies were defined using a spreadsheet matrix. While these pilot workshops demonstrated the importance of understanding decision nodes and dependencies, they also showed how difficult this is to do using a spreadsheet matrix. It became clear that a visual way of representing node and dependency networks was needed. A first attempt to graphically represent nodes and dependencies was made using the Python libraries NetworkX and Pyviz. Node and dependency data was imported from the Excel spreadsheet and the libraries were used to present the data in a visually appealing way in a browser interface. However, it was still necessary to define the nodes and dependencies in a matrix format. Furthermore, restrictions in the ability to manipulate the graphical plot and the fact that changes to the plot were not retained following a browser refresh further limited this approach's utility.

Several tools were considered for network plotting and visualization. PowerPoint and other presentation packages allow networks to be attractively represented, but each network needs to be created manually and any graphical manipulations to the network need to be manually applied back to the node and dependency matrix. PRSM (The Participatory System Mapper) is a good online tool for mapping nodes and dependencies via a browser interface. Its principal drawbacks are the need to manually lay out networks, which was found to be cumbersome for the complexity of network being created, limitations in the ability to customize network presentation and the relatively basic data import/output features. The Systems Dynamics (SD) simulation package Vensim was also considered. SD shares some characteristics of decision pathway mapping as SD models are built on causal loop diagrams that include nodes and directional dependencies. However, the significance of causal loops is different as, in SD, these represent reinforcing or regulating mechanisms within a dynamic system whereas, in a decision pathway, a loop represents a decision sequencing dilemma that needs to be resolved. Vensim has been developed principally for the structuring of quantitative dynamic simulations, which is not required for decision pathway definition. As with PRSM, Vensim is limited in the customization available for visual network presentation and does not provide automated network layout. It also does not incorporate the concept of sequencing of nodes which, while not required for SD, is essential for the modelling of decision pathways.

Having been unable to identify existing tools that provide the identified features, it was decided to develop a new tool. The key specific functions that were defined as required are:

1. The facilitation of decision node and dependency definition by mixed groups of transition actors and stakeholders:
    - Rapid definition, review and editing of nodes and dependencies
    - Graphical presentation of these in a visually appealing and intuitive way, with minimum manual effort
    - Ability to add, edit and delete nodes and dependencies via a graphical interface
    - Easily accessible, with no special software or hardware requirements
    - Easy file sharing and collaborative / workshop tools
2. The efficient generation of decision maps, pathways and analyses based on these nodes and dependencies:
    - Automated identification of dependency loops, and the ability to define how these are handled
    - Automated identification of optimal decision sequences
    - Graphical presentation of decision sequences as Gantt charts
    - Ability to define node durations, enabling Gantt charts to represent timelines
    - Data analysis and import / output functions

Pathplotter was developed with these functions during 2023 and 2024 and has been used in five workshops to define decision pathways for specific road freight decarbonization goals. The outputs of these workshops regarding road freight decarbonization are presented by (Churchman et al., 2025b) and are summarized in Appendix A. The focus of this paper is on the conceptualization and design of Pathplotter, the custom-developed decision pathway codesign tool that was used in workshops; and was subsequently further developed based on this experience.

While the concept of purposive design of transitions is not entirely novel, it is not mainstream within transitions literature (Gaziulusoy and Öztekin, 2019). Reasons for this may include the inherent complexity of designing transitions that span multiple systems; and the difficulty of bridging between the objectivist and subjectivist research paradigms on which most techno-economic and socio-technical / political transitions research are respectively based. Nevertheless, Design for Sustainability (DfS), Transitions Management (TM) and Participatory Design (PD) literature was found to contain important relevant insights and was used to inform the development both of Pathplotter and the codesign process that it supports. An overview of this literature is provided in section 2. Following this: section 3 summarizes the tool requirements identified from literature and in pilot workshops; section 4 presents the Pathplotter features that fulfil these requirements; section 5 considers the experience to-date of applying Pathplotter to the case of road freight decarbonization; and Section 6 concludes with a reflection on original contributions and opportunities for further development and application of Pathplotter.

At the time of writing, Pathplotter is available as freeware on https://pathplotter.net.

2. Literature review

2.1. Approach

To identify literature providing guidance on requirements for transition decision pathway specification, a semi-systematic review was carried out. A Scopus search was conducted for the terms "sustainab*" and "transition*" and "*design". The term "sustainab*" was included as the focus of the project was on the sustainable transition of road freight; and searching for "transition*" and "*design" on their own resulted in over 166,000 articles being identified, the large majority of which are in non-relevant fields. Results were further limited to the subject areas of "social science", "environmental science" and "energy", and restricted to relevant journals. This resulted in 1,029 papers being identified. Three relevance criteria were specified:

1) applicable to mixed private sector and institutional actor engagement;
2) system, pathway and codesign focus; and
3) process and tool insights.

Paper titles were reviewed and 975 were deselected as not relevant on the basis of these criteria. Abstracts of the remaining 54 papers were reviewed and 36 more were deselected. The remaining 18 papers were reviewed in full and nine more were deselected, leaving nine relevant papers. Citing papers and references of these nine papers were reviewed and five additional relevant papers were identified.

In addition, a targeted search was conducted for papers considering participatory design and stakeholder engagement in transport and energy transitions. A large proportion of this research focuses on the engagement of publics rather than private sector and institutional actors. Studies also frequently consider the benefits of participation and engagement from a democratic, legitimacy and knowledge perspective rather than the processes and tools required for effective participation and engagement. As a result, only one additional paper meeting the relevance criteria was identified, giving a total of 15 selected papers, which are listed in Appendix B.

The full text of the selected papers was qualitatively coded using NVivo, applying principles from grounded theory (Charmaz, 2006), using an iterative process of open, axial and selective coding (Williams and Moser, 2019). As a result of this process, four overarching themes were identified:

1. Levels of Design for Sustainability
2. Multidisciplinary, expert and diffuse design
3. Transition steering and planning
4. Collaboration and codesign

2.2. Literature review findings

The findings from the fifteen papers for each of the above four themes and the implications for decision pathway specification are summarized below.

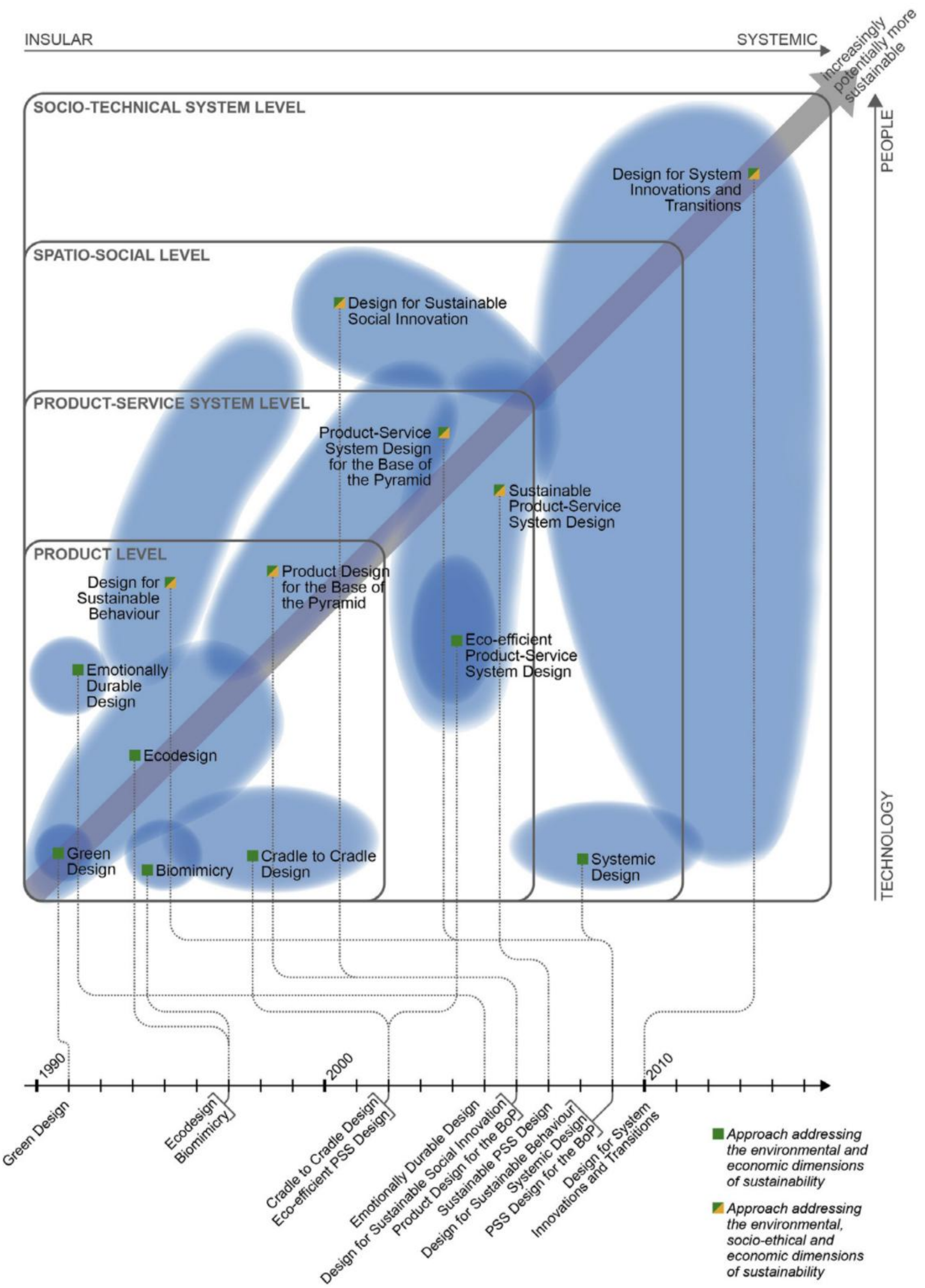
2.2.1. Levels of Design for Sustainability

Design for Sustainability (DfS) has evolved as a response of the design discipline to the now overwhelming evidence that radical changes to energy, transport, food and other systems are necessary to prevent catastrophic environmental failure (Gaziulusoy and Öztekin, 2019; IPCC, 2023). Ceschin and Gaziulusoy (2016) identify four levels of DfS: product level design, product-service system level design, spatio-social level design; and socio-technical system level design. All but the first of these levels treat sustainability as a system property rather than a property of individual system elements. A range of DfS approaches are identified and mapped to the four levels in figure 4-1.

Within this framework, the technology/people axis differentiates between views of innovation that focus on products and technology versus on user practices and behaviors. The insular/systemic axis differentiates between a single company focus and a system-wide focus. The four DfS levels are depicted as nested rather than as mutually exclusive, and the authors identify several interdependencies between the levels.

A possible conclusion from this could be that DfS should focus on the socio-technical system level, as this is the most holistic and encompasses the other levels. However, design work at this level is critiqued by the authors as being too “big picture” and insufficiently supported by an understanding of the micro-level product and service changes necessary to support the macro-level system change. Both they and Lähteenoja et al. (2023) conclude that designing for transitions requires the blending of design approaches across all four DfS levels.

Figure 4-1: Design for Sustainability evolutionary framework
(Source: Ceschin and Gaziulusoy (2016, p.144))



In a separate analysis, Gaziulusoy (2015) assesses several DfS approaches against five criteria that they argue are necessary to deliver truly sustainable outcomes: 1) strong sustainability; 2) systems thinking; 3) radicalism; 4) long term orientation; and 5) mindset change. None of the design approaches they review are found to fully meet the five criteria.

The overall conclusion from this work is that none of the DfS approaches considered are individually sufficient to design transitions of complex systems. Collectively however, they address a range of important transition design challenges, which suggests that a coordinated approach across design levels is necessary.

A key requirement for decision pathway specification is therefore that: *The decision pathway needs to span multiple DfS levels.*

2.2.2. Multidisciplinary, expert and diffuse design

Design that spans multiple DfS levels requires a diverse design capability that is unlikely to all sit with one person or organization. Considering the product-service system level, the design of a specific product such as a new vehicle is a very different skill set to designing a transport service (Joore and Brezet, 2015). If a socio-technical or spatio-social system view is taken, the design scope expands to encompass the socio-technical regime and landscape and/or other socio-spatial factors. However, this does not reduce the need for deep technical design expertise for each product/service component (Gaziulusoy and Ryan, 2017).

Another highlighted design dimension is that of expert versus diffuse design, with the former emphasizing technical knowledge and skills in the design process and the latter wide participation of system stakeholders and users (Lähteenoja et al., 2023). These two types of design are sometimes presented in literature as being in opposition, with “technocratic” expert-led change being portrayed as contradictory to democratic and participatory change. However, considering multiple DfS levels is likely to require diverse forms of expert and diffuse knowledge (Joore and Brezet, 2015; Costa et al., 2019). This reinforces the need for a multidisciplinary design approach. Within this, businesses are identified as playing an important role both as design architects and as change actors and stakeholders (Gaziulusoy, 2015; Ceschin and Gaziulusoy, 2016; Pineda et al., 2024).

A key requirement for decision pathway specification is therefore that: *Both expert and diffuse modes of codesign need to be accommodated, with experts likely to be from multiple disciplines.*

2.2.3. Transition steering and planning

Similar to the debate regarding expert versus diffuse design, the role of steering in transitions literature is contended, with diverging views tied to different disciplinary transitions (Van Assche et al., 2021). A codesign approach necessarily implies some form of steering, and the view adopted in this paper is that it is not a question of whether transitions should be steered, but how they should be.

DfS approaches have been criticized as neglecting the need for project planning and management in transitions (Rocha et al., 2019). TM as originally conceived also focuses on the definition of long-range transition goals rather than more concrete short- and mid-term planning

(Loorbach, 2010). While having a clear long-range vision is important, any view taken over a multi-decade time horizon is subject to a high degree of contextual uncertainty (Malekpour et al., 2020). Hyysalo et al. (2019a) argue that a mid-range horizon of c.10-15 years and a focus on interim rather than ultimate goals provide a more practically helpful basis for planning. This horizon is long enough for significant change to happen without being so long that contextual uncertainty overwhelms planning confidence. It also provides a stronger basis for project managing transitions and allows early design effort to be focused on the choices that need to be made sooner rather than later.

A key requirement for decision pathway specification is therefore that: *The 10-15 year mid-range planning horizon is a primary focus.*

2.2.4. Collaboration and codesign

Ryan (2008) proposes that the sustainability revolution is unlike the Information Technology (IT) revolution as there is no single easily defined technological sphere of "low carbon" technology to support. It is also unlike previous industrial revolutions as, in those, new technology enabled the progressive reshaping of the economy, and the future "unfolded" as a result, rather than the future being defined and the steps to get there needing to be designed. They argue that: *"Nothing like this has confronted human society before; it demands a level of collective intelligence, foresight, and purpose and a social commitment to experimentation and change that are truly unprecedented."* (Ryan, 2008, p.141).

Within this context, transition governance plays a critical role, with governance configurations potentially exercising more power than individual actors (Van Assche et al., 2021). While transition leadership contains elements of art as well as science (Van Assche et al., 2021), an attribute of good leadership is providing a clear basis for decision-making and action (Lähteenoja et al., 2023). Clarity of accountability and responsibility is also required (Hyysalo et al., 2019a; Lähteenoja et al., 2023). A decision pathway must therefore be perceived as feasible and have the buy-in of key stakeholders and actors, which is unlikely to be achieved without the participation of these in its specification. Aligned with this, van Langen et al. (2023) presents the concept of "Participatory Design of Participatory Systems" in which actors codesign, not only system choices, but also the process of codesign itself.

A key requirement for decision pathway specification is therefore that: *The decision pathway itself must be codesigned by key actors and stakeholders.*

2.3. Summary

The following are identified from literature as key process requirements for defining decision pathways, providing relevant guidance regarding design scope, participation, timeframe and pathway specification:

- *Scope:* The decision pathway needs to span multiple DfS levels
- *Participation:* Both expert and diffuse modes of codesign need to be accommodated, with experts likely to be from multiple disciplines
- *Timeframe:* The 10-15 year mid-range planning horizon is a primary focus
- *Pathway specification:* The decision pathway itself must be codesigned by key actors and stakeholders

3. Tool requirements to facilitate decision pathway specification

3.1. Required tool features

A systems design toolkit should facilitate collaborative inquiry, reasoning, visualization, modelling, simulation, and creation (Costa et al., 2019). Hyysalo et al. (2019b) propose six requirements for a codesign workshop toolkit that they apply in the 2030 Agenda Transition Arena project in Finland. Combining these toolkit requirements with the process requirements identified in section 2, two cross-cutting tool features are identified in Table 4-1. Considering each of these in turn:

3.1.1. The facilitation of decision node and dependency definition by mixed groups of transition actors and stakeholders

In section 1 it was proposed that path and system dependencies mean that transition design choices are interdependent, and a decision pathway is therefore required. In section 2 it was identified from literature that decision pathways must engage diverse expert and diffuse knowledge across multiple systems and DfS levels; and must be codesigned by actors and stakeholders. The facilitation of mixed groups of actors and stakeholders to define design choices, barriers and enablers (collectively termed "nodes") and dependencies between these is therefore a key tool feature.

3.1.2. The efficient generation of decision maps, pathways and analyses based on these nodes and dependencies

Once nodes and dependencies have been identified, establishing a common understanding of their implications for decision pathways can represent a substantial conceptual and cognitive challenge for even highly knowledgeable actors and stakeholders. The ability to present node and dependency maps in an intuitive format and to automate the derivation of pathways and analyses based on these maps was therefore identified as an essential tool feature. This aligns with the toolkit requirements proposed by Hyysalo et al. (2019b).

Table 4-1: Cross-cutting features of a tool to facilitate the definition of decision pathways

		The facilitation of decision node and dependency definition by mixed groups of transition actors and stakeholders	**The efficient generation of decision maps, pathways and analyses based on these nodes and dependencies**
Process requirements	The decision pathway needs to span multiple DfS levels	✓	
	Both expert and diffuse modes of codesign need to be accommodated, with experts likely to be from multiple disciplines	✓	
	The 10-15 year mid-range planning horizon is a primary focus		✓
	The decision pathway itself must be codesigned by key actors and stakeholders	✓	
Toolkit requirements (Hyysalo et al., 2019b)	Allow a group of 3-7 participants from different walks of life to deliberate and effectively form a path to a mid-range transition goal from the current state	✓	
	Provide participants with the means to analyze interrelationships between pathway steps and the timing of needed actions		✓
	Help participants to evaluate the realism of the suggested steps and the range of actions through which the pathway steps can become realized		✓
	Help participants to recognize pathway and step interlinkages and the most critical steps in which societal choices have to be made		✓
	Help participants to highlight alternative transition paths with respect to the most important change drivers and uncertainties		✓
	Consider the effects of the most important uncertainty and contingency factors in the pathways and the steps therein		✓

4. Pathplotter features

4.1. Pathplotter overview

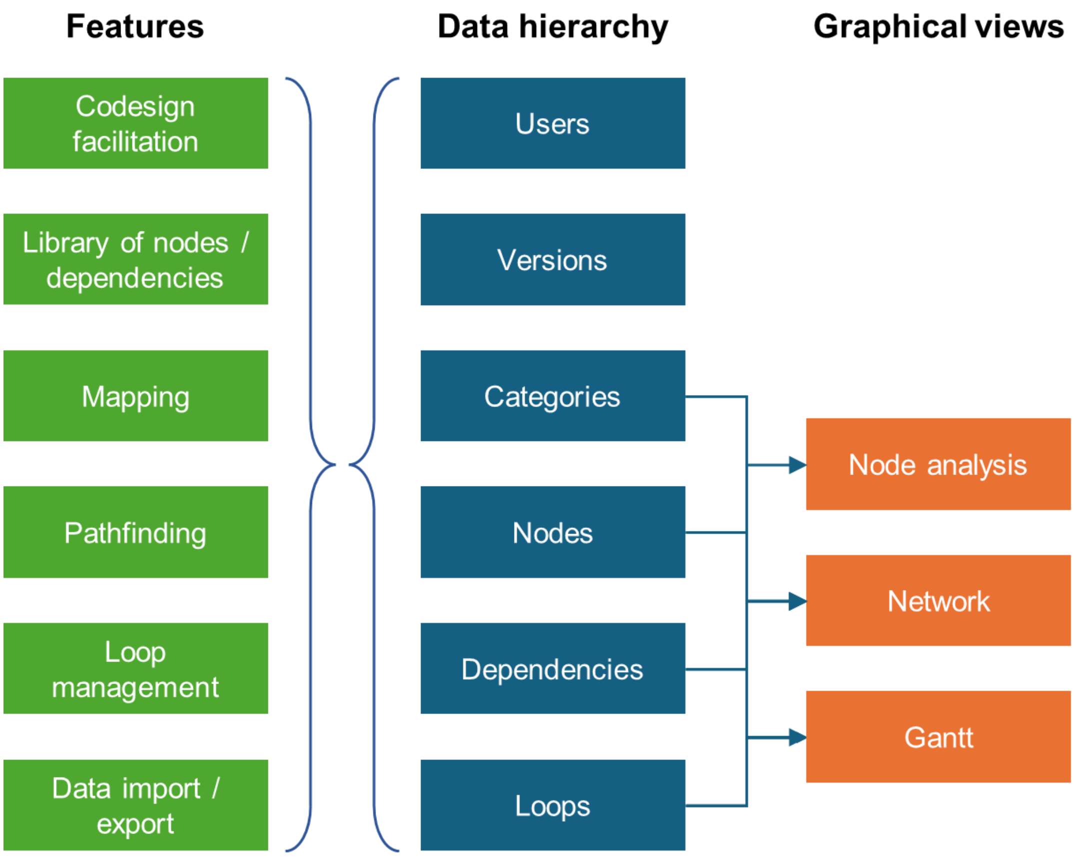
Pathplotter is a Progressive Web App (PWA) hosted on Microsoft Azure that was built to address the needs identified in section 1 to facilitate the definition of decision pathways by mixed groups of transition actors. Once signed in, users can create their own models ("versions"). Within a version, the user defines decisions, barriers and enablers (collectively called nodes) and dependencies between nodes. Each node is assigned to a node category. Nodes and dependencies can be specified either via a tabular or graphical interface. Once these are defined, Pathplotter uses pathfinding algorithms to identify circular dependency loops and optimum pathway sequences that minimize the number of dependencies completed out of sequence.

There are three graphical views: "Gantt", illustrated in figure 4-5; "network" illustrated in figure 4-6; and "node analysis", illustrated in figure 4-7. The network view is in the form of a PERT (Program Evaluation Review Technique) chart, with nodes presented in colors according to their category, and dependencies between nodes indicated by arrow links. Dependencies that are part of a circular dependency loop are colored gold, and nodes with no path to an end goal are highlighted with a red border. Tools are available to manage how circular dependency loops are handled in node sequencing. Nodes and dependencies can be added, deleted and edited via the graphical interface. There are three automated layout options: maintaining separation between nodes with linked nodes closer together (shown); aligning nodes in category columns; and positioning nodes horizontally according to Gantt sequence. Dependency links are curved to avoid passing through intervening nodes where possible. Nodes and dependency midpoints can also be positioned manually using a mouse or touch screen. These features have been developed to make the collaborative definition of nodes and dependencies; and visualization of the resulting network, loops and pathway; as seamless and intuitive as possible. All graphical views can be outputted as PNG image files.

Categories, nodes and dependencies can be disabled via toggle switches, and an option is available in graphical views to only show enabled elements. In addition to graphical views, Pathplotter provides a range of data interrogation, editing, input and output facilities. Versions can be copied to allow quick generation of version variants.

Figure 4-2 summarizes Pathplotter's logical structure.

Figure 4-2: Pathplotter logical structure



In addition to providing the above functional features, Pathplotter has been developed with the following usability objectives in mind: automation of all tasks that can be automated, so that workshop flow and discussion are not interrupted; a modern and visually clear presentation; ability to use on both mobile and desktop devices; intuitive zoom and scroll of graphical views; easy undoing and redoing of actions; web deployment to enable access on any device with no special software; and secure user login.

The remainder of this section provides a more detailed description of Pathplotter's functions and features.

4.1.1. Data hierarchy

The core of the structure is the data hierarchy represented by the blue items in figure 4-2. The levels of the hierarchy are:

- ***Users:*** Defined by who is logged in.
- ***Versions:*** The version contains data required to define a decision pathway. All versions belong to a single user, but a user can have any number of versions.
- ***Categories:*** These are node categories, which are user definable but must include the category "Goals". All categories belong to a single version, so editing a category in one version will not change categories in another version.

- ***Nodes:*** Nodes are decisions, barriers, enablers, or any other type of requirement or event that a user wishes to define. Each node belongs to a single category and version.
- ***Dependencies:*** Dependences (also referred to as "links" in Pathplotter) connect a "from" node that must be completed first and a "to" node that must be completed second. They are specific to a single version.
- ***Loops:*** Loops are comprised of two or more dependencies that together form a chicken and egg loop. If a loop is defined as a "Group" it means that every node within the loop will be assumed to occur simultaneously in the decision pathway.

For versions, categories, nodes and dependencies, there are views that allow users to display, filter, create, edit and delete elements for the versions that they own. Although loops are created automatically based on dependencies, there is also a view to display and filter loops and edit loop settings.

4.1.2. User groups

User groups are currently defined by the administrator. Users can copy a version they own to another user that they share a group with so that that user can view and edit the copy. Potential future functionality could include the ability for users to define their own groups and invite other users to these, and to have a single version, rather than version copies, shared by users for collaborative working.

4.1.3. Graphical views and settings

Gantt, Network and Node analysis views provide graphical presentations of version data and, in the case of Gantt and Network views, allow direct adding, editing, and deleting of data elements. There are also views for editing graphical view settings. Node analysis settings are defined per user; and Gantt and Network settings are defined per version.

4.2. User sign-up and security

Pathplotter has basic user sign-up and login functionality. Navigating to the home page without being logged in opens a sign in page that requires a username and a password. This page has a link to a new user sign-up page that requires a unique username, a password and a unique email address. The email address is not currently used but may be in the future for self-service management of user groups and password resets.

Once logged in, users land on a version selection page. There is a menu option for changing the password. All other Pathplotter views require a logged-in user. If a non-logged-in user enters a view URL directly, they are redirected to the log-in page. If a logged-in user attempts to access another user's data by entering a reference for an object that does not belong to them in a URL, they are redirected to their own version selection page.

Notwithstanding the above security measures, Pathplotter has not, at the time of writing, been professionally security tested, so should not be used for sensitive or confidential data.

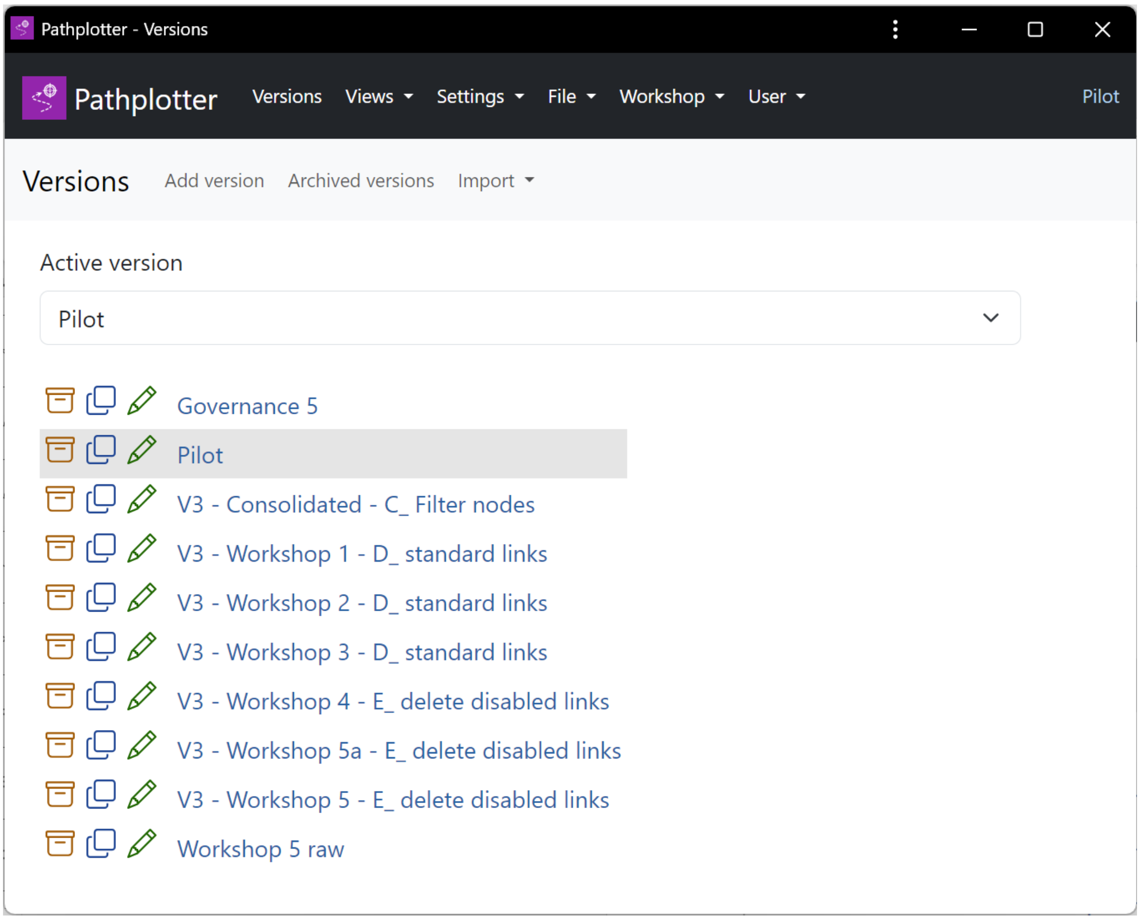
4.3. Element selection, adding, viewing & editing, deletion and copying

4.3.1. Element selection

The landing page for a newly logged-in user is the version selection page. If no version is selected, only version add and import links are available. Once a version is selected, links to all other views become available. The node selection view allows nodes to be filtered on category. The dependency selection view allows dependencies to be filtered on "from" node and/or "to" node.

Figure 4-3 presents the version selection page illustrating Pathplotter's user interface design. This shows two rows of drop-down navigation menus, which is the menu layout throughout the application. The top menu is shared by all views and the bottom menu is specific to the current view.

Figure 4-3: Version selection view



4.3.2. Element adding

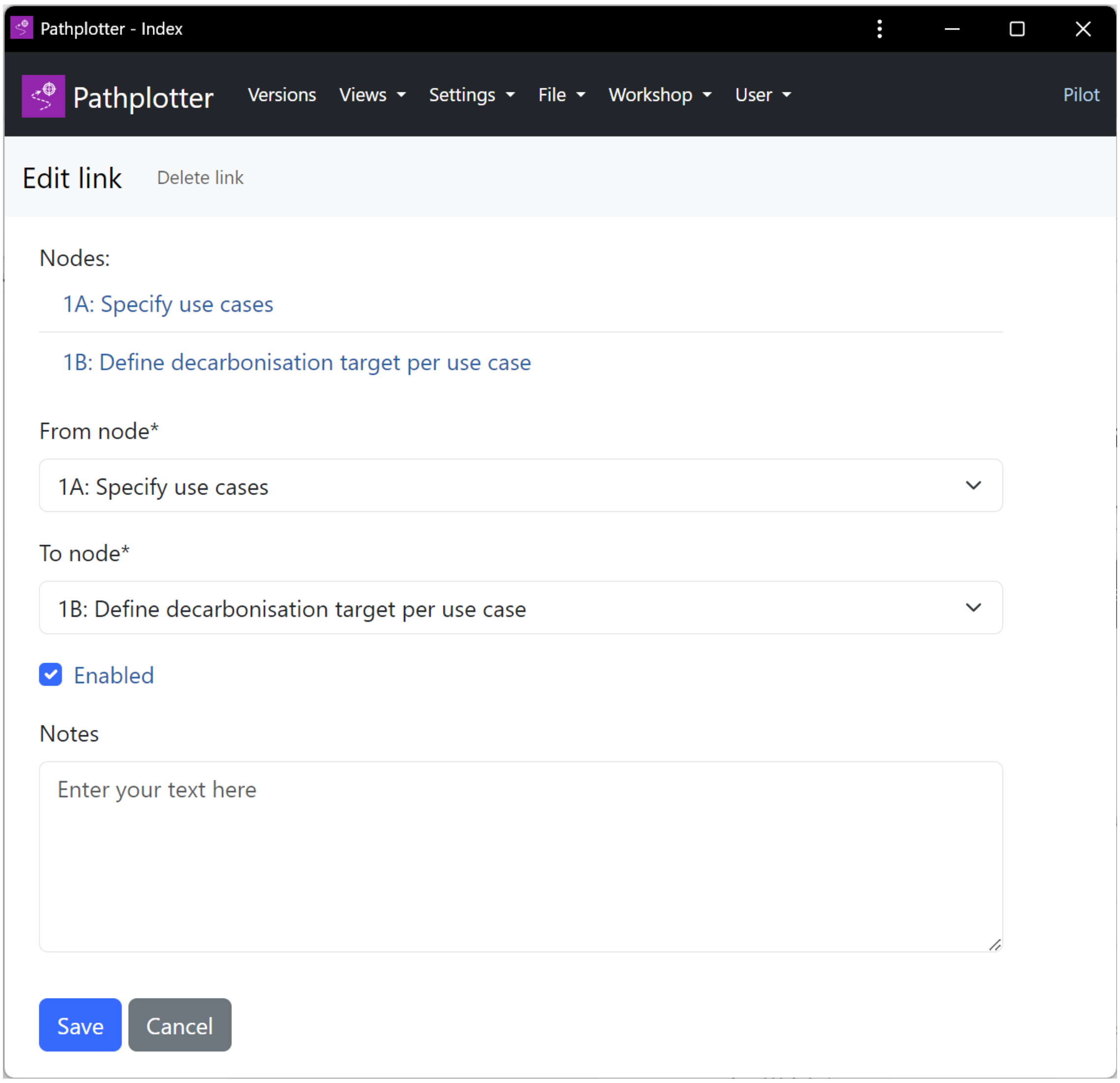
All element selection views except for the loop view have a menu link for adding a new element. Clicking on this opens a form for creating a new element. Each form includes validation checks to ensure only valid element data is added. There is no add loop view as loops are identified automatically based on defined dependencies.

4.3.3. Element viewing & editing

In all element selection views, clicking on an element opens a form for viewing and editing element data. In each of node, dependency and loop edit views, there are links to edit views for parent elements to allow easy navigation through the data hierarchy.

Figure 4-4 shows the edit link / dependency view as an example.

Figure 4-4: Edit link / dependency view



4.3.4. Element deleting

In version, category, node and dependency edit views, there is a menu item for deleting the element. Loops cannot be deleted as they are based on defined nodes and dependencies. There is a facility to archive versions so that they can be removed from the front version selection page without permanently deleting them.

4.3.5. Version copying

A version copy facility creates a "deep" copy of the selected version. In the copy, every data element and relationship between these is duplicated, thereby creating an entirely new and separate version.

4.4. Element enable / disable

In each of the category, node and dependency views there are toggle switches for disabling and enabling elements. If an element is disabled, it and other elements that reference it remain visible in their respective selection views. However, in the network, Gantt, loop and group views, if the "enabled" option is selected, the data shown is the same as if disabled elements had been deleted from the version. This is useful for testing what-if scenarios and for temporarily removing elements without deleting them entirely.

4.5. Loop finding

A key Pathplotter feature is the automatic detection of chicken and egg dependency loops. There are two loop finding modes: "accurate" and "efficient".

4.5.1. Accurate mode

This mode attempts to identify every loop based on the defined dependencies. It uses an iterative pathfinding approach that builds chains by starting with each defined dependency and then seeking other dependencies that connect to the start or end of the chain. If adding a dependency connects the beginning and the end of the chain, this is defined as a loop and the chain is closed. Identified loops are de-duplicated, so A-B-C-A is recognized as the same as B-C-A-B and C-A-B-C. If an added dependency forms a closed loop part way along a chain, or if no dependencies are available that connect to the beginning or end of the chain, the chain is closed to prevent further unnecessary iterations. When all chains have been defined as loops or are closed, all loops are found, and the iterations are concluded.

This method works well for sparse networks where the number of dependencies is not large compared to the number of nodes. However, it was found that there was a tipping-point of network density where even networks with a modest number of nodes could generate hundreds or even thousands of loops. As well as taking a very long time to generate all loops, identifying so many loops is not practically useful beyond indicating that the network is highly interconnected, which does not require every loop to be identified.

For this reason, the "efficient" loop detection mode described below was implemented. To avoid Pathplotter hanging for extended periods when attempting to identify loops in a dense network using accurate mode, if a predefined maximum number of loops are identified, Pathplotter automatically switches to efficient mode.

4.5.2. Efficient mode

In this mode, only loops containing either two or three dependencies are identified. The number of two and three link loops does not increase as dramatically with network density as the total number of loops and these can be identified more quickly. The resulting loop list is also a more manageable starting point for reviewing loops and removing weak dependencies to resolve these.

4.6. Groups

The alternative to removing weak dependencies to resolve loops is to define the loop as a group. There is a toggle switch for each loop in the loop selection view to do this. The implication of defining a loop as a group is that, if the "apply groups" option is selected in the Gantt view, the group is treated as a single entity and each node within it is assumed to occur simultaneously. Groups can only be applied in the "accurate" mode described above.

The application of groups can be effective if there are only a small number of groups. However, if there are two groups that share one or more nodes, these are merged by Pathplotter into a single "super-group". This means that if there are more than a small number of groups, it can rapidly become the case that many or even all nodes are treated as needing to occur simultaneously, which is not a practically useful conclusion. If it is possible to identify a weak link in a loop and remove this to resolve the loop, this was found to be usually preferable to defining the loop as a group.

4.7. Pathway sequence finding

There are parallels between the definition of decision pathways and other pathfinding problems such as geographic navigation and routing in computer networks. In each of these domains, there are nodes and dependencies, and a need to find the most efficient path to an end goal. No examples were found in literature of pathfinding being used for decision pathway definition. However, in geographic navigation and computer network routing, most if not all pathfinding algorithms are based on the short but highly influential proposal by Dijkstra (1959). Dijkstra (1959) poses the problem of a network of nodes, certain pairs of which are connected by links of a defined length. In "problem one", they propose an iterative approach to identify the shortest path from every node to every other node; and in "problem two" they suggest an approach to identify the shortest path between two specific nodes. Dijkstra's approach is both elegantly simple and exhaustive. It is also computationally intensive for large networks, and much subsequent pathfinding research has focused on reducing computational effort while still achieving close to the optimum result.

There are some differences between this pathfinding scenario and finding an optimal decision sequence. In the case of a decision sequence, it is nodes rather than links that have a "length" (or duration); dependencies can only be travelled on one direction; and loops have a different significance, as they represent sequencing dilemmas rather than redundant paths that can be discounted. However key transferable aspects from Dijkstra's method are that it is important to as far as possible eliminate duplicate paths early and to "close" paths that cannot be developed further to avoid wasteful unnecessary computations. These two principals have been applied in defining the algorithms used in Pathplotter for loop identification and path sequencing.

There are two scenarios for identifying pathway sequences based on defined nodes and dependencies: "no unresolved loops" and "unresolved loops". The far simpler scenario is when there are no unresolved loops, as in this case a sequence can always be identified in which all dependencies occur in the correct order. Each of these scenarios is considered separately:

4.7.1. No unresolved loops scenario

In this case, all nodes are treated as distinct items to be sequenced, unless they are part of a group or super-group, in which case the group/super-group is treated as the item to be sequenced. When a group/super-group exists, for the purpose of sequencing, all dependencies containing nodes in the group are replaced with a dependency from or to the group. In the case that both the from and to nodes in a dependency are in the same group, this dependency is ignored for sequencing.

Once this has been done, either an "earliest" or "latest" pathway sequence can be identified. The items to be scheduled are placed in a starting sequence where all start at time "0". For deriving the earliest sequence, every dependency is then cycled though repeatedly and, if the to-node is not in a later time position than the from-node, the to-node is placed in the position immediately after the from-node. Scheduling is complete when all dependencies are cycled in through and found to be in the correct order.

The latest sequence is derived in a similar way, but this time if a from-node is found not to be in an earlier position than a to-node, it is moved to immediately before the to-node. In this case, when the sequence is completed, nodes are in negative positions, so the overall sequence needs to be shifted to start at zero.

Sequence-finding can be done either with or without node durations. If "without durations" is selected, each node occupies a single timestep. If "with durations" is selected, time positions take consideration of node durations, and the overall sequence is a timeline rather than a step sequence.

A further feature was implemented that allows the timing of nodes to be fixed when "with durations" is selected. This is a useful facility to reflect specific deadlines or other timing constraints. It adds some additional complication to the sequencing algorithm as it means that, even when there are no unresolved loops, it may not be possible to create a sequence in which all dependencies are respected. For the sake of brevity, this more complex algorithm is not further detailed here.

4.7.2. Unresolved loops scenario

If there are unresolved loops, it is impossible to create a sequence in which all dependencies are completed in the correct order, meaning it is necessary to attempt to identify a "least bad" sequence with the minimum number of dependencies out of order. If there is one unresolved loop, there are as many of these sequences as there are dependencies in that loop, each corresponding to a different dependency being out of order. The number of potentially "least bad" sequences increases with the number and length of unresolved loops.

When loops have been identified using the "accurate" method, all loops are known, and it is possible to derive the minimum number of dependencies that must be out of order and all the sequences that contain this minimum number. However, when the "efficient" method is used, as not all loops are known, it is only possible to identify options by sequentially flagging dependencies to be completed out of order until a sequence can be created from the remaining dependencies.

An effective way of finding a "good" option in "efficient" mode was found to be flagging dependencies in descending order of the number of identified unresolved loops containing that dependency. The solution is found when it is possible to run the sequencing algorithm without generating sequence gaps. The generation of sequence gaps was the most efficient method identified for determining that the sequence algorithm would not complete and further dependencies needed to be flagged. When sequencing comparisons were made using the accurate and efficient loop finding modes, this approach usually identified an option that contained the minimum number of out of order dependencies as determined by the accurate mode. However, this cannot be guaranteed or proved when the number of loops is too large for the accurate mode to be used.

The complexity of pathway sequence finding when there are unresolved loops means that it was ultimately decided to always resolve loops where possible, first by removing weak dependencies and then, if there were unresolved loops remaining, by defining loops as groups.

In practice, in the scheduling scenarios that were considered, it was always possible to identify the weakest dependency in a loop, and, by disabling this, consciously decide the dependency that should be completed out of order. This approach avoided the conceptual and analytic complexity of groups and unresolved loops.

4.8. Gantt view options

The Gantt view presents node sequences in the familiar form of a Gantt chart. Node bars are color coded according to node category. There are several display options available:

- *"With durations" or "Without durations":* Determines if nodes are shown in single timesteps within a step sequence, or as having a defined duration within a timeline.
- *"Groups" or "no groups":* Determines if nodes in loops that have been defined as groups are treated as occurring simultaneously or not.
- *"Earliest" or "Latest" sequence:* Shows nodes positioned in the earliest or latest possible positions in the step or time sequence while minimizing the total sequence length and allowing the maximum number of dependencies to be completed in the correct order.
- *"Combined timing":* If selected, in addition to showing the selected earliest or latest sequence positions as solid bars, shows the other sequence positions as semi-transparent bars.
- *"Show out of sequence":* If selected, red curved arrows are superimposed on the chart indicating nodes that are in the wrong order based on a defined dependency.
- *"Order":* Allows nodes to ordered alphabetically, based on their sequence position or in descending order of the number of dependent nodes.

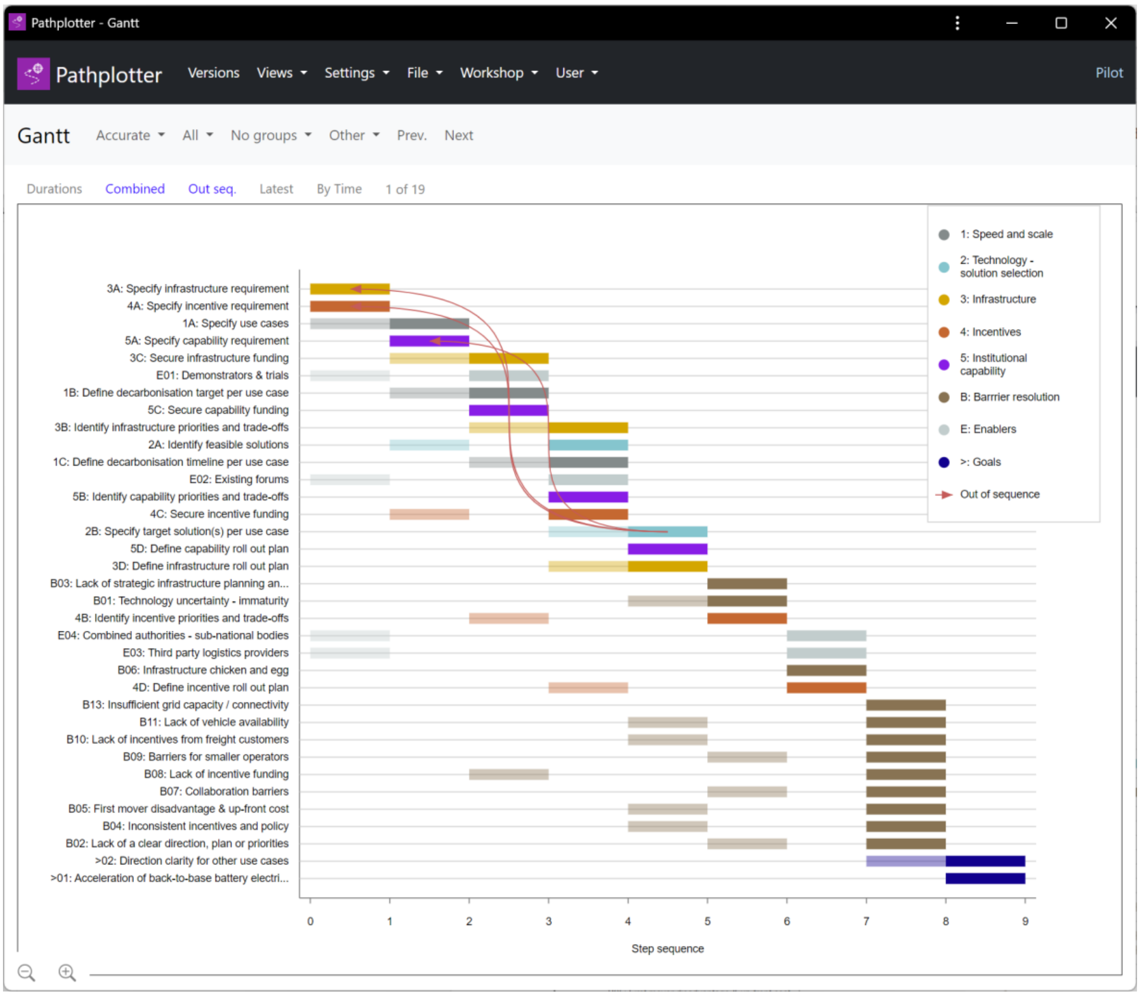
In the case where the accurate mode has been used and there are unresolved loops, there is also the facility to cycle through Gantt charts for all sequences containing the minimum number of out of order dependencies.

Clicking on a bar or node description text opens the edit view for that node. Clicking "Save" in the edit view returns to the Gantt view. This is particularly useful for altering node durations and seeing the timeline impact if "with durations" is selected.

The displayed Gantt chart can be exported as a PNG image file at any point. Various layout settings can be adjusted in "Gantt settings" including the horizontal and vertical plot dimensions and spacing for the x and y axes and legend.

Figure 4-5 shows an example Gannt chart with "Without durations", "Latest", "Combined timing" and "Show out of sequence" options selected.

Figure 4-5: Gantt view



4.9. Network auto-layout, view and edit options

The network view shows nodes as circles and dependencies as arrows connecting these. One of the initial reasons for developing Pathplotter was to create a tool that automated the layout of decision nodes and dependencies, as this was found to be cumbersome and time-consuming to do manually. Four auto-layout options are provided:

- *"Network" auto-layout:* This layout seeks to maintain an overall minimum spacing between nodes and to position nodes connected by dependencies close to each other, while keeping all nodes within the boundary of the plot. This is achieved by calculating a "force" magnitude and angle for each node based on the length of connected dependencies and distances from other nodes and plot boundaries. The force magnitude and angle are used to calculate an incremental node movement. This is conducted for all nodes for a defined number of iterations. Setting appropriate force and movement variables, which can be adjusted in network settings, results in networks that reach an equilibrium layout with the desired characteristics. Nodes with no connections are placed in a grid under the legend.

- *"Category" auto-layout:* This layout divides the plot space horizontally into columns for node categories, with the "goal" category in the rightmost column. Nodes in each category are then evenly spaced in each column to fill the vertical plot space. This view is particularly useful for initial definition of dependencies once nodes have been specified, as from and to nodes can be more easily located.
- *"Gantt" auto-layout:* This is a variation on the column layout, where the horizontal position of a node is defined by its position in the Gantt chart, as determined by the selected Gantt settings. As nodes without a path to a goal do not appear in the Gantt chart, these are placed in a grid under the plot legend as in the network layout.
- *"Links only" auto-layout:* This option does not move nodes but identifies if a dependency link between two nodes passes through another node and, if it does, moves the midpoint of the dependency so that it curves around intervening node. While this does not always prevent dependency links passing through nodes, particularly in dense networks, it substantially improves the readability and aesthetic appearance of the network views. As well as being available as a stand-alone auto-layout option, this is also run automatically as a final step for the above three auto-layout options.

Dependencies that are in unresolved loops are shown as gold arrows and those in groups as blue arrows. Nodes without a path to an end goal are shown with a red border.

There are several further network view options:

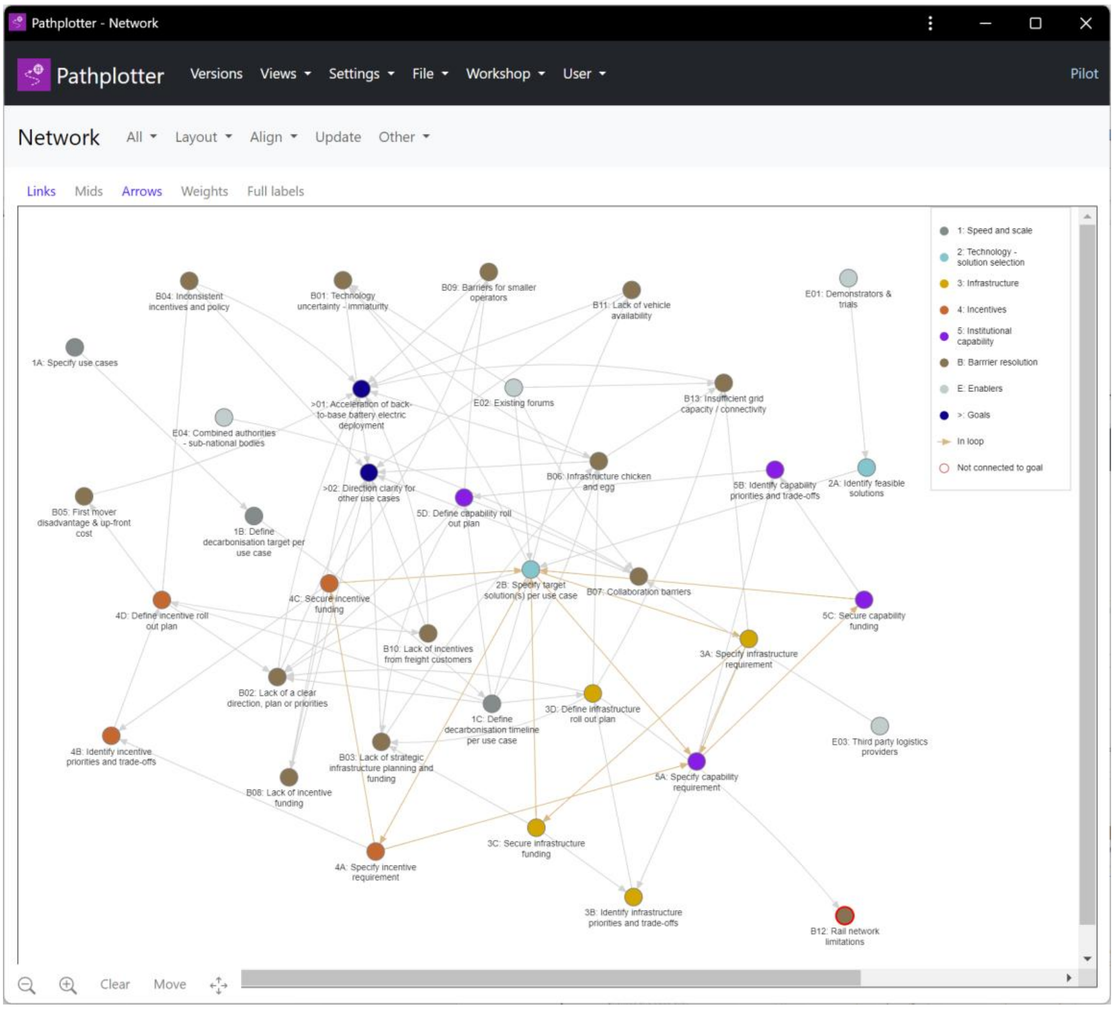
- *"All", "Enabled" and "Disabled":* Defines if the displayed network includes or excludes disabled elements and their child elements or, in the last option, only shows disabled elements and their children. In the case of "enabled only", dependencies are color coded as being in loops and groups based on the loops and groups that would exist if disabled elements were deleted.
- *"Links":* Determines if dependency links are displayed or not.
- *"Link midpoints":* Determines if dependency midpoints are shown. These are used to manually drag the midpoint of a dependency to change its path and for selecting a dependency for editing (see below).
- *"Arrows":* Determines if arrows are shown on dependency links.
- "No labels", "Codes only", "No codes" and "Full labels": Sets the format of node labels.

Manual layout facilities are also available. Individual nodes can be moved by clicking and dragging the node. The curve of dependency links can be changed by dragging the dependency midpoint. In addition to individual node adjustments, adjustments can be made to multiple nodes simultaneously. Multiple nodes are first selected by holding down the "Shift" key and either clicking on nodes individually or clicking and dragging across multiple nodes. Selected nodes are highlighted with a black border. Once "Shift" has been released, clicking and dragging any selected node will move all the selected nodes, while preventing any node leaving the boundary of the plot. Clicking the appropriate drop-down menu item will align the selected nodes to the left, right, top or bottom, or vertically or horizontally space the nodes. There are also menu options to clear and delete the selection.

While "Shift" is used for selecting multiple nodes, "Ctrl" is used to create new nodes and dependencies. Holding "Ctrl" and then clicking on an empty space will bring up the add node dialogue and, when this is saved, the new node will be placed in the clicked position. Holding "Ctrl" and clicking an existing node will highlight that node in blue and if, while still holding "Ctrl", another node is clicked, a dependency will be created between those two nodes. If multiple nodes are selected using "Shift" and then another node is clicked holding "Ctrl", dependencies from all the selected nodes to the final clicked node are added.

"Alt" is used for editing elements. If "Alt" is held while clicking on a node, the node edit dialogue is brought up. If "Alt" is held while clicking on a dependency link midpoint, the dependency edit dialogue is brought up.

Figure 4-6: Network view



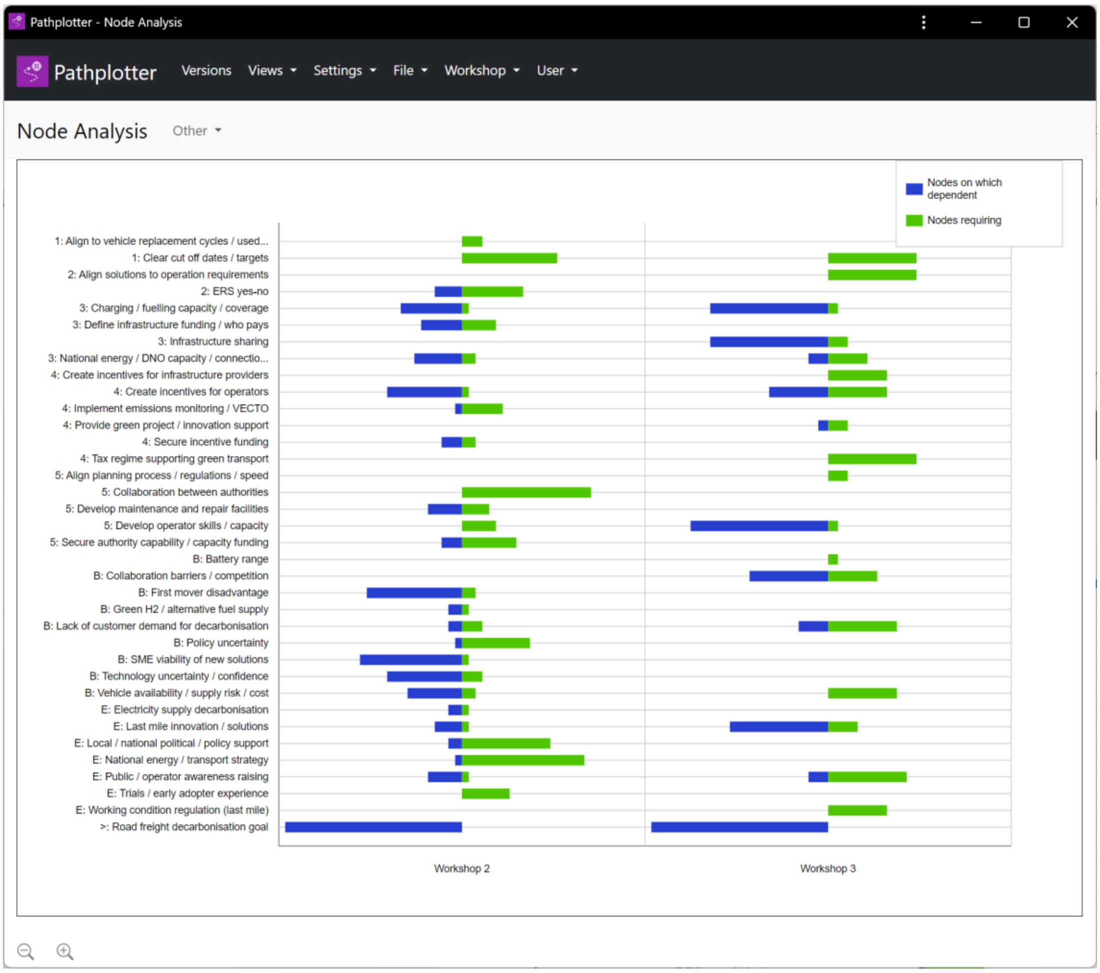
As with the Gantt view, the displayed network can be exported as a PNG image file. Parameter settings can be adjusted in "Network settings" including the horizontal and vertical dimensions of the plot.

Figure 4-6 shows an example network view following a "network" auto-layout.

4.10. Node analysis view

While the Gantt and network views are specific to an individual version, the node analysis view allows more than one version to be compared in a single view. The user first selects the versions that they want to display. For each of these versions, Pathplotter identifies for each node the percentage of nodes in the version that are directly or indirectly required by the node and therefore should precede the node, and the percentage of nodes that are directly or indirectly dependent on the node and therefore should follow it. Each node is then presented as a row and each version as a column. In each resulting cell, a blue bar represents the percentage of required nodes and a green bar the percentage of dependent nodes. A long blue bar means the node is highly dependent on preceding nodes and a long green bar means it is pivotal for subsequent nodes. This provides a good indication of whether the node should be earlier or later in the decision pathway.

Figure 4-7: Node analysis view



If standardized node names and categories are used across the displayed versions, the view provides a comparison of nodes identified across versions and shows how the degree to which they are highly dependent or pivotal varies.

As with Gantt and network views, the displayed plot can be exported as a PNG image file. Parameter settings including the horizontal and vertical dimensions of the plot can be adjusted in “Node analysis settings”.

Figure 4-7 shows an example node analysis view.

4.11. Standard nodes and dependencies

In the research conducted using Pathplotter, decision pathways were developed in multiple workshops by different participant groups focusing on different road freight decarbonization goals. While specific descriptions were different, nodes were identified in different workshops with similar or identical meaning. To enable cross-comparison between workshops, a shared library of standard node descriptions was created and the facility to map defined nodes to these standard nodes implemented. Node descriptions could then be replaced with standard descriptions. It then became possible to identify standard dependencies that are likely to always be true irrespective of road freight decarbonization goal if both the from-node and to-node exist. A benefit of doing this is that is becomes possible to create “starter” versions that include standard nodes and dependencies. It also allows gaps in dependencies identified in individual workshops to be filled with standard dependencies identified in other workshops.

4.12. Data import and export

Several data import and export features are provided:

- *Export / import version:* Exports / imports version data using a JSON data format. A principal benefit of JSON is that it is human readable and can be directly edited if desired provided the data structure and internal data integrity are maintained.
- *Export / import legacy version:* As above, except a format is used that is compatible with the previous desktop version of Pathplotter.
- *Import node file:* Imports node data from a CSV file generated either manually in Excel or exported from a Miro virtual whiteboard.
- *Export link survey / simple link survey:* Two options are provided for generating dependency surveys based on defined nodes as JSON files that can be imported into Jisc Online Surveys. Once imported, surveys can be made available to participants via a URL or QR code link so they can define dependencies directly.
- *Import link file:* Imports dependency link data from a CSV file generated by Jisc Online Surveys based on survey responses.

- *Export nodes:* Exports nodes, and corresponding standard nodes if defined, as a CSV file.
- *Export links:* Exports links as a CSV file.
- *Export node analysis:* Exports analysis of directly and indirectly required and dependent nodes per node as either a JSON or CSV file.
- *Export standard nodes:* Exports the library of defined standard nodes as a CSV file.
- *Export standard links:* Exports the library of defined standard links as a CSV file.

4.13. Undo / redo

Backups are stored for the previous 20 edits to the current version, and undo and redo buttons are provided to navigate through these.

4.14. Technical architecture

Pathplotter is a Progressive Web App (PWA) hosted on Microsoft Azure and uses a PostgreSQL database for non-static data.

The server-side code is written in Python using '*Django*'. Django provides a comprehensive framework for defining data models and forms, programming server-side functionality and APIs, and serving web pages and API data to web clients (browsers). A principal benefit of Django is that all code except for web page templates is written in Python, so no additional languages need to be learned for server-side programming.

Web templates are written in HTML, CSS and Javascript. Django provides helpful features that simplify aspects of HTML coding and reduce the amount of Javascript required. The CSS and Javascript library "Bootstrap 5" and the Python library "Django Crispy Forms" are used to provide a modern-looking web interface. Vanilla Javascript is used for most interactive web page features and Scalable Vector Graphics (SVG) for graphical elements. JQuery is used for asynchronous server data exchange and saveSVGasPNG for exporting PNG image files.

Iterative computational functions were originally built on the server-side in Python. However, this was found to result slow performance when the app was deployed on Microsoft Azure, so these functions were re-written in Javascript to run on the client-side to make use of the greater processing power typically available on web clients. Certain computations are completed in the background asynchronously to reduce the time users subsequently need to wait when loading views that require these computations.

5. Experience of using Pathplotter

Five workshops were conducted with mixed participant groups. Table 4-2 summarizes the road freight decarbonization goal, format and participants per workshop.

Table 4-2: Workshop summary

	Road freight decarbonization goal*	Recruitment approach (Format)	Participants
1:	Invest in public sector fleets to help catalyze rest of industry and kickstart manufacturers	Individually recruited (Online – MS Teams)	3 operator / shippers 1 public authority 1 expert / academic
2:	HGV** over 100km / > 12tonne decarbonized motive power	Individually recruited (Online – MS Teams)	1 operator / shippers 2 public authorities 1 expert / academic
3:	Last mile parcel delivery decarbonization in Wales	Co-hosted with Prof. Vasco Sanchez Rodrigues, Cardiff Business School (In person)	In addition to co-host: 4 expert / academics 1 public authority
4:	Decarbonizing urban HGV** movements	Co-hosted with Carolina Buneder and Cameron Cox, Transport for London (In person)	In addition to co-hosts: 2 public authorities 2 industry associations 2 energy / infrastructure providers 1 expert / academic
5:	Decarbonizing long distance HGV** movements of palletized goods	Individually recruited (In person)	1 operator / shipper 1 infrastructure provider 1 public authority 2 expert / academics

*: All goals were considered within the context of road freight in the United Kingdom

**: Heavy Goods Vehicle

Full findings from the five workshops are documented by (Churchman et al., 2025b) and a summary of findings are included in Appendix A.

Nodes and dependencies were successfully identified in each workshop and node analyses and Gantt charts were generated based on these. Positive feedback comments from participants include:

- *"It's a really insightful piece of work, and just gathering everyone's comments together, you've got a really good cross section of people on the call, and I completely agree it's only by that method [that it can be done]. I don't propose to know everything, and it's* *only by that collective effort that you get to the root cause and some real logical plans that say how they're all dependent on each other."* (Shipper / Operator)

- *"This will have very wide applicability, because it won't just work in transport to help decision making, it works across any industry that is looking at decarbonization or any large change process, to map all the different nuances of things you need to think about. It has really wide application."* (Transport planner)
- *"Using Pathplotter made it remotely tangible, whereas trying to squeeze that into some linear framework in a 2D matrix or something, you can do something, but you miss out on so many of the connections."* (Road freight expert)
- *"It helps you think through those interdependencies and, just thinking about our own work looking to develop road strategy, it helps you to think through what that route looks like."* (Transport planner)
- *"This process is very helpful when you're right at the start of something. I've just started with this piece of work, so everything that I've done up to now has been a brain dump. And then you filter it through and then you find out what's important."* (Transport planner)
- *"It shows that it's a system that needs reviewing and to get it purposeful it needs to be really thought about it a very deep way."* (Logistics expert)

The workshops were facilitated using a previous version of Pathplotter that, rather than being a web app, used the Python library "TKInter" to provide the graphical user interface. Limitations in this approach led to the decision to redevelop Pathplotter as a web app, making the tool more intuitive and accessible with a substantially improved visual appearance. Substantial work was also done to improve performance once Pathplotter was deployed to the cloud, including the migration of functionality from Python to JavaScript. The node analysis view was developed to make the identification of pivotal and highly dependent nodes more intuitive, and to allow these to be compared across multiple versions. Several data import and export tools were developed. In addition, a workshop voting tool was developed for use in workshops with larger numbers of participants. This revised version was successfully used in a follow up to workshop 3 hosted by the Welsh Government in January 2025.

6. Discussion

The experience of developing the decision pathway codesign process and Pathplotter tool; applying these in five mixed actor workshops; and then using an updated version of the tool in a follow up workshop has generated several insights. While the first five workshops were successful, the follow up workshop went more smoothly, and the feedback was more unequivocally positive. This was in part due to the refinements to the decision pathway codesign process and Pathplotter tool. Discussions in all workshops regarding decisions, barriers and enablers and the dependencies between these were collaborative, respectful and thoughtful. This is in contrast to some debates we have experienced regarding transition decisions themselves; for example the choice of vehicle energy source; that can quickly become polarized and political, with participants reiterating already well established positions. If there was the opportunity in future research, it would be very interesting to see if a codesign process that started with decision pathway definition using a tool like Pathplotter led to more collegiate and open subsequent dialogues on the decisions themselves.

A principal benefit of using a custom tool rather than an off-the-shelf application was that it was possible to be very agile in updating the tool in response on workshop learnings. This needed to be tempered with caution to ensure that bugs were not introduced from one workshop to the next. Nevertheless, without this agility, it would not have been possible to develop the tool as quickly; or gain the transition insights from the workshops that we did.

A final reflection is that tool accessibility, intuitiveness and appearance were found to be as important as functionality.

7. Conclusions

Pathplotter is a new software tool for the codesign of transition decision pathways. A synthesis of Transition Management (TM), Design for Sustainability (DfS) and Participatory Design (PD) literature resulted in the identification of two key requirements: 1) the facilitation of decision node and dependency definition by mixed groups of transition actors and 2) the efficient generation of decision maps, pathways and analyses based on these nodes and dependencies. Pathplotter has been demonstrated to be effective in fulfilling these requirements via its application in five decision pathway development workshops; and has been further developed based on experience from these workshops.

We believe that this work makes an original contribution by developing the decision pathway approach and supporting Pathplotter tool building on learnings from transitions and design literature. To our knowledge, no other tool provides the combination of features and ease of use offered by Pathplotter to facilitate decision pathway definition by mixed actor groups.

Pathplotter continues to be refined to improve useability, reliability and performance and to introduce features as the need for these become apparent. Further potential enhancements could include:

- The possibility for multiple users to work separately on a single version, similar to the file sharing features in Microsoft Office.
- Additional user self-service features such as password resets and version sharing.

The decision pathway approach supported by Pathplotter provides substantial opportunities for further research under two broad headings:

Identification of decision nodes and dependencies for road freight and other transitions

Decision pathways are relevant for any system transition that requires interdependent system-level design choices to be made. Research has an important role to play in identifying the decision nodes and dependencies that form the basis of decision pathways. Pathplotter can facilitate this research whenever either of the two needs for which it was developed exist: 1) the facilitation of decision node and dependency definition by mixed groups of transition actors and 2) the efficient generation of decision maps, pathways and analyses based on these nodes and dependencies.

Operationalizing for real-world transition delivery

This work has demonstrated that single workshops, while sufficient to demonstrate that mixed actor groups are able to define decision pathways for road freight decarbonization, are not sufficient to develop these to the point where they become actionable. For the latter, multiple workshops are likely to be required, attended by participants representing a full range of key actors and stakeholders. Subsequent design and decision-making based on the agreed decision pathway will then require an effective governance framework that has the full backing of government and relevant authorities. These are non-trivial requirements, but necessary if a design approach to transitions is to be adopted. Research has an important role, working with policymakers and transition actors, to develop actionable decision pathways and to define the governance frameworks that will be required to purposively enact transitions according to these pathways.

In this project, technology was used to facilitate and empower human intelligence rather than replace it. While artificial intelligence may have a role in sustainability transitions, we believe that the more important role is for humans, enabled by tools such as Pathplotter, to work together collaboratively to find pathways for the critical system transitions. It is only by doing this that we will collectively assure an acceptable future for humanity, other species and the planet, while also maintaining system functions that are necessary for human wellbeing today.

Appendix A: Summary workshop findings

Removed in thesis to avoid duplication – please see paper 3.

Appendix B: Papers identified from literature review

Table 4-3 lists the fifteen papers identified from the semi-systematic literature review.

Table 4-3 Papers identified from semi-systematic literature review

Title	Reference
Scopus search results, filtered for relevance	
A critical review of approaches available for design and innovation teams through the perspective of sustainability science and system innovation theories	(Gaziulusoy, 2015)
A Multilevel Design Model: The mutual relationship between product-service system development and societal change processes	(Joore and Brezet, 2015)
Evolution of design for sustainability: From product design to design for system innovations and transitions	(Ceschin and Gaziulusoy, 2016)
Roles of design in sustainability transitions projects: A case study of Visions and Pathways 2040 project from Australia	(Gaziulusoy and Ryan, 2017)
Design for sustainability transitions: Origins, attitudes and future directions	(Gaziulusoy and Öztekin, 2019)
Developing policy pathways: Redesigning transition arenas for mid-range planning	(Hyysalo et al., 2019a)
Codesign for transitions governance: A Mid-range pathway creation toolset for accelerating sociotechnical change	(Hyysalo et al., 2019b)
Transition co-design dynamics in high level policy processes	(Lähteenoja et al., 2023)
The role of design in sustainable transitions: The case of mobility in Greater Copenhagen	(Pineda et al., 2024)
Citing and referenced papers, filtered for relevance	
Climate change and ecodesign part I: The focus shifts to systems	(Ryan, 2008)
Bridging Decision Making under Deep Uncertainty (DMDU) and Transition Management (TM) to improve strategic planning for sustainable development	(Malekpour et al., 2020)
Design for sustainability models: A multiperspective review	(Rocha et al., 2019)
A framework for a systems design approach to complex societal problems	(Costa et al., 2019)
Steering as path creation: Leadership and the art of managing dependencies and reality effects	(Beunen and Van Assche, 2021)
Additional targeted search of participatory design and stakeholder engagement literature	
Participatory Design of Participatory Systems for Sustainable Collaboration: Exploring Its Potential in Transport and Logistics	(van Langen et al., 2023)

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Paper 5: Purposive transition governance for road freight decarbonization

Phil Churchman, Kate Pangbourne, Thijs Dekker, Vasco Sanchez Rodrigues

Abstract

Road freight decarbonization, like other complex system transitions, presents a formidable political, social and organizational as well as technical and economic challenge. While technical and economic aspects have received considerable research focus, there is much less research on political, social and organizational aspects. Purposive road freight decarbonization furthermore needs an effective governance framework to coordinate system-level decision-making that reflects all these important system dimensions. Findings from literature regarding governance requirements for purposive system transitions are synthesized to form a novel governance framework organized around the three pillars of governance processes, effectiveness and legitimacy. This framework is validated and further developed via thirteen semi-structured interviews and a review workshop with transport authorities and industry associations. Conclusions are drawn regarding maintaining system functions and managing asymmetric power relations during transitions; key governance enablers; and the importance of achieving input, throughput and output legitimacy. Governance tensions and connections are also identified, and the implications of these are discussed.

Keywords: Road freight decarbonization, Governance, Purposive transition, Abduction, Retroduction, Legitimacy

1 Introduction

Globally in 2022, heavy and medium duty road freight transport accounted for 1,830 million tonnes (IEA, 2024), or 5% of a total 36,800 million tonnes (IEA, 2023) of CO_2 emissions. In the United Kingdom in 2023, heavy goods vehicles over 3.5 tonnes represented 21 million tonnes or 5% of a total 426 million tonnes of CO_2 emissions (DfT, 2023b).

Road freight, particularly long-haul freight, is often cited as a hard to abate sector (Shell / Deloitte, 2021). However, its abatement must be achieved if we are to reach net zero. Given the urgency of the climate crisis, the transition must be rapid and radical, yet to date it remains slow and incremental. In this paper we propose that the lack of effective transition governance is a key contributor to this.

Zero emission trucks are entering the market and the United Kingdom (UK) government is providing financial stimulus to encourage logistics operators to acquire electric vehicles (DfT, 2023). Other road freight decarbonization opportunities exist (Greening et al., 2019). Some opportunities, such as improving vehicle aerodynamics or reducing rolling resistance, result in incremental decarbonization. Changing motive technology or mode shift to rail or water can deliver radical decarbonization, however these actions have major energy system, infrastructure and vehicle supply dependencies. They also have substantial operational and service implications for fleet operators and customers; and require operators to engage with new partners and service providers. Radical road freight decarbonization can therefore be considered a wicked problem, which is defined as being *"ill-defined, ambiguous, and contested, and featuring multilayered interdependencies and complex social dynamics"* (Termeer et al., 2017).

Purposive transition is core to the framing of this study and assumes that, due to system dependencies, rapid and radical road freight decarbonization will only occur if it is made to do so purposively, meaning it is deliberate, structured, planned, and organized. Smith et al. (2005) identify that a purposive transition is necessary when high coordination between actors is needed, and there are resources required to execute the transition that are external to the established regime. Radical road freight decarbonization actions fulfil both these criteria.

Patterson et al. (2017) define governance as *"the structures, processes, rules and traditions that determine how people in societies make decisions and share power, exercise responsibility and ensure accountability"*. Competing actor values, beliefs and vested interests make transitions deeply political, and conflict is inevitable (Steurer and Bonilla, 2016; Downie, 2017; Churchman et al., 2023). Transition governance must therefore include effective mechanisms for managing conflict in addition to making and enforcing transition decisions. Politics, conflict resolution, decision-making and decision enforcement are however under-analyzed in transitions governance literature (Voß et al., 2009; Patterson et al., 2017; de Geus et al., 2022).

Aligned with these conclusions, Churchman et al. (2025) identify that rapid and radical road freight decarbonization requires: 1) techno-economically feasible solutions; 2) a shared understanding of the design choices that need to be codesigned; and 3) a politically and socio-technically feasible codesign framework to make these design choices. This paper specifically addresses the third requirement and considers the research question: "What are the governance requirements for rapid and radical road freight decarbonization?". The remainder of the paper is organized as follows: section 2 describes the research approach used; section 3 proposes the governance framework developed from literature; section 4 presents the validation and further development of this framework via thirteen interviews and a workshop with transport authorities and industry associations; and section 6 concludes with a reflection on original contribution; the research question; governance tensions and connections; and opportunities for further research.

2 Methodological approach

An abductive approach (Stanford Encyclopedia of Philosophy, 2021)[1] was used to define a governance framework for purposive road freight decarbonization drawing on insights from literature. This framework is summarized in Section 3. The framework was then retroductively (Danermark et al., 2019)[2] validated and further developed via thirteen interviews with transport authorities and industry associations; and a workshop with five transport authority representatives. Interview and workshop commentary was transcribed and qualitatively coded using NVivo, and weightings were applied to coded themes by workshop participants. The results from this work are presented in Section 4.

3 Framework development

In the context of public administration, governance is described as enacted via policy networks that are "the formal and informal institutional linkages between governmental and other actors including professions, trade unions and big businesses." (Rhodes, 1997, p.2). The participation of private actors in governance creates a blurring of accountability and responsibility as private actors are not generally led by democratic principles (Low, 2004; Jessop, 2005). The multi-scalar aspect of transport governance also adds complexity due to the different structures that exist across countries and regions, and the lack of clarity about the tiering of responsibilities between spatial levels (Marsden and Rye, 2010).

Several governance frameworks for sustainability transitions are proposed in literature. Three prominent approaches are Earth System Governance (ESG); Adaptive Management (AM); and Transition Management (TM):

ESG is a product of the Earth System Science Partnership, created to develop strategies for Earth System Management (ESM) (Biermann et al., 2010). ESG considers governance architecture; state and non-state agency; adaptiveness of mechanisms and processes; accountability and legitimacy; and questions of just allocation and access. Four cross-cutting themes identified are power, knowledge, norms, and scale.

AM was developed in the context of socio-ecological systems (Olsson et al., 2004). While the focus of AM is on local community governance, it recognizes that this needs to be founded on

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[1] Abductive analysis identifies the most probable theory or explanation based on available information.

[2] Retroductive analysis considers a predefined theory and assesses the conditions under which this theory would be true.

vision, leadership and trust; be supported by necessary legislation creating a social space for co-management; and be enabled by appropriate knowledge and information flows.

TM was developed by Loorbach (2010) building on socio-technical systems and innovation theory (Geels, 2004), which in turn is founded on science and technology studies (STS) (Jasanoff, 1996). TM considers the strategic, tactical, operational and reflexive management activities required to develop long-range transition visions. Hyysalo et al. (2019b) further develop the role of TMs to define mid-range pathways that provide transition steering and coordination.

Foxon et al. (2009) compare TM and AM and propose that combining the iterative learning from AM with the longer-term transition perspective of TM could lead to a more resilient governance framework. Patterson et al. (2017) critically assess approaches to understanding transitions and make three overarching observations: the deeply political nature of transitions; the challenges of thinking about transformations ex-ante; and the tensions between steering change and recognizing its open-ended and emergent nature.

ESG, TM and AM all offer valuable insights and heuristics, but none provide a complete answer for transition governance (Foxon et al., 2009; Bosman and Rotmans, 2016). More recent work has proposed how these methods could be operationalized to support transition decision-making (Halbe et al., 2020), but the emphasis remains on long-range visioning and nurturing bottom-up innovation rather than purposive system-level steering of transitions.

To identify literature that provides insights into how to purposively govern transitions, a Scopus search was conducted for paper titles containing words associated with complex system transition: “wicked”, “transition”, “transformation*” or “complex” in combination with words associated with coordinated decision-making: “governance”, “management”, “stakeholder*” “collabor*” or “codesign”. After filtering for reviews and articles in the appropriate subject areas (social sciences, environmental science and energy), 3,204 papers were identified. Papers were then deselected that were in non-relevant journals, for example in the fields of education, agriculture, healthcare and information technology. This reduced the number of papers to 903. Further filtering papers based on title relevance reduced the number to 95. Filtering on abstracts resulted in 32 papers remaining and filtering these on full paper content resulted in 12 papers being selected.

A synthesis of the full text of the selected papers was then conducted, in which key governance themes were identified and clustered. This resulted in three governance pillars being defined: processes, effectiveness and legitimacy, each containing three sub-themes. Further targeted searches for literature associated with each of the three pillars using Google Scholar and Scopus identified a further nine relevant papers, bringing the total to 21. Table 5-1 shows these papers aligned to the identified governance pillars and overall transition governance.

Table 5-1: Governance themes aligned to 21 source papers

Governance pillar	Governance theme	Sources
Overall transition governance		(Patterson et al., 2017; Wannags and Gold, 2020; Grewatsch et al., 2023)
Processes	Deliberation	(Dentoni et al., 2018)
	Decision-making	(Dentoni et al., 2018)
	Enforcement	(Dentoni et al., 2018)
Effectiveness	Driving purposive transition	(Beer and Nohria, 2000; Marsden and Bonsall, 2006; Laes et al., 2014; Bosman and Rotmans, 2016; Avelino and Grin, 2017; Termeer et al., 2017; Hyysalo et al., 2019a; Hyysalo et al., 2019b; Keating and Katina, 2019)
	Maintaining system functions	(Foxon et al., 2009; Hyysalo et al., 2019a; Hyysalo et al., 2019b)
	Managing conflict and asymmetric power relations	(Ansell and Gash, 2008; Voß and Bornemann, 2011; Bosman and Rotmans, 2016; Steurer and Bonilla, 2016; Downie, 2017; Normann, 2017)
Legitimacy	Input	(Mena and Palazzo, 2012; Schmidt, 2013; de Geus et al., 2022)
	Throughput	(Schmidt, 2013; Doberstein and Millar, 2014; Iusmen and Boswell, 2017; Schmidt and Wood, 2019; Steffek, 2019; de Geus et al., 2022)
	Output	(Mena and Palazzo, 2012; Schmidt, 2013; de Geus et al., 2022)

Notably, while there is much research discussing desirable and undesirable characteristics of governance, little was found that considers the actual processes of governance. Only one reference was identified that proposes specific processes for system-level transition governance and steering (Dentoni et al., 2018). Wohlgezogen et al. (2020) highlight barriers to publishing cross-disciplinary research that addresses wicked societal problems. These barriers resonate with our own observations on the difficulty of bridging objectivist techno-economic and subjectivist socio-technical and political transitions research; and they may in part explain this research gap.

Insights from the 21 identified source papers are summarized below under the three pillars.

3.1 Governance processes

Dentoni et al. (2018) identify a systems and network governance approach as essential to "harness wickedness". In exploring governance requirements, they consider three governance processes of deliberation, decision-making and enforcement:

3.1.1 Deliberation

While multi-Stakeholder Partnerships (MSPs) bring together actors from different backgrounds, there are often power imbalances between actors. If governance is framed within a deliberative democratic ideal, power imbalances must be neutralized for deliberation to be effective. However, Dentoni et al. (2018) highlight that many studies find that affirmative efforts to neutralize power imbalance do not compensate for the dominance of certain participants, power plays and coalitions. If power imbalances cannot be fully neutralized, it is nevertheless important to ensure that all relevant voices are heard and considered at the deliberation stage.

3.1.2 Decision-making

As with deliberation, an idealized decision-making process would be based on equal representation and influence of all interested parties. In practice, this is rarely if ever the case. Measures need to be taken to manage asymmetric power relations to the extent possible, to ensure that potentially vulnerable and marginalized groups are represented and that private economic interests to not overwhelm environmental and social objectives. However, some degree of compromise and appeasement of private interests is likely to be necessary, and the decision-making process must accommodate this. Recognizing that both formal and informal decision-making processes exist, clear decision-making structures, roles, and rules nevertheless need to be defined.

3.1.3 Enforcement

The extent to which decisions are advisory or compulsory has strong implications for legitimacy and the nature of enforcement. Churchman et al. (2023) find a dichotomy between actors who believe that key road freight decarbonization decisions should be made centrally, and those who believe that all options should be left on the table so that operators and shippers can select solutions that work best for them. The nature of enforcement therefore also has significant political implications. Irrespective of the form of enforcement, decisions need to be expressed in a form that allows delivery against these to be monitored and reported.

3.2 Governance effectiveness

Despite a large governance literature, there is little consensus on what represents effective governance. For the purpose of this paper, effectiveness is defined as the achievement of desired transition goals and the avoidance of substantial negative unintended consequences. Marsden and Bonsall (2006) conclude that, when goals are expressed as targets, this can drive outcomes, but due to system complexities, these may not always be those that were intended. Recognizing this challenge, the reviewed literature identifies three relevant dimensions of governance effectiveness which are summarized below.

3.2.1 Drive purposive transition

Despite the urgency of the climate crisis, purposive transition governance is understudied. Termeer et al. (2017) contribute one of the few works to engage deeply on this topic and challenge the concept that incremental change is necessarily slow. They propose continuous transformational change with a focus on enabling and accelerating “small in-depth change” to reconcile the needs of incrementality and speed. To achieve this, they suggest three intervention strategies:

1. Provide basic conditions for enabling small in-depth wins
2. Amplify small wins through sensemaking, coupling, and integrating
3. Unblock stagnations by confronting social and cognitive fixations with counterintuitive interventions

For the first intervention strategy, Beer and Nohria (2000) propose four preconditions for change in an ambiguous and turbulent world: 1) stay in motion; 2) have a global direction; 3) look closely and update often; and 4) converse candidly.

The second intervention strategy is comprised of three interrelated sub-strategies: sensemaking, coupling, and integrating. In sensemaking, what is happening in transformational change is observed and its importance to the world is communicated via storytelling. Coupling is identifying connections between interventions at structural levels and across domains, increasing the opportunity for learning and reinforcement. Integrating is connecting interventions to the adaptive approaches of existing institutions so that these can be scaled.

The third strategy is relevant if forceful interventions are required in the face of serious stagnations, which can be a result of path dependencies, vested interests or “dialogues of the deaf”. Such interventions require examination of the mechanisms that reinforce stagnation patterns. “Context variation” is proposed as a way of disrupting social and cognitive fixations that underpin stagnations.

3.2.2 Maintain system functions

In general, transitions literature emphasizes the destabilization of incumbent actors and system functions to make space for new actors and functions. However, since we depend for our health, security and wellbeing on critical systems such as energy, transport and food, system functions must be maintained through the transition. Little literature has been found that considers this important aspect of system transition, apart from the observation by Foxon et al. (2009) that AM gives greater emphasis to the maintenance of system functions than TM.

To maintain system functions, we propose it is first necessary to identify concretely what these are and define the parameters that represent good system functioning. Once these parameters are defined, transition design can then incorporate ex-ante analysis to assess whether transition pathways will maintain system functions within required thresholds. Processes can be established to monitor system functions during the transition so action can be taken if thresholds are or appear likely to be breached. Adaptive mid-range planning (Hyysalo et al., 2019a) can then be implemented to enable these course adjustments.

3.2.3 Manage conflict and asymmetric power relations

Due to competing vested interests and complex system interdependencies, conflict is unavoidable in system transitions (Downie, 2017; Normann, 2017). This means that governance must include mechanisms for managing conflict and for decision-making in the likely absence of full consensus. Negotiation between actor groups is a necessary element of this (Steurer and Bonilla, 2016). This challenging requirement is further complicated by power differences between actors. For example, SME road freight operators individually have much less influence than large operators and other road freight actors including shippers, vehicle manufacturers and energy and infrastructure providers (Smart Freight Centre, 2021; Centre for Sustainable Road Freight, 2023).

Ansell and Gash (2008) identify that the success of collaborative governance depends on prior history of conflict or cooperation, incentives for stakeholders to participate, power and resource imbalances, leadership, and institutional design. While examples of effective collaborative governance are identified, other examples highlight where powerful stakeholders manipulate the process, public agencies lack commitment to collaboration, and distrust becomes a barrier to good faith negotiation. Their evidence suggests that strongly interdependent actors can work together to achieve rapid change, even in high conflict and low trust situations. However, without such interdependence, trust and time become necessary to negotiate decisions.

Voß and Bornemann (2011) find that conflict, asymmetric power relations and politics are often neglected in the reflexive governance approaches of AM and TM. They suggest two requirements to address this: (1) detailed rules and procedures to avoid domination and capture by powerful political interests, and (2) alignment of governance with actual political practices and existing patterns of governing.

3.3 Governance legitimacy

The importance of legitimacy within liberal democracies emerges clearly from literature; and recent history also demonstrates its significance. The *gilets jaunes* and farmers protests in

France (Goury-Laffont, 2024; Yildiz, 2024), the anti-nuclear movement in Germany (Jahn and Korolczuk, 2012), the backlash against pro-environmental and road safety policies in England and Wales (DfT, 2023a) are all examples of where social legitimacy has directly influenced policy formulation and outcomes.

While legitimacy could be defined broadly as social acceptability, three more specific legitimacy aspects are identified in literature: input, throughput and output (Schmidt and Wood, 2019). Input legitimacy relates to the diversity and representativeness of societal perspectives engaged in the decision-making process. Throughput legitimacy reflects the quality of decision-making processes and rules. Output legitimacy concerns the extent to which the results of decision-making are perceived as addressing collective problems.

While it is helpful to consider input, throughput and output legitimacy, we suggest these cannot be entirely separated. For example, for climate change deniers, pro-climate policies could be seen as failing on output legitimacy. However, climate change denial rhetoric associates climate action with the making of decisions based on the interests of "elites" (input legitimacy) and the mechanisms and regulations of the state and supra-state (throughput legitimacy). This makes it impossible to analyze the politics of climate change action without considering all three forms of legitimacy.

Some writers who oppose centralized governance criticize throughput legitimacy, as it is seen as an attempt to give authority to technocratic bodies (Iusmen and Boswell, 2017; Steffek, 2019). However, this study is founded on the assumption that the transition of complex socio-technical systems needs to be purposively codesigned by actors and policymakers, implying the need for at least some degree of centralized governance and technical understanding of the system being changed. If such "technocratic" governance is necessary, we propose that a consideration of throughput legitimacy is required to ensure that governance processes remain as far as possible aligned with societal needs and expectations.

Within an interpretivist paradigm, diverse governance participation (input legitimacy) is often associated axiomatically with good governance. However, de Geus et al. (2022) find that, in the five case studies they consider, while inclusion and participation were emphasized in each case, the way these principles were applied was opaque and the process for closing down options and making final decisions was a black box. This suggests that assuming input legitimacy naturally leads to throughput and output legitimacy may be flawed.

4 Framework validation and enhancement

Thirteen semi-structured interviews and a review workshop were held with transport policymakers and industry associations to validate and further develop the governance framework within the specific context of road freight decarbonization. All interviews were with one participant except one transport authority interview that had two participants. Table 5-2 lists the questions asked in interviews.

Table 5-2: Semi-structured interview questions

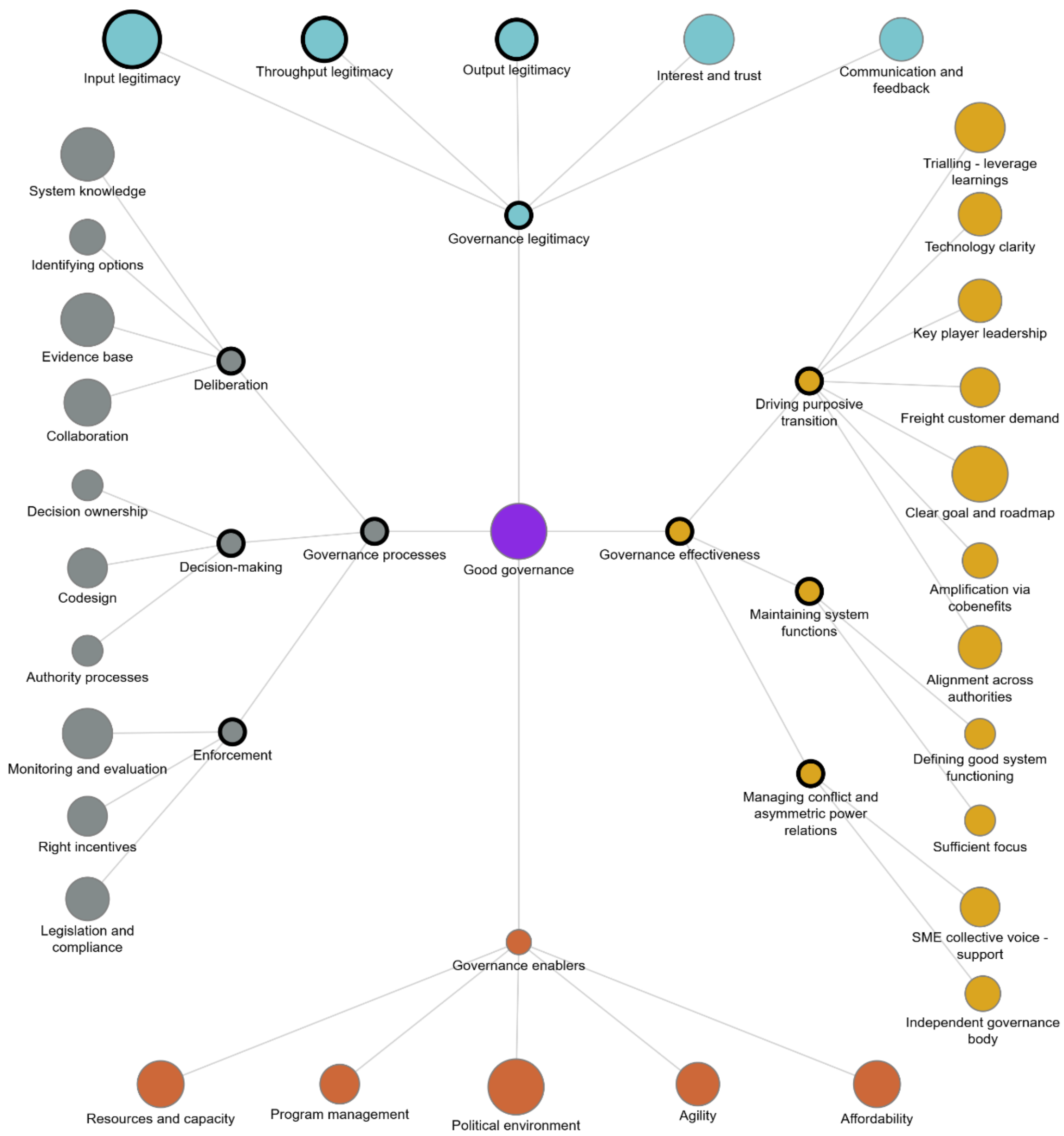
Section	Questions
Governance processes	• For each of the three governance processes, what are the key requirements for successful road freight decarbonization? • Are there any governance requirements not covered by the three processes? What are these and why are they important?
Governance effectiveness	• For each of the three governance effectiveness requirements, what are the key requirements for successful road freight decarbonization? • Are there any important governance effectiveness requirements not covered by the three mentioned? What are these and why are they important?
Governance legitimacy	• In what priority order would you place the three types of legitimacy, and why? • For each type of legitimacy, what are the key requirements for successful road freight decarbonization?
Other	• Are there other governance requirements not covered by the framework? What are these and why are they important?

Interview recordings were transcribed and qualitatively coded to identify transition governance themes. Pillars and themes were then reviewed in a workshop with five transport authority representatives. Additional commentary was captured and weightings were assigned to themes by workshop participants.

Figure 5-1 shows the themes identified from interviews aligned to the four pillars. All identified governance process and effectiveness themes aligned to one of the pre-defined theme categories and are shown as nested under these. Two new legitimacy themes were identified that did not fall within the pre-defined themes of input, throughput and output legitimacy, and are therefore shown at the same level as these. Additional important governance enablers emerged from interviews that did not fall under one of the three pre-defined pillars, so a fourth "governance enablers" pillar was created.

Figure 5-1: Governance themes from interviews

(Size of circle reflects weight assigned to theme in workshop; theme categories not weighted; themes / theme categories from literature highlighted with black border)



The remainder of this section summarizes the points raised by interview and workshop participants for each theme. Illustrative anonymized participant quotes for each theme are included in appendix A.

4.1 Governance processes

4.1.1 Deliberation

4.1.1.1 System knowledge

There was a shared view that current decision making is hampered by different parties operating in silos, each with only partial information. Both transport authority and industry association representatives highlighted that decision making would not be effective if decision makers did not have a good understanding of current freight activities and why these are done the way they are. A lack of freight expertise in transport authorities was identified as a gap, and as a result freight experts were seen being needed to facilitate deliberation and decision making. System knowledge was also seen as variable within operators with, for example, transport managers potentially having a different view to board members. However, it was noted that, given uncertainty and the complexity and scope of the multiple systems involved, there would never be perfect system knowledge.

4.1.1.2 Identifying options

Having a robust and transparent process for identifying and assessing options was highlighted as key. It was seen as important to initially identify the range of options, and to then have a multi-criteria analysis of these. Making options understandable to all stakeholders was seen as important, meaning it may be necessary to "dumb down" option descriptions and analyses. Early elimination of options that are unlikely to be feasible or politically acceptable was seen as helpful. However, it was noted that the list of available options was not static as new options become available and existing options are proved to be non-viable.

4.1.1.3 Evidence base

Establishing a robust evidence base to support deliberation was identified as necessary, but also challenging. Reluctance to share data was seen as an obstacle. Available data was highlighted as not being in the right form or sufficiently detailed to support transition planning by authorities. The short timeframes in which data had to be obtained was highlighted as a further challenge. While it was proposed that policy needs to be supported by the best available evidence, it was at the same time noted that it is impossible to have perfect information, and that decisions need to be made despite this.

4.1.1.4 Collaboration

The need for better collaboration between the public and private sectors on freight and logistics was highlighted. One participant observed that in the current Zero Emission Heavy Goods Vehicles and Infrastructure Demonstrations (ZEHIDs) in the UK, some participants were keeping their data proprietary while others were being much more open. However, another participant said that collaboration on the ZEHIDs had been very good. Collaboration was also identified as being required between operators, energy providers, government and vehicle manufacturers to establish shared charging / fueling infrastructure. A further form of collaboration mentioned was collaborative purchasing of vehicles. It was noted that collaboration was required across sectors that were not accustomed to working together, and these sectors often spoke “very different languages”.

4.1.2 Decision-making

4.1.2.1 Codesign

It was proposed that neither a fully top-down nor bottom-up process would be effective, and that it was necessary to combine elements of both. Getting the right people around the table and then keeping them there for the duration of the decision-making process was seen as challenging. In addition to engaging operators and authorities, it was proposed that codesign participants should include energy providers and those responsible for enforcing decisions. Having a design board with voting and non-voting members was suggested as a way of achieving the required breadth of input and engagement while ensuring effective decision-making.

4.1.2.2 Authority processes

Transport authority representatives highlighted the need to align with authority assurance and appraisal processes. The nature of these processes was identified as being different depending on whether decisions were national, regional or local, with more people needing to be involved the wider the impact of the decision. Aligned with this, one participant said that the complexity of decisions and impacts meant that the decision process “is always going to be painfully slow”. However, failure to follow consultation and engagement processes was seen as very likely to cause problems later.

When decisions include a commitment to spend, these typically need to be supported by a cost benefit analysis, which was flagged as being challenging for decarbonization actions that could result in costs going up. Consequently, it was proposed that a new approach to decision appraisal may be required.

4.1.2.3 Decision ownership

Clear ownership of decisions was seen as necessary. An industry association representative expressed the view that, although they expected to be consulted, executive decisions are necessary, and this requires clear decision ownership and responsibility. A transport authority representative said that clarity of decision ownership was also important when working across multiple levels of government. However, they didn’t see anyone being ready to take responsibility for key decisions such as technology choices. It was noted that, even when decision-ownership is clear, there is in some cases a reluctance to make decisions due to uncertainty and dependence on other decisions. Regarding technology selection decisions, it was proposed that, while government would determine what was defined as a zero-emission vehicle, individual operators would still need to make their own choices from the options available based on the technology that would work for them.

4.1.3 Enforcement

4.1.3.1 Monitoring and evaluation

Industry association representatives proposed that both quantitative and qualitative measures are required, and that funding and resources for monitoring and evaluation need to be identified at the deliberation stage. It was highlighted that operators are concerned that there may be a need for more vehicles due to loss of payload and charging times, and that there needs to be monitoring to capture this. Transport authority representatives expressed the view that monitoring and evaluation had historically been an area of weakness, although it was also suggested that this had received significant focus in Ultra Low Emission Zones (ULEZs).

4.1.3.2 Right incentives

A transport authority representative suggested that there are fewer levers available to policymakers to decarbonize road freight than public transport. Another argued that, while authorities can influence the choices operators make, if operators are not able to move the goods they will find a way around incentives. An industry association representative proposed that "carrot" incentives are generally seen as preferable to "stick" incentives, although an emissions trading scheme and increasing the price of diesel were identified by another participant as potentially effective incentives. Negative unforeseen consequences of manufacturer quotas from the point of view of operators were also identified, with operators being told by manufacturers they can only buy diesel vehicles if they also buy battery electric vehicles, even if the latter do not meet operational needs. It was nevertheless proposed that both carrot and stick incentives are necessary for operators to make low-carbon choices.

4.1.3.3 Legislation and compliance

Expecting operators to make low carbon choices without legislation was seen as being unlikely to be successful. However, it was noted that the extent of regulation required would vary depending on the requirement. It was suggested that road freight is already very "compliance heavy" and that compliance was potentially a better term to use than enforcement. It was also argued that regulation was "pointless" without enforcement.

4.2 Governance effectiveness

4.2.1 Driving purposive transition

4.2.1.1 Clear goal and roadmap

The need for a clear goal and roadmap was identified in ten of thirteen interviews. "Goal" was expressed variously as mission, vision, narrative, end objective, north star, direction, scope or "what good looks like". In all cases, it was seen as being necessary to provide a common understanding of the aiming point of the transition. There were differing views on how prescriptive the goal should be with regards to the specification of decarbonization solutions, but there was agreement on the requirement to decarbonize needing to be unambiguous. A shared view was expressed that expecting the industry to transition in one step, whether this was early or last minute, was unrealistic for reasons including fleet replacement cycles; differing operational requirements and constraints; and different operator profiles. A phased roadmap, potentially incorporating the concept of small in-depth change in which earlier phases lay the foundations for later ones, was seen as necessary.

4.2.1.2 Technology clarity

While some participants said that government should not be prescriptive regarding technology choices, other participants likened current technology uncertainty to a "Betamax vs VHS situation" and "a Mexican standoff". Although the banning of internal combustion engines (ICEs) was seen as helpful, clarity on the specific technologies that would be deployed at scale was argued to be necessary for infrastructure planning, as no government has sufficient funds to deploy infrastructure to support all technologies. Technology uncertainty was seen as a particular barrier for SME operators, as buying an incorrect truck could bankrupt their company. At the same time operators were seen as being resistant to having electric technology options imposed on them as there are perceived as favoring larger operators. However, while technology choices remain open, it was seen as difficult to engage with shippers on how duty cycles could be adapted to be compatible with battery electric vehicles.

4.2.1.3 Alignment across authorities

The requirement for alignment across authorities was identified in six interviews, with a shared view being expressed that relevant policymaking is siloed and split across multiple levels of government. Local and national policy were identified as often being at odds on planning and infrastructure matters. Different local authorities were also identified as placing different and incompatible requirements on operators. Lack of trust and data sharing across authorities was seen as a specific challenge.

4.2.1.4 Freight customer demand

Freight customers were identified as having an essential role to play as operators have no choice but to align to their requirements, and these requirements therefore need to be compatible with decarbonization. Current freight procurement was seen as still being primarily driven by cost and service delivery rather than environmental impact.

4.2.1.5 Key player leadership

Large operators and shippers were identified as having a key transition leadership role to play in four respects. Firstly, they were seen as having the resources required to trial new technologies and vehicles, and to accommodate this within their operations. Secondly, it was considered necessary for these actors to be at the table for key decisions. Thirdly, these organizations were perceived as being able to take decarbonization action more independently, without the same need for public sector coordination as smaller operators. Finally, early investment by key players was viewed as important for establishing the public infrastructure that smaller players could then benefit from.

4.2.1.6 Trialing - leverage learnings

Technology trials were seen as helpful to ensure solutions deliver anticipated outcomes; to provide a necessary evidence base; and to help build the case for large scale adoption. One perceived risk was that, if only larger operators participate in trials, solutions may be developed that do not work for smaller operators. Lack of communication of the outcome of trials was also seen as being patchy, particularly if a trial is unsuccessful, as it was considered that there are as many lessons to be learned from unsuccessful trials as successful ones.

4.2.1.7 Amplification via co-benefits

Emphasizing benefits in addition to decarbonization was seen as helpful to building support for the transition. Examples mentioned are the fact that drivers tend to like battery electric vehicles as they are quieter, cleaner and less tiring to drive. Reduction in particulate emissions was also seen as an important co-benefit for local stakeholders.

4.2.2 Maintaining system functions

4.2.2.1 Defining good system functioning

It was identified as being important not to focus only on vehicles, but on wider logistics systems and supply chains. Some degree of disruption was seen as unavoidable with a transition of this scale and complexity, but the need to manage disruption so that priority flows are maintained was highlighted.

4.2.2.2 Sufficient focus

Participants identified that transition projects can give insufficient focus to maintaining system functions and that, while this important, achieving this can be difficult.

4.2.3 Managing conflict and asymmetric power relations

4.2.3.1 SME collective voice – support

Transport authorities identified that engaging with SME operators was challenging due to the large number of these and their limited capacity to participate in consultation forums. It was nevertheless seen as important to get input from SMEs throughout the deliberation and decision-making process rather than just at the end. It was also noted that may SMEs do not buy new vehicles and are therefore reliant on vehicles that are available in the second-hand market.

An industry association representative highlighted that decision-makers need to consider the impact of decisions on SMEs. For this, they argued that a collective voice is required. It was also proposed that an independent monitoring role was needed to ensure that transition decisions did not result in SMEs being priced out of the market.

4.2.3.2 Independent governance body

Linked to the above point, an independent governance body was seen as required by industry association representatives to ensure that the impact on smaller operators was considered in decision making and that SMEs were not unfairly disadvantaged, for example by technology selection decisions. It was also identified that an independent body is required to coordinate decision-making across multiple authorities and that this body needs to "have teeth".

4.3 Governance legitimacy

4.3.1 Input legitimacy

Most participants identified input legitimacy as being fundamental, as it is the foundation on which the other elements of legitimacy are based. Representation, equality and accessibility were seen to be key elements of this, with two participants noting that policymaking was generally dominated by white males. Soft skills were identified as important to ensure that stakeholders felt safe to express their true views. It was suggested that, while public bodies tend to gather stakeholder input, the focus was often on meeting legal requirements rather than genuine consultation. It was acknowledged that it was unlikely that all stakeholders would agree with decisions, but if they had been consulted and they could see their views had been properly considered, they would be more likely to accept the outcome.

4.3.2 Throughput legitimacy

It was suggested that when authorities had in the past received pushback on measures that had been taken, it was often because the decision-making process had not been seen as good enough, or stakeholders had not been sufficiently engaged. Even if stakeholders provide input, if they cannot see how that input has been used, it was proposed that they will still not trust the process.

4.3.3 Output legitimacy

Making decisions relevant to stakeholders by communicating how these would impact them directly in addition to broader societal benefits was identified as a key element of achieving output legitimacy. Another proposed aspect was that funding being allocated to support a decision demonstrated policy commitment. It was questioned whether legitimacy of a measure can be asserted if, despite positive societal benefits, it failed to achieve popular support.

4.3.4 Communication and feedback

Across all aspects of legitimacy, stakeholder communication and feedback were identified as critical. This was seen as needing to include regular progress updates and communications, not only of project deliveries, but also of metrics demonstrating the positive impact of the actions taken. The importance of ensuring that the language used in communications is appropriate for the audience was also highlighted, as was the importance of communicating proposals to politicians in a way that makes clear their relevance to the political agenda.

4.3.5 Interest and trust

Lack of interest and trust amongst stakeholders was identified as a significant challenge to road freight decarbonization. While stakeholders were seen in general as being supportive of climate change action, they were also seen as being subject to more direct near-term challenges that often took priority. Politicians and public authorities were seen as giving less focus to road freight that passenger transport, as the public were perceived as broadly not caring about freight except when it directly impacted on their lives.

Regarding trust, industry associations proposed that past policy experience had reduced operator confidence that policymakers understood or took into consideration their needs. The changing of goalposts, for example end of sale dates for diesel cars, was seen to have reinforced a lack of operator confidence that policies were well thought through and would remain in place. Examples were provided of industry representatives voicing skepticism that decarbonization targets could be achieved and of a major retailer challenging local sustainable transport policy where this added time and cost to last-mile deliveries.

4.4 Governance enablers

4.4.1 Political environment

Specific political influences on governance were identified:

- The frequency of change of ministers resulting in changes in policy, which is particularly disruptive when a policy needs to be enacted over multiple election cycles.
- While politicians may support strategic policy objectives, they may either not understand or not support the practical actions required to achieve these.
- Due to the nature of the UK electoral system, gaining support for any policy that provides overall benefits but has negative local impacts was seen as extremely difficult.
- The need for a rigorous evidence trail of policy discussions and decisions was seen as required.
- The direct support of a policy by a prominent politician, for example a city mayor, was seen as being extremely helpful.

4.4.2 Resources and capacity

Lack of resources and capacity was seen as a significant challenge for both authorities and operators. Local and regional authorities were identified as often relying on only one or two individuals for freight expertise, if this expertise was available at all. Only the largest operators were seen as having the dedicated expertise and capacity required to engage with decarbonization opportunities. As a result, decarbonization and sustainability forums were perceived as often drawing on the same small pool of individuals from a limited number of organizations. One proposed way of addressing resources constraints was to use trusted partners to facilitate consultation and decision-making.

4.4.3 Program management

Four program management themes were identified:

- A transition timetable that is well understood and is stuck to
- A program management office that tracks transition activity
- Clarity of activity ownership and responsibilities
- Ensuring governance processes are clearly communicated and followed

The term “program” rather than “project” management is used as, while project management is primarily concerned with actions, milestones and resources, program management also encompasses stakeholder engagement, communication and governance.

4.4.4 Agility

The need for governance agility and adaptability was highlighted by six participants. A principal theme was that major unforeseen events such as covid and geopolitical threats inevitably changed priorities and requirements. Current strategic transport planning, which typically runs on a 10 ten-year cycle, was seen as insufficiently responsive. It was also suggested that there will be things that we don't get right first time, and that it is necessary to be able to recognize this and adjust. A further dimension of flexibility raised was to be able to adapt solutions to local requirements and opportunities.

4.4.5 Affordability

The need for option assessment and decision making to consider affordability in relation to public and private expenditure was identified. It was noted that this is particularly important for road freight operators given the low margins in the sector.

5 Conclusions

5.1 Original contribution

To our knowledge, no other research has considered the specific governance requirements of purposive road freight decarbonization. Furthermore, while there is research on the governance required to deliver major system change, this has tended to be somewhat theoretical and focused on bottom-up innovation rather than system-level steering (Avelino and Grin, 2017; Rosenbloom, 2017; Halbe and Pahl-Wostl, 2019). However, recent work is starting to address this gap e.g. (Lovell et al., 2022; Churchman et al., 2023; Lähteenoja et al., 2023; Pineda et al., 2024).

5.2 Reflection on research question

The work has provided substantial insights regarding the research question: "What are the governance requirements for rapid and radical road freight decarbonization?" and has reinforced the importance of governance to coordinate decision-making for this transition. An abductive synthesis of literature identified three governance pillars: processes, effectiveness and legitimacy: and important themes were identified for each pillar. These themes were retroductively validated and further developed in thirteen interviews and a workshop with policymakers and industry associations. A fourth pillar of "governance enablers" was also identified from interviews. In the review workshop that followed the interviews, additional valuable insights were gathered, and weightings were assigned to each theme. No themes were added or removed in the workshop, providing a good validation of the framework developed from literature and interviews. Overall feedback from participants was positive and reinforced the need for a transition governance framework. Example quotes are included in appendix A.

5.3 Governance connections and tensions

There are several tensions and connections within the governance framework that represent trade-offs and coordination requirements. Some notable examples of these are:

5.3.1 Tensions

5.3.1.1 "Driving purposive transition", "Maintaining system functions" and "Managing conflict and asymmetric power relations"

Tensions are apparent between the effectiveness dimensions of driving purposive transition, maintaining system functions and managing conflict and asymmetric power relations. Road freight decarbonization represents a major system change in which some degree of disruption and conflict is inevitable. One way of minimizing these would be to compromise on driving purposive transition. However, this is likely to mean that the transition will only happen slowly, if at all. On the other hand, driving purposive transition cannot be at the expense of major system failures or via a pathway that is only feasible for the largest operators.

5.3.1.2 "Agility" and "Technology clarity" / "Clear goal and roadmap"

The importance of agility and the ability to consider new options as these develop was reinforced. Equally, the needs for technology clarity and a clear goal and roadmap to allow vehicle, infrastructure and energy providers and operators to invest with confidence were emphasized. There are clear tensions between these requirements.

5.3.1.3 "Deliberation" and "Decision-making"

It was highlighted that policy- and decision-making should be based on the best possible evidence, but at the same time that perfect knowledge is impossible, and uncertainty is inherent in a transition of this scale. We propose that this can only be addressed based on an understanding of the decisions that need to be made and requirements of actors to make these decisions. It is also the case that certain decisions should be made early in the transition process, whereas others can or should be made later. Identifying and prioritizing focus on decisions that need to be made early may provide a means of resolving this tension.

5.3.2 Connections

5.3.2.1 "Input legitimacy" / "Throughput legitimacy" and "Governance processes"

Stakeholder engagement via governance processes forms the basis of input legitimacy. Likewise, the responsibilities and mechanisms that define how governance processes are conducted are the foundations of throughput legitimacy. Governance processes and governance legitimacy are as a result closely linked.

5.3.2.2 "Output legitimacy" and "Governance Effectiveness"

Governance effectiveness is determined by the degree to which intended transition outcomes are achieved. Output legitimacy is founded on stakeholder perceptions of transition outcomes, and the positive and negative repercussions of these. It can therefore be argued that output legitimacy and governance effectiveness are two sides of the same transition outcomes coin.

5.3.2.3 "Political environment" and "Governance legitimacy"

The political environment is rooted in the democratic forces that determine public sector priorities; and the strategic and economic vested interests that underpin private sector action. The broad definition of governance legitimacy as social acceptability means that this cannot be disassociated from these democratic forces and vested interests, and the political environment that they inform.

5.3.2.4 "Right incentives", "Legislation and compliance", "Affordability", "Resources and capacity", "Key player leadership", and "Freight customer demand"

All these themes are connected by a market-based view that private-sector actors will only make the choices required for road freight decarbonization if these are compatible with their interests. While some actors may take a more enlightened view than others regarding their responsibility to society and the planet, few will intentionally risk bankruptcy for the sake of achieving environmental goals. It is therefore necessary for politicians and policymakers, via regulation, legislation and incentives, to create an environment that encourages required actions by private sector actors. There is also a need to reconcile these requirements with "Governance legitimacy" and "Political environment" discussed above. These connections lie at the heart of why road freight decarbonization is a "wicked" problem.

5.3.2.5 "Political environment" and "Alignment between authorities"

A primary cause for different priorities between national, regional and local authorities is the different democratic and political forces at play at these different levels. It is identified in literature that devolution (in the UK) and the distribution of transport policymaking across multiple levels of government create additional challenges in delivering transport decarbonization. It is also identified that, while setting decarbonization goals is (relatively) politically easy, making the contentious decisions required to achieve these goals is much more difficult. Distribution of responsibility between authorities creates ambiguity of accountability and increases the potential to blame other bodies for failure to achieve goals.

5.3.3 Implications

The tensions and connections described above highlight some of the substantial challenges of rapid and radical road freight decarbonization. However, decarbonization remains necessary to avert the worst climate change scenarios. We believe that the Orwellian doublethink represented by arguing that decarbonization is urgent and non-negotiable, but at the same that it is a wicked problem that can only be addressed incrementally is untenable.

If the opposite of a wicked problem is, like witches in "The Wizard of Oz", a good problem, we need to find how to make the problem of road freight decarbonization good. A possible place to start would be to collectively, systematically and purposively acknowledge, engage with and seek resolutions to the above-described tensions and connections.

5.4 Opportunities for further research

5.4.1 Delivering road freight decarbonization

While we believe the developed framework provides a good conceptual foundation for the governance of road freight decarbonization, further work with authorities and actors is required to operationalize the framework including the definition of:

- Detailed governance roles and responsibilities
- Governance processes and rules of engagement
- Monitoring and escalation mechanisms to address roadblocks and other exceptions

The definition of these detailed elements will need to be codesigned by and/or negotiated with stakeholders. There is an important role for research to facilitate this process by providing relevant evidence regarding the requirements of this specific transition and for wider research into how complex system transitions can be effectively governed and steered. Explicitly investigating the governance tensions and connections discussed in Section 5.1 may provide a fruitful framing for this research.

5.4.2 Road freight decarbonization in other countries

The focus of this study has been on road freight decarbonization in the UK. We believe the approach is likely to be applicable to other national contexts, although further research is required to confirm this.

5.4.3 Governance of other transitions

Purposive governance of transitions is understudied. This analysis has focused on road freight decarbonization, but other critical transitions such as those of other freight modes, passenger transport, energy systems and food systems also require system-level design choices to be made.

Many of the governance themes identified in this research may also be applicable to these wider transitions.

Appendix A: Illustrative participant quotes

Governance processes

Deliberation

Collaboration

- "Sharing of data is problematic, either from a company competitive point of view, or just for SME's having the resources and understanding how to do it." (Industry Association 4)
- "There is a significant need for the public and private sector to collaborate more on freight and logistics." (Transport Authority 3)

Evidence base

- "In all the engagement stuff I've done, where you've got operators and trade associations and businesses and local authorities, you find that there's a conversation, but nobody will share any actual facts and figures." (Industry Association 1)
- "You will never have the perfect evidence base. But as civil servants, we always strive to have as much evidence as we can to inform policy decisions." (Transport Authority 11)
- "The quality of almost everything we've been involved in ... is the data doesn't drill down into enough detail ... in the way that we would want it to." (Transport Authority 6)

Identifying options

- "If ministers ... take a view on a certain technology ... then it's quite important to understand the scope that the options are being developed in." (Transport Authority 11)
- "You'd have to look at all the options rather than just pluck one idea out of thin air. And then you'd go through a process, you'd do a multi criteria analysis." (Transport Authority 8)

System knowledge

- "When it comes to road freight and commercial vehicles, there aren't many people that really fully understand the nuances of the industry." (Industry Association 2)
- "Having lots of different actors who are not traditional people that would get involved with freight, energy companies and so on, getting all those people together can be quite challenging." (Transport Authority 12)
- "Half the time you're dealing with half-truths or half-baked sets of information that doesn't really allow you to [identify] the most optimum solution and bring all the different [stakeholders] with you." (Transport Authority 3)
- "It's bringing everyone to the table to understand how everything fits together because the solutions are not going to be simple, and when you implement them, you need to consider that complexity." (Transport Authority 5)
- "If you don't understand why it works that way in the first place, you won't come up with the case for how to change it, because you're not understanding the fundamentals of their business model." (Transport Authority 7)

- "Having everyone at a baseline level of knowledge to be able to have that conversation could be quite challenging, because we don't have [many] freight experts in local government." (Transport Authority 8)

Decision-making

Authority processes

- "If the approval and assurance process has not been fully followed, if we've not explained, consulted and engaged multiple times with multiple stakeholders at multiple levels ... things break down." (Transport Authority 2)
- "Our conventional tools for cost benefit analysis don't help us. Generally they're not aimed at decarbonizing because decarbonizing is often more expensive than business as usual in the short term. It probably needs new approaches to enable decision making that is not entirely based on conventional cost benefit analysis." (Transport Authority 8)

Codesign

- "We have voting members on the board and then we have non-voting members, and that's quite a useful way, because everyone gets to skill up and teach in, but when it comes to voting, it's different." (Transport Authority 9)

Decision ownership

- "If nobody takes ownership for it, it won't change. Even if it's going to be a group of people coming together, the first stage has to be to nominate somebody to be the person that's the owner of it." (Industry Association 1)
- "We're not a democracy. I don't expect ... to vote and that vote somehow has some meaning. Because at the end of the day, someone has to make an executive decision." (Industry Association 3)
- "Whilst government will have a role in setting the scope of what is considered zero emission, there won't be one place where a decision will be taken about which technology is best for each individual operator, because that would be a commercial decision for them, and will also be informed by wider factors like ... installing public refueling or recharging infrastructure." (Transport Authority 11)
- "You need to know who leads what and who's responsible for what when it comes to deliberation and decision making. You need to have a good understanding of accountability." (Transport Authority 5)

Enforcement

Legislation and compliance

- "Putting in regulations without enforcing them ... is pointless regulation." (Industry Association 1)
- "I'd probably call it compliance rather than enforcement, but it's making sure there's a clarity of what the legislation is." (Industry Association 2)

Monitoring and evaluation

- "Operators are concerned you may need more vehicles because the payload is compromised or you need to stop to charge. There is going to need to be a way to understand how we measure and monitor that impact." (Industry Association 4)
- "It's important because, if you are making regulatory decisions, they have quite a long timeframe if you're looking at net zero, so it's right we need to be able to look back at it

effectively and say, did we get it right or do we need to change things?" (Transport Authority 12)

- "It's about keeping everyone on board and measuring progress towards the set ambition." (Transport Authority 7)

Right incentives

- "Operators would absolutely support that in a safety perspective you need regulation. In this space [decarbonization], operators prefer the carrot approach, and that's why the fuel duty differential has been very successful." (Industry Association 4)
- "It's not for us to tell [operators] which vehicles to drive as such, but we can influence which vehicles they drive. But if they can't physically move, it's almost a demand management measure, then they will work a way out." (Transport Authority 2)
- "On public transport, we've got more levers to pull. But for freight it is pretty limited." (Transport Authority 8)

Governance effectiveness

Driving purposive transition

Alignment across authorities

- "All the other disciplines, economic policy and planning policy for instance. These are all massively important for anything that we'll be talking about here. Planning policy, for instance, has a markedly different strategic objective [than transport policy]. You've got policies running against each other and it's trying to align those." (Transport Authority 2)
- "The process of sharing information on freight and the ability of the public sector to plan for that effectively is [limited], because they don't have the capacity or the resources ... to deal with the things that we think are important. " (Transport Authority 3)
- "There are pockets of good practice and there's people out there saying we need to sort this out, but it's like swimming uphill when you haven't got the policy leaders and the policy positions aligned at the right levels." (Transport Authority 3)

Amplification via cobenefits

- "When operators have transitioned to battery electric, they say they're quieter, they're cleaner and the drivers really love them. It's selling the positives for the organization." (Industry Association 4)

Clear goal and roadmap

- "I think you need a clear narrative of what it is beginning to end. Is it a vision, mission, something that's ties it together. Otherwise ... it starts to drift apart. " (Industry Association 1)
- "Something that's completely missing is the pathways to change are not very well articulated for the industry. If your end goal is net zero, let's work out how we get there by steps of low carbon renewable fuels or increased use of biofuels or biomethane, and then look at electrification and then see how we can optimize the operations." (Industry Association 2)
- "Industry can do this through market innovation. And what we need the politicians to do is to have an overall framework that allows that phasing in and phasing out happen, but equally then not interfere, just let the market do its work." (Industry Association 3)

- "[There will need to be] phased implementation ... you're not going to go from one minute having diesel vehicles to the next minute everything's methane, that's just unrealistic." (Industry Association 4)
- "To get click quick and clear action, you need to make it really clear what the pathway is and now you're going to do it. But that's easier said than done because it's how all the dots join up across policy areas, and nationally, regionally and locally." (Transport Authority 3)
- "In terms of the change bit, you've got to align with a fleet replacement cycle, because it's only the new vehicles you'll get to be the cleaner ones." (Transport Authority 7)

Freight customer demand

- "You need to buy-in from customers, because while customers are saying we need to reduce our [scope 3] emissions, they're not necessarily prepared to pay for it." (Industry Association 4)

Key player leadership

- "The other one that jumped out for me was key player leadership, [for example] DHL and Amazon, because early investment will ensure the public infrastructure will be in place that others can then piggyback off for their own transition." (Transport Authority 11)

Technology clarity

- "At the moment, the government have been fuel and technology agnostic and [have said] they'll let the market decide. From everything I've seen, that leads to uncertainty - I refer to it as a Mexican standoff." (Transport Authority 3)
- "We're driven by SMEs. So if I have one or two HGVs and I have to purchase another one, it's a massive undertaking. If I buy the wrong truck, it bankrupts my company. How am I going to make a decision? That's the number one question facing the industry." (Transport Authority 4)

Trialling - leverage learnings

- "That is something that is very useful to also build the case for things, both externally and internally. It's something that is definitely useful when it comes to planning the change and making sure that everyone's on board with it." (Transport Authority 5)

Maintaining system functions

Defining good system functioning

- "If you're carrying out quite radical change, there will be some disruption. It's about understanding and managing disruption so that your priority freight flows are always maintained." (Transport Authority 9)

Sufficient focus

- "Maintaining system functions is more important than most people would think. People do understand it, but it's how to bridge that. It's not an easy one to do." (Transport Authority 2)

Managing conflict and asymmetric power relations

Independent governance body

- "To manage conflicts and the asymmetric power relations, some independent body is required. [This needs to] ensure that once you've set the course, you've got to get to zero, but by incentivizing reduction in carbon from the fleet in such a way that those vehicles then can be cost competitive to diesel. " (Industry Association 2)

SME collective voice - support

- "The history of [SME] fleets is they don't buy brand new vehicles. They buy second hand refurbished HGVs which have been used by larger companies. The trouble is that when you decarbonize, there isn't a second hand market you can go to." (Transport Authority 4)
- "But if you're talking to smaller operators at a regional level, just making the time for those kinds of meetings might be a challenge [for them]." (Transport Authority 8)

Governance legitimacy

Input legitimacy

- "Every time [authorities] consult, they think we're going to get masses of push back. Well, you are, but at least you know what the pushback is." (Industry Association 1)
- "But too often, there's a feeling that the consultation process is about submission rather than outreach and engagement." (Industry Association 2)
- "When you get to that decision making, you won't have total consensus, but you'll be able to say, we've heard a lot of voices, we've discussed the evidence, and everyone's been informed and been able to feed in in an informed way." (Transport Authority 3)
- "Taking input [legitimacy], I do think decision making is not very representative. Elected representatives probably more so, but in terms of your officers and civil servants, it's not great. " (Transport Authority 8)

Throughput legitimacy

- "Did you tell the person who [gave the input] that you did something with it? If they don't see you've done something with it, they will still not trust the process." (Transport Authority 7)

Output legitimacy

- "They've got the legitimacy of being given the money to do it. People have bought into the fact that it's an essential part of the mix." (Industry Association 2)

Communication and feedback

- "You can't say six months after a big upheaval [that it was worked]. People want more than that. [For example] they want to know that 20 mile per hour zones have led to a fall in accidents and greater road safety." (Transport Authority 1)
- "Completing the feedback loop and telling people what you've done with what they've said is the thing which is never done. That is really critical." (Transport Authority 7)

Interest and trust

- "Having confidence in what government is saying and the goal posts won't change. With the phase out date for cars and vans, we had the 2035 date which was stretching, that was moved to 2030 and then moved back, and now the new government may be moving it back again." (Industry Association 4)
- "It is a challenge equally with the private sector, because they're fed up of years of nothing really happening. They say that we've said all this before ... we're not convinced it's going to work because look at your track record." (Transport Authority 3)
- "A city or regional authority is a challenging world to get action on freight, because there's always higher priorities. " (Transport Authority 8)

Governance enablers

Affordability

- "Especially given the make up of the UK freight industry where profit margins are so small and cost of hardware is so high." (Transport Authority 10)
- "Subsidies aren't available. The number of vehicles we are talking about (is huge)." (Transport Authority 4)

Agility

- "If we go back 100 years, we were transitioning from horse drawn vehicles to using trains [and then] lorries. However, for the lorries to start getting across Britain, lots of petrol stations had to be put in place, not by government but by the private sector. That took decades. The problem we've got is, we can't wait 30-40 years because of the climate emergency. So what happened in the past is not an example that we can say will happen again." (Transport Authority 4)

Political dimensions

- "You have politicians who say they want to do these things, and then you present them with the reality of what change means." (Transport Authority 3)
- "If there's anything that is seen as potentially unpopular with local people, it really is like pushing treacle up hill." (Transport Authority 6)
- "I guess there's an element of political interest and will as well, because if you've got a leader, say a mayor who was super interested in decarbonizing freight, it would probably happen." (Transport Authority 8)

Project management

- "You need the responsible person. You need the clear management process, the project management. " (Industry Association 1)
- "There needs to be a program around it, which has proved to be really helpful for us." (Transport Authority 5)

Resources and capacity

- "The big players do see these things as important ... but where it falls down is they don't have the capacity or people to spend the time working with us to bridge the gap, because commercially they don't see it as a priority." (Transport Authority 3)
- "You need an external person, it's almost a peer review, who you can say to ..., “these are the options, what is your feedback?”" (Transport Authority 5)
- "Sometimes you'll have capital funding to do something but lack the revenue funding to have the people to implement these things, or for ongoing implementation if it is something that requires ongoing revenue funding. " (Transport Authority 8)
- "There's not much knowledge and understanding of the freight sector." (Transport Authority 8)

Other

Feedback

- "This process that you're taking us through is almost a rehearsal for if we were developing the actual policy." (Transport Authority 1)

- "Nothing based on what we've discussed today that immediately strikes me as missing from that. I think that's quite comprehensive." (Transport Authority 12)
- "I really this framework." (Transport Authority 5)
- "I think this is a really strong framework and it's addressing the right things. " (Transport Authority 7)
- "Those 3 pillars you've referenced, and the evidence-base are really critical to tackle the right opportunities and issues." (Transport Authority 7)
- "I think it's really important and we forget about it at our peril. Because of decarbonization, is only going to increase the importance, because everything else is going to decarbonize by itself." (Transport Authority 8)

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Paper 6: Hydrogen for long-haul road freight: A realist retroductive assessment

Phil Churchman, Thijs Dekker, Kate Pangbourne, Vasco Sanchez Rodrigues

Abstract

This study considers the important question of energy supply choice for decarbonizing general-purpose long-haul road freight. This question must be resolved if operators, infrastructure providers, energy providers and vehicle manufacturers are to make the investments necessary to enable this critical transition. There are two principal innovations in the study approach: the consideration of socio-technical and political as well as techno-economic factors; and the application of realist retroductive option assessment. The study first focuses on perhaps the most contentious of the options being widely discussed: hydrogen. A literature review is conducted to identify ten requirements for an energy supply choice to be feasible. For hydrogen, "what would need to be true" conditions are identified for each requirement. Considering these, evidence from literature is used to assess the likelihood of each condition becoming true within the lifespan of a vehicle bought today. A higher-level analysis is then conducted for the other principal low carbon options: battery electric, electric road systems (ERS) and biofuels. The approach is found to be effective for assessing option feasibility in the context of high uncertainty, and we believe it can also be applied to other systemic choices and transitions. It is concluded that there are conditions where battery electric, ERS and biofuels can become feasible within the lifespan of a vehicle bought today, if they are not already. However, this is found to be very unlikely to be the case for hydrogen, meaning hydrogen can be disregarded as a vehicle purchase consideration at this time.

Keywords: Hydrogen, Road freight, Decarbonization, Techno-economic, Socio-technical, Political

1. Introduction

One of the most prominent and contentious debates in road freight decarbonization is whether hydrogen is a viable fuel for long-haul freight, and if it should be developed in parallel with other low carbon options. Some argue that all options are required and operators should make their own choices on the technology to adopt (EU Science Hub, 2021). Others suggest that hydrogen cannot be feasible for reasons including high energy losses and that, while hydrogen remains on the table, deployment of other decarbonization solutions will be slower (Ainalis et al., 2023). However, there is broad consensus that hydrogen is not a feasible solution today, and that several unaddressed challenges would need to be resolved for it to become feasible (Wanniarachchi et al., 2023). While these challenges remain, some analyses conclude that the rational choice is for operators to defer the transition to low-carbon energy source options until such challenges are resolved and the option landscape becomes clearer (Winkelmann et al., 2024). This conclusion inevitably leads to further delay in the low carbon transition of this sector.

General purpose long-haul road freight requires a comprehensive charging / fueling network and interoperability across (in the UK) thousands of operators (Connected Places Catapult, 2024). Small operators are an important part of road freight (GOV.UK, 2021), with operators with fewer than 50 employees representing 99% of total UK operators; and 35% of UK heavy goods vehicles (HGVs) in fleets of fewer than 10 vehicles (Centre for Sustainable Road Freight, 2023). Many smaller operators will not be able to deploy mixed technology fleets because of operational and resource constraints (Smart Freight Centre, 2021). The cost for decarbonizing UK road freight is estimated at circa £20bn based on either an electric or hydrogen-based network (DUKFT, 2023), and these costs will be substantially higher if a suboptimal mix of technologies are implemented nationally (Hall and Lutsey, 2019). This means it is unlikely to be feasible to deploy full national networks of both hydrogen and electric HGVs for general-purpose long-haul road freight in the short to medium term.

Battery electric vehicles appear certain to be part of the road freight mix for short-medium distances, and the range of applications is likely to grow as the charging network and battery technology further develop (Nykvist and Olsson, 2021). Electric road systems (ERSs) provide another electricity-based solution where electricity is supplied directly to the vehicle while in motion via an overhead catenary or other means (Ainalis et al., 2023). Large scale battery electric and ERS deployment both share a requirement for an increase in low-carbon electricity generation, storage and distribution capacity (ICCT, 2022). Battery electric and ERS trucks are technologically identical apart from the addition of equipment to connect to the external power supply and a reduced battery size for ERS trucks. Both offer high end-to-end energy efficiency (Deshpande et al., 2023; ICCT, 2023). However, ERS requires major investment in physical infrastructure before a single ERS vehicle can be deployed (ITF, 2022).

Hydrogen trucks come in two varieties, hydrogen internal combustion engine (ICE) and hydrogen fuel cell. These both require a hydrogen fuel supply but have different vehicle technologies. Hydrogen ICE trucks use modified diesel engines whereas hydrogen fuel cell trucks are battery electric trucks with the addition of hydrogen storage and a fuel cell to convert hydrogen to electricity, and a reduced battery size. Hydrogen ICEs incur a 75-80% energy loss (Hosseini and Butler, 2020) and fuel cells incur 40-60% energy loss in addition to a 10-15% energy loss in the electric drive train (Wu et al., 2018; Basma and Rodríguez, 2022). While ICE technology is well developed, fuel cells remain expensive and challenging to manufacture and have unresolved reliability issues (Advanced Propulsion Centre UK, 2021). Both types of hydrogen truck can carry hydrogen either in liquid or compressed gaseous form. The former increases the range of vehicles but requires the hydrogen to be liquefied and maintained at minus 253 Celsius (Daimler Truck, 2024), incurring a substantial additional energy loss and cost penalty (Al Ghafri et al., 2022). Based on a hydrogen energy density of 33 kWh/kg (Møller et al., 2017) and a liquefaction energy requirement of 13kWh/kg using current methods (Hunt et al., 2023), the energy loss through liquefaction is 13 / (33 + 13) or c. 30%.

There are four principal sources of low carbon hydrogen currently identified: 1) "Green" hydrogen produced by the electrolysis of water using electricity generated from low-carbon sources; 2) "Blue" hydrogen produced from steam reforming of methane with carbon capture and storage (CCS); 3) "By-product" hydrogen produced from the chlor-alkali process (Paulu et al., 2024); and 4) "White" hydrogen that is naturally trapped in geological formations (Zgonnik, 2020; Pierce, 2024). The last of these, while possibly providing an abundant, clean and cheap source of hydrogen, is also highly speculative and subject to widely varying estimates of production potential and environmental risks (Pierce, 2024). A further possible source of "orange" hydrogen is also proposed, which artificially provokes the natural processes that result in the generation of white hydrogen (Osselin et al., 2022). However, this is more costly and speculative than white hydrogen and is not considered within the scope of this paper.

It is understandable that operators and infrastructure providers are hesitant to commit to a certain technology when facing such a complex option landscape. When operators purchase a vehicle, they are not doing so only based on the economics and capabilities of the vehicle today, but also on the expected performance and operating cost of the vehicle versus other technologies during its lifespan. This is because the latter will determine the operator's competitiveness while using the vehicle, and the value of the vehicle when it is resold to the next owner. If there is a high degree of uncertainty regarding future vehicle economics and capabilities, operators are likely to stick with tried and tested diesel vehicles for as long as possible.

Based on UK DfT (2023) data, 82% of HGVs registered in Great Britain at the end of 2023 were thirteen years or younger since first registration. A separate analysis based on the volume of HGVs deregistered per year versus total numbers of licenced vehicles results in an estimated average HGV lifespan of twelve years, which reduces to 9.75 years for HGVs over 18 tonnes. Based on these analyses, a thirteen-year lifespan is taken as a conservative assumption for vehicles used for general-purpose long-haul road freight.

We propose that if the deployment of hydrogen for general-purpose long-haul road freight is unlikely within the thirteen-year lifespan of vehicles being purchased today, it can be disregarded as a purchase option for organizations buying vehicles at this time. The removal of this option would reduce the complexity of purchase choices and may increase adoption of other low-carbon vehicle technologies including battery electric, biomethane and hydrogenated vegetable oil (HVO) where these meet feasibility requirements. This scenario would not rule out the possibility that dedicated fleets with an economic supply of low-carbon hydrogen could adopt hydrogen in the near term, or that hydrogen could play a wider long-term role in future vehicle renewal cycles.

However, there is substantial resistance to making this decision. There are powerful lobbyists and economic vested interests for all options, and policymakers are reluctant to back specific vehicle technologies (DfT, 2022). This is exacerbated by the fact that there are research studies advocating every option (Månsson et al., 2014; Moriarty and Honnery, 2019; Winkler et al., 2022; Ainalis et al., 2023), and others that conclude that all options must remain on the table and more research is required (Greening et al., 2019; Haugen et al., 2022).

The ontologically realist assessment presented in this paper adopts a retroductive analysis approach. The significance of adopting a realist ontology is that, unlike relativist ontology, it assumes that reality and truth are independent of context and the individual values, norms and beliefs of humans. We propose that this is a necessary assumption if actors are to codesign system transitions as, to do this, actors need to reach a common view of the system to be transitioned, the choices required, and the options available for these choices.

Retroduction is a methodological alternative to more commonly used deductive and inductive research methods. The "retro" in retroduction implies a form of backcasting in which analysis considers a predefined theory, in this case that a certain energy source option could be feasible; identifies the conditions under which this theory would be true; and assesses the likelihood of these conditions being met (Meyer and Lunnay, 2013; Fletcher, 2017). Retroduction allows an ontologically realist view of the future to be taken while at the same time recognizing that complex and emergent causal mechanisms of systems are very hard to "prove" deductively using traditional positivist methods (Bhaskar, 2013). Both qualitative and quantitative approaches can be relevant for retroductive analysis (Papachristos and Adamides, 2016; Fletcher, 2017). Realist retroductive analysis aligns with the "answer first" approach used by management consultancies to efficiently assess strategic options, which is also known as the "pyramid principle" of problem structuring and communication (Minto, 2009). The realist retroductive approach is to our knowledge novel for the assessment of sustainability solutions; and Mukumbang et al. (2021) specifically identify its use in studies generally to be "minimal and inadequate". Retroduction is more widely, although still not extensively, used in ontologically relativist (rather than realist) social science research (Meyer and Lunnay, 2013; Papachristos and Adamides, 2016; Belfrage and Hauf, 2017). Realist retroduction is a powerful and, we would argue, under-exploited tool for research seeking to inform policy and decision-making in the context of high systemic complexity and uncertainty.

Two core research questions are considered:

1. What systemic conditions would need to be true for hydrogen to be feasible for general-purpose long-haul road freight?

2. How likely is it that these conditions will be met within the lifespan of vehicles being bought today?

In addition, a higher-level assessment is conducted for other energy source options.

The purpose of realist retroductive option assessment (RROA) is to assist decision-makers to select between available options. A relevant body of academic work is Decision Making under Deep Uncertainty (DMDU). Under the banner of DMDU, a suite of approaches has been developed to increase the robustness and adaptability of decision-making regarding systems that are subject to high uncertainty (Marchau et al., 2019; Stanton and Roelich, 2021). Of these, the method that is conceptually closest to RROA is Robust Decision Making (RDM), as this seeks to identify decision options that are valid across a range of contextual and systemic input variable assumptions. However, an important distinction is that, while RDM applies quantitative modelling to identify the range of potential system outcomes that result from adjusting contextual and system variables, RROA applies logical argumentation supported by available quantitative and qualitative evidence.

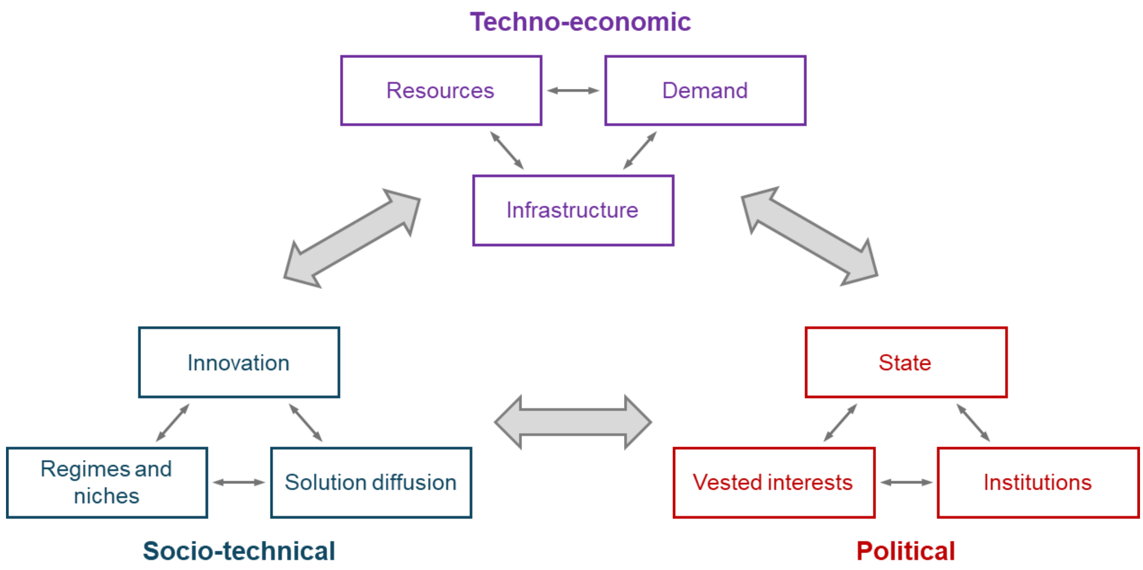
The assessment draws on a wide range of peer reviewed and grey literature. Appendix A categorizes the referenced literature by perspective offered and source type.

The remainder of the paper is organized as follows: section 2 presents the multi-perspective requirements framework developed from literature; section 3 documents the assessment of hydrogen conducted using this framework; section 4 presents a higher-level assessment for other energy source options; and section 5 concludes with a reflection on original contribution, study limitations, and opportunities for further research.

2. Multi-perspective framework

Cherp et al. (2018) identify techno-economic, socio-technical and political perspectives, shown in figure 6-1, as all being important for national energy transitions. The techno-economic perspective considers the technical and economic benefits, limitations, and costs of different technology solutions; the socio-technical perspective considers how innovations emerge and ultimately displace incumbent socio-technical systems; and the political perspective considers how policy processes, networks, vested interests and the state interact to enable or hinder sustainability transitions (Churchman et al., 2025a). Most research into road freight decarbonization is techno-economic (Meyer, 2020). However, political and socio-technical aspects are also identified as important for this transition and are starting to receive greater attention (Churchman and Longhurst, 2022; Neagoe et al., 2024). The lack of research considering all three perspectives in combination is a significant research gap.

Figure 6-1: Techno-economic, socio-technical and political perspectives of national energy transitions
(source: Reproduced from Cherp et al. (2018, p.186))



Building on this framework, table 6-1 includes ten systemic conditions that are proposed as needing to be fulfilled for an energy source option to be a feasible road freight decarbonization solution. These were identified based on the literature referenced in table 6-1; and interviews and workshops from previous studies with policymakers, industry participants and experts (Churchman and Longhurst, 2022; Churchman et al., 2023; Churchman et al., 2025b). These conditions have been defined to be as far as possible mutually independent. However, they are not exhaustive, for example "Vehicle and infrastructure reliability, performance, longevity and safety are adequately proven" (Barthelemy et al., 2017; Kurtz et al., 2019; Kurtz et al., 2020), and "Sufficient vehicles can be produced" (Shabani et al., 2019; Advanced Propulsion Centre UK, 2021; Xun et al., 2021) could also have been added. In addition, broader political and social conditions could have been included, for example: "public acceptance of solution" and "a supportive policy framework". However, these other conditions are moot if the ten conditions are assessed as unlikely to be fulfilled, and wider conditions such as public acceptance of solution and a supportive policy framework are to at least some extent dependent on these ten conditions. It was therefore decided to focus on the ten conditions only.

Table 6-1: Systemic conditions for energy source option to be a feasible road freight decarbonization solution

Condition	References
A: Techno-economic – Energy	
A1: Projected energy supply capacity satisfies projected demand at acceptable per-unit cost	(Cebon, 2020; Kim et al., 2020; Ajanovic et al., 2022; Lu et al., 2022; Raeesi et al., 2024)
A2: Total “well-to-wheel” emissions[1] of carbon, other greenhouse gases (GHGs) and non-GHG pollutants are a substantial reduction compared to diesel	(Mojtaba Lajevardi et al., 2019; Booto et al., 2021; Ren et al., 2022)
B: Techno-economic - Vehicles	
B1: An acceptable return on capital on vehicles can be achieved	(Basma et al., 2022; Gunawan and Monaghan, 2022; Rout et al., 2022)
B2: Vehicle capabilities allow operators to meet customer requirements	(Wang, 2015; Anderhofstadt and Spinler, 2019; Olabi et al., 2021; Aryanpur and Rogan, 2024)
B3: Emission increases from vehicle manufacture do not outweigh energy emission reductions	(O’Connell et al., 2023)
C: Techno-economic - Infrastructure	
C1: Emissions from infrastructure build do not outweigh net energy and vehicle emission reductions	(Marsden et al., 2022; O’Connell et al., 2023)
D: Socio-technical	
D1: Energy, infrastructure and vehicle timelines can be aligned	(Haugen et al., 2022; Li et al., 2022)
D2: The risk of backtracking is minimized	(Edmondson et al., 2019; Marsden and Schwanen, 2024)
E: Political	
E1: The solution provides energy and freight transport security	(House of Commons Transport Committee, 2022; HM Government, 2023)
E2: The solution aligns with economic and strategic interests of actors required for its implementation	(Downie, 2017; Iordache et al., 2017; Normann, 2017)

[1] Well-to-wheel emissions are the total emissions resulting from the extraction/generation, processing, storage and distribution of energy and the consumption of energy in the vehicle.

If it is assumed that government policymaking is rational and seeks to encourage actor choices that are aligned with system-level feasibility, feasibility for vehicle purchasers could be expected to mirror these conditions. While it is possible that exogenous political factors and/or non-rational policymaking could create a divergence between system-level feasibility and feasibility for vehicle purchasers, it is assumed for the remainder of this analysis that this is not the case.

While conditions are often treated in studies as factors that can be traded off against each other when comparing different solutions, each of the conditions in table 6-1 are individually necessary. This means that failure to meet any one condition is likely to render the energy source option infeasible as a decarbonization option, irrespective of other factors. This assessment does not assess decarbonization options versus other options, but whether the option itself is feasible for general-purpose long-haul freight within the lifespan of vehicles being bought today.

3. Assessment of hydrogen against conditions

This section considers the research question "How likely is it that these conditions will be met within the lifespan of vehicles being bought today?" for each of the ten conditions identified in section 2. Referencing relevant peer reviewed and grey literature, specific "what would need to be true" requirements for each condition are proposed.

Evidence from literature is then drawn upon to assess the likelihood of the condition being fulfilled within the lifespan of vehicles bought today as follows:

- GREEN: Likely to be feasible based on identified evidence
- AMBER: Feasibility unclear – more information required
- RED: Likely not to be feasible based on identified evidence

The assessments are based on logical reasoning supported by quantitative and qualitative evidence from a mixture of peer reviewed and grey literature sources. This hybrid quantitative / qualitative approach is aligned with the "broad critical scrutiny" advocated by critical realism (Bhaskar, 2013), and contrasts with the principally quantitative approaches typically used for techno-economic analyses. As well as permitting consideration of qualitative evidence in the assessment of techno-economic requirements, it allows socio-technical and political requirements, which are often inherently qualitative in nature and as a result not readily amenable to quantitative analysis, to be evaluated. Quantitative evidence presented includes cost, energy/fuel efficiency and vehicle range implications of energy source options.

3.1. Techno-economic requirements

3.1.1. Energy

A1: Projected energy supply capacity satisfies projected demand at acceptable per-unit cost – RED

What would be considered an "acceptable" per-unit cost is a subjective judgement. However, a relevant objective reference is the current cost of diesel per 100 kilometers travelled for a given vehicle type, as it is a comparison against this reference that operators would make if they were considering switching to hydrogen today. Basma and Rodríguez (2023) provide the estimates in table 6-2 for a 2023 model long haul truck based on weighted average 2023 fuel prices in the European Union (EU). These estimates make the favorable assumption that that the minimum level of taxation as proposed in the Revision of the Energy Taxation Directive in Europe (European Commission, 2021) is applied.

Table 6-2: Comparison of green hydrogen and diesel fuel cost per 100km
(source: (Basma and Rodríguez, 2023))

Long-haul truck fuel type	2023 fuel cost (EU weighted average)	Consumption per 100km	Fuel cost per 100km
Diesel	€1.22	30.7 liters	€37.5
H2 ICE	€10.30*	10.23 kg	€105.7
H2 fuel cell	€10.30*	8.32 kg	€85.7

*: Green hydrogen cost

One reason for the high cost of green hydrogen is the 40-50% energy loss incurred in the electrolysis of water (Burton et al., 2021). A 2030 estimated fuel cost for green hydrogen of €7.77 (Basma and Rodríguez, 2023) reduces the cost for the two hydrogen options to €64.6 per 100km for H_2 fuel cell and €79.5 per 100km for H_2 ICE. We suggest that this is still unlikely to meet the requirement of being an acceptable per-unit cost compared to diesel. Based on this, we propose that a "what would need to be true" requirement for this condition is:

> <u>A sufficient supply of low carbon hydrogen that is substantially cheaper than green hydrogen produced via current methods is secured.</u>

It is possible that "blue" or "white" hydrogen could fulfil this requirement. Green hydrogen would only meet the requirement if substantial advances were made in electrolyzer efficiency (Burton et al., 2021). By-product hydrogen only makes up 3.5% of hydrogen produced in the EU today and 85% of this is already used for other purposes (Paulu et al., 2024). Neither blue nor white hydrogen have been realized or proven at scale and are subject to several development uncertainties (Fan et al., 2021; Zoback and Smit, 2023; Boretti, 2024). Favorable assumptions are therefore necessary regarding the rapid proving and development of blue or white hydrogen and the subsequent deployment of large-scale production and distribution capacity for this requirement to be fulfilled. While this cannot be ruled out, we believe that this is unlikely and have assessed this condition as RED.

A2: Total "well-to-wheel" emissions of carbon, other greenhouse gases (GHGs) and non-GHG pollutants are a substantial reduction compared to diesel - AMBER

Hydrogen is the smallest molecule that exists and has a high propensity to leakage. While hydrogen is not a direct greenhouse gas, it has been found to have negative indirect climate impacts via its chemical interactions with atmospheric methane, ozone and water vapor, resulting in a global warming potential (GWP) of 6-16 times that of CO_2 for the same mass of gas (Warwick et al., 2022; Sand et al., 2023). Hydrogen is however a much lighter molecule than CO_2, meaning that hydrogen leakage is estimated as only partially offsetting rather than eliminating the benefits of decarbonization at a 20% leakage rate (Sand et al., 2023). However, there is a high uncertainty range in hydrogen's GWP and in the total "well-to-wheel" leakage that will occur. Based on this, we propose that a "what would need to be true" requirement for this condition is:

> It is confirmed that hydrogen leakage can be contained to a level at which its negative climate effects do not substantially offset benefits from carbon emission reduction.

Considering the impact of hydrogen adoption on carbon and methane emissions, these are dependent on how the hydrogen is produced:

- Green hydrogen is as low carbon as the electricity used to produce it.
- "Grey" hydrogen produced from methane without CCS represents most of the hydrogen produced today and can result in higher GHG emissions than diesel engines (Zemo Partnership, 2021). This should therefore be ruled out as a transportation fuel.
- Blue hydrogen produced from methane with CCS can capture 60-85% of CO_2 emissions from the production process, but this results in an additional energy loss (CCC, 2018; Ajanovic et al., 2022). The undersea or geological storage of captured CO_2 entails a risk of further CO_2 leakage (Gholami et al., 2021). There is also a risk of methane leakage from blue hydrogen production, which is itself a strong greenhouse gas (Ajanovic et al., 2022). As a result, there are question marks on whether blue hydrogen reduces global warming impact compared to the direct use of fossil fuels (Howarth and Jacobson, 2021).
- By-product hydrogen, to be low carbon, needs to be produced using green electricity. Also, as discussed above, by-product hydrogen volumes are only a small proportion of hydrogen produced in the EU today and most is already used for other purposes (Paulu et al., 2024). By-product hydrogen can only therefore make a small contribution to the

quantity of hydrogen required if hydrogen is to be used for large scale road freight decarbonization.

- White hydrogen reserves can also contain methane, creating the risk that methane could be released as well as hydrogen in its extraction (Pierce, 2024)

Based on this, we propose that a further "what would need to be true" requirement for this condition is:

> Blue or white hydrogen are proven to offer substantial well-to-wheel carbon equivalent emissions reductions compared to diesel if these are to be used as alternatives to green hydrogen.

The use of the term "carbon equivalent" includes the impact of methane emissions in addition to carbon. Because of substantial open questions regarding both "needs to be true" requirements, this condition is assessed as AMBER.

3.1.2. Vehicles

B1: An acceptable return on capital on vehicles can be achieved – RED

Return on capital on vehicles purchased is determined by the total cost of ownership/operation (TCO) of vehicles and revenues for freight services minus non-vehicle costs over the lifespan of vehicles. If the TCO increases, revenues minus other costs also need to increase if return on capital is to be maintained. Based on this, we propose that a "what would need to be true" requirement for this condition is:

> Any increases in vehicle total cost of ownership/operation are compensated by increased freight service prices and/or subsidies.

Xie et al. (2023) predict the cost of a long-haul diesel truck in the US to remain roughly constant at c. $180k in the period to 2040. By contrast, they predict the cost of a fuel cell truck to decrease dramatically from c.$550k in 2022 to c. $260k in 2030 and c. $210 in 2040. Based on this analysis, Basma and Rodríguez (2023) predict hydrogen fuel cell long-haul trucks will not achieve TCO parity with diesel until close to 2040, with higher vehicle purchase price and fuel costs being offset by lower road tolls / charges and maintenance costs. Road toll reductions are based on the favorable assumption that no road tolls are applied to zero emission trucks. Fuel cost assumptions are those shown in section 3.1.1, including the favorable assumption that the minimum level of taxation as proposed in the Revision of the Energy Taxation Directive in Europe (European Commission, 2021) is applied.

Lower fuel efficiency means that hydrogen ICE trucks, despite lower purchase costs, are projected to not achieve TCO parity within the modelled period.

The projected reduction in the cost of a fuel cell truck is principally driven by large projected cost reductions for fuel cells and hydrogen storage systems. Xie et al. (2023) identify an order of magnitude (factor of 10) variation in cost estimates of fuel cells and a factor of 4 variation in cost estimates of hydrogen storage systems across all modelled time periods. This implies a high degree of uncertainty in hydrogen fuel cell truck purchase costs and TCO.

Even with the large assumed TCO reduction estimated by Basma and Rodríguez (2023), hydrogen fuel cell trucks do not achieve TCO parity with diesel until close to 2040, and marginally less optimistic assumptions would push the point at which parity is achieved to beyond 2040. Until parity is achieved, hydrogen trucks will either require subsidy or increased freight service prices to provide an acceptable return on capital. The current political and economic climate suggests that large scale subsidies are unlikely. There is also currently very little evidence that freight customers are willing to accept substantially higher freight prices for low carbon transport. While it cannot be ruled out based on the evidence reviewed that this condition could be met within the lifespan of trucks bought today, we consider this unlikely. On this basis, the condition is assessed as RED.

B2: Vehicle capabilities allow operators to meet shipper requirements – GREEN

Road freight customers expect both speed and flexibility in service delivery. Operators' ability to meet these requirements are determined by the operational capabilities of vehicles including range, payload and refueling time. This must equal or exceed the service delivery capability of diesel vehicles, or customer service requirements must adjust to accommodate reduced capabilities. Based on this, we propose that a "what would need to be true" requirement for this condition is:

> Vehicle range, payload and fueling time are comparable to or better than diesel vehicles, or customer requirements adjust to compensate.

The ability of hydrogen trucks to match the range, payload and refueling times of diesel trucks provides one of the strongest techno-economic arguments for hydrogen, as little or no adjustment to customer requirements is needed if a minimum necessary hydrogen fueling network is available. Compressed hydrogen powered trucks can achieve a 250-350 mile range (Basma and Rodríguez, 2022) and can be fueled in a similar time to diesel vehicles. Liquid hydrogen trucks can achieve a c.750-mile range although, as noted in section 1, the liquefaction process and liquid hydrogen storage incur substantial additional energy losses. Nevertheless, based on operational vehicle capabilities, this condition is assessed as GREEN.

B3: Emission increases from vehicle manufacture do not outweigh energy emission reductions – GREEN

Manufacturing vehicles generates carbon emissions. This means that when comparing new technology vehicles with diesel trucks, lifetime carbon emissions for the vehicle should include emissions from vehicle manufacture. Based on this, we propose that a "what would need to be true" requirement for this condition is:

> Any increase in the embedded carbon cost of vehicles is more than offset by carbon reductions from energy consumption over the lifespan of the vehicle.

O'Connell et al. (2023) estimate that the carbon emitted when producing a diesel truck is less than 5% of the carbon released from the production and consumption of fuel by the vehicle during its lifetime. While they find that the manufacture of a hydrogen fuel cell truck may result in c.30% more carbon emissions that the manufacture of a diesel vehicle, this increase is small in absolute terms compared to the impact of emissions from fuel. As result, this condition is assessed to be GREEN.

3.1.3. Infrastructure

C1: Emissions from infrastructure build do not outweigh net energy and vehicle emission reductions – AMBER

The building of new infrastructure generates a large amount of carbon emissions, particularly if this requires large quantities of cement, concrete or steel. Cement, concrete, iron and steel together account for over 15% of global carbon emissions (Nature, 2021; Kim et al., 2022). As a result, Marsden et al. (2022) argue that infrastructure must be taken into account in transport projects. Based on this, we propose that a "what would need to be true" requirement for this condition is:

> The embedded carbon cost of infrastructure is substantially lower than net carbon reductions from vehicle production and energy consumption over the lifespan of the infrastructure.

No estimate of the total carbon emissions from building hydrogen production, distribution and fueling infrastructure has been found. However, research suggests that large scale geographic storage facilities will be needed (Raeesi et al., 2024). In addition, a pipe distribution network is likely to be required as transporting gaseous hydrogen in trailers over long distances is costly and raises practical challenges due to the large volume of gas required (Cheng and Cheng, 2023). The storage and transport of liquid hydrogen raises different challenges due to the very low temperatures that need to be maintained (Aziz, 2021). The construction of this infrastructure will result in large carbon emissions, but the inability to quantify this based on available information means this condition is assessed as AMBER.

3.2. Socio-technical requirements

D1: Energy, infrastructure and vehicle timelines can be aligned – RED

Operators will only buy hydrogen vehicles if they are confident that sufficient vehicles, hydrogen supply and distribution / fueling infrastructure are available. Conversely, energy providers, infrastructure providers and vehicle manufacturers will only build required delivery capacity when they believe that the demand from operators will be there. This means that, in addition to fulfilling the other requirements in this list, energy, infrastructure and vehicle timelines need to be aligned. This alignment will need to happen in phases when existing diesel vehicles are due for replacement. Based on this, we propose that a "what would need to be true" requirement for this condition is:

> <u>Energy supply, infrastructure and vehicles can be progressively made available to align with vehicle replacement cycles.</u>

To meet this requirement, energy, infrastructure, and vehicle suppliers need to plan and invest ahead of demand, so that required energy, infrastructure and vehicle capacity is available as demand materializes. This will require well-coordinated industrial planning, and a demand forecast in which providers are confident. Hydrogen investments are currently focused on trials in the UK and other countries (DESNZ, 2024; IEA, 2024) and, to our knowledge, no large-scale implementation and roll out plans are currently in place. While it is possible such plans could be established within the lifecycle of vehicles being bought today, this is uncertain. If plans were established, the subsequent construction of required hydrogen production, distribution and fueling infrastructure would require multiple coordinated projects, each of which represents a major investment over a multi-year timeframe. We as a result consider it unlikely that alignment between energy, infrastructure and vehicle timeframes will happen within the lifespan of vehicles being bought today, and assess this condition as RED.

D2: The risk of backtracking is minimized – RED

Edmondson et al. (2019) make a strong theoretical argument that negative policy mix feedback undermines the achievement of policy outcomes. A real-world demonstration of this is provided by backtracking on decarbonization goals when these run contrary to political or economic objectives (Financial Times, 2023; The Guardian, 2023). If hydrogen production cost can be reduced by relaxing carbon reductions, ongoing robust regulation and monitoring is required to protect against emissions backtracking. There will however also be a political incentive to relax regulations, as countries with more relaxed controls will have an economic competitive advantage over those with more stringent ones. Based on this, we propose that a "what would need to be true" requirement for this condition is:

> <u>There is not an easy path and clear incentives to backtrack on emissions reduction.</u>

Considering each potential source of low-carbon hydrogen:

- Green hydrogen requires low-carbon electricity from renewable or nuclear sources for the electrolysis of water. If fossil fuel demand reduces, basic economics suggests that fossil fuel prices will also reduce unless measures are taken to substantially reduce fossil fuel supply. Governments and oil companies have so far shown little sign of doing this and fossil fuels continue to be extracted at record rates (UNEP, 2023; Financial Times, 2024). If electricity produced from fossil fuels becomes cheaper than low-carbon electricity, there will be an economic incentive for hydrogen producers to use this rather than low-carbon electricity to produce hydrogen.
- Blue hydrogen produced from methane with CCS may or may not be cheaper than green hydrogen, but it will always be more expensive than grey hydrogen produced without CCS. It also only achieves 60-85% CO_2 capture, with energy losses increasing with the percentage of CO_2 captured (Ajanovic et al., 2022). There will therefore be an ongoing incentive for energy producers to relax CCS requirements for carbon capture.
- Producers of by-product hydrogen will, like green-hydrogen producers, have an economic incentive to use the cheapest source of electricity available, which may be from fossil fuels if fossil fuel supply is not restricted.
- If white hydrogen meets more optimistic predictions, it could be a "game changer" for energy production (WEF, 2024). In this case, if it was also as inexpensive as these predictions suggest it could be, there would be little chance of backtracking. However, its exploitation is at a very early stage and there are many uncertainties regarding its extraction and distribution (Stalker et al., 2022; Joseph and Oghenegare, 2023; ABN-AMRO, 2024).

Overall, we suggest that fulfillment of this requirement would be only achieved if:

- Plentiful low-cost white hydrogen can be practically extracted and transported to where it is required; and/or
- Fossil fuel supply is substantially reduced.

If either one of these statements does not become true, substantial cost incentives will remain to backtrack on carbon reduction. Given white hydrogen is early in the exploration cycle, we believe the first statement is unlikely to be true within the lifespan of trucks bought today. As discussed above, there is also no evidence of governments and oil companies acting to substantially reduce fossil fuel supply. We therefore assess this condition as RED.

3.3. Political requirements

E1: The technology provides energy and freight transport security – AMBER

Freight transport security depends on factors independent of the vehicle technology including the attractiveness of the industry to drivers and the regulatory environment that influences whether operators can generate a profit (House of Commons Transport Committee, 2022). Vehicle technology could also have an impact on the ability of operators to generate a profit via the other requirements considered in this assessment, but to avoid duplication, these arguments are not repeated here.

However, another important political requirement is the maintenance of energy security. Many countries are seeking to increase energy security in the face of geopolitical risks (HM Government, 2023; IEA, 2023a). Any new vehicle technology that increases reliance on scarce or uncertain energy sources, or on energy provided by countries considered unfriendly, is likely to be politically unattractive. Based on this, we propose that a "what would need to be true" requirement for this condition is:

Dependence on unsure energy sources is not increased.

The extent to which hydrogen would increase dependence on unsure sources depends on how the hydrogen is produced. Green hydrogen produced from electricity generated by local renewable sources potentially increases energy security (Hassan et al., 2024). On the other hand, blue hydrogen is produced from natural gas and, at the time of writing, countries supporting Ukraine that import natural gas from Russia are likely to wish to reduce rather than increase their natural gas consumption (IEA, 2023a). White hydrogen could increase or reduce energy security depending on the relationship with countries with exploitable naturally occurring hydrogen reserves. By-product hydrogen could reduce dependence on unsure sources if nationally produced green energy is used for its production. Given the multiple factors determining whether dependence on unsure energy sources would increase, reduce or remain unchanged, and that these factors will vary by country, this condition is assessed as AMBER.

E2: The solution aligns with economic and strategic interests of actors required for its delivery – GREEN

Within a liberal market economy, companies will only invest in a given transition path if it is in their economic and strategic interest to do so (Hunt et al., 2022). A principal determinant of this for private sector companies is if a viable business case exists. Based on this, we propose that a "what would need to be true" requirement for this condition is:

Viable business cases exist for energy, infrastructure and vehicle providers.

It is possible that, if existing energy companies are more prepared to invest in a hydrogen transition that leverages established fossil-fuel assets, this could reduce dependency on public funding. There is substantial interest and R&D investment from both established and new entrant energy companies, utilities and vehicle manufacturers to develop and promote a hydrogen transition (Corporate Europe Observatory, 2023; Energy News Network, 2023). This suggests that these companies see viable business cases and strategic potential for hydrogen in general and for hydrogen road freight as part of this. For this reason, this requirement is assessed as GREEN.

3.4. Summary findings

Table 6-3 summarizes the assessments from sections 3.1 – 3.3. The overall assessment is that it is very unlikely that all requirements for hydrogen being a feasible energy source for general-purpose long-haul road freight will be met within the lifespan of vehicles that are bought today due to the fundamental nature of the challenges to be addressed, particularly for conditions A1, B1, D1 and D2. Over a longer-term horizon, "learning by doing" may result in technological developments that would increase the likelihood of the conditions being met. However, the high energy losses of hydrogen are a result of the physics of the required energy conversions, and it is hard to see how these will be resolved even in the long term.

Table 6-3: Assessment summary

Condition	**Needs to be true within lifespan of vehicles bought today**	**Assessment**
Techno-economic - Energy		
A1: Projected energy supply capacity satisfies projected demand at acceptable per-unit cost	• A sufficient supply of low carbon hydrogen that is substantially cheaper than green hydrogen produced via current methods is secured.	RED
A2: Total "well-to-wheel" emissions of carbon, other greenhouse gases (GHGs) and non-GHG pollutants are a substantial reduction compared to diesel	• It is confirmed that hydrogen leakage can be contained to a level at which its negative climate effects do not substantially offset benefits from carbon emission reduction. • Blue or white hydrogen are proven to offer substantial well-to-wheel carbon equivalent emissions reductions compared to diesel if these are to be used as alternatives to green hydrogen.	AMBER
Techno-economic - Vehicles		
B1: An acceptable return on capital on vehicles can be achieved	• Any increases in vehicle total cost of ownership/operation are compensated by increased freight service prices and/or subsidies.	RED
B2: Vehicle capabilities allow operators to meet customer requirements	• Vehicle range, payload and fueling time are comparable to or better than diesel vehicles, or customer requirements adjust to compensate.	GREEN

Condition	Needs to be true within lifespan of vehicles bought today	Assessment
B3: Emission increases from vehicle manufacture do not outweigh energy emission reductions	• Any increase in the embedded carbon cost of vehicles is more than offset by carbon reductions from energy consumption over the lifespan of the vehicle.	GREEN
Techno-economic - Infrastructure		
C1: Emissions from infrastructure build do not outweigh net energy and vehicle emission reductions	• The embedded carbon cost of infrastructure is substantially lower than net carbon reductions from vehicle production and energy consumption over the lifespan of the infrastructure.	AMBER
Socio-technical		
D1: Energy, infrastructure and vehicle timelines can be aligned	• Hydrogen supply, infrastructure and vehicles can be progressively deployed to provide a feasible transition path for operators, vehicle manufacturers and infrastructure providers.	RED
D2: The risk of backtracking is minimized	• There is not an easy path and clear incentives to backtrack on emissions reduction.	RED
Political		
E1: The solution provides energy and freight transport security	• Dependence on unsure energy sources is not increased.	AMBER
E2: The solution aligns with economic and strategic interests of actors required for its implementation	• Viable business cases exist for energy, infrastructure and vehicle providers.	GREEN

3.5. Implications for policy and practice

3.5.1. Vehicle purchasers

If vehicle purchasers' views align with the above assessment, it means that hydrogen can be removed as a consideration for current new vehicle purchases for general-purpose long-haul freight, as the operational competitiveness and resale value of vehicles purchased today are very unlikely be undermined by hydrogen vehicles within their lifespan. This means decarbonization effort should focus on other potential solutions at this time, recognizing that these also need to fulfil the feasibility conditions in table 6-1.

As hydrogen technology develops, it may reach a point where assessments against the above conditions become predominantly green. Should this occur, operators should at that point assess new purchase decisions on this basis. It is also possible that, while hydrogen may not be suitable for general-purpose long-haul freight, it is suitable for specific freight applications with dedicated vehicles. An assessment for such applications could be made against the above conditions on a case-by-case basis to determine if hydrogen should be considered.

3.5.2. Energy and infrastructure providers

While energy and infrastructure providers need to consider demand through the whole infrastructure lifespan, they will also not wish to build large-scale assets a long time in advance of demand. If providers agree with the above assessment, they may choose to defer major investments in building hydrogen infrastructure until there is a greater probability of the above conditions being met and demand as a result being present for that infrastructure.

In the meantime, energy and infrastructure providers have a critical role to play in developing and testing hydrogen production, storage and distribution solutions, as proving these is necessary if the assessments in table 6-3 are to become green.

3.5.3. Vehicle manufacturers

Vehicle manufacturers have made great strides in developing low carbon electric and hydrogen trucks. This work is essential for creating the foundation for road freight decarbonization. As discussed above, fuel cells remain expensive and challenging to manufacture and have unresolved reliability issues, so some manufacturers are focusing instead on hydrogen ICE vehicles. If vehicle manufacturers apply a similar assessment approach to the one used in this study for each of the vehicle technologies they are exploring, this may help them prioritize R&D investment and strategic planning.

3.5.4. Policymakers

Should policymakers agree with the above assessment, hydrogen development focus should be on supporting research and development, running pilots and potentially deploying hydrogen for specific use-cases where the feasibility conditions in table 6-1 can be met. The focus for general-purpose long-haul freight should instead be on low carbon solutions that can be deployed in a shorter timeframe such as battery electric and biomethane, where these solutions fulfil feasibility conditions. As with vehicle purchasers, energy / infrastructure providers and vehicle manufacturers, a longer-term consideration of hydrogen can also be maintained provided this does inhibit the shorter-term deployment of other solutions.

A further implication for policymakers is that, in all decarbonization scenarios that reduce the use of fossil fuels, if fossil fuel supply is not reduced, simple market economics means that the resulting reduction in fossil fuel prices will create strong economic incentives to backtrack on emission reductions unless these are counteracted by increasingly large taxes on fossil fuels or subsidies on green alternatives: *"Even if countries were to enact policies that raised the cost of* *fossil fuels, like a carbon tax or a cap-and-trade system for carbon emissions, history suggests that technology will work in the opposite direction by reducing the costs of extracting fossil fuels and shifting their supply curves out"* (Covert et al., 2016, p.126). For this reason, we propose that a critical role of policymakers is to create regulations that result in the reduction of fossil fuel supply.

3.5.5. Hydrogen system developers and investors

There are many established and start-up companies committed to the establishment of a hydrogen energy system to replace the direct use of fossil fuels in transport, building heating and various industrial processes. Hydrogen can be produced from fossil fuel sources and, as a gas, it shares some of the physical storage and distribution characteristics of natural gas. It therefore provides a transition path that better leverages established energy system capabilities and avoids early retirement of existing infrastructure and assets to a greater degree than an electricity-based transition. For many stakeholders this is both economically and politically attractive.

This study specifically assesses the likelihood of hydrogen becoming feasible for general-purpose long-haul road freight within the lifespan of a vehicle bought today. It does not comment on the feasibility of hydrogen for other applications, or over a longer timeframe. On this basis, we would recommend to hydrogen system developers and investors seeking to make the case for hydrogen that they: 1) adopt a realist retroductive approach to assess and prioritize other potential hydrogen applications; and 2) focus R&D effort for long-haul road freight on establishing if the conditions assessed as red or amber in this study could be turned green in the medium to long term.

4. Assessment of other energy source options

The central goal of this study is to assess the feasibility of hydrogen as potentially the most contentious and uncertain of the technology options for long-haul road freight currently under widespread consideration. If vehicle purchasers agree with the finding from section 3 that hydrogen is very unlikely to be feasible within the lifespan of a vehicle bought today, this simplifies their vehicle selection decision for the reasons described in section 3.5.1.

However, having conducted a realist retroductive assessment of hydrogen for this application, it is natural to ask how other low-carbon vehicle options would fare if assessed using the same approach. Table 6-4 presents a high-level assessment of the principal low carbon alternatives to hydrogen for long-haul road freight.

Table 6-4: High-level assessment of low carbon alternatives to hydrogen for long-haul road freight

Condition	Hydrogen (from table 6-3)	Battery electric	Electric Road System (ERS)	Biomethane	Hydrogenated Vegetable Oil (HVO)
Techno-economic - Energy					
A1: Projected energy supply capacity satisfies projected demand at acceptable per-unit cost	RED	AMBER Dependent on grid and connection capacity expansion (Gaete-Morales et al., 2024; Milence, 2024)	AMBER Dependent on grid capacity expansion (Gaete-Morales et al., 2024)	AMBER Insufficient supply for all road freight, but feasible for lower volumes. Generally higher cost than fossil fuel equivalents (IEA, 2023b; RAC Foundation, 2025)	
A2: Total "well-to-wheel" emissions of carbon, other greenhouse gases (GHGs) and non-GHG pollutants are a substantial reduction compared to diesel	AMBER	AMBER Dependent on renewable electricity generation and/or effective large-scale CCS (Gustafsson et al., 2021)		AMBER Dependent of auditing of fuel source to confirm renewable (de Man and German, 2017; European Court of Auditors, 2023b)	
Techno-economic - Vehicles					
B1: An acceptable return on capital on vehicles can be achieved	RED	AMBER Dependent on vehicle, electricity and infrastructure usage costs (Nykvist and Olsson, 2021; Ainalis et al., 2023; Deshpande et al., 2023)		AMBER Comparable vehicle and maintenance cost to diesel. Typically higher fuel price (Madhusudhanan et al., 2020; Basma and Rodríguez, 2023)	

Condition	Hydrogen (from table 6-3)	Battery electric	Electric Road System (ERS)	Biomethane	Hydrogenated Vegetable Oil (HVO)
B2: Vehicle capabilities allow operators to meet customer requirements	GREEN	AMBER Dependent on range, operating cycle and payload requirements (Scania, 2025a)	AMBER Dependent on ERS coverage (de Saxe et al., 2023; Deshpande et al., 2023)	GREEN Comparable range and refueling times to diesel. If biofuel unavailable, fossil fuel can be used as a backup (Prima, 2025; US Department of Energy, 2025b)	
B3: Emission increases from vehicle manufacture do not outweigh energy emission reductions	GREEN	GREEN Emissions from long-haul truck manufacture are a small percentage of lifetime emissions (Iyer et al., 2023)			
Techno-economic - Infrastructure					
C1: Emissions from infrastructure build do not outweigh net energy and vehicle emission reductions	AMBER	AMBER Continued development of renewable electricity generation and distribution capacity required (Hall and Lutsey, 2019; Taljegard et al., 2020) – no analysis found on emissions from infrastructure build		GREEN Can use existing energy distribution infrastructure (Prima, 2025; US Department of Energy, 2025b)	
Socio-technical					
D1: Energy, infrastructure and vehicle timelines can be aligned	RED	AMBER Requires coordinated roll out of infrastructure aligned to demand growth (DHL, 2024)	AMBER Requires large up-front infrastructure build prior to vehicle deployment (de Saxe et al., 2023; Deshpande et al., 2023)	GREEN Standard diesel (HVO) / modified petrol (biomethane) trucks (Jahirul et al., 2010; Prima, 2025). Can use existing energy supply infrastructure (Prima, 2025; US Department of Energy, 2025b)	

Condition	Hydrogen (from table 6-3)	Battery electric	Electric Road System (ERS)	Biomethane	Hydrogenated Vegetable Oil (HVO)
D2: The risk of backtracking is minimized	RED	AMBER Dependent on fossil fuel supply reduction to prevent fossil fuel prices undermining renewable generation	GREEN Once infrastructure built, substantial economic incentive to use it	AMBER Dependent on fossil fuel supply reduction to prevent fossil fuel prices undermining biofuels	
Political					
E1: The solution provides energy and freight transport security	AMBER	GREEN Once electricity distribution infrastructure in place, electricity generation can be from any source	AMBER Possible vulnerability of ERS to damage or failure (Zuo and Li, 2024)	AMBER Biofuel supply capacity is limited due to land availability restrictions and ecological and food security impacts (Prima, 2025; US Department of Energy, 2025b)	
E2: The solution aligns with economic and strategic interests of actors required for its implementation	GREEN	GREEN Electric trucks available for most vehicle categories (Scania, 2025b; Volvo Trucks, 2025), infrastructure providers engaged (Gridserve, 2025; Milence, 2025).	AMBER Likely to require a public / private partnership and long term risk sharing for infrastructure build (House of Commons Library, 2023)	AMBER May require financial / regulatory incentives (European Court of Auditors, 2023a; US Department of Energy, 2025a)	

The first observation on this assessment is that, for all options excluding hydrogen, none of the conditions are assessed as red. Nevertheless, more than half of the conditions are still assessed as amber. In addition to dependencies on specific operational requirements, this principally reflects uncertainty in future capital and operating costs; and in the ability to execute the necessary coordinated deployment of energy supply infrastructure. A key policy-making goal should therefore be to reduce these uncertainties to the extent possible.

It is once again important to note that the conditions assessed in table 6-4 are necessary but not exhaustive. For example, the environmental and human health impacts of battery production and materials mining (Cabrera-Jiménez et al., 2025) and the environmental sustainability of biofuel production (Soam and Hillman, 2019; Jeswani et al., 2020) are not assessed. This means that the assessment cannot be used to definitively rule a given energy source in. However, the absence of red assessments against the criteria also means that, unlike for hydrogen within the lifespan of a vehicle bought today, none of these energy sources can be ruled out.

ERS offers the best energy efficiency of all options, addresses the range limitations of battery electric and would substantially reduce the size of batteries requires in vehicles, and thereby address the cost and payload penalties of large batteries (de Saxe et al., 2023). However, it requires a phased roll out of major infrastructure, the financial risk of which would almost certainly need to be underwritten by national governments (Sällberg and Numminen, 2024). This requirement, together with potential public resistance to the building of catenaries over the trunk route network (Burghard et al., 2024), may present a barrier to ERS implementation in some countries. However, in any location where there is a credible government commitment to build an ERS that covers a vehicle's operating cycle, this will become the clear first choice for vehicles once that ERS is available.

If ERS is not an available option, the next consideration is whether a battery electric vehicle can work operationally and economically. Where this is the case, this should be the next first choice for operators. There is the possibility of a more gradual roll out path for battery electric than for ERS, and the feasibility of battery electric for individual freight operations can be assessed on a case-by-case basis. Back-to-base operations where vehicles are not in use for a full 24-hour period provide clear "low hanging fruit" opportunities for battery electric deployment, followed by operations with defined sources and destinations where destination charging is an option. Further adoption of battery electric is dependent on 1) the deployment of a sufficient number of "megawatt" chargers at locations that allow charging and driver rest breaks to be coordinated; or 2) swappable battery solutions.

For any freight operation for which there is not a feasible ERS or battery electric option, biofuels should be considered as an interim solution. Supply limitations and environmental impacts mean that biofuels cannot be the long-term answer for all road freight, but they provide a short-term opportunity to reduce emissions for a proportion of freight while ERS and/or battery charging networks are being deployed.

5. Conclusions

5.1. Main findings

The principal finding from this assessment is that, based on the evidence identified, hydrogen can be ruled out as a purchase consideration for current purchasers of general-purpose long-haul road freight vehicles. This is because, not only is it not a feasible solution now, it is very unlikely to become feasible within the lifespan of a vehicle using a different energy source purchased today, meaning hydrogen will not undermine that vehicle's operational competitiveness or resale value. The main reasons for this are:

- the current high cost and restricted supply of hydrogen, and early development stage of low carbon hydrogen production and distribution;
- the high total cost of ownership of hydrogen vehicles and the several favorable assumptions that are required for this to reduce to a level that would support an acceptable return on investment;
- the high degree of industrial coordination that would be required to align energy, infrastructure and vehicle timelines, and the time it would take to execute a plan that would deliver this; and
- the high and ongoing risk of emissions backtracking that would exist if hydrogen was adopted as a vehicle energy source.

A higher-level assessment of other energy source options concludes that, while no option currently meets the needs of all general-purpose long-haul freight, there are circumstances where each could be feasible. This means that these options should be considered by vehicle purchasers where feasibility conditions can be met today. Where they are not feasible today, operators, energy and infrastructure providers, vehicle manufacturers and policymakers should collaborate to determine the actions required to address feasibility barriers.

5.2. Contribution to research

The study makes two original research contributions. The first is specific findings regarding the feasibility of hydrogen and other energy source options for general-purpose long-haul road freight. While studies on the feasibility of hydrogen for road freight exist, e.g. (Haugen et al., 2022; Ainalis et al., 2023; Wanniarachchi et al., 2023; Raeesi et al., 2024), no other identified studies have considered feasibility conditions spanning techno-economic, socio-technical and political transition dimensions. Furthermore, the assessment of whether conditions will be met within the lifespan of vehicles bought today is, to our knowledge, novel and provides a focus on current transition choices rather than on how technology may evolve over a longer time horizon, which is even more uncertain and of limited relevance to current vehicle purchase decisions.

The second contribution is the application of a realist retroductive assessment approach to identify "what would need to be true" conditions for a defined transition option to be feasible; and to assess the likelihood of these conditions being fulfilled within a defined timeframe. While the application of retroductive methods exists in research, e.g. (Meyer and Lunnay, 2013; Papachristos and Adamides, 2016; Belfrage and Hauf, 2017), this is principally within ontologically relativist or constructionist rather than realist research, and Mukumbang et al. (2021) identify that its use in realist studies remains "minimal and inadequate". This study applied realist retroductive assessment to the feasibility of hydrogen and other energy sources for general-purpose long-haul road freight drawing on secondary research data. However, the realist retroductive assessment approach would be equally applicable for studies considering:

- Other complex system transitions
- Other transition choices and options
- Other time horizons
- Primary data

Given the inherent uncertainties and conflicting vested interests associated with complex system transitions, we believe that the realist retroductive approach can provide a more practically helpful approach than either deductive or inductive methods for actors seeking to make system-level transition choices.

5.3. Study limitations

This is a high-level assessment of a highly polarized and politically charged debate. Although we argue that this assessment is logically founded, objective and evidence-based, others making the same claim may reach different conclusions. Primary research engaging a cross section of transition stakeholders would be valuable. In gaining this input, we propose that the retroductive "what needs to be true" approach is helpful in engaging with the widely differing viewpoints and in separating objective assessment from subjective opinions and vested interests.

This paper has focused on requirements for energy source options to be feasible decarbonization solutions for general-purpose long-haul road freight, assuming that the current economic and political order is not radically altered. A subjective argument that is used against the adoption of hydrogen is that it is a means for the oil and gas industry, which is argued to be either a principal culprit for or willing enabler of the climate crisis, to remain relevant and that this industry cannot be trusted to act in the interests of sustainability (Vezzoni, 2024). A broader argument still is that all approaches that rely on large scale deployment of technology and engineered solutions or require top-down "technocratic" governance processes will lead humanity further down the path of unsustainability (Caniglia et al., 2021). A further deconstructionist argument is that it is ultimately global capitalism and consumerism that are responsible for the climate crisis, and that any approach that does not renounce these will never achieve decarbonization goals (Feola, 2020). While we are sympathetic to these arguments, this analysis has not considered these, partly because their subjectivity means they do not fit well into the realist framing of this assessment. Moreover, it is our view that if radical deconstruction of the political and economic order is necessary for decarbonization, in the absence of a catastrophic scenario that would itself bring extreme human suffering, this will not be achieved within the timeframes required to materially mitigate climate change. We understand however that others may hold a different view.

While the ten preconditions were defined and assessed on the basis of international literature, the previous interviews and workshops that also informed the conditions were conducted in the UK. This means that there may be underlying assumptions in the assessment that, while true in a UK context, may not be true in all other countries. The key assumptions that we are conscious of are a liberal market economy in which private sector actors make their own operational and investment choices; insufficient public funds or political will to support extensive long-term subsidies to vehicle purchasers and infrastructure providers; and the lack of a low-cost, abundant and environmentally sustainable white hydrogen supply. The assessment could be different for countries where one or more of these assumptions are not true.

5.4. Opportunities for future research

There are substantial opportunities for further research stemming from each of the two contributions described in Section 5.2:

5.4.1. Assessment of road freight decarbonization options

While energy supply selection is a rather tangible and hotly debated topic, other important transition choices exist for road freight decarbonization related to areas including public and private sector capability development; energy, infrastructure and vehicle supply; funding, incentives and risk sharing; realignment of supply chains; and the prioritization of different road freight segments. All these transition choices could also be assessed using a realist retroductive approach if classical deductive and inductive approaches are found to be lacking in their ability to support actor decision making.

5.4.2. Wider application of realist retroductive assessment

Beyond road freight decarbonization, the realist retroductive approach can in principle be applied to the assessment of any option for any system transition. It provides the greatest benefit over other assessment approaches when there is a need for decision making clarity on transition choices and feasibility criteria; and at least some feasibility criteria are subject to substantial uncertainty. The benefits over other more widely used approaches are potentially less if there is not a need for such clarity or when there are fewer feasibility criteria that need to be considered and/or these are subject to lower uncertainty.

To apply the realistic retroductive approach, it is necessary to identify a specific transition choice and a specific option to be assessed. It is also helpful to identify the actors who will make the decision, as this enables the “what needs to be true” conditions and assessment timeframe to be defined so that, in addition being relevant to the achievement of transition goals, they are also relevant to the specific decisions that need to be made by these actors. The choice of primary and/or secondary data on which to base the assessment will be influenced by the transition choice and feasibility criteria being assessed; and on the data and resources available to conduct the assessment.

Appendix A: Literature analysis

The referenced literature is categorized in table 6-5 according to source type and perspective.

Table 6-5: Literature breakdown by perspective and source type

Source type	Perspective
Academic peer reviewed	**Techno-economic** (Jahirul et al., 2010; Wang, 2015; Covert et al., 2016; Barthelemy et al., 2017; de Man and German, 2017; Møller et al., 2017; Wu et al., 2018; Anderhofstadt and Spinler, 2019; Kurtz et al., 2019; Mojtaba Lajevardi et al., 2019; Moriarty and Honnery, 2019; Shabani et al., 2019; Hosseini and Butler, 2020; Kim et al., 2020; Kurtz et al., 2020; Madhusudhanan et al., 2020; Taljegard et al., 2020; Zgonnik, 2020; Aziz, 2021; Booto et al., 2021; Burton et al., 2021; Fan et al., 2021; Gholami et al., 2021; Gustafsson et al., 2021; Howarth and Jacobson, 2021; Nykvist and Olsson, 2021; Olabi et al., 2021; Xun et al., 2021; Ajanovic et al., 2022; Al Ghafri et al., 2022; Gunawan and Monaghan, 2022; Haugen et al., 2022; Lu et al., 2022; Osselin et al., 2022; Ren et al., 2022; Rout et al., 2022; Stalker et al., 2022; Winkler et al., 2022; Ainalis et al., 2023; Cheng and Cheng, 2023; de Saxe et al., 2023; Deshpande et al., 2023; Hunt et al., 2023; Iyer et al., 2023; Joseph and Oghenegare, 2023; Sand et al., 2023; Wanniarachchi et al., 2023; Zoback and Smit, 2023; Aryanpur and Rogan, 2024; Boretti, 2024; Gaete-Morales et al., 2024; Hassan et al., 2024; Paulu et al., 2024; Raeesi et al., 2024; Zuo and Li, 2024) **Socio-technical / political** (Papachristos and Adamides, 2016; Downie, 2017; Iordache et al., 2017; Normann, 2017; Edmondson et al., 2019; Feola, 2020; Caniglia et al., 2021; Haugen et al., 2022; Hunt et al., 2022; Kim et al., 2022; Li et al., 2022; Burghard et al., 2024; Marsden and Schwanen, 2024; Sällberg and Numminen, 2024; Vezzoni, 2024) **Multi-perspective** (Månsson et al., 2014; Cherp et al., 2018; Soam and Hillman, 2019; Jeswani et al., 2020; Meyer, 2020; Churchman and Longhurst, 2022; Churchman et al., 2023; Neagoe et al., 2024; Winkelmann et al., 2024; Cabrera-Jiménez et al., 2025; Churchman et al., 2025a; Churchman et al., 2025b) **Critical realism and retroduction** (Meyer and Lunnay, 2013; Belfrage and Hauf, 2017; Fletcher, 2017; Mukumbang et al., 2021; Stanton and Roelich, 2021)
Academic report / letter	**Techno-economic** (Greening et al., 2019; Cebon, 2020) **Multi-perspective** (Nature, 2021; Marsden et al., 2022; Centre for Sustainable Road Freight, 2023; DUKFT, 2023)

Source type	Perspective
Book	**Critical realism and retroduction** (Minto, 2009; Bhaskar, 2013; Marchau et al., 2019)
Corporate	**Techno-economic** (ABN-AMRO, 2024; Daimler Truck, 2024; DHL, 2024; Milence, 2024; Gridserve, 2025; Milence, 2025; Prima, 2025; Scania, 2025a, 2025b; Volvo Trucks, 2025)
Government	**Multi-perspective** (EU Science Hub, 2021; European Commission, 2021; GOV.UK, 2021; DfT, 2022; House of Commons Transport Committee, 2022; Warwick et al., 2022; DfT, 2023; European Court of Auditors, 2023b, 2023a; HM Government, 2023; House of Commons Library, 2023; DESNZ, 2024; US Department of Energy, 2025b, 2025a)
Media	**Techno-economic** (Pierce, 2024) **Socio-technical / political** (Energy News Network, 2023; Financial Times, 2023; The Guardian, 2023; Financial Times, 2024)
NGO / Intergovernmental	**Techno-economic** (CCC, 2018; Hall and Lutsey, 2019; Advanced Propulsion Centre UK, 2021; Zemo Partnership, 2021; Basma and Rodríguez, 2022; Basma et al., 2022; ICCT, 2022; Basma and Rodríguez, 2023; ICCT, 2023; O'Connell et al., 2023; Xie et al., 2023; IEA, 2024; RAC Foundation, 2025) **Socio-technical / political** (Corporate Europe Observatory, 2023) **Multi-perspective** (Smart Freight Centre, 2021; ITF, 2022; IEA, 2023a, 2023b; UNEP, 2023; Connected Places Catapult, 2024; WEF, 2024)

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Closing discussion and conclusions

1 Thesis recap

This thesis has adopted a multidisciplinary approach to consider the problem that, while rapid and radical road freight decarbonisation is necessary as part of a wider strategy to mitigate climate change, decarbonisation progress of this sector is slow and there is no clear pathway to achieving this outcome. In Introduction section 4, four foundational propositions were proposed based on previous work:

- Barriers are socio-technical and political as well as techno-economic
- The road freight system is complex and interconnected
- Actors are individually constrained
- Road freight decarbonisation needs to be purposively codesigned

Building on these, two key research gaps were identified:

- Political and socio-technical aspects of road freight decarbonisation
- Purposively codesigned transitions

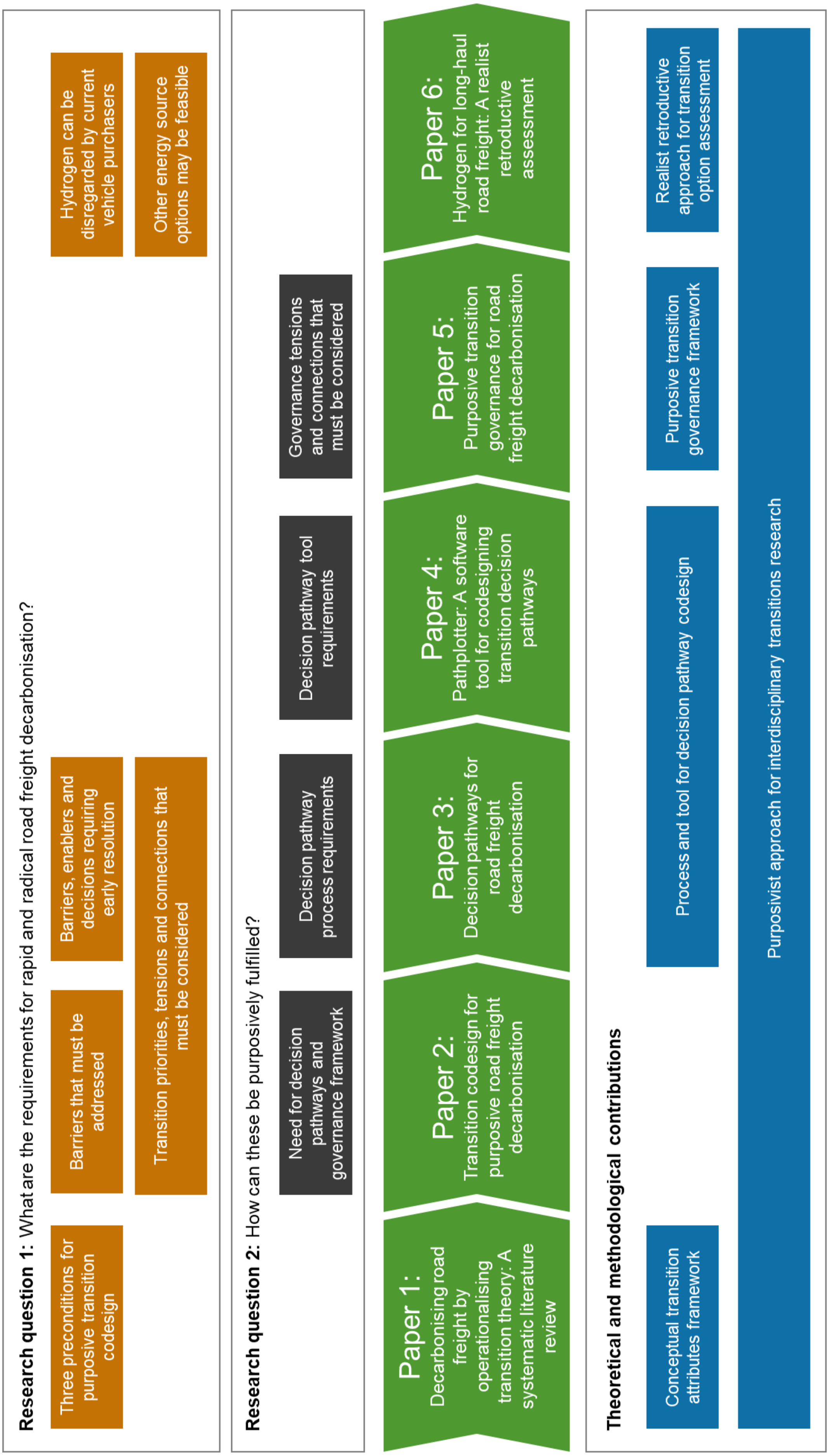
To address these gaps, two research questions were addressed:

- What are the requirements for rapid and radical road freight decarbonisation recognising political and social-technical as well as techno-economic dimensions?
- How can these requirements be purposively fulfilled?

The research was presented in six papers. These papers include, in addition to findings regarding the two research questions, original theoretical and methodological contributions in the form of a conceptual transition attributes framework; a process and tool for decision pathway codesign; a purposive transition governance framework; a realist retroductive approach for transition option assessment; and a "purposivist" approach for interdisciplinary transitions research.

Figure C-1 shows the alignment of research question findings, further summarised in section 2, and theoretical and methodological contributions, further summarised in section 3, to the six papers. Following these sections, section 4 considers research limitations; section 5 reflects on the challenges of interdisciplinary, multi-perspective research into purposive system change; section 6 reviews research impact to-date and considers directions for future work; and section 7 closes the thesis with some final reflections.

Figure C-1: Research question findings; and theoretical and methodological contributions



2 Findings summary

This section summarises findings from the six papers for each of the two research questions. Together with the theoretical and methodological conclusions summarised in section 3, they provide specific insights, and a toolkit for policymakers, industry participants and researchers seeking to purposively bring about this difficult but necessary transition.

2.1 What are the requirements for rapid and radical road freight decarbonisation recognising political and social-technical as well as techno-economic dimensions?

The four papers (1, 2, 3 and 6) that address the first research question provide specific insights regarding transition preconditions, priorities, tensions and connections; and systemic barriers, enablers and decisions that need to be addressed to deliver road freight decarbonisation.

2.1.1 Paper 1

Based on a systematic literature review, paper 1 crystallises high level codesign requirements in the form of three decarbonisation preconditions:

1) Techno-economically feasible options able to deliver this outcome need to exist;
2) A shared understanding of the design choices that need to be coordinated is required; and
3) A politically, socially and organisationally feasible codesign framework to make these design choices needs to be established.

2.1.2 Paper 2

Paper 2 investigates each of the preconditions from paper 1 and identifies transition priorities, tensions and connections:

Precondition 1: Techno-economically feasible options need to exist:

There is broad consensus that a change of vehicle energy source and/or mode shift to rail or water are necessary to achieve radical decarbonisation. However, there are differences in views on the feasibility of solutions and strongly opposing positions on hydrogen, biofuels and mode shift. Furthermore, there is a split between participants who feel that all options including emerging technologies should be kept on the table versus those who favour progressing rapidly with solutions that are already proven at scale. While some participants consider incremental decarbonisation solutions as valid alternatives to solutions capable of achieving radical decarbonisation, others feel we should concentrate our efforts on the latter.

Precondition 2: A shared understanding of the design choices that need to be coordinated is required:

Two distinct camps of opinion are identified. The first of these favours strong leadership by government giving clear direction on solution selection and transition timescales. Participants in this camp emphasise the need to reduce transition uncertainty and to provide actor coordination. They often also argue the need for government incentives to drive the transition. The second camp proposes that government intervention should be kept to a minimum and that all options should remain available so that operators and shippers can select solutions that work best for them. These participants believe that market forces and freight customer preferences should drive transition action rather than government policy and incentives. In general, industry participants favour centralised policymaking while authorities see greater benefits in devolved transport policy. There are also differing views on the geographic and sectoral levels at which design decisions need to be made, which has important implications for transition arena design.

Another key theme that emerges is the need to provide transition paths that work for smaller operators. There is broad consensus that large, medium and small operators working in combination are required to maintain the current levels of efficiency and flexibility of the road freight sector. However, while larger operators are more able to organise their operations to progressively transition to low carbon vehicles as customer demand and infrastructure permit, smaller operators do not have this flexibility, and purchasing the wrong vehicle could put their business at risk.

Precondition 3: A politically, socially and organisationally feasible codesign framework needs to be established:

While several areas of consensus are identified, there are four transition attribute statements on which strongly opposing views are expressed:

- Incumbents should not feel punished
- Sources of legitimacy other than decarbonisation itself are required
- It is important to consider political windows of opportunity
- The transition should connect to a clear political idea and the political context

In addition, the following transition barriers are highlighted:

- Technology uncertainty / immaturity
- Lack of clear direction or plan
- Lack of strategic infrastructure planning or funding
- Inconsistent incentives and policy
- First mover disadvantage
- Chicken and egg between infrastructure provision and demand
- Collaboration barriers

2.1.3 Paper 3

Considering precondition 2 from paper 1, paper 3 applies a novel decision pathway codesign process and tool called “Pathplotter”. Five mixed actor workshops are conducted, each considering a different road freight decarbonisation goal. Pivotal barriers, enablers and decisions (collectively termed nodes) are identified that must be addressed early in the transition due to multiple other nodes being dependent on them. Table 3-2 lists pivotal nodes that are identified in two or more of the five workshops conducted.

A bibliometric analysis of literature by Meyer (2020) confirms that, prior to the date of their study, most research considering road freight decarbonisation focused on techno-economic rather than socio-technical or political transition aspects. Notable exceptions to this include work by Macharis et al. (2016), Lebeau et al. (2018) and more recently Paddeu et al. (2024). However, these studies remain a small proportion of road freight decarbonisation research. Set against this, reviewing the pivotal nodes in table 3-2 reveals most of these to be socio-technical (e.g. trials / early adopter experience, develop maintenance and repair facilities, public / operator awareness raising, lack of customer demand for decarbonisation, technology uncertainty / confidence); political (e.g. clear cut off dates / targets, collaboration between authorities, policy uncertainty, local / national political / policy support); or related to decision-making governance (e.g. ERS yes / no, define technology standards, define infrastructure funding / who pays). Some of these points are considered in grey literature, e.g. Basma and Rodríguez (2023), ITF (2022) and McKinsey & Company / WEF (2022). However, their limited consideration in peer reviewed literature is identified as a substantial gap.

Relevant insights are also provided from unstructured commentary. One point raised in all five workshops is the need for public authorities to develop capabilities to support the transition. The lack of sufficient depth of expertise and enough staff with key required skills is identified as a particular issue.

A further point is that, in general, while some freight customers express an interest in decarbonisation, road freight procurement is seen as most often being determined by price and operational performance rather than environmental factors. The provision of transition incentives to operators is seen as helpful, but ultimately of marginal impact if road freight customers are not also driving the transition.

Targets and cutoff dates are identified as being important to creating an environment where effective collaboration and sufficiently rapid action can happen. Maintaining targets and cutoff dates through political transitions and electoral cycles is highlighted as a key challenge.

Discussion in three workshops identifies hydrogen as being less mature than battery electric and higher cost due to large energy losses and an insufficient supply of green hydrogen. Another point that emerges from three of the workshops is differing views on whether key decisions such as technology selection should be made centrally by government or whether individual operators and shippers should be free to make their own choices. It is proposed that, in a UK context, managing the tension between these two positions a key challenge that needs addressing if rapid and radical decarbonisation is to be achieved.

Several of the points raised that are specific to the road freight decarbonisation goals considered in the individual workshops are also socio-technical or political in nature, for example: collaborative purchasing and new vehicle delivery models (workshop 1); the importance of a long term vision and VECTO emissions reporting (workshop 2); the tensions between infrastructure provider and freight operator viewpoints (workshop 4); and the contrast in motivators between operator / shippers (e.g. supermarkets with their own truck fleets) and third freight party operators (workshop 5).

These findings reinforce the importance of stakeholder engagement and codesign for road freight decarbonisation as advocated by Macharis (2005) and Paddeu et al. (2024). In addition, while techno-economic factors remain important, the findings from this study make a strong case for more work considering socio-technical, political and decision governance factors.

2.1.4 Paper 6

A specific barrier to road freight decarbonisation highlighted in papers 2 and 3 is technology uncertainty, in particular regarding the feasibility of hydrogen for long-haul road freight. This paper applies a realist[1] retroductive[2] assessment to consider the research questions "What systemic conditions would need to be true for hydrogen to be feasible for general-purpose long-haul road freight?"; and "How likely is it that these conditions will be met within the lifespan of vehicles being bought today?". Ten techno-economic, socio-technical and political conditions are considered. The likelihood of each condition being true for hydrogen within the lifespan of a vehicle being bought today is assessed as follows:

- GREEN: Likely to be true based on identified evidence
- AMBER: Unclear – more information required
- RED: Likely not to be true based on identified evidence

[1] Realist ontology, unlike relativist ontology, assumes that reality and truth are independent of context and the values, norms and beliefs of humans.

[2] Retroductive analysis considers a predefined theory, in this case that hydrogen could be feasible, and assesses the conditions under which this theory would be true.

In addition, a higher-level assessment is conducted for four other road freight energy source options: battery electric, electric road systems, biomethane and hydrogenated vegetable oil (HVO). The results of these assessments are summarised in table 6-4.

It is concluded that it is highly unlikely that hydrogen will be a feasible option within the lifespan of vehicles bought today. For other options, more than half of the conditions are assessed as amber. This reflects, in addition to dependencies on specific operational requirements, uncertainties in future capital and operating costs; and in the ability to execute the necessary coordinated deployment of energy supply infrastructure. A key policy-making goal should be to reduce these uncertainties to the extent possible.

Electric road systems offer the best energy efficiency of all options. However, they require a phased roll out of major infrastructure, the financial risk of which would almost certainly need to be underwritten by national governments. In any geography where there is a credible government commitment to build an ERS that covers a vehicle's operating cycle, this will become the clear first choice for vehicles once that ERS is available.

If ERS is not an available option, the next consideration should be whether a battery electric vehicle could work operationally and economically. For any freight operation for which there is not a feasible ERS or battery electric option, biofuels should be considered as an interim solution. Fuel production limitations and environmental impacts mean that biofuels cannot be the long-term answer for all road freight, but they provide a short-term opportunity to reduce emissions for a proportion of freight while ERS and/or battery charging networks are being deployed.

2.2 How can these requirements be purposively fulfilled?

The four papers (2, 3, 4 and 5) that consider this research question investigate how requirements identified in response to the previous research question can be purposively addressed by road freight actors and policymakers.

2.2.1 Paper 2

A headline conclusion from paper 2 is that codesign pathways are needed that define the sequence and timing of decisions that address transition barriers and establish enablers. Such pathways need to be based on a clear understanding of system dependencies and have the support of a critical mass of road freight actors and policymakers. For both reasons, it is necessary that pathways are themselves codesigned by relevant actors with the required system understanding and ability to represent and make commitments on behalf of their respective organisations. In addition, the need for a codesign governance framework that incorporates identified codesign attributes and provides mechanisms for managing codesign conflict is highlighted.

2.2.2 Paper 3

Building on paper 2's finding that codesign pathways are required, this paper presents the application of a novel process and tool in five workshops to develop decision pathways for specific road freight decarbonisation goals with mixed groups of road freight actors and policymakers. These workshops confirm that it is possible to use the developed process and Pathplotter tool (presented in more detail in paper 4) to:

- Map transition nodes and dependencies;
- Identify and resolve chicken and egg dependency loops;
- Specify a decision pathway that allows dependencies to be respected; and
- Identify pivotal nodes on which other nodes depend and therefore must be addressed early in the decision pathway.

There was strong agreement amongst workshop participants regarding the value of mixed participant groups codesigning decision pathways. However, there are also learnings that need to be considered if the decision pathway approach is to be operationalised for real-world transition codesign:

- The approach needs to work for both intuitive and process thinkers: while some participants were comfortable with the process of mapping nodes and dependencies, others found this process challenging. The process will need to accommodate both types of participants if it is to be operationalised.
- Sufficient time for reflection and iteration is required: Workshops were between 2.5 and 3 hours in length. While only single workshops could be accommodated by participants for this research, if the process is operationalised, multiple workshops will be required, and pathways will need to be developed iteratively through these workshops.
- The process and outputs must align to decision-maker needs: Some participants identified that one of the biggest challenges they face is engaging decision-makers, which include politicians and senior business leaders. This means that decision pathways need to be presented in a form that makes choices and the implications of these clear to decision-makers and focuses attention on critical path decisions and quick wins.

2.2.3 Paper 4

Pathplotter is a custom-developed web application used to facilitate the workshops and analysis conducted for paper 3. It addresses two specific needs identified in pilot workshops:

1. The facilitation of decision node and dependency definition by mixed groups of transition actors and stakeholders

2. The efficient generation of decision maps, pathways and analyses based on these nodes and dependencies

The requirements of a tool to meet these needs are based on a systematic review of Design for Sustainability (DfS), Transitions Management (TM) and Participatory Design (PD) literature (table 4-1). A review of existing network mapping and visualisation tools confirms that none of the tools identified adequately meet these requirements, leading to the decision to develop a bespoke tool.

2.2.4 Paper 5

This paper builds on the finding from paper 2 that a codesign governance framework is needed that incorporates identified codesign attributes and provides mechanisms for managing codesign conflict. A purposive transition governance framework is developed from literature and then validated and further developed in thirteen interviews and a workshop with transport authority and industry association representatives. The framework is presented in section 3.3. Several tensions are identified between framework elements that represent trade-offs and coordination requirements:

- Between "Driving purposive transition", "Maintaining system functions" and "Managing conflict and asymmetric power relations"
- Between "Agility" and "Technology clarity" / "Clear goal and roadmap"
- Between "Deliberation" and "Decision-making"

There are also connections where elements, while not necessarily being in tension, are interdependent. These tensions and connections further reinforce the "wicked" nature of road freight decarbonisation, and the need for effective transition governance to manage this wickedness. It is proposed that a good starting point for addressing wickedness may be to systematically engage with and seek resolutions to the identified governance tensions and connections.

3 Theoretical and methodological contributions

In addition to the findings related to the two research questions summarised in section 2, five novel theoretical and methodological contributions are developed in the thesis:

3.1 Conceptual transition attributes framework

Based on a systematic review of socio-technical and political transitions literature, 16 transition codesign attributes are identified under the headings of Actors, Arenas, Design, Policy and Politics. Attributes classified under "Actors" provide guidance on the motivators, constraints and strategies of road freight incumbents and new entrants (Marcucci et al., 2017; Paddeu et al., 2024). The "Arenas" grouping comes from the concept of transition arenas (TAs) (Loorbach, 2010; Hyysalo et al., 2019a), and represents the physical or virtual space in which actors come together to assess transition options and make decisions. The concept of "Design" recognises that, if a transition is to be purposively enacted in a complex system, multiple coordinated transition decisions are required (Taefi et al., 2016; Macharis and Kin, 2017). "Policy" includes measures used by government at all levels to affect the transition according to the specified design (Sørensen et al., 2018; Thaller et al., 2021). "Politics" encompasses the institutional and political environment that, while not necessarily specific to the transition, has a strong influence on it (Nordtømme et al., 2015; Normann, 2017).

A grounded theory approach is used to organise the 16 identified attributes into the framework presented in figure 1-2. This framework can be used in two ways: 1) as a heuristic for conceptualising socio-technical and political aspects of system transition codesign; and 2) as an assessment framework for considering if systemic conditions are supportive, neutral or in opposition to effective transition delivery. An earlier version of the framework is applied in the second capacity in paper 2.

3.2 Process and tool for decision pathway codesign

The identification of the need for decision pathways to enable rapid and radical system transitions (Hyysalo et al., 2019b; Van Assche et al., 2021) led to the development of a workshop process and "Pathplotter" tool for mixed actor groups to identify transition barriers, enablers and decisions (collectively termed "nodes"); and dependencies between these. Based on these nodes and dependencies, chicken and egg loops can be identified and addressed; node sequences and timelines can be developed; and pivotal nodes that must be addressed early in the transition can be identified. This process and tool can be applied to any transition where system complexity and decision dependencies mean it is necessary for mixed actor groups to come together and codesign decision pathways. Pathplotter design principles and features are presented in full in paper 4. At the time of writing, Pathplotter is available as freeware at www.pathplotter.net.

3.3 Purposive transition governance framework

Earth System Governance (ESG) (Biermann et al., 2010), Adaptive Management (AM) (Olsson et al., 2004) and Transition Management (TM) (Loorbach, 2010) are identified from literature as prominent theoretical frameworks for governing complex sustainability transitions. While each of these offer valuable insights and heuristics, none are found to provide a complete answer for transition governance (Foxon et al., 2009; Bosman and Rotmans, 2016). To address this gap, a purposive transition governance framework is developed based on a systematic literature review. This is then validated and further developed via 13 interviews and a workshop with road freight policymakers and industry association representatives. The resulting framework, summarised in figure 5-1, can be used to guide the definition of governance mechanisms, roles and responsibilities for road freight decarbonisation. It can potentially also be applied to other complex system transitions that are subject to considerations of legitimacy, asymmetric power relations and the need to maintain system functions at the same time as delivering radical system change.

3.4 Realist retroductive approach for transition option assessment

There are certain road freight decarbonisation choices that are strongly contended due to conflicting vested interests and differing beliefs regarding feasible transition paths (Ainalis et al., 2023; Winkelmann et al., 2024). A prominent example of this is the debate regarding the feasibility of hydrogen for long haul road freight that is assessed in paper 6. The need to consider political, socio-technical and techno-economic factors, high system complexity and high contextual uncertainty mean that more commonly used inductive and deductive methods are limited in their ability to support decision-making (Mukumbang, 2021; Land, 2024). Key features of the realist retroductive approach developed in paper 6 to address these limitations are:

- Identifying a specific design choice and time horizon to be assessed
- Identifying conditions that would need to be true for the design choice to be feasible
- Using evidence from available primary and / or secondary data to assess the likelihood of each condition being met within the defined timeframe:
  - GREEN: Likely to be true based on identified evidence
  - AMBER: Unclear – more information required
  - RED: Likely not to be true based on identified evidence
- Based on the sum of these assessments, assessing the likelihood of the design choice being feasible within the defined timeframe

It is also found to be helpful to identify the actors who will make the decision, as this enables the "what needs to be true" conditions and assessment timeframe to be defined so that, in addition to being relevant to the achievement of transition goals, they are also aligned to the specific decision-making requirements of these actors.

The realistic retroductive assessment approach emphasises the use of available evidence to support decision-making. This is aided by the specification of "what needs to be true" conditions that are individually required, irrespective of other conditions. This means that options can be eliminated if a single condition is demonstrated to be highly unlikely to be fulfilled, thereby removing the need to assess other conditions for that option for which clear evidence may not be available. In addition to technology option assessment for road freight decarbonisation, the realist reproductive approach is applicable to other decisions and sustainability transitions where there is a need for decision making clarity on transition choices and feasibility criteria; and at least some decisions are contended and subject to substantial uncertainty.

3.5 Purposivist approach for interdisciplinary transitions research

The purposivist approach for interdisciplinary research developed during the thesis is presented in Introduction section 7.1 and in more detail in Thesis Appendix B. This draws on the work of authors including Sayer (2000), Bhaskar (2013), Meyer and Lunnay (2013), Mingers (2015), Hoddy (2019) and Mukumbang (2021). It provides a theoretically coherent alternative to positivist and interpretivist approaches when considering techno-economic, socio-technical and political dimensions of systems; and when the research objective is not only to understand system "wickedness", but also to identify how wickedness can be addressed in order to purposively deliver system transitions.

4 Research limitations

4.1 UK focus

While the peer reviewed and grey literature drawn upon considers road freight decarbonisation in a global context, the primary research conducted has focused on road freight decarbonisation within the UK. Implications of this include:

- The political and social context considered is the UK's, which is characterised by having a liberal market economy, democratically elected government, and significant devolution of transport, environment and planning responsibility to national and sub-national authorities.
- The existing freight transport and logistics system is mature, efficient and highly competitive.
- There is an individual and business expectation of decision-making freedom and a resistance to state interventions that are perceived as heavy-handed or intrusive.

Further work would be required to determine the extent to which findings are transferable to other countries that do not share these characteristics.

4.2 Focus on road freight decarbonisation

This thesis has focused on road freight decarbonisation and therefore has not considered the decarbonisation of passenger transport, other freight transport modes, or sustainability transitions in other sectors. It seems probable that the approaches and tools developed in this thesis can also be applied to other sustainability transitions in which individual actors are constrained due to system dependencies, meaning that system-level transition choices need to be codesigned. However, further work would be required to confirm this.

4.3 Focus on the decarbonisation of road freight movements

The focus of this thesis has been on the decarbonisation of road freight movements rather than freight demand reduction. The latter decarbonisation lever was not considered after paper 2 as this research found a consensus amongst participants that demand reduction would only have a marginal decarbonisation impact. This is reinforced by the projections presented in Introduction section 2 that, even in optimistic carbon reduction scenarios, the volume of road freight is projected to increase in the UK and globally. Nevertheless, work considering freight demand reduction is important and complementary to the work conducted.

4.4 Time and resources of a PhD project

The work was constrained by the time available to complete the PhD, there being no funding beyond that provided by my University of Leeds doctoral scholarship, and there being no resource for data gathering or analysis beyond myself.

5 Reflections on challenges of inter-disciplinary research into purposive system change

One of the principal challenges of this thesis has been conducting inter-disciplinary, multi-perspective research with a normative goal of facilitating purposive system change. At times, adopting an approach that does not sit within a single disciplinary domain and seeks to understand systems with a goal of facilitating purposive system change has felt like an uphill battle. However, there is an increasingly large body of opinion that addressing wicked problems such as road freight decarbonisation requires a research approach that bridges disciplinary camps and research traditions (Castrejon-Campos et al., 2020; Wohlgezogen et al., 2020). The below expands on this challenge and how it has been addressed in this thesis.

5.1 Bridging positivist and interpretivist paradigms

Most transitions research, while not necessarily being wholly at one end of the spectrum or another, has a positivist or interpretivist orientation. The purpose of research, and what constitutes good research, is different in each of these paradigms (Ryan, 2018). Historically, techno-economic research has tended to be principally positivist and political and socio-technical transitions research has tended to be principally interpretivist (Zolfagharian et al., 2019). Positivist research frequently considers engineered and often centralised solutions that require technology expertise and industrial capability to deliver (Wan Alwi et al., 2014). By contrast, interpretivist research more often considers decentralised solutions that rely on the change of societal norms and behaviours (Sovacool et al., 2020). The approaches and governance associated with the implementation of these respective types of solution are radically different. The expert-led and centralised approaches favoured by positivists can be critically characterised as “technocratic” (Geels, 2018). Conversely, grassroots and community-led solutions favoured by interpretivists can be seen as incrementalist and naïvely idealistic (Pel et al., 2023).

This creates a problem when it is observed that complex system transitions require a consideration of techno-economic, socio-technical and political dimensions. If a researcher stays clearly within either a positivist or interpretivist framing, the philosophical, methodological and normative positions are broadly mutually consistent and self-reinforcing. However, when an attempt to combine the two is made, as is necessary to consider all three dimensions, philosophical, methodological and normative dissonances are rapidly encountered (Lowe and Phillipson, 2009). It seems likely that this difficulty explains why so little research attempts to combine the two paradigms, or combine techno-economic, socio-technical and political perspectives. Mixed methods approaches are only a partial answer as they require quantitative and qualitative research elements to be separated (Schoonenboom, 2023), which often leads to findings that recognise the tensions between techno-economic, socio-technical and political transition dimensions, without offering a means to reconcile these (Mertens, 2014).

The approach that has been adopted in this study to address this problem has three linked elements:

- The argument that, irrespective of the demand reduction that is ultimately achieved, there will remain a large volume of road freight that must be decarbonised, and this will require engineered solutions that encompass vehicles, energy and infrastructure.
- The recognition that, despite these being solutions that would typically be researched within a positivist paradigm considering principally techno-economic factors, socio-technical and political factors are also important and must be considered.
- The adoption of the critical realist research approach “purposivism” to enable the study of all relevant dimensions as part of the broad critical evaluation advocated by critical realism.

While I believe that the study has demonstrated both the practical feasibility and theoretical coherence of applying a purposivist research approach to the study of road freight decarbonisation, it remains an outlier in the body of transport and energy transitions research. It would therefore benefit from constructive engagement from other researchers and broader application in a variety of transition contexts.

5.2 Conducting robust critical realist research

What constitutes robust research is different under positivist and interpretivist research paradigms (Ryan, 2018). Positivism seeks to test predefined theories. To do this, it is necessary to demonstrate repeatability across multiple independent data points to assert that experimental observations can be generalised to reality. This typically requires the use of quantitative methods and application of statistical tests to results. Interpretivism, by contrast, seeks to develop theories that aid qualitative understanding and focuses on individual perceptions. Its epistemologically subjectivist/constructionist and ontologically relativist philosophical foundations mean that demonstrating repeatability and asserting generalisability are not only not needed, but are also irrelevant as it is assumed that reality and meaning are at least partiality created by human observers, and therefore by definition are not repeatable or generalisable. The assessment of rigour is instead based on the demonstration of a clear research methodology that is firmly rooted in an identified research philosophy and framework.

The purposivist and critical realist approach adopted in this study requires the abductive development of theories based on available data and literature, and the retroductive testing of these theories to confirm their applicability within a specific context. This approach assumes that reality exists independently of human observers and researchers, but that its stratified and emergent nature requires broad critical analysis (Bhaskar, 2013). This requires the use of qualitative methods and grounded theory to abductively develop theories (Bruscaglioni, 2016). In addition, the predictive assessment of the impact of actions for which there is no precedent on systems that are too complex to comprehensively model means generalisability of theories needs to be based on expert opinion and logical reasoning rather than repeated experiments. While the use of simulations such digital twins and system dynamics models can aid this process, these are themselves based on qualitative assumptions of system causal mechanisms and structures, are only partial system representations, and require expert interpretation to ensure results are not extrapolated beyond the predictive capability of the model.

While critical realism is becoming established as a meta-theory for the social sciences (Hoddy, 2019), the principles of what constitutes robust research are less well defined in literature than is the case for positivist or interpretivist research (Fletcher, 2017; Hoddy, 2019). Recognising this gap, the following robustness principles are drawn from Mingers (2015), Bhaskar (2016), Sayer (2000) and Mukumbang (2021):

- Has relevant qualitative and / or quantitative data been accessed?
- Have appropriate abductive and retroductive methods been defined and followed?
- Are findings triangulated across multiple methods and data sources where feasible?

- Is there a clear separation of foundational assumptions that reflect the normative position of the researcher and research findings that are an objective application of research methods to data?

These principles have been applied throughout the thesis.

5.3 Purposive system codesign

The combination of the ideas of codesign and purposive system transition has also proved to be challenging. Considering each of these:

Codesign is a widely used term that means different things to different researchers. Within interpretivist research, it is often aligned to the idea of coproduction and reflects a democratic and participatory ideal of societal decision making (Turnhout et al., 2020). As actors responsible for policy and decision-making for road freight decarbonisation are predominately public authorities and private businesses, codesign in this context needs to engage these actors and enable effective collective policy and decision-making to achieve desired decarbonisation goals while maintaining critical system functions. The conception of codesign that is therefore adopted in this thesis is collaborative design and decision making by policymakers and industry actors to bring about rapid and radical system change.

Techno-economic research in general assumes that, if evaluation criteria are clearly defined, there are objectively better and worse outcomes against these criteria. Techno-economic transitions research typically seeks to evaluate system interventions against defined criteria. However, this research often treats political and socio-technical factors as exogenous context rather than an endogenous part of the system to be transitioned.

There is on the other hand a broad aversion amongst interpretivist researchers to the “technocratic” imposition of solutions on society, in part because there is a concern that any solution that is implemented top-down will be driven by the vested-interests of elites and will fail to take account of the needs and interests of disadvantaged and oppressed societal groups (Olsson, 2022). Related to this, interpretivist transitions research often focuses on distributional, procedural and recognitional transition justice (Wågsæther et al., 2022). The fulfilment of all justice requirements can be hard to reconcile with rapid, radical and purposive transition action. Perhaps for these reasons, interpretivist transitions research is more often retrospective and reflexive than forward-looking, predictive and purposive.

This study is founded on the assumption that, due to system complexity and dependencies, rapid and radical road freight decarbonisation compatible with achieving carbon reduction goals will not happen unless it is made to do so purposively. The need to reconcile this with needs for transition justice and legitimacy was a significant motivator in the decision to conduct the research presented in paper 5. It is proposed that well-designed and effectively executed transition governance is the principal means by which this reconciliation can be achieved. Tensions between transition speed and scale, and transition justice and legitimacy are inevitable. The ability to establish governance that effectively balances these tensions and allows necessary trade-off decisions to be made will be a critical determining factor in whether we can deliver road freight decarbonisation that achieves both effective climate change mitigation and political and social acceptance.

6 Publications, impact and directions for future work

6.1 Publications

The thesis incorporates six papers, which at the time of submission are at varying stages of review and publication (table C-1):

Table C-1: Papers written and status

Paper	Status
1. Decarbonising road freight by operationalising transition theory: A systematic literature review	Revisions submitted in December 2024: European Transport Research Review
2. Transition codesign for purposive road freight decarbonization	Published: Transportation Research Part D – Transport and Environment https://doi.org/10.1016/j.trd.2023.103980
3. Decision pathways for road freight decarbonization	Published: Transportation Research Part D – Transport and Environment https://doi.org/10.1016/j.trd.2025.104831
4. Pathplotter: A software tool for codesigning transition decision pathways	Submitted in March 2025: The Design Journal
5. Purposive transition governance for road freight decarbonization	Revisions submitted in May 2025: Transport Policy
6. Hydrogen for long-haul road freight: A realist retroductive assessment	Published: Renewable and Sustainable Energy Reviews https://doi.org/10.1016/j.rser.2025.115898

The focus on publication, in addition to meeting the requirements of the alternative thesis format, was motivated by a desire to maximise the visibility and impact of the work; to gain early reviewer feedback; and, as far as possible, to ensure all components of the thesis reach the standard for publication in high-quality journals.

6.2 Impact

There have been significant engagements with Transport for London and the Welsh Government resulting from thesis research. At the time of writing, dialogue with the Welsh Government is ongoing. In addition, as a result of the research, I was invited to become an associate member of the Freight Energy Forum organised by the UK Department for Transport (DfT).

6.2.1 Transport for London (TfL)

This engagement was a collaboration with Carolina Buneder and Cameron Cox (permission given to share names) of TfL who co-hosted and recruited participants for a decision pathway workshop as part of research for paper 3. Participants recruited by TfL included representatives of energy infrastructure providers, vehicle manufacturers, freight operators, two transport authorities and a transport decarbonisation NGO. Outputs from the workshop, in addition to being incorporated into research findings, were used by TfL as input into their planning for heavy goods vehicle decarbonisation in London.

6.2.2 Welsh Government (WG)

A decision pathway workshop, co-hosted with Professor Vasco Sanchez Rodrigues (permission given to share name) of Cardiff Business School, was conducted as part of the research for paper 3. This workshop included a WG representative. Following the workshop, discussions were held with senior WG officers responsible for freight and energy policy. These led to a second workshop in Jan 2025 hosted by WG to further develop a decision pathway for last mile parcel delivery decarbonisation in Wales. Participants in the second workshop included, in addition to WG officers and freight and logistics experts, representatives of two national parcel delivery companies and a transport decarbonisation NGO. I facilitated the workshop using further developed versions of the decision pathway process and Pathplotter tool, drawing on lessons learned from papers 3 and 4. The workshop outputs and participant feedback provide a compelling endorsement of the process and Pathplotter tool, and the WG co-hosts have expressed interest in continuing with the collaboration.

6.2.3 Freight Energy Forum

The Freight Energy Forum was created by the DfT to bring together senior representatives from the freight and energy sectors, and government to support the freight sector's transition to net zero. As an associate member, I do not attend the main forum meetings, but participate in follow up briefings and discussions organised by the DfT.

6.3 Communication and dissemination

Please see Thesis Appendix C for a summary of the communication and dissemination activities conducted.

6.4 Potential directions for future research

There are three proposed opportunities for work stemming from the project:

6.4.1 Operationalisation of purposive codesign for UK road freight decarbonisation

Within a purposive framing, the goal of transitions research is to achieve better transition outcomes. This study has demonstrated the potential of purposive transition codesign, but further collaboration between transport, logistics and energy research, and road freight policymakers and actors is required to translate this into policies and decisions that deliver rapid and radical decarbonisation while maintaining essential road freight functions. Existing work at national, regional and local levels is an important reference point for this. Within the UK, national Zero Emission Heavy Good Vehicles and Infrastructure Demonstrations (ZEHID) trails represent the largest scale current collaboration between policymakers, road freight operators and energy infrastructure providers considering road freight decarbonisation. There are also smaller-scale initiatives at devolved national, regional and city levels. Some of these initiatives may provide an opportunity to apply, validate, and further develop the approaches presented in this thesis. The outcome of the initiatives will also define the context and opportunities for future road freight decarbonisation research in the UK.

6.4.2 Application of purposive codesign to other transitions and geographic contexts

It has been concluded in this study that, due to system complexity and interdependencies, purposive codesign is required for rapid and radical road freight decarbonisation within the UK. It seems likely it could also be applicable to other transitions and geographic contexts that share these system characteristics. A substantial opportunity exists to explore the application of purposive codesign to these wider transition challenges, and to further develop the frameworks and tools presented in this thesis to facilitate this.

6.4.3 Building a multi-disciplinary research capability to address major societal challenges

The need for a multi-disciplinary approach to inform the purposive transition of complex techno-economic, socio-technical and political systems is reinforced by this thesis. However, it is also concluded that the challenges of conducting interdisciplinary research limit research's ability to inform real-world policy- and decision-making for purposive transitions. These challenges are deeply rooted in the differing cultures, philosophies and methods of disciplines. Recognising that this diversity enhances the richness of research, work is nevertheless required that enables knowledge and approaches from multiple disciplines to be brought to bear in a way that better aids transition policy and decision-making.

7 Closing reflections

I have greatly valued the opportunity that conducting this thesis has provided to investigate socio-technical, political and techno-economic dimensions of road freight decarbonisation. The evidence is manifest that rapid and radical decarbonisation is necessary to avert the most extreme climate change scenarios. Through my previous MSc research, I gained an understanding of the road freight decarbonisation solutions available and the techno-economic, socio-technical and political barriers to implementing these. I also identified gaps in literature of research considering socio-technical and political dimensions of this transition; and of research in general that considers how transitions can be purposively enacted. During the work for this thesis, I have gained a better understanding of the root causes of these gaps and have developed and applied frameworks, approaches and tools to help address these.

I conclude the thesis excited by the potential for techno-economic, socio-technical and political transitions research to aid purposive transition decision-making and action. However, I am even more aware than before of the philosophical and methodological challenges of conducting the interdisciplinary work necessary to bridge these transition domains. I believe that this compartmentalisation needs to be overcome if research is to have the positive impact on delivering this essential transition that it can and must have.

Even if these academic barriers can be addressed, many open questions remain on how road freight decarbonisation can be purposively delivered in the present economic, social and geo-political climate. This includes threats to established institutions and social norms; and an increasingly aggressive rhetoric that runs counter to the co-operation that would be necessary to affect purposive transition delivery. These challenges are beyond the scope of this thesis, but we need to assume that they can be addressed and that a collaborative path to this and other sustainability transitions is possible. The alternative is to accept a dystopian vision of ever-increasing emissions and environmental degradation, and escalating competition for the right to control and consume a dwindling pool of planetary resources that will further increase already large social and geographic inequalities. I believe that research has a vital role to play in engaging with policy- and decision-makers to find a pathway to a better future than this.

My hope is to be able to contribute to this impact by working with other researchers, policymakers and industry decision-makers to further develop and apply the frameworks, approaches and tools developed in this thesis. It seems likely that these are also applicable to other complex system transitions in which actor decision-making must be coordinated. Ultimately, I believe it is our collective duty, not only to identify why sustainability transitions are "wicked", but also to find how to overcome this wickedness so that the systems that are necessary for human wellbeing today are also compatible with a positive future for humans, other species and the planet.

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Thesis Appendix A: Ethics approval

Dear Philip Churchman

Your research ethics application reference: 0148

Amendment reference number: BESS+ FREC 2024-0148-1728

Your research project: Transition co-design for purposive United Kingdom road freight decarbonisation

I am pleased to inform you that the above amendment application has been reviewed by the Business, Environment, Social Sciences BESS+FREC Faculty Research Ethics Committee (FREC) which has issued a favourable ethical opinion based on the application submitted. **Please retain this email in your project file as it is evidence of the Committee's approval.**

Matters you should note:

- Ethics approval does not infer you have the right of access to any member of staff or student or documents and the premises of the University of Leeds. Nor does it imply any right of access to the premises of any other organisation, including clinical areas. The Committee takes no responsibility for you gaining access to staff, students and/or premises prior to, during or following your research activities.
- It is your responsibility to comply with all relevant Health and Safety, Data Protection and other legal and professional requirements and guidelines.
- You are expected to keep a record of all your approved documentation, as well as documents such as sample consent forms, risk assessments and other documents relating to the research project. This should be kept in your project file.
- Audits are undertaken on approved ethics applications. Your project could be chosen for such an audit. You should therefore ensure your project files are kept up to date and readily available for audit purposes. You will be given a two week notice period if your project is selected.
- Please always include the above research ethics application reference and Amendment request reference in any correspondence with the Research Ethics team.

If you need to make amendments to the original research project as submitted, you are expected to seek approval from the Committee before taking any further action. Changes could include (but are not limited to) the project end date, project design or recruitment methodology, or study documentation. Please go to https://secretariat.leeds.ac.uk/research-ethics/how-to-apply-for-research-ethics-amendment/ or contact the Research Ethics team for further information at Research Ethics.

I hope your research project continues to go well.

Best wishes,

Ms Taylor Haworth, Phoenix Lead, Research Ethics, Secretariat, University of Leeds

On behalf of Dr Judith Hanks, Chair, BESS+ FREC

Thesis Appendix B: Purposivist research approach

1. Research philosophy overview

1.1. Ontology

Ontology considers the nature of reality and truth (Moon and Blackman, 2014). Realists assume that there is a reality that is independent of context and the values, norms and standards of those observing it. Relativists by contrast do not consider truth and reality to be absolute, but to be the product of context, values, norms and standards. Bounded relativists propose that members of societal groups share a common view of reality but that realities differ between groups. Naïve and structural realists differ in the extent to which they believe it possible to fully understand reality with appropriate methods or whether understanding is determined by definitions, technologies, measurements and norms which change over time. Critical realism, which is the ontological position adopted in this thesis, argues that reality exists independently of human observers, but is complex, stratified and emergent, and may as a result never be fully knowable. Critical realism is explored in more depth in section 4.

1.2. Epistemology

Epistemology is concerned with how meaning and knowledge are acquired by people (Moon and Blackman, 2014). Subjectivism asserts that meaning is imposed on objects by people. Objectivism proposes that meaning exists within objects and people seek to discover that meaning. Constructionism argues that meaning is developed through the interplay between people and objects. Constructionism can be seen as a “natural denouement” of the conflict between objectivism and subjectivism (Pegues, 2007). However, Fischer (2019) suggests that it can also create space for factually disprovable non-truths to be given weight and influence. Epistemology is explored further in section 5.

1.3. Theoretical approach

The different theoretical approaches adopted by social scientists represent different views of what science is, and is for (Moon and Blackman, 2014). Positivism is founded on realist ontology and objectivist epistemology, and assumes that the empirical methods used in the natural sciences are equally applicable to social sciences. It typically applies deductive reasoning and quantitative methods. Interpretivism is founded on relativist ontology and subjectivist or constructionist epistemology, and focuses on understanding the subjective meanings and experiences of individuals within their social context. It typically applies inductive reasoning and qualitative methods. Critical theory considers power relationships, political agendas and oppressed social groups, and includes feminist, advocacy and emancipatory studies.

1.4. Axiology

Axiology concerns the nature of value and embodies normative considerations of what "ought to be". While ontology and epistemology consider what constitutes science, axiology considers its purpose. Deane (2018) argues that the difficulty of reconciling different theoretical approaches is less due to ontological and epistemological differences, and more due to axiological differences, as research adopting different theoretical approaches has different purposes and is founded on different values. In simple terms, the respective goals of research adopting the three theoretical approaches summarised in the previous sub-section are:

- Positivism: to explain, predict and control
- Interpretivism: to understand and communicate
- Critical theory: to emancipate, critique and change power relations

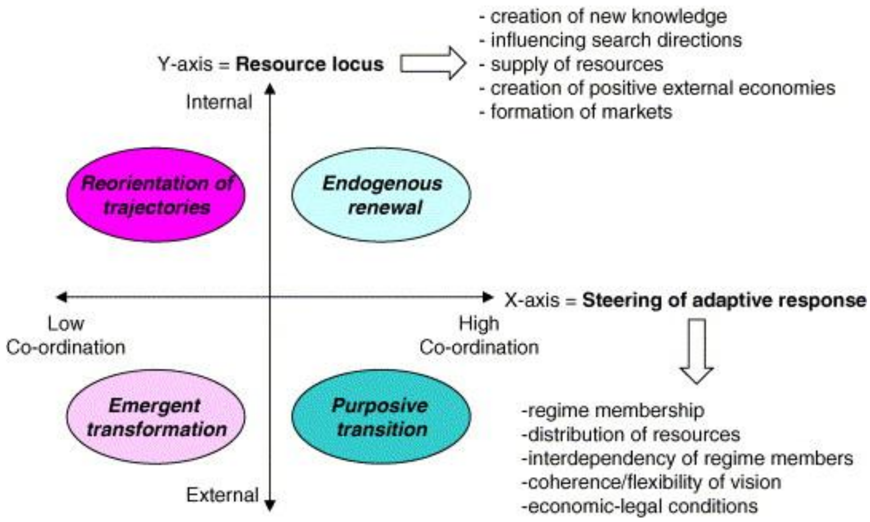
As with critical theory, the research goal of this thesis is to facilitate purposive system change. However, unlike critical theory, the change objective is sustainability rather than social emancipation; and politics and power, while being important transition considerations, are not the central change objectives. For these reasons, critical theory is not considered further in this thesis.

The tensions between positivism and interpretivism in social science are well documented in literature, e.g. (Mingers, 2004; Carminati, 2018). However, the requirement for system codesign invokes the need for elements of both positivism and interpretivism, as codesign demands both the broad system understanding sought by interpretivism and the prediction and control sought by positivism. The remainder of this appendix explores the consequences of this.

2. Purposive transition codesign

As discussed in Introduction section 4, due to system complexity and dependencies, many road freight actors are unable to take significant decarbonisation action alone, meaning that key system-level decisions are required. In the absence of top-down making of these decisions by government, these need to be purposively codesigned by industry actors and policymakers. This aligns with the analysis of Smith et al. (2005), who identify that a purposive transition is required when high coordination between actors is needed and the resources to execute the transition are external to the established regime (figure AB-1).

Figure AB-1: Coordination of actors and locus of resources framework
(source: Smith et al. (2005, p.1499))



Actions that have the potential to deliver radical road freight decarbonisation such as changing vehicle energy source or shifting to lower carbon modes require high coordination and engagement with actors outside of the incumbent regime, and therefore fall into the purposive transition quadrant. However, other decarbonisation actions align with other parts of the matrix. For example, improving the aerodynamics of vehicles can be done by individual companies, with the only external dependency being on vehicle manufacturers who are internal to the current regime, placing this in the "reorientation of trajectories" quadrant. Purposive transition actions also require interdisciplinary engagement of policymakers, industry participants, experts and academics, necessitating new ways of collaborative and participatory working (Bennett and Brunner, 2022). The specific challenges of purposive transition go some way to explain why greater progress has been made on incremental decarbonisation opportunities such as improving vehicle aerodynamics than more radical ones such as vehicle energy source change or mode shift.

3. The challenges of positivism and interpretivism

When seeking to purposively codesign transitions to address systemic problems such as climate change, we are in uncharted territory. This is the first time that human-induced climate change has happened, and it has never been solved before, so we lack a precedent to draw on. Every branch of forward-looking sustainability transitions research is therefore in some form making predictions of how different actions will impact the future, without the ability to empirically validate the accuracy of these predictions. A positivist response to this challenge is to create artificial future realities in the form of simulations such as climate models, system dynamics models and digital twins. These models are useful as they can be used as a sandbox to explore different assumptions of system structure and mechanisms. They also provide virtual lab environments for scenario testing. However, like physical labs, the extent to which scenario results can be considered predictive of real-world outcomes depends on the extent to which the structure and mechanisms of the model are a sufficiently comprehensive and accurate mirror of the system being modelled. This is a greater challenge still for models of highly complex systems as, once they pass a certain threshold of complexity, the structure and mechanisms of the model can become opaque to researchers. This makes it even more difficult to assert that model outputs can be generalised to reality.

Interpretivist research has a different problem. As it is ontologically relativist, truth and reality are not considered absolute, but as being the product of context, cultural norms and individual standards. If this is applied naïvely, it treats one person's view that human-induced climate change is happening and another's that it is not as equivalent, because interpretivism cannot contain the idea that there is far stronger empirical evidence for the former than the latter view. More practically, purposive system change requires a predictive view of how action will influence the future system. If the system is considered not to be "real" but instead a product of individual and collective perceptions, prediction no longer considers how the system will be affected by actions, but instead how people's *perception* of the system will be affected. While predicting system change based on a realist assumption is hard, predicting people's future perceptions of system change is arguably even harder. It could also be seen as changing the responsibility of those in authority from minimising the actual impacts of climate change to minimising its *perceived* impacts. It may even be that the latter can be more easily manipulated through misinformation and dehumanising those who are suffering the worst effects of climate change than by implementing concrete actions for mitigation and adaptation.

Positivism and interpretivism also present methodological challenges. Positivist research is typically epistemologically objectivist and methodologically quantitative. This is because, for objective phenomena to be empirically proven, positivism requires that they be demonstrated to show the same behaviour under repeated experiments. Interpretivist research, being typically epistemologically subjectivist and methodologically qualitative, is the opposite of this. In its "naïve" form, there is no value assessment of views based on the expertise of the person expressing them. Equal emphasis can be given to views expressed by one person as to those expressed by many. It can be permissible for the researcher's own views to influence the research process and for the views emphasised in findings to be selected by the researcher. Interpretivist research also often places limited emphasis on causality (Land, 2024).

Both qualitative research into objective phenomena and quantitative research into subjective phenomena can be seen as methodologically flawed as they confuse positivist and interpretivist research paradigms. As mixed methods approaches strictly require quantitative and qualitative research elements to be separated, they do not overcome this constraint. The study of purposive system change requires the synthesis of assumptions regarding system behaviour from expert opinion and qualitative insights, and the use of logical reasoning to assert their generalisability. For this to be scientifically justifiable, this qualitative analysis needs to have stronger safeguards against researcher bias than can be the case in interpretivist research driven by normative research goals. However, unlike in much positivist research, it must also recognise that subjective opinions of research participants matter, whether they are based on a factually correct system understanding or not, as opinions have real world consequences in social and political systems.

4. The argument for critical realism

It is proposed that critical realism provides a more theoretically appropriate and practically useful foundation for governing change in organisations and systems than other ontological framings. Sayer (2004, p.6) proposes that *"Critical realist philosophy offers an alternative both to the spurious scientificity of positivism and to idealist and relativist reactions to positivism."* Fleetwood (2004, p.26) further argues that *"The recoil from (correctly) abandoning positivism appears to have 'catapulted' postmodernists and post-structuralists into substituting one mistaken ontology for another. If unchecked, this could easily take organisation and management studies down an alley as blind as the positivist one from which it has struggled to escape."*

Critical Realism is founded on work by Roy Bhaskar in his 1975 book "*A Realist Theory of Science*". Bhaskar rejects both "classical empiricism", in which knowledge objects are representations of phenomena, and "transcendental idealism" in which knowledge objects are human constructs imposed on phenomena (Bhaskar, 2013). Instead, he proposes "transcendental realism" in which knowledge objects are structures, mechanisms and causal relationships that generate phenomena. A central argument is that the systems we are studying are open rather than closed, meaning we cannot know everything about the system or how it may change. For this reason, asserting phenomena events as knowledge is not legitimate as a change in exogenous factors could change these phenomena. By contrast, asserting structures, mechanisms and causal relationships within the system as knowledge is legitimate. Bhaskar suggests that these knowledge objects have a reality independent of both phenomena events and the human scientists studying the phenomena.

Bhaskar further argues that constant repeatability of phenomena is neither necessary nor sufficient to prove causal laws. He proposes that empirical testing of repeatability should be replaced with a process of postulating structures, mechanisms and causal relationships and then subjecting these to broad, critical, empirical scrutiny. An implication is that there is the possibility for "imagined" knowledge, following adequate empirical scrutiny, to become considered as real. Bhasker argues that transcendental realism, unlike classical empiricism and transcendental idealism, fulfil both requirements for an adequate theory of science:

1. Its capacity to sustain knowledge as a produced means of production; and
2. Its capacity to sustain the idea of the independent existence and activity of the objects of scientific thought.

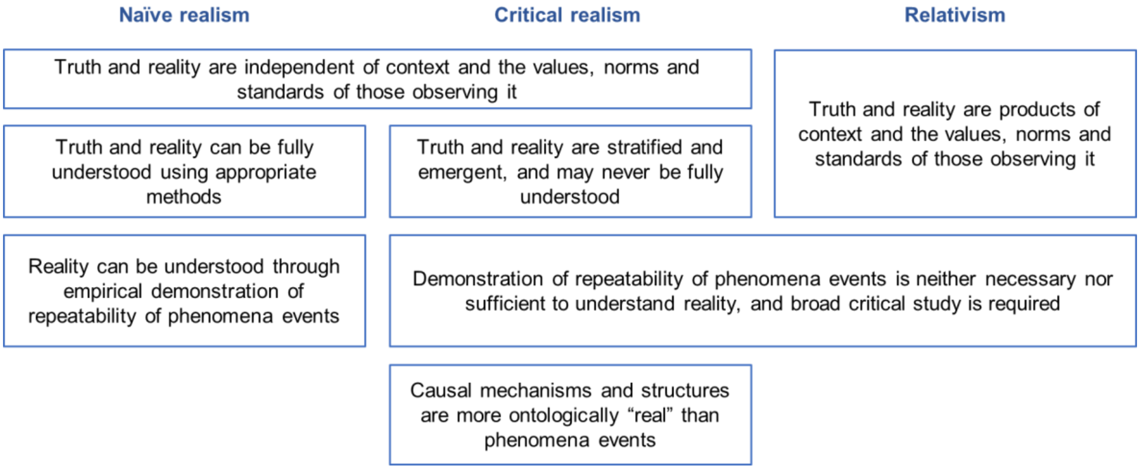
Aligned with the above, Smith (2006) proposes that benefits of adopting a critical realist approach to research are that, by recognising the reality of structures and mechanisms, it provides greater explanatory power and helps overcome inconsistencies between stated theoretical research assumptions and practice. In focusing on structures, mechanisms and causal relationships, Bhaskar asserts that the "being" of these (ontology) should not be subjugated to differing views on the nature of knowledge (epistemology). He describes the giving of primacy to the latter, which he suggests both classical empiricism and transcendental idealism do, as an "epistemic fallacy".

Grounded theory is identified as well aligned with critical realism (Hoddy, 2019), and critical realism is proposed as providing greater confidence in the scientific validity of the use of grounded theory to understand and explain complex systems (Kempster and Parry, 2011). While Bhaskar could be read as dismissing classical empirical research approaches, Downward et al. (2002) argue there remains a place for methods seeking stable empirical regularities alongside inductive research techniques such as grounded theory, reinforcing the need for epistemological pluralism in critical realist research.

Critical realism asserts that reality is "intransitive" (exists independently of humans), emergent and stratified. Stratification exists between the "real" (the whole of reality), the "actual" (what occurs) and the "empirical" (what is observed and experienced) (Sayer, 2000). A second form of stratification is multiple layers of causal relationships, with causal mechanisms at one level being determined by those at lower levels (Mingers, 2000). The consideration of reality as emergent and stratified means that social and political systems can be viewed as being as appropriate for critical realist study as natural systems (Carolan, 2005; McAnulla, 2006). Critical realism is also proposed as a viable alternative to the dominant empirical approach to econometric forecasting as, while not necessarily improving forecasting accuracy, it better reflects the inherent ambiguity and uncertainty of economic systems (McAnulla, 2006). Danermark et al. (2019, p.135) argue that: *"the ability to switch between theorising on different levels of abstraction and observations of concrete reality, without yielding either to arbitrary theorising or to short-sighted observations, is in the core of social science working procedure."*

Figure AB-2 provides a high-level summary of the differences between naïve realism, critical realism and relativism.

Figure AB-2: Summary of differences between naïve realism, critical realism and relativism (source: Author's synthesis of Moon and Blackman (2014))

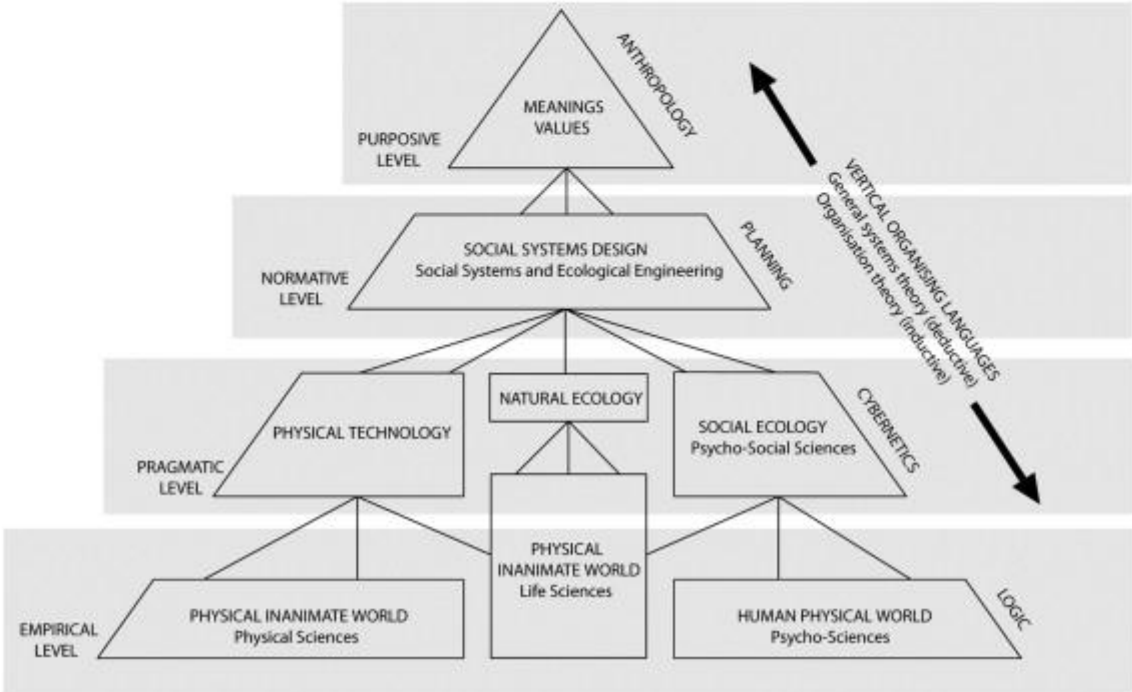


5. The argument for pluralist epistemology

While positivism is broadly aligned to realism and interpretivism to relativism, the more fundamental alignments of these research frameworks are epistemological, as positivism is objectivist and interpretivism is either subjectivist or constructionist. It is this epistemological distinction that means that research methods generally fall onto one or other framework, with little overlap.

When considering transitionary research, Mitchell et al. (2015) propose that three "transdisciplinary outcome spaces" should be explicitly defined to guide research: an improvement in the situation or field of inquiry; the generation of relevant stocks and flows of knowledge; and mutual and transformational learning by the researcher(s) and involved participants. To guide researchers in achieving these three outcomes, they advocate a systematic approach that links empirical, pragmatic, normative and purposive levels (figure AB-3). This is helpful in several ways. Firstly, it suggests that transdisciplinary research is only likely to be successful if there is a defined unifying purpose. Secondly, it integrates objectivist and subjectivist insights at all levels and sees no philosophical or practical inconsistency in this. Thirdly, it combines social ecology and physical technology within a single "pragmatic" level. Fourthly, it incorporates a perspective that social systems can be planned and designed to achieve desired normative purposes. Fifthly, it identifies systems and organisations theory as languages for linking and organising the four levels. The framework demonstrates, albeit at a high level, how epistemologies and methods from different disciplines can and in fact must be combined to plan, design and act our way to a decarbonised future. Aligned with this reasoning, purposivism adopts a pluralist epistemology that recognises the need for both objectivist and subjectivist inquiry as part of the broad empirical scrutiny advocated by critical realism.

Figure AB-3: Transdisciplinary research framework
(source: Mitchell et al. (2015, p.87))



6. Abduction and retroduction

Positivist research can be described as logically deductive (testing a predefined theory through experimentation and observation) and interpretivist research as inductive (developing theory from specific observations). By contrast, critical realist approaches can be described as a combination of "abductive" in which probable theories regarding causal mechanisms are developed from incomplete information and "retroductive" in which the researcher considers the contextual conditions under which the causal mechanisms would take effect and the observed empirical trends would occur (Meyer and Lunnay, 2013; Fletcher, 2017).

Qualitative analysis and grounded theory are helpful methods for the abductive stage of critical realist analysis (Belfrage and Hauf, 2017) and abduction is indeed central to grounded theory (Reichertz, 2009). Aligned with this, Mukumbang et al. (2019) argue that qualitative interviews are a powerful and underutilised tool in realist research. Both qualitative or quantitative approaches can be helpful for retroduction, with Papachristos and Adamides (2016) applying system dynamics simulations while Fletcher (2017) uses qualitative research. Land (2024) also observes that the application of abduction followed by retroduction is an effective way of incorporating a consideration of causality into qualitative research.

Mukumbang (2021) proposes that abduction and retroduction combined with critical realism provide a more ontologically and epistemologically grounded alternative to mixed methods within a pragmatist theoretical framework. They also note that, while abductive and retroductive reasoning are explicitly referenced in literature much less frequently than deductive and inductive reasoning, they are often implied in stated research methods.

7. Systems Thinking framing

Systems Thinking (ST) is commonly used as an umbrella term for approaches that consider the implications of causal relationships for system analysis and design. ST has been used in studies considering sustainable development (Halbe et al., 2015), urban sustainability (Kutty et al., 2020), circular economy (Iacovidou et al., 2021) and resilient ecosystem services (Biggs et al., 2015).

Mingers (2015) suggests that ST is well aligned with critical realism. They highlight the range of “hard” (epistemologically objectivist) and “soft” (epistemologically subjectivist) methodologies provided by ST. Identifying that systems have multiple dimensions that are physical, social, conceptual and cognitive, they argue that their exploration needs a variety of hard and soft methods. This requires both quantitative and qualitative research and the flexible epistemological positioning offered by critical realism.

8. Relevant heuristics

Heuristics are models or frameworks that aid conceptualisation of system structure and behaviour. They generally stem from interpretive study and consequently, for the reasons described in section 3, are not always helpful for predicting specific transition outcomes. While they do not therefore necessarily provide the answer for transition design, they can aid abductive theory development.

Heuristics that have been found to be helpful for conceptualising purposive road freight decarbonisation are the Multiple Streams Framework (Kingdon, 1984), Multi-Level Perspective (Geels and Schot, 2007), Transition Management (Loorbach, 2010), Advocacy Networks (Normann, 2017) and Policy Mix Feedback Loops (Edmondson et al., 2019).

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Thesis Appendix C: Communication and dissemination

1. Collaborations

In addition to the engagement of individual industry participants, experts and transport authority representatives in interviews and workshops, there were three significant collaborations during the thesis (table AC-1). These collaborations were extremely valuable in providing implicit endorsement for the work, practical assistance in securing workshop participation, and intellectual and practical critique.

Table AC-1: Collaborations

Collaboration	Activity
Transport for London Carolina Buneder and Cameron Cox	Co-hosting decision pathway workshop considering decarbonisation of urban HGV movements
Cardiff Business School Professor Vasco Sanchez Rodrigues	Co-hosting original and follow-on decision pathway workshops considering last mile parcel delivery decarbonisation in Wales
Welsh Government James Brown and Jon Moody	Co-hosting follow-on decision pathway workshop considering last mile parcel delivery decarbonisation in Wales

2. Conference presentations

At the time of writing, thesis work has been presented or accepted for presentation at 14 conferences (table AC-2). A submission to NECTAR 2024 was also accepted, but I was not able to attend due to a conflict with another conference. As with paper publications, the motivation for presenting at these was to maximise exposure and potential impact of the work, and to gain the benefit of critical examination and feedback. The presentation at the University Transport Studies Group (UTSG) 2023 conference won the Smeed prize for the best paper and presentation by a PhD student.

Table AC-2: Conference presentations

(all are full 20-30 minute presentations unless otherwise specified)

Conference*	Presentation title
CSRF 2022 – Online	Transition codesign for purposive road freight decarbonisation
CSRF 2023 – Cambridge UK	Transition codesign for purposive road freight decarbonisation
CSRF 2024 – Shanghai China	Policy and decision pathways for road freight decarbonisation
ERSS 2022 – Manchester UK (Poster)	Transition design choices for purposive United Kingdom (UK) road freight decarbonisation
ETC 2024 – Antwerp Belgium	Codesigning decision pathways for road freight decarbonisation
ETC 2025 – Antwerp Belgium	Hydrogen for long-haul road freight: A realist retroductive assessment
hEART 2024 – Espoo Finland	Policy and decision pathways for road freight decarbonisation
LRN 2023 – Edinburgh UK	Transition codesign for purposive road freight decarbonisation
RGS 2023 – London UK	Transition codesign for purposive road freight decarbonisation
TPM 2025 – Manchester UK (Presentation plus 1 hour workshop)	Policy and decision pathways for road freight decarbonisation (Deferred from 2024 due to original dates coinciding with the UK general election)
UTSG 2022 – Edinburgh UK	How socio-technical and political transitions research can assist the purposive decarbonisation of United Kingdom road freight
UTSG 2023 – Cardiff UK	Transition codesign for purposive road freight decarbonisation ** Won Smeed Prize for best paper and presentation by a PhD student**
UTSG 2024 – Huddersfield UK	Purposivism: A critical realist research framework for purposive transport transitions
UTSG 2025 – Dublin Ireland	Purposive transition governance for road freight decarbonization

*CSRF – Centre for Sustainable Road Freight; ERSS – Energy Research and Social Science; ETC – European Transport Conference; hEART – European Association for Research in Transport; LRN – Logistics Research Network; RGS – Royal Geographical Society; TPM – Transport Practitioners Meeting; UTSG Universities Transport Studies Group

3. Guest lectures, webinars and articles

In addition to conference presentations, the work has been presented in three guest lectures and webinars, and published in articles in the Chartered Institute of Logistics and Transport (CILT) magazine “Focus” and the “Freight Carbon Zero” newsletter (table AC-3).

Table AC-3: Guest lectures and webinars

Body	Presentation
Chartered Institute for Logistics and Transport (CILT)	Professional development webinar
Heriot Watt – Centre for Logistics and Sustainability	Guest lecture
University of East Anglia	Guest lecture
CILT Focus magazine	Article
Freight Zero Carbon newsletter	Article

4. Transport authority and industry engagement

Organisations represented by interview and workshop participants include:

- Ten national, regional and local transport authorities
- Eight major manufacturers and retailers
- Six road freight operators
- Four road freight industry associations
- Four transport decarbonisation non-governmental organisations (NGOs)
- Three power utilities
- Nine senior logistics experts and academics

This engagement, as well as providing rich research input, has helped create a broad awareness of the work.