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Transition codesign for purposive road freight decarbonization

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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.

1. Introduction

Trucks and vans represent c. 8.5% of United Kingdom (UK) carbon emissions (BEIS, 2021; DfT, 2017). 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; ICCT, 2022; Meyer, 2020). There is however 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

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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 (Cerreta et al., 2021; Förster et al., 2015), "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 (Downie, 2017; Edmondson et al., 2019; Normann, 2017; Salas Gironés et al., 2020; Steurer and Bonilla, 2016). 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 participants, 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) (UK.GOV, 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 A) for each of the three proposed road freight decarbonization preconditions.

2.1. 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

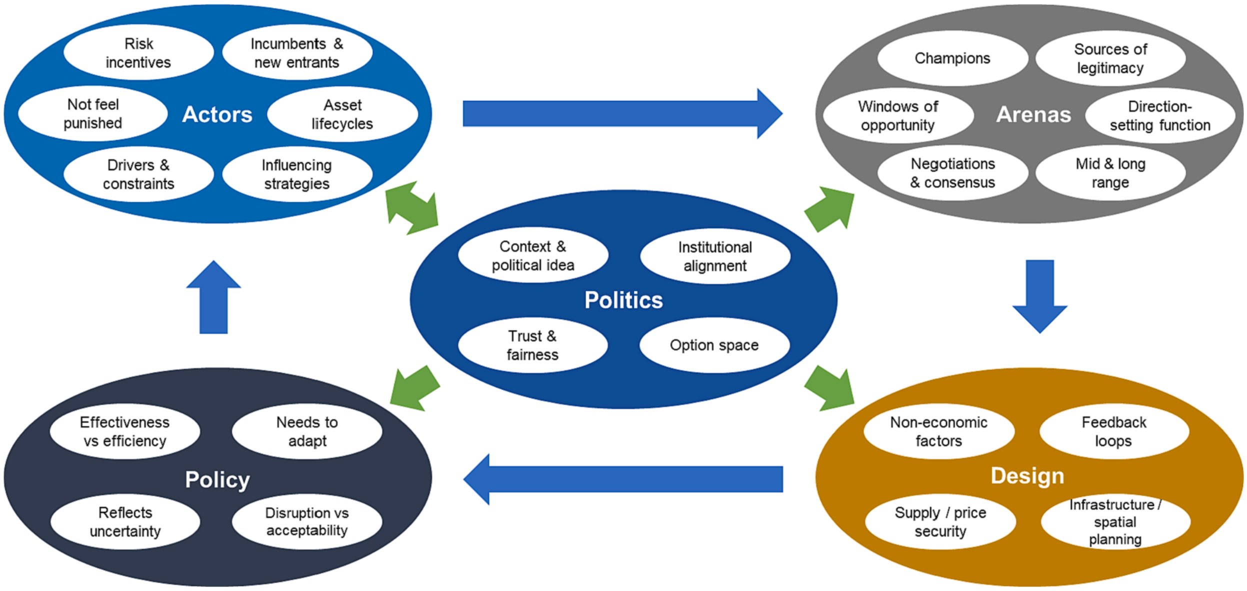

Fig. 1. Conceptual model of socio-technical and political transition attributes for purposive road freight decarbonization. Source: Churchman et al. (2023).

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 (World Economic Forum, 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 (Driscoll, 2014; Sternberg et al., 2013). 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 policy-making 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:

[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.

Table 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**

- *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
- *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) use qualitative methods to develop the conceptual model in Fig. 1 which groups 24 codesign attributes under five headings: Actors, Arenas, Design, Policy and Politics (see Appendix A 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.

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 A 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 min 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

[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.

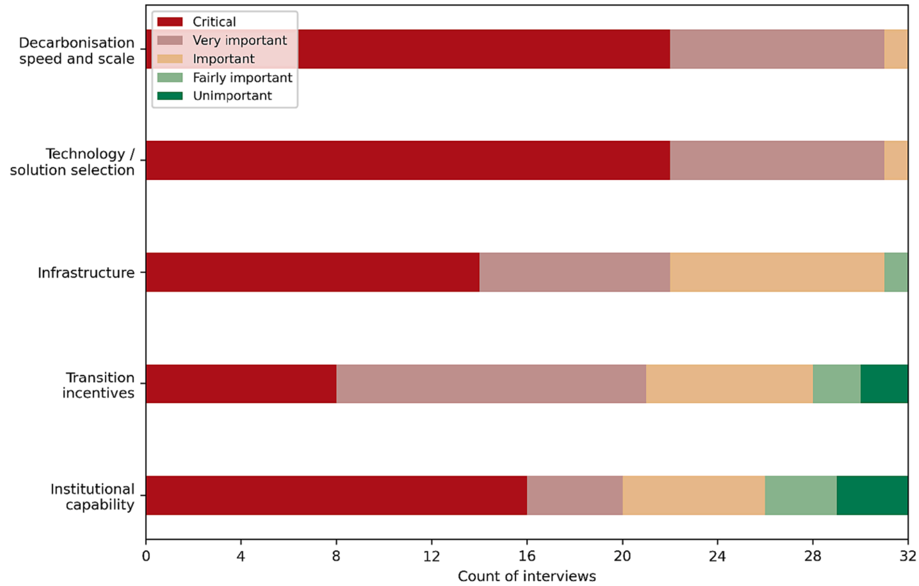

Fig. 2. How important is it that the identified aspects of transition codesign are coordinated?

engaged in 32 interviews (see Table 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.

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., Figs. 2 and 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

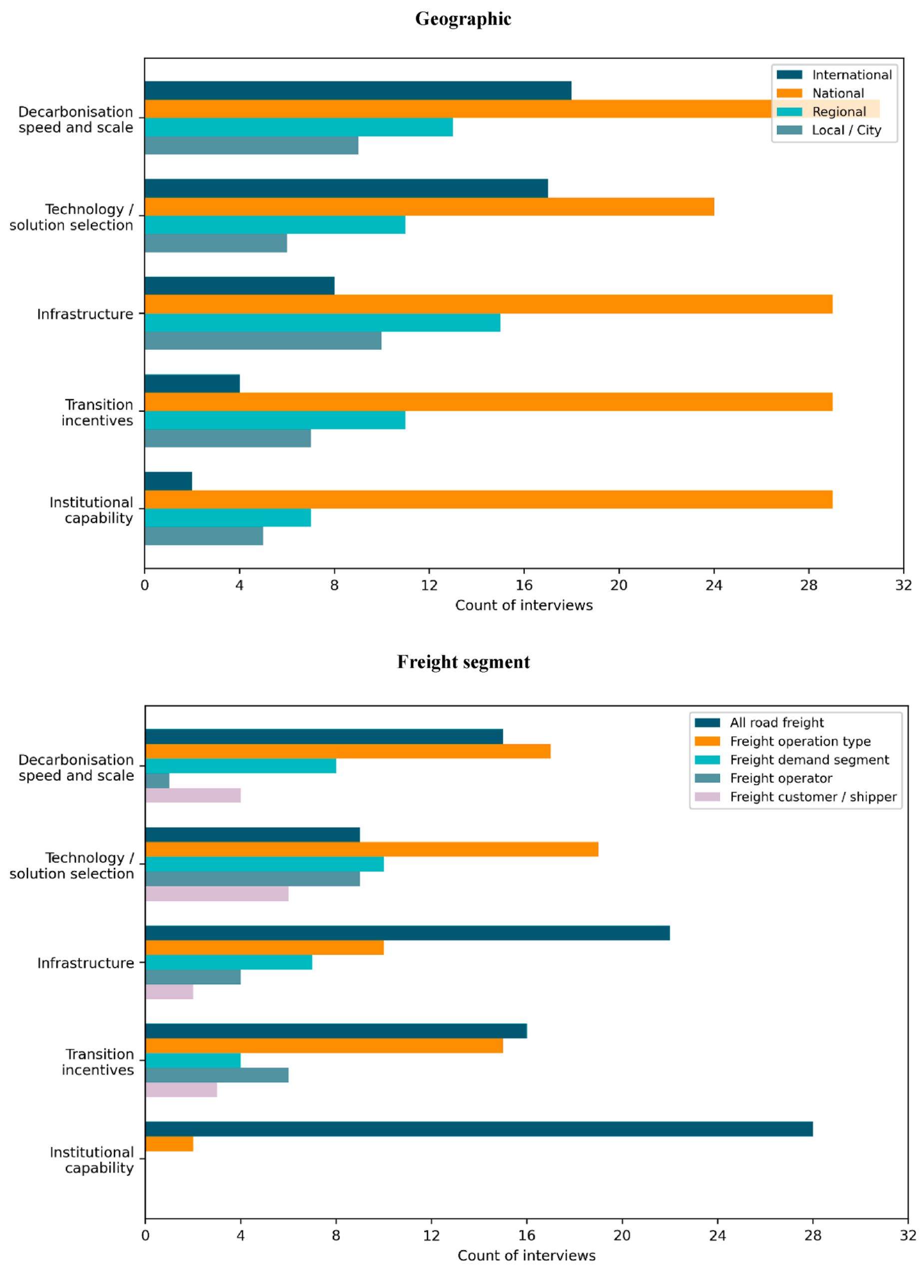

Fig. 3. At what levels do design decisions needs to be made?

participants in an interview expressed the same opinion, this is only counted once in the presented results.

4. Interview design

Please see Appendix A 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

Table 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 seen as marginal.

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 (see Table 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.

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 Fig. 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.

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 revealed 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 Fig. 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.

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

Based on responses to these questions, attributes were grouped into three categories:

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 A), 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 barriers. 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:
  - o Opposing positions regarding hydrogen, biofuels and mode shift to rail
  - o The benefit of keeping emerging technology options open versus proceeding rapidly with solutions that are already proven at scale
  - o 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:
  - o Top-down versus market-led approach to defining decarbonization speed and scale per use case, technology selection and infrastructure provision
  - o The use of direct incentives to freight operators versus demand incentives driven by freight customer requirements
  - o Whether a level playing field for smaller operators is required and feasible
  - o Centralized versus devolved policymaking
- A politically, socially and organizationally feasible codesign framework to make these design choices:
  - o Whether additional sources of legitimacy are required
  - o Whether incumbents should feel punished
  - o Whether road freight decarbonization planning should consider political windows of opportunity
  - o 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 (ONS, 2022; UK.GOV, 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.

Table 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)
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 me 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
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.	

(*continued on next page*)

Table 3 (*continued*)

Questions	Response options
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

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.

9. Glossary

Techno-economic: Technical and economic evaluation of technologies and solutions, enabling an objective comparative assessment of options. Analysis is typically quantitative.

Socio-technical: The dynamics of technology innovation and diffusion in societies, as new technologies develop, challenge, and ultimately displace incumbent technologies. Analysis is typically qualitative and often case-study based.

Codesign: Used in this study to describe the process whereby public and private sector organizations work together to make collective decisions and collaboratively design solutions. Often used in different sense in social science literature to describe the participative engagement of publics to co-produce future societal visions.

Arenas: Decision-making bodies that codesign specified transition decisions.

Purposive: The intentional realization of a desired outcome based on a rigorous understanding of the current system, design of the future system, and specification of a pathway to migrate from the first to the second.

HGVs: Heavy Good Vehicles, defined in the UK as all vehicles over 3.5 tonnes.

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Appendix A

Table 3 includes the open and closed questions that were asked in the interviews.

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