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Decision pathways for road freight decarbonization[☆]

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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, policy-makers 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 was 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 under-studied transition aspects.

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).

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).

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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".

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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., 2023a). 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. (2023a) 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

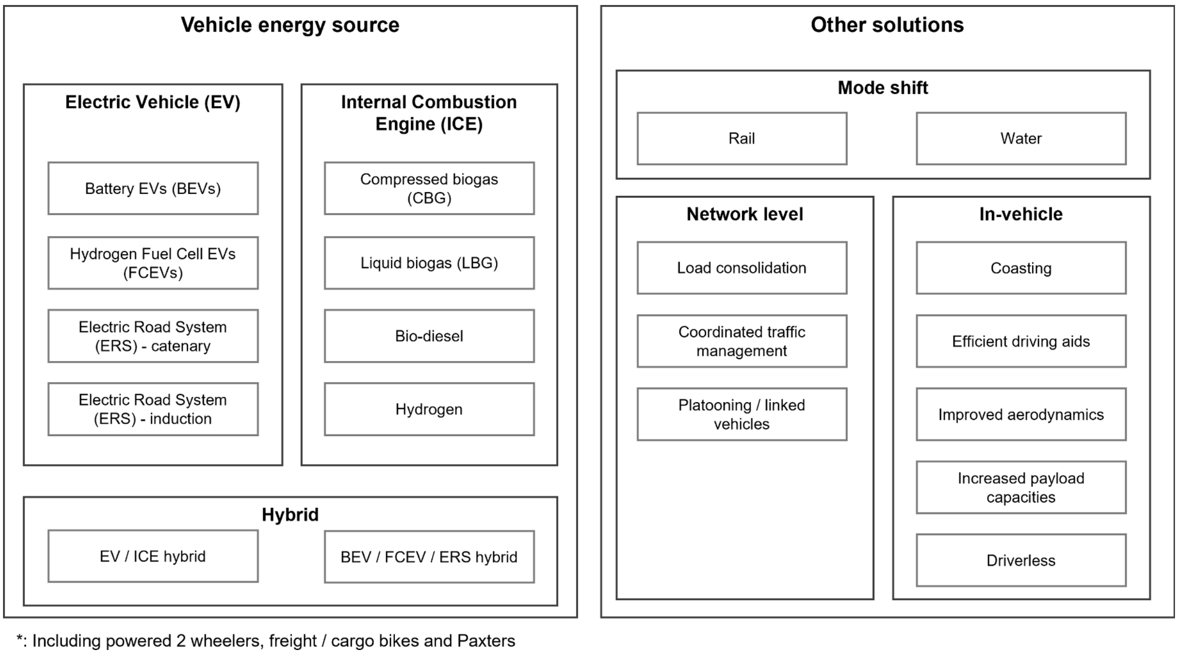

Fig. 1. Technical decarbonization opportunities – not exhaustive ().
Source: adapted from Churchman and Longhurst (2022)

motive technologies 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. Fig. 1 summarizes some of the principal available decarbonization opportunities.

If it is assumed that in all likely future scenarios there will remain a substantial volume of road freight, alternative fuels or new motive technologies 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. (2024b) 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.

Table 1
Workshop summary.

	Road freightdecarbonization 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 100 km/>12 tonne 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.

- 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. (2024a). At the time of writing, Pathplotter is available as freeware at https://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 considered 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 1 summarizes the selected decarbonization goal, format and participants per workshop.

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. (2023b) covering key techno-economic, socio-technical and political system dimensions were provided to participants:

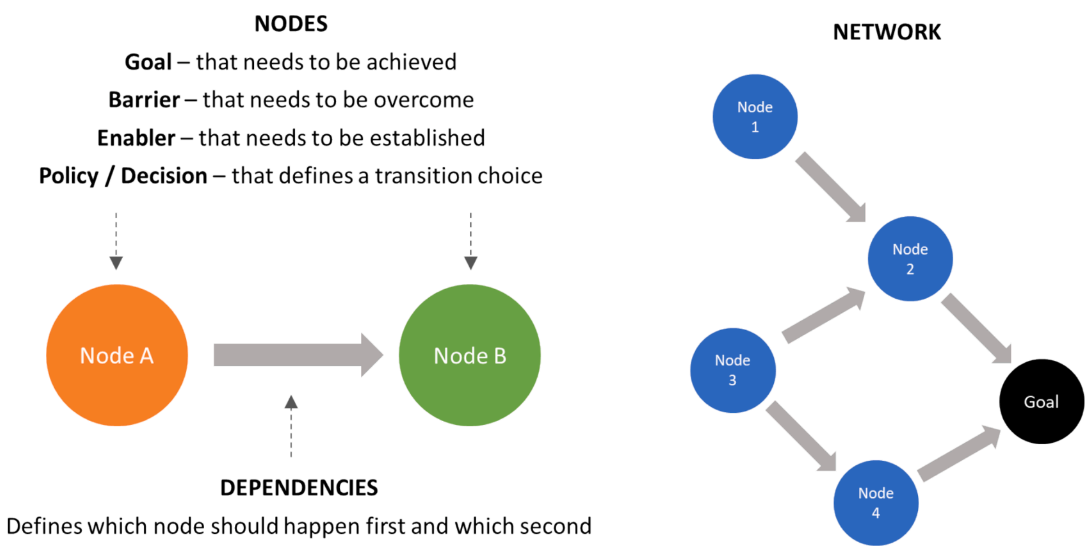

Fig. 2. Decision pathway nodes, dependencies and network.

Speed and scale: Decisions that determine what proportion of road freight will be decarbonized, and how quickly
Technology selection: Decisions regarding the choice of decarbonization solution or technology that will be adopted
Infrastructure: Decisions regarding the deployment of necessary infrastructure including but not limited to energy supply, fueling/charging, vehicle supply and maintenance
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
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 (Fig. 2).

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.

3.2.2.1. 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.

3.2.2.2. 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

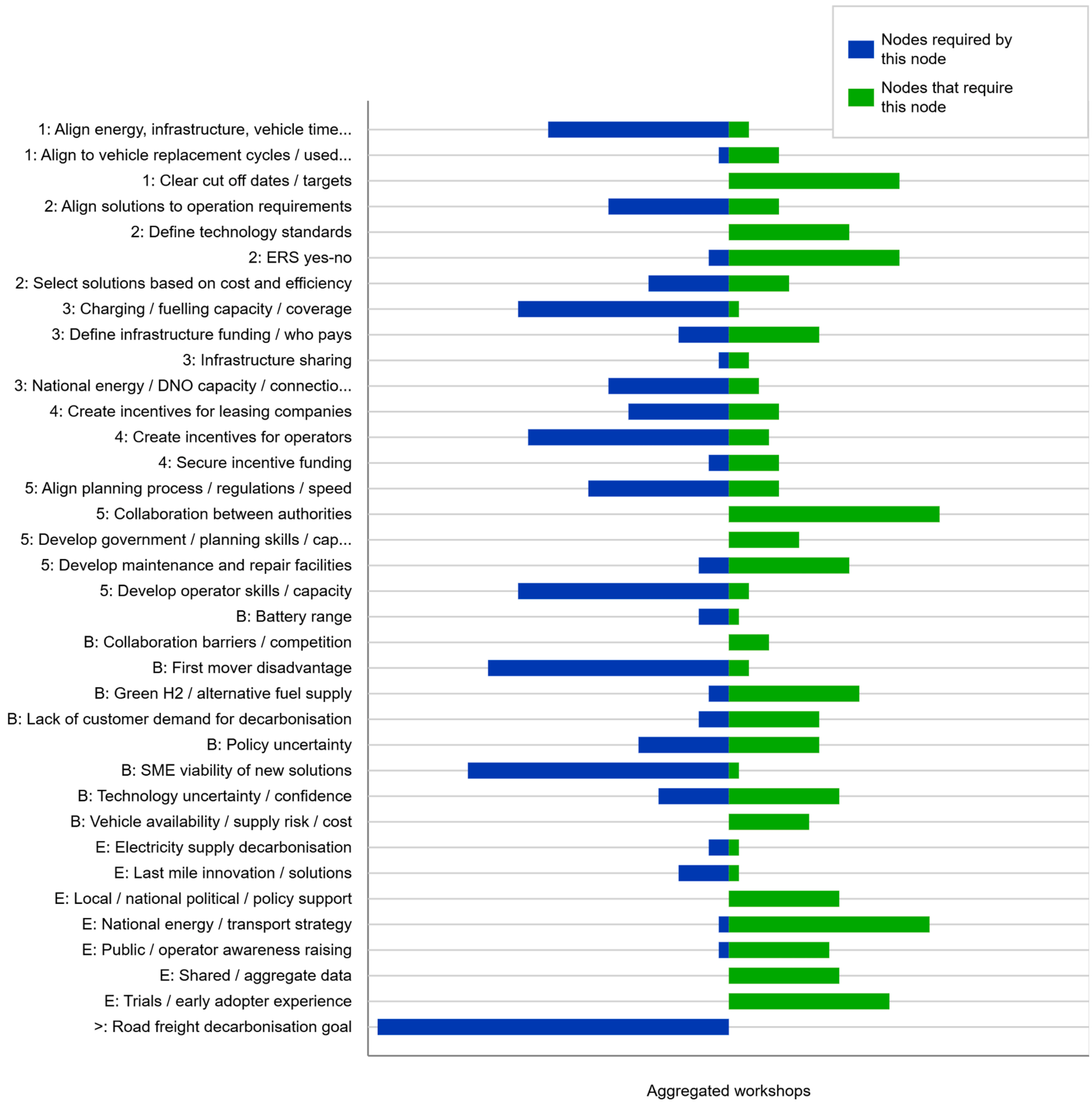

Fig. 3. Aggregate node analysis – nodes identified in two or more workshops Key: 1: Speed and scale; 2: Technology selection; 3: Infrastructure; 4: Incentives, cost and risk; 5: Institutional capability; B: Barriers; E: Enablers; >: Goal.

Appendix B.

Fig. 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 2 provides information on the number of dependent nodes and the workshops in which nodes were identified for the most strongly pivotal nodes.

Fig. 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 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.

4.2.2. *Unstructured commentary shared across multiple workshops*

Table 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.

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.

4.2.3.1. 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.

4.2.3.2. 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.

4.2.3.3. 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.

Table 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

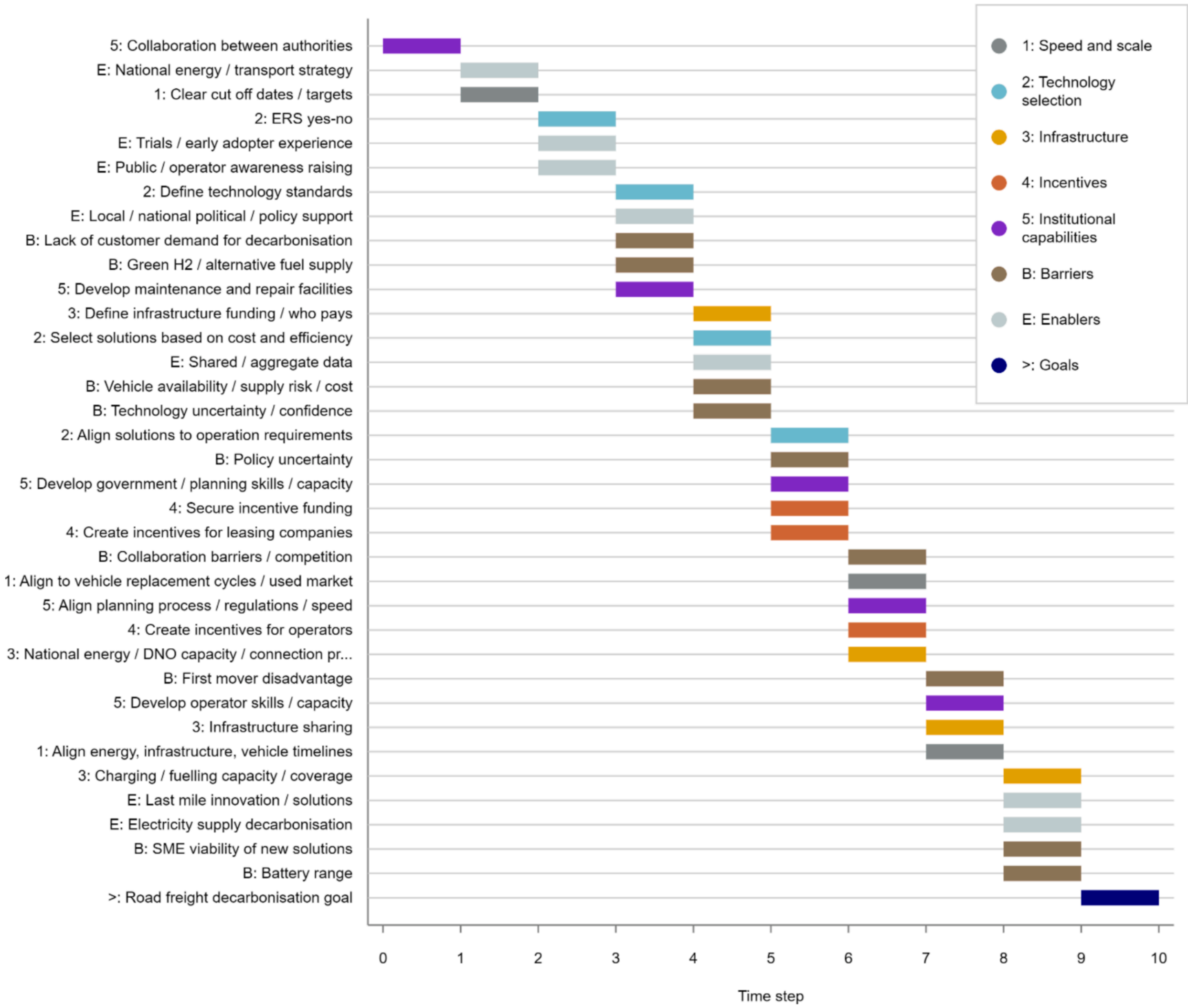

Fig. 4. Aggregate pathway node sequence.

Table 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
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

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.

4.2.3.4. 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.

4.2.3.5. 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?

This 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 seen 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.

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

[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.

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.

CRediT authorship contribution statement

Phil Churchman: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Thijs Dekker:** Writing – review & editing, Validation, Supervision, Methodology. **Kate Pangbourne:** Writing – review & editing, Validation, Supervision, Methodology.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A:. Pathplotter overview

Pathplotter is a Progressive Web App (PWA) hosted on Microsoft Azure. It was developed to address two needs:

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

Once signed in, users can create their own models ("versions"). Within a version, the user defines node categories, nodes and dependencies. Nodes and dependencies can be specified either via either a tabular or graphical interface. Pathplotter then 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 available: "node analysis", illustrated in Fig. 3, "Gantt", illustrated in Fig. 4, and "network" illustrated below in Fig. 5. 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. 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 exported 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.

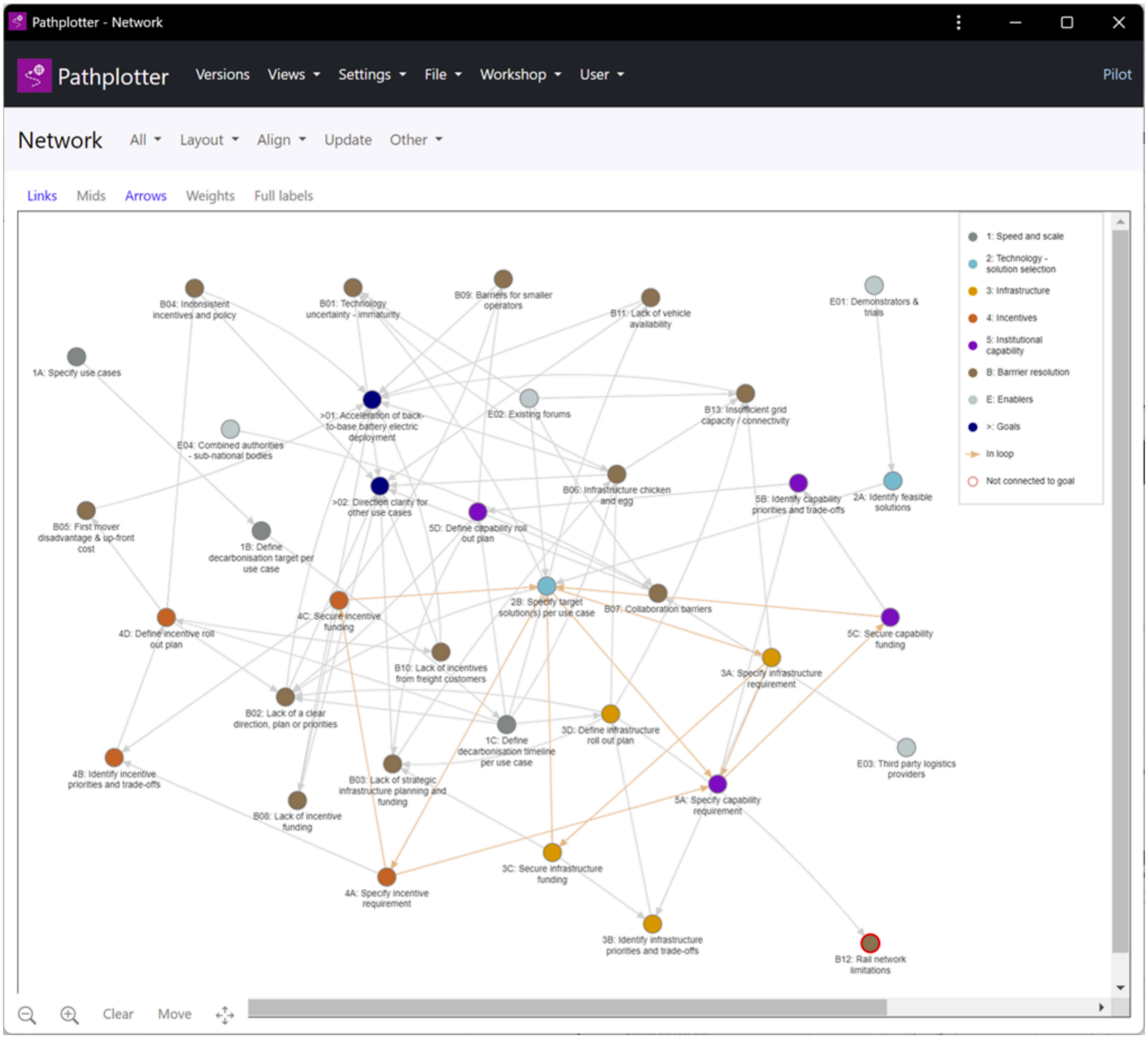

Fig. 5. Network/PERT view – Illustrative data from pilot workshops

Appendix B:. Aggregate workshop network/PERT view

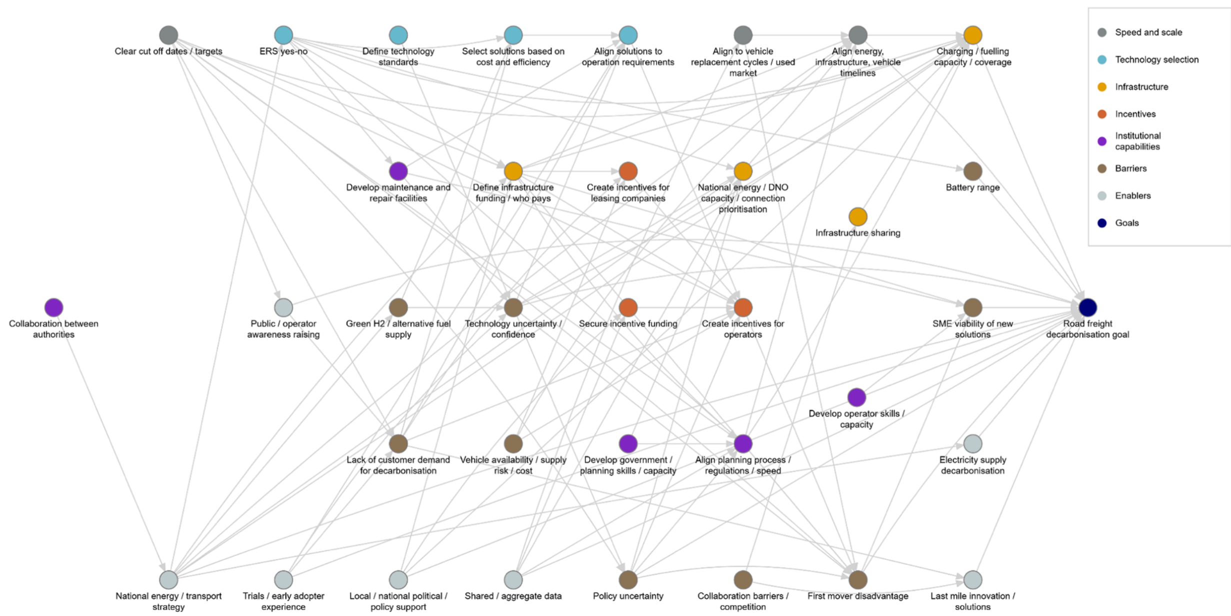

Fig. 6. Aggregate workshop network/PERT view

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