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Decarbonising road freight by operationalising transition theory: a systematic literature review

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Abstract

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

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

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

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

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

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

1 Introduction

Rapid and radical decarbonisation is necessary to achieve climate change mitigation goals [1]. Considering the case of the United Kingdom (UK), goods vehicles over 3.5 tonnes represented 21 million tonnes or 5% of a total 426 million tonnes of CO_2 emissions in 2022 [2]. The global picture is similar, with heavy and medium duty road freight transport accounting for 1,830 million tonnes [3], or 5% of a total 36,800 million tonnes [4] of CO_2 emissions. Global road freight demand is forecast to substantially increase to 2050 in both "current ambition" and "high ambition" decarbonisation scenarios [5].

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

Li and Strachan [6] argue that deliberate, planned, and explicit transition choices are required to overcome path dependencies within the freight system that cause lock-ins to fossil fuel technologies. This means that decarbonising road freight movements requires purposive action by actors and policymakers. Cherp et al. [7] put forward that successful energy transitions require combining socio-technical, political, and techno-economic perspectives. The *techno-economic perspective* considers the technical and economic benefits, limitations, and costs of different technology solutions. The *socio-technical perspective* considers how innovations emerge and ultimately displace incumbent socio-technical systems [8, 9]. The *political perspective* considers how policy processes [10], networks [11, 12], vested interests [13] and the state [14] interact to enable or hinder sustainability transitions.

A bibliographic analysis by Meyer [15] confirms that most literature studying road freight decarbonisation is techno-economic. However, actors observe that the challenges of purposive road freight decarbonisation are political and socio-technical as well as techno-economic [16]. Furthermore, while political and socio-technical transitions research identifies transition challenges and complexities, it often does not consider how transitions can be purposively achieved [17, 18]. Building on these observations, this paper considers the research question "What practical insights are provided by socio-technical and political transitions research that can aid purposive road freight decarbonisation". Given substantially different socio-technical and political contexts in different countries, research was selected that considers transitions principally within a European or comparable socio-technical and political context.

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

2 Methods

The review was completed according to the ROSES framework for systematic evidence synthesis in environmental research [19]. The ROSES checklist is provided in supplementary material.

2.1 Search

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

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

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

Results were limited to articles and reviews in English language; and the relevant topic areas of Energy, Social

Table 1 Search terms

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

Sciences, Environment and Business (for Scopus) and Environmental Sciences, Environmental Studies, Transportation and Business (for Web of Science). See Appendix A for the full Scopus and Web of Science search expressions. These resulted in a de-deduplicated total of 5,506 papers from 251 journals being identified.

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

2.2 Scopus and web of science results screening

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

2.2.1 Rules-based relevance screening

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

2.2.2 Rules-based purposive screening

While socio-technical and political transitions research can provide important insights, it is often retrospective and reflective rather than forward-looking and purposive in focus. This means that insights, while theoretically interesting, may not provide ex-ante guidance to actors seeking to purposively enact transitions. A distillation of literature by authors including Paddeu and Aditjandra [20], Lebeau et al. [21] and Churchman and Longhurst [16] suggests that literature is more likely to provide ex-ante guidance if it has three features: 1) a forward-looking perspective; 2) a design framing; and 3) an actor/stakeholder focus. To systematise and provide auditability of the screening based on these criteria, a rules-based framework was developed based on terms contained in abstracts. The screening terms and conditions were iteratively developed until it was found that a good screening ratio was achieved without excluding any papers that had previously been identified as helpful or were likely to be so based on paper titles. The screening removed papers that did not contain in the abstract:

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

2.2.3 Qualitative abstract screening

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

2.2.4 Qualitative full text screening

As for abstract screening but based on full text review.

2.3 Google Scholar results screening

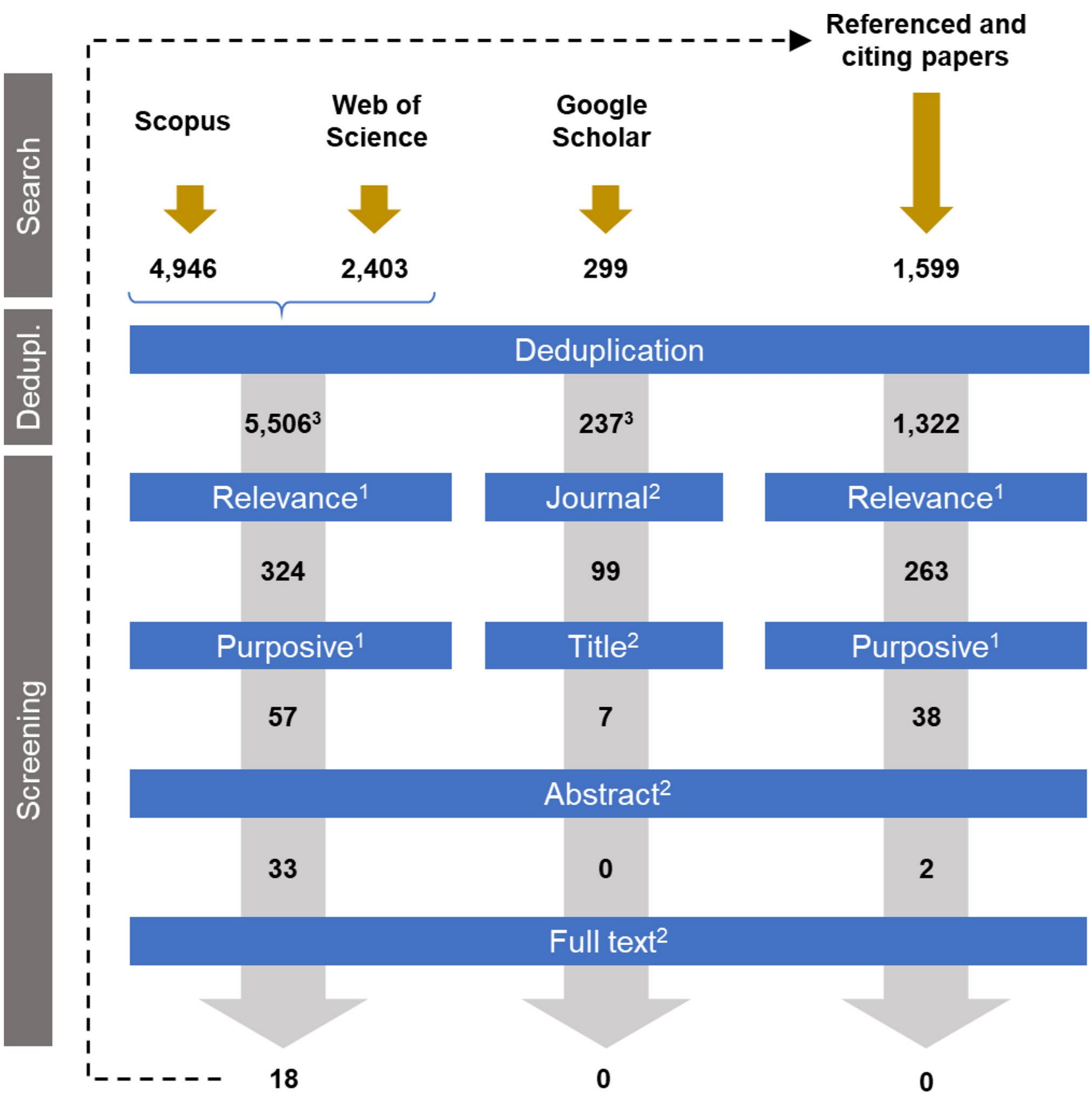
Downloaded Google Scholar search results did not include paper abstracts, which meant that the rules-based screening used for Scopus and Web of Science results could not be applied. Instead, deduplicated papers were qualitatively screened based on source title and then on title. Abstracts were individually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

2.4 Referenced and citing papers

The screening of papers from Scopus, Web of Science and Google Scholar searches resulted in eighteen papers remaining selected. As a final step, all papers that were referenced by or that cited one of these eighteen papers were identified using Scopus and Web of Science. Any papers that had already been captured in the original search were deduplicated. The four screening steps in Sect. 2.1 were then applied to the remaining papers. No additional papers remained selected following this process, providing further validation of the search parameters used in the original Scopus and Web of Science searches.

2.5 Results

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



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

Fig. 1 Paper selection and screening results

3 Synthesised findings

Full paper content from the eighteen selected papers was coded using NVivo software, applying principles from grounded theory [22, 23]. An iterative process of open, axial and selective coding [24] was applied. Open coding is unconstrained and typically generates a long list of codes. Axial coding synthesises and clusters codes according to key overarching themes. Selective coding refines codes and themes to communicate identified insights and relationships more effectively. Sixteen socio-technical and political transition attributes were identified clustered under the five themes of "Actors", "Arenas", "Design", "Policy" and "Politics". Figure 2 presents these attributes and themes as a new conceptual socio-technical and political transitions framework. The arrows in Fig. 2 represent linkages between the five transition themes. These are discussed further in Sect. 4.

Qualitative coding using NVivo was used as the analysis method as the purpose of the review was to identify and synthesise qualitative transition insights. Qualitative coding is extensively used in social science research to extract insights from unstructured textual data from interviews, workshops, focus groups and other sources [22], and we have found it to be equally effective applied to literature. Bibliometric and narrative reviews that are more commonly used in systematic literature reviews are helpful for establishing the landscape of existing literature and identifying gaps, but we believe are less effective for the extraction and synthesis of diverse qualitative insights or for qualitative theory building.

In the remainder of this section, we will focus on the sixteen socio-technical and political transition attributes in more detail. Attributes classified under **"Actors"** provide guidance on the motivators, constraints and strategies of road freight incumbents and new entrants[1]. The **"Arenas"** grouping comes from the concept of transition arenas (TAs), which is central to Transition Management (TM) theory. Loorbach [25] presents TM as the governance of the transition of complex systems. Within the TM framework, TAs are where *"groups of stakeholders envision and build transition visions, goals and pathways of change, and suggest immediate actions to be taken"* [26]. The concept of **"Design"** recognises that, if a transition is to be purposively enacted in a complex system, multiple coordinated actions are required that form a pathway to a defined target outcome. **"Policy"** includes measures used by government at all levels to affect the transition. The complexity of systems and the need to balance disruption with acceptability requires policy mixes that may span local, regional and national scales [27]. **"Politics"** encompasses the institutional and political environment that, while not necessarily specific to the transition, has a strong bearing on it.

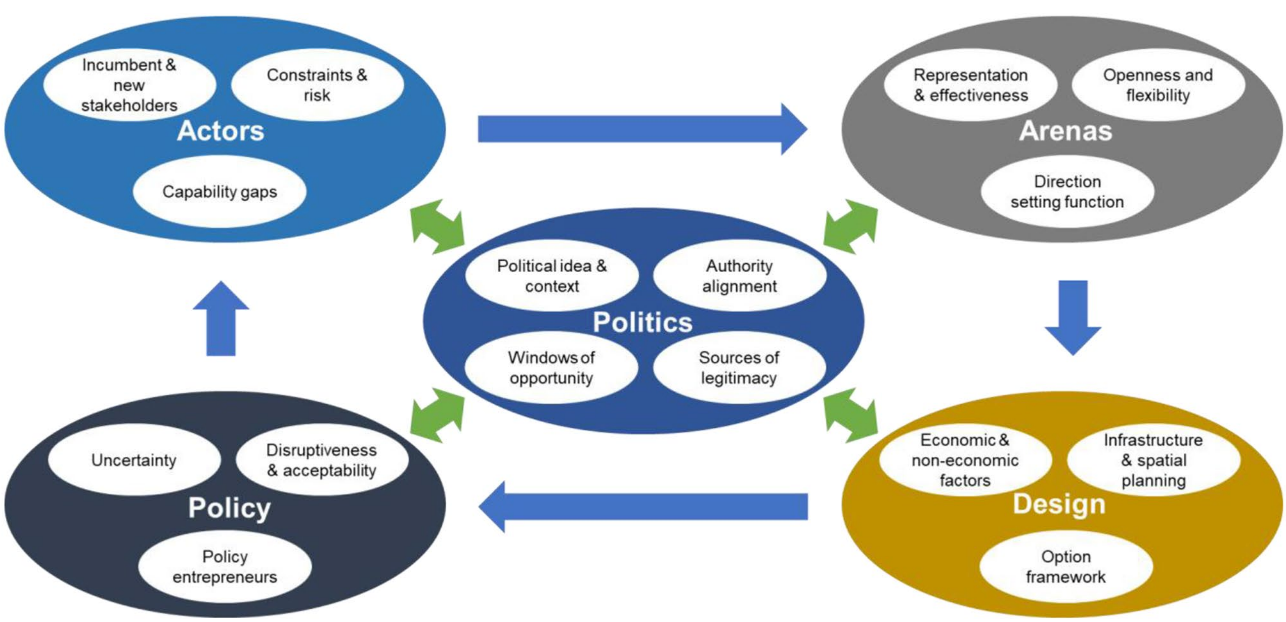


Fig. 2 Conceptual socio-technical and political transition framework for purposive road freight decarbonisation

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

3.1 Actors

3.1.1 Actor constraints and risk must be considered

Actors include operators; shippers; infrastructure, energy, and vehicle providers; authorities; and, in a local context, residents and local businesses [28, 29]. A prerequisite for all actors is that they understand how the transition will serve their own objectives [30]. Green innovations may come with disadvantages compared to conventional technologies and may therefore be associated with greater operational and financial risk [31]. In situations where cost and risk are certain but benefits and the ability to capture these are uncertain, there will be significant reluctance on the part of operators to support the transition [32]. Existing operations also tend to be highly optimised around existing technologies and operating models [32].

In the context of bus decarbonisation, Mohamed et al. [33] highlight that bus operators require a technology that will be stable for the 12–16 year lifespan of a bus. They conclude as a result that the additional cost and risk of switching Canadian buses to electric vehicles exceeds the financial capacity of operators and that risk may need to be transferred to authorities. Churchman et al. [34] similarly identify the importance of asset lifecycles for road freight operators. Nordtømme et al. [32] propose that ways need to be found to alleviate risk for private actors who take a lead in decarbonisation.

3.1.2 Incumbent and new stakeholders need to be engaged

Radical decarbonisation requires engagement with new stakeholders that are not part of the established sociotechnical regime, for example renewable electricity and charging infrastructure providers. In addition, existing stakeholders may need to take on new functions, for example the involvement of local government in charging [35]. Edmondson et al. [36] argue that policy mixes need to create incentives for incumbents as well as emerging niche actors and that, without these, the regime may mount significant opposition. Xu and Su [37] make an additional point that, in the early stages of a transition, it is rarely possible to pick with certainty which actors will be the eventual winners and losers, and therefore to know who to protect and who to destabilise.

Taefi et al. [38] and Ballantyne et al. [39] find that transport planners have historically been more concerned about passenger than freight transport. Set against this is the key role of authorities in communicating responsibilities for road freight decarbonisation and requirements for individual and collective action [29].

3.1.3 Actor capability gaps should be addressed

Ballantyne et al. [39] find that local authorities have not historically focused on freight transport and lack key freight planning knowledge and skills. In the context of bus decarbonisation, lack of required skill sets in bus operators is identified as a substantial transition barrier [33]. Bus electrification in the United Kingdom and Sweden has also resulted in local authorities taking on additional responsibilities, thereby requiring new skills and capabilities to be developed [35]. Learning from the experience of bus decarbonisation, it seems reasonable to assume that freight decarbonisation will also require authorities and operators to develop new capabilities.

3.2 Arenas

3.2.1 Representation and effectiveness must be reconciled

There is consensus in the identified literature that stakeholder engagement in transition planning is necessary. The road freight sector is highly fragmented [16]. However, a maximum number of approximately 25 participants is suggested for an arena to remain an effective negotiation and decision-making body [40]. If all stakeholders are to be represented with this number of participants, certain groups will need to be represented by trusted bodies such as industry associations [28]. The selection of arena participants must therefore be carefully considered to enable effective stakeholder representation while ensuring the arena remains effective as a negotiation and decision-making body.

3.2.2 Barriers to collaboration need to be overcome

It is observed that, in the context of collaborative initiatives, stakeholders with competing interests are required to trust each other and the collaborative initiative itself [29]. A lack of willingness to share information and resources with competitors is identified as a manifestation of lack of trust and/or lack on alignment of individual interests with the initiative. Paddeu and Aditjandra [20] find in the case example they consider that operational factors including an urban consolidation centre's location and special delivery requirements prevented implementation of a freight partnership's proposals.

Cooperation between political entities is also identified as necessary, with this being highlighted as a primary determinant of transport futures in Mexico City [41]. It is proposed that it may be possible to accommodate different stakeholder priorities in different ways, for example through flexibility in implementation details or by expanding policy scope to encompass an issue that is important for a subset of stakeholders [42].

3.2.3 A direction setting and coordination function is required

Salas Gironés et al. [43] argue the need for a direction-setting function in transformative change processes which favours societally desirable changes over others. Hausknost and Haas [44] suggest that, in some cases, the role of institutions is to define the attributes of transformation success, while in others it is necessary for them to "pick winners". Conversely, the lack of clear guidance from authorities is identified as a significant transition inhibitor [33]. In a case study, Marcucci et al. [28] found the local chamber of commerce was able to provide a "compensation room" between public and private interests.

3.3 Design

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

Several of the identified papers highlight the need for a framework for option identification, evaluation, and selection. One dimension of this is the framing of different concepts for decarbonisation, for example the "four A's of sustainable city distribution" of Awareness; Avoidance; Act and shift; and Anticipation of new technologies [30]. A second dimension is framing how options are identified and assessed, for example via Multi Actor, Multi Criteria Analysis (MAMCA) [21].

The assessment of different options necessarily requires some form of foresight or prediction of option impacts. Auvinen et al. [45] propose a combination of participatory definition of futures by stakeholders, policy impact assessment and simulation modelling as potential ways that an action-oriented approach can be adopted for socio-technical transitions.

Differences are found between stakeholders in the degree of desired arena formality. In the UK case they considered, Lindholm and Browne [40] find that freight industry participants typically seek a greater degree of formality, whereas local authorities prefer greater flexibility. Churchman et al. [34] also find polarised views between stakeholders who would prefer clear direction from government versus those who believe operators should be free to choose solutions that work for them.

3.3.2 Infrastructure provision and spatial planning are critical

Thaller et al. [27] find that infrastructure provision is the most cited requirement by transport transition stakeholders. Anderhofstadt and Spinler [46], Denstadli and Julsrud [31] and Xu and Su [37] observe that the switch to alternative fuel heavy duty vehicles, e-vans and passenger vehicles requires a comprehensive charging or fuelling infrastructure. Taefi et al. [38] conclude that to enable this, local authorities will need to redistribute scarce and expensive public space. However, Ballantyne et al. [39] find that land use was rarely considered in freight planning by local authorities.

3.3.3 Economic and non-economic factors are important

Anderhofstadt and Spinler [46] identify that a truck's reliability, an available fuelling/charging infrastructure and the possibility to enter low-emission zones are key factors when purchasing alternative fuel powered heavy-duty vehicles. Taefi et al. [38] similarly conclude that the market uptake of electric vehicles for urban freight cannot be explained by financial incentives alone and that the effectiveness of legal measures such as privileged loading zones is underestimated by policymakers.

Considering mode shift, Gomez and Vassallo [47] find that there is not strong evidence that this has either influenced road freight volume or promoted the shift of freight to alternative modes. They propose that mode shift also requires improving efficiency, quality and availability of competing modes. Lam and Mercure [48] argue that conventional welfare economics, which recommends the comprehensive pricing of carbon emissions, may not be the most effective approach for transport systems, as this does not account for the dynamics of technology diffusion. Denstadli and Julsrud [31] elaborate on such dynamics in relation to the adoption of e-vans:

- "Institutional isomorphism" where the managerial behaviour of companies in sectors can become homogenous through learning and information sharing or via imitation of successful competitors;
- The strong influence of small and medium-sized enterprise owners' norms and attitudes on company practices; and
- The role of customer pressure and signalling of a green company image.

3.4 Policy

3.4.1 Policymaking should address uncertainty

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

(1) Anderhofstadt and Spinler [46] argue that a key aspect of transport transitions is the progressive reduction of user uncertainty, and that information gathering about reliability and operating costs is an important determinant of the rate of adoption of low-emission heavy-duty vehicles.
(2) Ballantyne et al. [39] and Axsen and Wolinetz [49] consider uncertainty in relation to the response of vehicle users and freight stakeholders to policy instruments.
(3) Taefi et al. [38] discuss uncertainty in the speed with which local authority measures can be implemented, with freight EV users being more pessimistic than policymakers.

Transition design and policy needs to progressively reduce user uncertainty and be resilient to multiple outcomes on each uncertainty dimension. Approaches such as Dynamic Adaptive Planning [49] or Anticipatory Governance [50] may be appropriate ways to achieve this.

3.4.2 Policy entrepreneurs can aid but also mis-direct policy

Related to the above finding regarding business actor influencing strategies, Denstadli and Julsrud [31] discuss the importance of innovation champions who promote the adoption of a specific technology. Salas Gironés et al. [43] however take a partially contrary view. In a case study of automated vehicle (AV) policy in the Netherlands in the period 2010–2019, they conclude that policy was strongly influenced by policy entrepreneurs with access to policy venues. They observe that policymakers were influenced by think tanks, NGOs, industry representatives, businesspeople and other policymakers "selling" their solutions. During the agenda setting phase, policy entrepreneurs were able to present AVs as a solution to societal problems such as congestion, without any specific commitments to deliver policy outcomes. After experimentation over a multi-year period, the programme was discontinued with limited tangible result.

3.4.3 Policy mix needs to balance disruptiveness and acceptability

Thaller et al. [27] consider the balance of disruptiveness and acceptability in policy mixes for passenger transport. They find that a well-balanced combination of diverse policy instruments is required to adequately address both dimensions. Sørensen et al. [42] observe that in all three road charging cases they studied, measures that were expected to encounter resistance were combined with more popular measures. Creating transparency on how revenues raised will be returned to the public is also identified as a key success factor.

3.5 Politics

3.5.1 Authorities and departments within authorities need to align

Nordtømme et al. [32] identify institutional barriers resulting from challenges of coordination between different authoritative bodies and levels. In the case of an urban consolidation centre trial in Oslo, differing priorities between the Agency for Urban Environment, the city procurement office and the local police authorities contributed to the failure of the trial to proceed. Ballantyne et al. [39] note that while freight is recognised as necessary for the urban economy, it is often not prioritised in transport plans, meaning the local plans may not align with regional or national road freight objectives.

3.5.2 Political windows of opportunity may need to be considered

Multiple Streams theory hypothesises that effective policymaking occurs when problem, solution and political streams come together [43, 51]. The convergence of the three streams is termed a policy window. Edmondson et al. [36] identify that, over the course of a transition, windows of opportunity can allow actors to obtain favourable policy outcomes. However, changing conditions can cause these windows to close and the beliefs of actors can also change over time [52, 53]. Sørensen et al. [42] highlight that as well as predictable windows associated, for example, with election cycles, unforeseen windows of opportunity can open suddenly. They argue it is therefore necessary to continually map the need for initiatives and prepare status reports at the political level to keep issues on the agenda.

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

Sørensen et al. [42] observe that the successful implementation of congestion charging in London was aided by the clear mandate that mayor Ken Livingston had for its implementation, and that the authorities responsible for its delivery reported ultimately to him. Salas Gironés et al. [43] conclude that addressing societal transition challenges requires coupling of problems and solutions, and that this coupling is dependent on the political environment and the ideologies and beliefs of those in charge of making decisions. Conversely, Axsen and Wolinetz [49] identify that lack of political acceptability is the largest barrier to the implementation of road pricing. Kern and Howlett [54] find that in the Dutch energy process, potentially incoherent, inconsistent or incongruent policy mixes emerged, and that local political inertia and resistance to change counteracted the TM-inspired governance mechanisms.

Salas Gironés et al. [43] observe that theoretical transition processes often focus on societal engagement as a principal driver of direction-setting and that this, despite being desirable, neglects the fact that transformative innovation is inherently political in nature, with contestation, conflict, winners and losers. Steurer and Bonilla [41] find that effective negotiation with private sector participants is a critical determinant of transport futures.

3.5.4 Sources of legitimacy other than decarbonisation itself may be required

Klenert et al. [55] observe that substantial carbon prices only exist in countries where there is high government trust. They also propose that perceived fairness and political acceptability can be enhanced with careful design of exemptions and usage of revenues. They note however that implementing exceptions in freight transport may be more challenging than with personal transport. Churchman and Longhurst [16] likewise find that freight operators did not always believe that government either understood or were interested in their challenges and were not confident that disconnected policymaking across authorities would deliver policy that worked for them.

Hausknost and Haas [44] recognise the challenge of political institutions imposing transition choices and emphasise the need for legitimacy when centralised choices are required. Hyysalo et al. [26] propose that more practical sources of legitimacy than the normative justification of sustainability are required. In the context of the portfolio of Finnish energy transition goals that they considered, this was derived from referencing existing energy and climate governance structures, broad consultation and an emphasis on experimentation and trials. Sørensen et al. [42], Anderhofstadt and Spinler [46] and Thaller et al. [27] find that trials are an effective way to create legitimacy.

4 Linkages and feedback

4.1 "Collaboration" feedback loop

The blue arrows in Fig. 2 highlight that:

- Actors will only participate in arenas if they see a benefit in doing so
- Arenas will only aid purposive decarbonisation if they enable effective negotiation and decision-making
- The design defined in arenas should inform transition policy
- Policy should have a pro-transition influence on actor behaviour

The fact that these linkages form a closed sequence suggests the existence of a feedback loop, and this indeed is intuitively the case. The codesign process needs ideally to reinforce and as a minimum not to weaken the highlighted linkages.

4.2 "Political" feedback loops

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

4.3 "Pervasive" attributes

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

4.4 Summary

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

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

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

An implication of the conceptual purposive transition model is that actors need to be willing and able to work in arenas to make collective design choices. Although many UK road freight operators and shippers publicly support decarbonisation, collective decision making and commitment to specific bold decarbonisation action requires a level of confidence in the ability to deliver decarbonisation while maintaining a successful business which is not yet present for many operators [29]. This challenge is exacerbated by the fact that the UK road freight market is highly fragmented, with only one operator, DHL, having a market share of over 5%. The sector is as a result characterised by high competition and low barriers to entry [56]. This means that operators that are operationally or financially disadvantaged by implementing decarbonised solutions risk losing business to operators who have not taken such action. This leads to the first of the transition preconditions: *techno-economically feasible options able to deliver rapid and radical decarbonisation need to exist.*

The UK government has set a target of phasing-out light good vehicles (LGVs) by 2030, heavy goods vehicles (HGVs) under 26 tonnes by 2035 and HGVs over 26 tonnes by 2040 [57]. There is broad consensus that battery electric is the most suitable zero emission motive technology for lighter and shorter distance applications [58]. For heavy duty and long-haul applications, the government is funding Zero Emission Road Freight Demonstrations (ZERFDs) to demonstrate hydrogen fuel cell and battery electric technologies [59, 60]. In addition, the government advocates transition from road to rail, cargo-bikes and inland waterways [61]. Other measures that have the potential to reduce carbon emissions include supply chain reconfiguration; logistics coordination at a network level; increased individual vehicle capacity, utilisation and fuel efficiency; and freight demand reduction [62].

The existence of technically feasible solutions on its own is, however, insufficient. System dependencies mean that operator action needs to be supported by that of other actors. To reduce uncertainty and aid alignment, the road freight industry has called for a clear transition roadmap [63] and for a frank discussion on the cost of decarbonisation [64]. New technologies will have major implications for vehicle and road taxation, vehicle and driver licencing, and vehicle maintenance and safety standards, which are currently overseen by different government authorities.

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

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

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

Actors: Key road freight decarbonisation actors include freight operators, freight customers/shippers, vehicle manufacturers, infrastructure providers, energy providers and local, regional and national authorities [29, 65]. Different combinations of these are likely to be required to participate in different design choices. Each actor group has goals in addition to decarbonisation. For freight operators, COVID, Brexit and the war in Ukraine have added major new stresses to the pre-existing challenges of an aging workforce, poor driver facilities, low margins, just-in-time supply chains and devolved regulation [56, 66]. In developing decarbonisation plans, each actor must inevitably consider the risk that decarbonisation action creates for other goals. Freight operators consistently highlight the importance of asset lifecycles, total cost of ownership and confidence in resale values in new vehicle purchase decisions. Recent experience of the implementation of EURO vehicle standards, Direct Vision and Clean Air Zones by local authorities has made operators sceptical that new regulations are sufficiently thought through or that unintended consequences have been considered [16]. Because of the large number of road freight operators, industry associations such as Logistics UK and the Road Haulage Association will play a key role in representing these actors in codesign arenas.

Arenas: Transition arenas are important for road freight decarbonisation for several reasons. Firstly, the diverse actor goals and constraints mentioned above need to be understood and factored into the transition design. Secondly, arenas provide a forum to increase actor understanding of potential solutions. Thirdly, they enable a view to be taken across national, regional and local levels [67]. Finally, and perhaps most importantly, they provide a foundation of participation and legitimacy for transition codesign. One of the key challenges of a TA will be to allow participation of diverse actor groups while not permitting any one group to dominate decision making or block progress. Freight Quality Partnerships (FQPs) have been established in the UK and other countries to aid collaboration between road freight stakeholders. FQPs are partnerships between local government, local businesses, the freight industry and other parties with a common interest in freight deliveries in a region or city [28, 40]. It is possible that the FQP concept could be combined with that of TAs to provide direction setting and mid-range planning for road-freight decarbonisation. The success of FQPs is however mixed [68, 69], and lessons would need to be learned from past experience of these.

Design: There is consensus in the selected papers that road freight technology adoption and investment decisions must consider non-economic as well as economic factors [31–33, 46]. A transition design developed by an arena must therefore also consider non-economic factors including infrastructure availability, legal and regulatory incentives, and differing actor motives for seeking to decarbonise. A further transition consideration is maintaining capacity stability [70]. Experience of the Brexit transition and Covid pandemic combined with chronic driver shortages has confirmed the vulnerability of road freight to supply disruption [71, 72]. The design needs to take account of these factors while still effectively driving decarbonisation.

Policy: Policy uncertainty is cited by UK freight operators as a significant inhibitor to new technology adoption [16]. Other important aspects of uncertainty include the reliability, performance and cost of new technologies, roll out of supporting infrastructure and availability of skilled staff able to operate and maintain vehicles. Policy should aim to reduce these uncertainties, especially at the early stages of the transition. The selected papers highlight the need for policy mixes that balance disruptiveness and acceptability. Increasing tax on diesel would be an example of a disruptive road freight incentive that on its own may be unwelcome to operators. However, if this was phased in according to a clearly defined schedule that aligned to vehicle replacement cycles and was accompanied by measures giving privileged access for low emission vehicles to city loading areas, this may make the policy package more acceptable. This example illustrates the importance of coordinating national policy (e.g., setting of fuel duty) with local policies (e.g., allocation of city loading spaces).

Politics: Sørensen et al. [42] use the successful implementation of congestion charging in London as an example of where politics worked effectively to deliver what could have been a highly challenging transition. UK road freight operators on the other hand cite devolution of transport policy to national, regional and local authorities as a significant barrier [16]. Hausknost and Haas [44] argue that political decisions determine the transition option space. In the case of road freight decarbonisation, the option space is the suite of feasible technologies and transition pathways. At this point, all main technology options remain on the table in the UK [73]. While this can be presented as maximising the option space, radical decarbonisation options involving motive technology or mode shift depend on the provision of major new infrastructure which requires a clear decision on the technologies to be developed. Political leadership needs to strike a balance between leaving options open and providing required technology and pathway clarity.

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

6 Conclusions

6.1 Contribution

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

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

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

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

6.2 Limitations

The principal limitations of the review are:

- Socio-technical and political transitions focus: Techno-economic transition considerations and a comparison of different technical solutions have not as a result been considered.
- Consideration of European and other comparable political and socio-technical contexts: Research that focuses on substantially different socio-technical and political contexts such as in developing countries or centrally planned economies has as result not been considered.
- Selection of insights specifically relevant to road freight decarbonisation: Insights that are not relevant to this transition but may be relevant to personal

transport decarbonisation or other sustainability and societal transitions have not been captured.
- Project resource constraints: While every effort has been made to ensure that the review is systematic and repeatable based on the ROSES framework, resources were not available to allow a full independent validation of the review.

6.3 Further research opportunities

Opportunities for further research that emerge from the review include:

6.3.1 Testing and developing transition attributes with road freight actors

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

6.3.2 Investigating multi-scalar transition design and governance

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

6.3.3 Applying purposive transition framework to other business-centred transitions

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

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

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

6.4 Final reflections

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

Appendix A: Search expressions

Scopus search

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

Web of Science search

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

Filters applied to Web of Science results:

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

Appendix B: Relevance exclusion terms applied to titles and abstracts

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

Appendix C: Selected papers

Table 2 18 selected papers

Author (Year)	DOI link
Road freight transitions	
Anderhofstadt and Spinler [46]	http://doi.org/10.1016/j.trd.2019.06.003
Ballantyne et al. [39]	http://doi.org/10.1016/j.jtrangeo.2013.08.013
Denstadli and Julsrud [31]	http://doi.org/10.3390/su11143878
Nordtømme et al. [32]	http://doi.org/10.1016/j.tranpol.2015.08.005
Taefi et al. [38]	http://doi.org/10.1016/j.tra.2016.06.003
Paddeu et al. [29]	https://doi.org/10.1016/j.retrec.2024.101424
Paddeu and Aditjandra [20]	https://doi.org/10.3390/SU12010441
Lebeau et al. [21]	https://doi.org/10.1016/j.cstp.2018.07.003
Lindholm and Browne [40]	https://doi.org/10.18757/ejtir.2013.13.1.2986
Macharis and Kin [30]	https://doi.org/10.1080/15568318.2016.1196404
Marcucci et al. [28]	https://doi.org/10.1016/j.retrec.2017.09.001
Passenger and general transport transitions	
Axsen and Wolinetz [49]	http://doi.org/10.1016/j.enpol.2021.112457
Mohamed et al. [33]	http://doi.org/10.1016/j.trd.2017.09.019
Salas Gironés et al. [43]	http://doi.org/10.1016/j.techfore.2020.120243
Steurer and Bonilla [41]	http://doi.org/10.1016/j.tranpol.2016.06.002
Thaller et al. [27]	http://doi.org/10.1016/j.trd.2021.102714
Aldenius et al. [35]	https://doi.org/10.1016/j.trd.2022.103204
Auvinen et al. [45]	https://doi.org/10.1016/j.techfore.2014.07.011

Abbreviations

AV Automated Vehicle
FQP Freight Quality Partnership
HGV Heavy Goods Vehicle
TA Transition Arena
TM Transition Management
UK United Kingdom

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12544-025-00755-4.

Supplementary Material 1
Supplementary Material 2
Supplementary Material 3
Supplementary Material 4

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Author contributions

The first author, with guidance from the other authors, identified the research gap and questions, designed the approach, conducted the systematic literature review, developed the conceptual model and applied this to the selected case. The second and third authors provided challenge and input throughout the project on research questions, methods and desired impact, and conducted multiple detailed reviews of findings and the manuscript. Their complementary experience was critical in developing the multi-perspective approach that was adopted.

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Data availability

The following supplementary materials are provided: Python code for applying relevance rules-based screening and generating output spreadsheet. ROSES checklist. Input Excel spreadsheet containing Scopus, Web of Science and Google Scholar search results; application of purposive rules-based and qualitative screening; and relevance keywords. Output Excel spreadsheet with relevance rules-based screening applied.

Declarations

Competing interests

The authors report there are no competing interests to declare.

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