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Review

Moving on from a Diesel Mindset—Understanding Enablers and Challenges for Electrifying Road Freight Using Stakeholder Engagement

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Abstract: Achieving net zero by 2050 requires the decarbonisation of road transport. Electrification is recognised as a market-ready solution for certain transport segments, but it still poses a considerable challenge when applied to road freight. Any consensus on the technology choice for road freight electrification has still not been established. Embedding stakeholder input in the approach to address the technology adoption challenge has proven useful in uncovering various perspectives, which can provide useful insights into managing such transitions. This review paper hence took a three-step approach where the findings from the initial step of the literature search were taken up for the second step of stakeholder validation and feedback. The third step involved an analysis of the input gathered and the subsequent literature review to arrive at the conclusions. The outcome from the stakeholder engagement suggests that any specific technology can only support the transition to electrified road freight if enabled by system changes around policy, infrastructure, user behaviour, and the societal setup A follow-up literature review validated the need for a sociotechnical approach to such transitions where system changes are involved. The review also found gaps in the literature when it comes to embedding such sociotechnical approaches to technology adoption for road freight transport.

Keywords: road freight electrification; stakeholder engagement; electric road system; sociotechnical transition

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1. Introduction

Greenhouse Gases (GHGs) emitted from fossil fuel combustion, specifically carbon dioxide (CO_2), are acknowledged as a significant contributor to the rise in global temperature [1]. Emissions from transport are rising the fastest among all sectors (energy, transport, agriculture, land-use change, forestry, and waste) and contributed to about a quarter of the global CO_2 emissions in 2018 [2]. Road vehicles, which include passenger cars, goods or freight vehicles, public service vehicles, and two- and three-wheelers, currently account for nearly three quarters of the global transport CO_2 emissions in 2022 [3]. To decarbonise road transport, electrification is the acknowledged solution [4,5], but the current viability of transitioning to electric varies depending on the vehicle type and the use case. The Committee for Climate Change (CCC) report in 2020 indicated that for cars and vans (also classified under Light Commercial Vehicles or LCVs), battery electric vehicles are now a widely available market-ready alternative and are likely to become cost-saving by the late 2020s, but that zero-emission options for road freight, in particular the long-haul sector (requiring the use of Heavy Goods Vehicles or HGVs—vehicles with a maximum permissible total weight of more than 3.5 tonnes), are expected to take longer to achieve widespread market uptake as there are a number of technological and economic barriers [6]. The report however emphasised that transport sector-wide decarbonisation will require transition to vehicles with zero tailpipe emissions and that the options for HGVs include battery-electric vehicles, hydrogen fuel-cells and electric road systems. Hence, zero-emission technologies around electric propulsion will remain a key aspect to explore.

When discussing system transitions, for example, the electrification of road transport, technological developments are highly popular as they promise the continuation of business as usual and appeal to economic actors whose primary motivation is to follow the paths of economic growth. The focus therefore in the road freight transport sector has been on the identification and promotion of technology developments more than anything else. Several technology-led solutions are either proposed or under development and have been put forward in response to the requirement to decarbonise long-haul freight. However, the viability of these technology-led solutions is being questioned [7]. A report [8] by Strategy& in 2020 highlighted how all the zero-emission-capable electric propulsion-based technology options (battery electric, hydrogen fuel cell, and catenary hybrid) for long-haul road freight vehicles exhibited disadvantages in criteria around loading capacity (powertrain weight of 2200 kg for diesel engine versus 4300 kg for battery electric for same output of 300 kW), fuel cost, investment needed (EUR 79,000 purchase cost for diesel engine trucks versus EUR 192,000 for battery electric trucks and EUR 235,000 for fuel cell electric trucks), and range (1500–2000 km for diesel engine versus 400–800 km for battery or fuel cell electric engine) when compared to conventional combustion engine trucks. A lack of consensus on a single pathway to decarbonisation by 2050 was reflected in a study [9] by Gustafsson et al. in 2021 where they concluded that for HGVs, no alternative energy carrier will be enough to single-handedly replace fossil fuels. A report by the Department for Transport on Future of Freight [10] mentioned that the most cost-effective mix of zero-emission technologies to power HGVs was still unclear. Hence, while electrifying the fleet is the ideal option for the future based on the requirement to reduce emissions, we are still faced with significant inertia in the transition to a decarbonised freight transport sector due to limitations regarding technology capability and high costs. A lack of clarity in the choice of electrification will create investment risks, which can weaken the chances of transitioning to a fully electrified road freight.

While the identification of technology alternatives was achieved through a search of the related literature, the need for capturing input from stakeholders was identified to take an expert view on those alternatives and brainstorm the possible challenges and enablers to adopting those technologies. A workshop involving two Taskforces (41 and 45) of the International Energy Agency (IEA) involved with electric road freight was organised. The input from stakeholders thus gathered was further analysed, and a follow-up literature review was carried out to arrive at an understanding on how to recognise and approach the road freight electrification challenges. The paper is organised as follows: Section 2 provides additional context regarding the challenges associated with road freight electrification and the basis for the research question; Section 3 covers the approach adopted for the stakeholder input and the research questions asked; Section 4 provides the key results and analysis based on stakeholder input and a further search of the literature; Section 5 has a discussion on the findings; and Section 6 contains the conclusions.

2. Background

With the Paris Agreement [11], there is an international commitment to limit global temperature rise to 1.5 °C, which would further require that global GHG emissions reach net zero (defined as the net emissions generated in a process as being zero) by 2050 [12]. Transport-related activities account for a quarter of CO_2 global emissions [2], and road transport accounts for around three quarters of global transport-related CO2 emissions. Electrified propulsion with zero tailpipe emissions is the most widely adopted solution to decarbonisation. This is reflected in the rising sales of electric vehicles. However, the rate of adoption of electrification is different across different segments.

2.1. Focus on Road Freight

Data from the Electric Vehicle (EV) outlook report [13] by the International Energy Agency (IEA) in 2022 indicate that the number of electric cars globally has tripled to 16.5 million from 2019 to 2021 and that electric car sales accounted for 9% of the global market in 2021. Sales of electric Light Commercial Vehicles (LCVs) also increased by 70% in 2021 capturing 2% of the LCV market share. The uptrend was also noted in the bus segment where the global stock of electric buses rose to 4%. However, in the heavy-duty truck segment, the share of electric trucks was only 0.1%. Even the emission projections from the IEA [14] show a decline in emissions for passenger road vehicles by 14% from 3.6 Gt in 2018 to 3.1 Gt by 2030, but for road freight, the projected decline is less acute at 4% from 2.4 Gt to 2.3 Gt. Within the road freight segment, heavy-duty freight trucks are disproportionate contributors as they represent only one tenth of all vehicles but contribute to roughly 40% of their emissions [4].

There is a clear requirement to prioritise the decarbonisation of the freight sector, in particular that part of the freight sector using HGVs for long-haul freight. The challenge is that the disbenefits of electrification, such as limited range, long down time for recharging, and higher cost, are felt most acutely when the application demands higher energy reserves and greater intensity of use. The International Council on Clean Transportation (ICCT) stated that "Electric-drive heavy-duty vehicle technologies are essential to fully decarbonize the transport sector" [4]. It is also recognised that there are a number of barriers that have to be overcome if this is to be realised. These barriers include technology limitations, which are also allied to cost, and a lack of available infrastructure [15].

2.2. Challenges to Road Freight Electrification

In a study by Çabukoglu et al. [16] in 2018, which looked at daily usage profiles of 5000 trucks, the conclusion was that even with the best-case improvement in cell energy density (to 2000 Wh/kg and up from 280 Wh/kg) only 70% of current use cases are achievable if a BAU approach is the end goal. Further, there is the additional mass of the battery storage to consider upon the operational requirements of the HGVs. In the UK, a report by the government in 2019 highlighted the impact that electrification would have on vehicle payload [17], which would require an increase in the vehicle fleet size and/or utilisation and lead to higher utilisation of the road network, etc. Heinz et al. [18] performed a study to find the best-performing powertrain option for heavy-duty trucks in Austria. They found that for higher tonnes per kilometre (tkm) requirements, HGVs with Diesel/CNG Hybrid were best-performing but not the Battery Electric Vehicles due to the limited range and increased gross vehicle weight. A truck study report in 2020 highlighted how all the alternate powertrain options (battery electric, hydrogen fuel cell, and catenary hybrid) for long-range heavy-duty vehicles exhibit disadvantages in criteria around loading capacity, fuel cost, investment needed, and range when compared to conventional combustion engine trucks [8]. Talebian et al. [19] made pathways for a 64% emission reduction target by 2040 for British Columbia where road freight electrification using battery electric and fuel cell electric vehicles were explored. They suggested that the amount of renewable energy required to support the pathway will exceed the existing projected renewable (hydroelectric) energy generation by at least two and a half times.

The challenges to electrification indicated above are reflected in the diversity of road freight electrification pathways and in the corresponding assumptions and dependencies used for building those pathways. For example, both the IRU [20] and the ICCT [4] reports published in 2017 focussed on road freight electrification, but the former focused on the Electric Road System (ERS) and omitted fuel cell or battery electric, and the latter emphasised catenary/road-inductive and fuel cell but omitted plug-in electric for HGVs. The Low Carbon Vehicle Partnership (LowCVP—now ZEMO) in the UK points to high-blend biofuels as an option to reduce GHG emissions during a transition period [21]. A report by Shell in 2021 suggested natural gas as the transition technology but suggested synthetic fuel and biodiesel also as part of the mix along with battery and fuel cell electric in 2050 [22]. The UK Connected Places Catapult in their report [23] in 2019 found battery electric as more cost-effective than hydrogen fuel cell vehicles in the run up to 2050 but dismissed catenary electric due to the high associated infrastructure cost. A Climate Change Committee report in 2020 assumed that weight allowance, operators willing to charge twice a day, and significant improvement in battery technology would be in place by 2050 for net zero to be achieved for HGVs [24]. The T&E report in 2018, however, assumed that that the required amount of emissions reduction assumes renewable and decarbonised electricity will be available to enable complete road freight electrification [25].

2.3. Need to Look beyond Technology

A lack of consensus for a single pathway to road freight electrification by 2050 was reflected in a study [9] by Gustafsson et al. in 2021 where they concluded that no alternative energy carrier will be enough to single-handedly replace fossil fuels. Improvements in technology can be expected to 'close the capability gap', but studies have shown that with even the most optimistic improvements it is unlikely that full electrification of the HGV fleet will be realised if business as usual (BAU) is the end goal. It is believed that if issues around regulations and actual operating costs are successfully dealt with, then the electric drive train can become mainstream for heavy-duty trucks, but large-scale production will take until 2030 [26]. However, it will still be another 20 years until there is parity on total cost of ownership for battery and fuel cell electric vehicles with diesel, and this assumes that the required infrastructure is forthcoming (for example, a network of recharging points every 50 km across the whole motorway road network of the UK) and again that the appropriate policy mix is in place [24]. A report by the Energy Systems Catapult in the UK in 2021 [27] highlighted that the role of societal change has mostly been under-represented in most of the prominent scenario studies. The report pointed that a technoeconomic approach-based model may be challenging to realise as real-world hurdles caused by societal aspects may impact any net-zero solution adoption. Another report by the UK Energy Research Centre highlighted the dependence on socioeconomic and political developments for the electrification-led net-zero pathway for transport [28]. The requirement for infrastructure provision in support of electrification was noted by a study by CEPA and Frazer-Nash [7], but that this was dependent on sufficient government support around infrastructure and investment in R&D.

There have been various approaches to technology transitions, like Multilevel Perspective [29], Technology Innovation Systems [30], Strategic Niche Management [31], and Transition Management [32]. A qualitative approach based on views from stakeholders has not been found in road freight studies [33]. Stakeholder participation in planning and strategy making have generally been at the forefront of creating more societal and systemic support for decisions [34]. Such qualitative research highlights the study of the subject from insiders' perspective and allows the research design to be subject to change during the study [35].

2.4. Research Questions

The literature review identified several challenges, and these included a lack of consensus on road freight electrification technology and transition pathway and the need for considering aspects beyond technology, like regulations, socioeconomic and political developments, and infrastructure enablement for the transition to electrified road freight. The question that has to be asked is, with a lack of clarity on viable alternative(s) to the diesel engine, will fully electrified road freight be possible to be achieved by 2050? Will improvements in technology be enough or do we need to look at aspects (challenges and enablers) beyond technology and what are those aspects to look into and can they be explored further for a more viable and faster transition to electrified road freight?

3. Approach

The purpose of the research was to identify through literature search, review, and stakeholder validation and feedback, the factors deemed to have a significant impact on the technology adoption for road freight electrification. Initial literature search involved sifting and reviews. The literature review methodology was based on SALSA framework [34]. For validation of findings, a participative approach involving transition stakeholders was undertaken. Such an approach helps to generate foresight by systematic analysis of divergent views and provides insiders' views, which can assist in system changes [35]. For the subsequent literature review and stakeholder feedback analysis, in addition to the SALSA framework, a thematic analysis involving low- and high-level abstraction to generate codes and themes from qualitative data [36] was carried out. The three key steps and the methodologies involved are covered in the following sections.

3.1. Initial Literature Search

A multilevel search for relevant literature was undertaken with the first level covering search string synonyms of "road freight emissions" and "heavy good vehicle emissions" and the second level containing search string synonyms of "decarbonisation", "zero-emission", "emission reduction", and "technology forecast". An Internet search on reports from government, regulatory, and semiautonomous bodies; independent research organisations; climate/environmental organisations, and prominent companies in the energy sector was also carried out using these search strings. Using a rapid review covering the title, abstract, executive summary, and conclusion sections of those reports, shortlisting of reports/articles was performed. The criteria used were road freight focus, coverage of decarbonisation solutions, and 2050 technology forecast. The focus on the UK/EU markets was because of their stated 2050 net-zero policy objective; however, studies that had a global focus but included specific reference to either the UK or the EU market were also covered. Finally, a systematic and critical review was conducted on shortlisted reports/articles.

3.2. Stakeholder Validation and Feedback

The involvement of experts and stakeholders in transition scenario analysis has been found to help fill the gap between the outcomes of research and subsequent implementation [37]. A stakeholder workshop was hence organised to discuss the initial literature search findings and gather insights (challenges and enablers) on the transition to road freight electrification. International Energy Agency has two Taskforces focussed on road freight electrification: Taskforce 41 is focussed on electric freight vehicles and has an objective to monitor technological progress and analyse the potential contribution of electric freight vehicles to emission reduction targets. Similarly, Taskforce 45 is focused on electrified roadways with a vision to develop a global understanding and awareness of electrified roadway-related technology developments, deployment activities, and international standard creation. A workshop involving Taskforce members and other relevant stakeholders was hence planned.

Considering that the literature search before the workshop emphasised the significance of societal, policy, and infrastructure elements in addition to technology for road freight electrification, it was crucial to adopt an analysis approach that encompassed these broader system elements. PESTEL approach [38–40] was hence used, which includes Political, Economic, Sociological, Technological, Environmental, and Legal factors. Other approaches, like Strengths, Weakness, Opportunity, and Threat (SWOT), Technology Acceptance Model (TAM), and Porter's five forces, were found to be either too broad or too specific. For example, approaches like TAM are user-centric and do not account for external factors [41]. Other frameworks, like SWOT, did not consider societal factors. PESTEL approach, however, is aligned to all the elements which were identified during the literature search.

The high-level approach for the workshop was adapted from the qualitative research methodology by Kvale [42] and involved thematising, designing, discussions, transcribing, reporting, and analysing. The overall approach for designing and executing the workshop is summarised below in Figure 1.

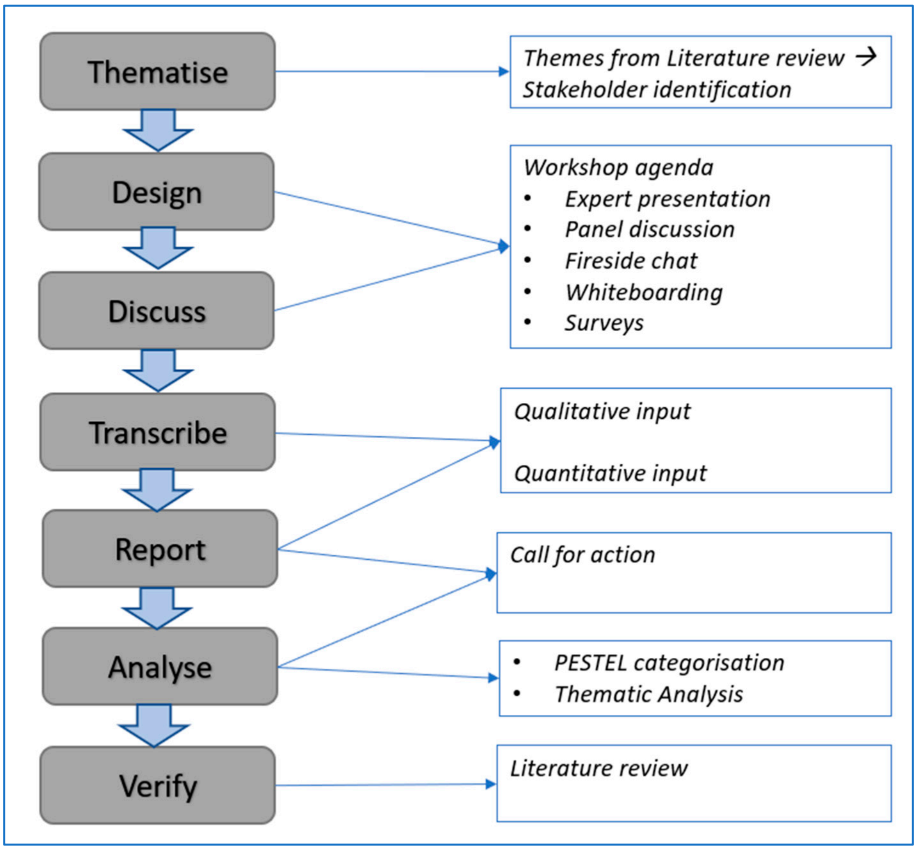

Figure 1. Seven-step approach based on Kvale [42] used for the workshop.

The workshop was designed to gather insights on the challenges and enablers of road freight electrification, based on the identified literature search theme. While the stakeholder selection was focussed on wider coverage, the design of the workshop was also accordingly focussed on capturing the views and insights from across the audience. Hence components, such as presentation, brainstorming, discussion, and deliberation, were embedded in the workshop design [43]. While the presentations by stakeholders could be used to validate or negate the literature search findings, semistructured discussions in form of panel discussions, fireside chats, and whiteboarding sessions helped to uncover biases and underlying motives, which may not be otherwise uncovered in structured approaches, like presentations and literature reviews [44]. Hence, while detailed insight from experts was sought, at the same time, avenues for gathering views from the broader audience were also needed. Hence, expert-led presentations, fireside chats, and expert-led panel discussion sessions were placed on the agenda for gathering detailed expert views. To gather broader audience views and direction, a whiteboarding session and a few surveys were included in the agenda. Surveys were created using the freely available tool Mentimeter. Surveys were conducted anonymously where the initial part of the survey captured the categories of the respondents based on their base location/country and their area of knowledge and expertise. Surveys and the whiteboarding session served as the formal mechanisms to gather data from all participants, regardless of whether they had a speaking session. Whiteboarding session was kept for the very end so that all the thoughts captured in the earlier sessions can be summarised and a call for action from the audience can be taken accordingly. This aligned with the workshop's overall flow, transitioning from identifying challenges to exploring enablers through a call to action. Given that the design of the workshop was spread across two and a half days, breakout groups were not planned, and the idea was to involve everyone from the audience in every component of the workshop design. For those two and a half days, day 1 had expert-led presentations and panel discussions on the electric road freight innovation system, day 2 included in-depth and semistructured discussions on the topics of electric freight vehicles and electrified roadways, and day 3 covered the conclusion with an open session on identifying how governments, logistics and industry can be mutually supportive in moving on from the present diesel mindset in road freight transport.

3.2.1. Stakeholder Selection

A search for similar workshops was carried out to identify the stakeholder groups within and beyond the Taskforce members. A stakeholder is defined as an individual or a group who can be affected by or can affect the achievement of the organisation's objectives [38,45]. A stakeholder workshop by Catapult UK in 2019 [23] on road freight decarbonisation had stakeholders from industry and academia. Another workshop organised in Sweden focussed on finding HGV electrification scenarios had stakeholders from policy, industry, and academia [46]. An IEA report [47] in 2017 analysed the existing electrification technologies for HGVs and used outcomes from a stakeholder workshop to identify barriers and opportunities for possible electrification scenarios. The workshop had stakeholders from truck manufacturers, industry associations, industries (components/solution suppliers), nongovernmental and nonprofit organisations, academic and research institutions, consultancy firms, and governmental bodies. Another study [48] about road freight in Ireland identified stakeholders as road haulers, freight forwarders, exporters, industrial organisations, and state-owned agencies. Hence, in addition to the Taskforce members, representatives from the stakeholder bodies indicated in earlier road freight-related research/workshop reports were also looked for. The objective was to have as broad a coverage as possible so that more divergent views can be captured. Amongst various nonprobability sampling methods [49], purposive sampling was used to identify and gather stakeholders because purposive sampling is a better method when one wants to focus in depth on smaller samples that have specific characteristics or perspectives that are relevant to the research question. Forty-six participants from across the globe (43% EU; 26% UK; 13% US; 9% Canada; and 9% RoW) joined the workshop representing road freight stakeholders from government, academia, infrastructure, logistics, vehicle industry (Original Equipment Manufacturer—OEM and suppliers), and nongovernmental body segments. More details can be found in Table A1 in Appendix A where the profiles of the speakers and of the panel experts are listed.

3.2.2. Transcribing and Analysis

Design of the workshop enabled multiple sources of qualitative and quantitative output. Minutes for all the sessions were captured during the workshop. Many quantitative data points and qualitative insights were shared by the experts during presentations and panel discussions. Thematic analysis [36] was utilised to compare and examine the various lines of thinking derived from qualitative and quantitative data collected during the workshop, including survey responses and figures shared by speakers. PESTEL categorisation provided a good framework to be applied using thematic analysis. Each speaker was invited to present the challenges from a distinct perspective. The framework based on the PESTEL approach defines system as being constructed of political, environmental, societal, technical, economic, and legal components. Each speaker was therefore selected based on their ability to cover one or a combination of the PESTEL components. While day 1 was focused on capturing stakeholders' views around road freight electrification challenges, day 2 was focused on the possible and available solutions. The selection of presentations was based on covering the gamut of solutions from technology to user-based ones. On day 3, participants were asked to evaluate the suitability of solutions (discussed on day 2) in the context of the challenges identified (on day 1). In this way a common vision would begin to emerge whereby participants would jointly define a realistic vision of the future based on achieving alignment of challenges to solutions. This, in turn, would be supported by identification of actions necessary to support the emerging common vision.

3.3. Literature Search and Review

Workshop findings were used to arrive at an approach to a literature review for conducting further analyses and arriving at conclusions. This approach allowed the researchers to quickly review and identify relevant literature to support their analysis without conducting a full-scale review. The focus was on peer-reviewed articles so that more scientific evidence could be gathered for analysis and conclusion. The overall approach for the literature review is summarised below in Figure 2.

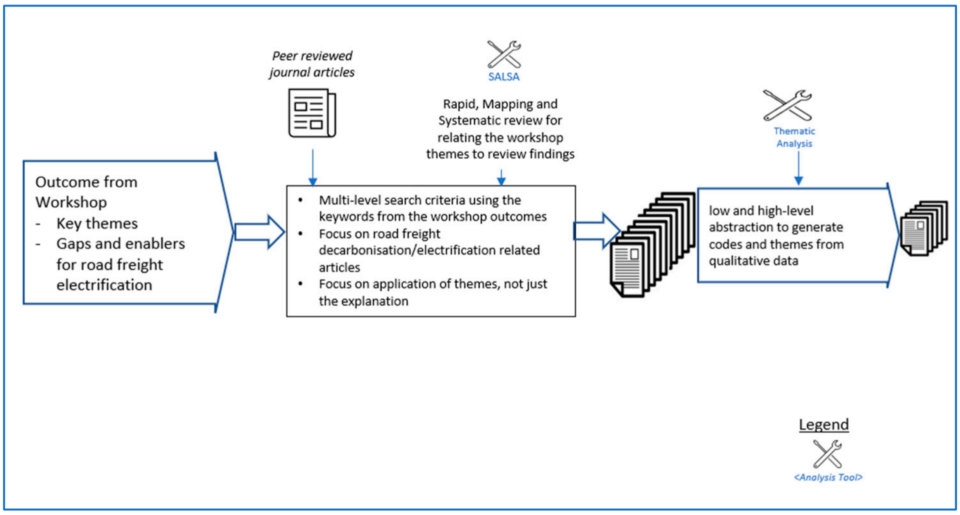

Figure 2. Approach to literature review post the stakeholder workshop.

4. Results

The initial literature search set the context and the background (covered in the earlier section in the report) for the stakeholder validation and feedback. While zero emission was suggested in the literature as a technically possible option, the commercial viability and adoption enablers needed further discussion. Speaker presentations during the stakeholder workshop threw more light on the existing solutions for road freight electrification. Details were shared about various challenges associated with those solutions The panel discussion and fireside chat helped to uncover some of the biases and brought the challenges and enablers beyond technology to light. Intermittent surveys conducted helped to validate the themes which were emerging from the discussions. And finally, the whiteboarding session held on the last day captured some key calls to action from the audience. The input captured from the workshop was hence categorised into the following three themes, which also aligned with the research objectives identified earlier.

4.1. Solutions for Road Freight Decarbonisation

During the presentations, it was commonly expressed that technological advancements have brought road freight closer to being net-zero ready. One speaker noted that electrifying 30% of road freight in the US would require 200 TWh out of a total capacity of 4125 TWh, which is not an insurmountable challenge. Similarly, achieving a peak demand of 90 GW out of a total of 1000 GW in the UK is also considered feasible. An emerging electric truck OEM representative acknowledged that range is a primary obstacle for road freight electrification, but they believe it is possible and that the cost of lithium would decrease. Additionally, shared infrastructure, such as electric roadways, could lower overall ownership costs. A technology stakeholder from a catenary infrastructure company explained that a 26-ton articulated lorry covering 116,000 km over 7 years has an annual fuel cost of approximately GBP 23,000 assuming a fuel consumption of 23 litres/100 km. However, with a catenary system efficiency of 85% compared to a diesel engine efficiency of 42% and an energy price of GBP 14 pence/kWh, the annual cost would be GBP 14,000, resulting in annual savings of around GBP 9000. Even after adding infrastructure costs, there would still be lifetime savings of approximately GBP 12,000 per truck compared to a diesel truck.

Although the technology was deemed viable, there was uncertainty about which specific technology option to invest in. An OEM stakeholder highlighted that while LNG and diesel are short-term combustion options, they are investing in both battery and fuel cell electric systems for the long term. The energy density of diesel remains the biggest challenge for alternate fuel systems. A representative from the logistics industry indicated that system costs and charging times are significant concerns when transitioning to electric, but automated truck-charging solutions could help address these issues.

The above points were also indicated across the surveys, which were conducted during the workshop with an aim to obtain the opinions of the participants on achieving net zero for road freight. The surveys conducted at various points during the workshop were completed by 21 stakeholders. The survey results below in Figure 3 indicate that while 78% of the stakeholders believed that net zero is possible to achieve by 2050, 81% of the stakeholders believed that no single technology could come out as the winner. This view was reflected across stakeholders from governmental bodies, vehicle manufacturers, research organisations, infrastructure providers, logistics providers, and independent bodies. This corroborates the investment risks mentioned above in the article and highlights the need to make the transition to new technology more effective and viable.

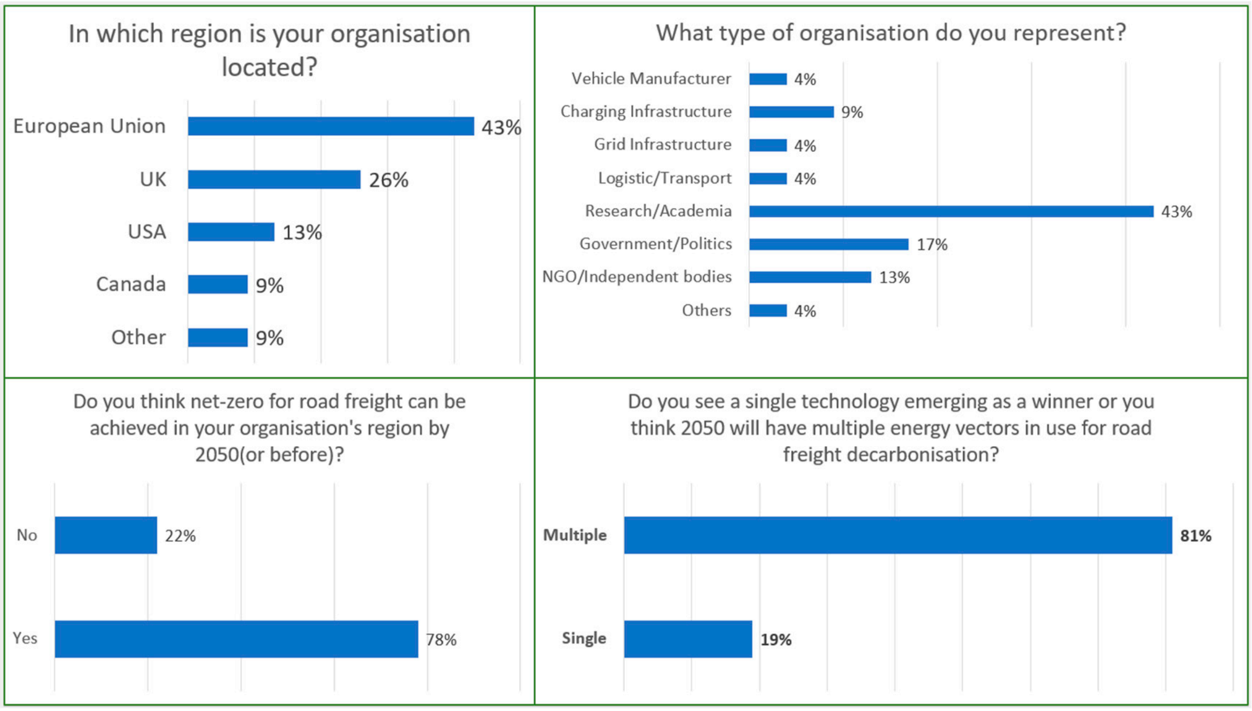

Figure 3. Survey results for 21 participants across multiple road freight domains.

4.2. Challenges and Enablers within and beyond Technology

While the survey results indicate that technology is available to support road freight electrification, stakeholders in the workshop provided various insights into the challenges and enablers of achieving road freight electrification. While some emphasised the need for technological advancements, an OEM representative noted that the greatest challenge is that diesel fuel currently cannot be surpassed in terms of energy density. On the other hand, an infrastructure panellist pointed out that heavy-duty electric trucks have a greater impact on the grid than anticipated and that system interruption on the Electric Road System

(ERS) requires careful consideration. However, an emerging electric truck OEM speaker suggested that solid-state batteries may address these concerns, but they are not expected to be commercially available for another five years. In the meantime, Lithium Nickel Manganese Oxide (NMC) batteries with an energy density of 270 Wh/Kg are best-suited for commercial vehicles.

As the workshop progressed, valuable insights emerged indicating the importance of considering aspects beyond technology.

4.2.1. Infrastructure

A panel speaker from an energy distribution organisation highlighted the need to create charging hubs and the importance of connecting to fleet owners. A combination of overnight chargers and splash-and-dash chargers was suggested for HGVs. The speaker also suggested that the electric road system will be better because it will reduce the dependency on the battery. In the post-workshop feedback, the speaker also highlighted multiple challenges of the ERS, some of which are mentioned below:

- Overhead lines to move the large supplies along the side would require substations to be built along the motorway.
- There could be challenges in dealing with landowners who do not want the assets crossing or being built on their land.
- The foundations for each structure will be piled foundations to cater to the cantilevered structure and forces and not undermine the motorway. One piled foundation will cost about GBP 20,000.
- What design characteristics will be applied to the catenary to cater to wind loadings, ice loadings, and snow loadings? That is, the thickness of the ice, amount of wet snow accretion, angle, and wind speed. These numbers are essential as they dictate the characteristics of the various structures, like terminal poles, intermediate poles, and angle poles.
- Installing the conductors and steel poles will shut lanes of the motorway for the installation, maintenance, and any fault repairs.

The above speaker also highlighted the need for and the investment required for hub charging solutions, which can have 8–150 kW rapid chargers for BEVs. One suggestion from the same speaker was to consider places close to the port for the charging infrastructure setup. One participant in the fireside chat highlighted the challenges related to the grid and suggested a need for an interconnected grid to handle the demand. Representatives from technology and academia touched upon the need for efficient transport planning and route optimisation to improve both long-haul and last-mile logistics efficiency. Another technology representative shared details about a wireless charging system for road freight with cloud-based energy management system. It was noted by one industry body representative that the charging infrastructure should be treated as a national infrastructure.

4.2.2. Policy Alignment and Collaboration

One panellist emphasised the need for collaboration among utilities, infrastructure, government, research, and automotive companies for road freight electrification to be successful. However, another speaker from an environmental group noted that policy makers need to balance multiple priorities, such as Covid, Brexit, driver shortages, fuel prices, and spending reviews, and that road freight electrification may not be their top priority. The defined scope of various organisations prevents any single entity from having a comprehensive view. For example, the DfT focuses only on tailpipe (tank-to-wheel) emissions and not on well-to-tank emissions, resulting in misaligned investments and policies. Thus, a common and synergised approach may be difficult to achieve because policies are not aligned with a radical change, and progress is determined more by individuals who are unable to break from a diesel mindset.

Another area of collaboration highlighted by a stakeholder from the logistics industry was regarding the impact of operational conditions on range estimation. For instance, an electric truck manufacturer has been collaborating with operators to estimate the range of their vehicles. An ERS can also help reduce battery stress and improve battery life. However, the adoption of an ERS requires maximum collaboration among all electrification options, making it challenging to achieve despite its technological benefits. Additionally, one panellist mentioned that the timeline for utilities to provide project power requirements has not been well understood.

4.2.3. Societal and Behavioural Factors

One of the questions raised during the discussion was whether we need electric vehicles to replicate current vehicles, or can we be smarter and change the system or change our behaviour to suit our new vehicles? It was noted in a panel discussion that dynamic charging on the road can reduce the amount of behaviour change needed because the charging will happen while the truck is being driven. One of the panel discussions focussed on the challenges around system change and ways to overcome those challenges. The panellists highlighted the need for focussing on people, society, and attitudes beyond engineering solutions. Policy and political constraints were seen as a barrier. Customer behaviour changes, for instance, the need to have goods delivered the next day needs to be questioned. Experiential learning (from running a BEV truck fleet) was also highlighted as a way to overcome adoption challenges. Making system usage changes, like allowing the charging infrastructure on bus depots to be used by trucks during the day while buses use them at night, can help improve electric truck adoption. Continued discussions in the fireside chat session touched upon the need for new metrics, which can help bring the system change, for example, for a large fleet, the focus can be on delivery times, while for small fleets, the cost can be the performance measure. There was also a suggestion to focus on step change rather than changing multiple systems at once, for example, focussing on fleet electrification first and then working on generation aspects.

The survey results below in Figure 4 show that aspects beyond technology improvements are considered important for overcoming the barriers to electrification.

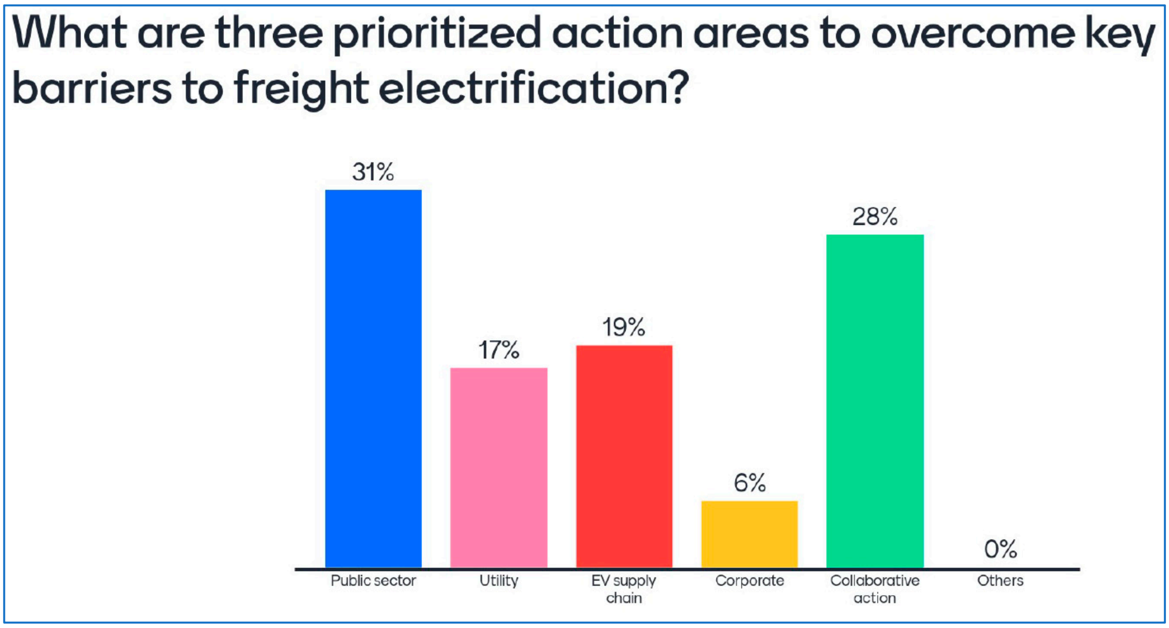

Figure 4. Survey results for 21 participants across multiple road freight domains on priority action areas.

4.3. Call for Action

As one of the objectives of the workshop, a call for action was captured from various stakeholders. A whiteboarding session conducted on the last day of the workshop focussed on solution options and highlighted the need for system-level changes around PESTEL. The key points captured from the session and from various other speaker sessions and fireside chat discussions are summarised below in Table 1. Please note that the themes in the first column in Table 1 below are aligned to the PESTEL categorisation, which was identified earlier as a part of the analysis.

Table 1. Call for action across various themes.

Overarching Themes/ Questions/Challenges	**Call for Action**
List any other key challenge/barrier not listed in the table shown	Interoperability, space availability, political decision making, health and safety-related charging, and other high-voltage infrastructure
What could be an effective radical new policy or policy change needed?	- Road pricing aligned to electrification outside the current toll-based ways - Carbon pricing - Reduce risk through creating niches that can be explored without penalty - Polluters to pay tax to help fund transition - Proactive grid investments given high lead-time difference between vehicle development and grid readiness - Charging station to be treated as national infrastructure - Policy focus aligned to step-wise change, like focus on fleet electrification first and then look at generation. For example, China reduced the battery price by focussing on electrification - Any solution that requires broader stakeholder collaboration might be tougher to achieve; hence, policy makers can use that also as a parameter to evaluate electrification solutions
What is the behaviour change you would look for?	- Expecting next-day delivery for less-urgent items - Induct next-gen truck drivers and professionals in the distribution sector - Create avenues of BEV experience for truck drivers, can expedite adoption
What is the operational change you would look for?	- Change from one-shift to two-shift operation to align to charging availability - Night driving (or slow autonomous driving) can be adopted to help with peak power demand, recharging action as a part of routine behaviour - New performance metric for the sector. For example, move from Total Cost of Ownership—TCO to Total Climate Impact—TCI, cost driven KPIs for small fleets and delivery times driven KPIs for large fleets
Infrastructure	- More interconnected grids to better handle required loads
System costs a concern for logistics industry	- Automated smart charging solutions to be promoted - Policy instruments, like carbon pricing, to adjust TCO
Collaboration across actors/stakeholders	- Bus depots can be used for buses at night, and during the day, they can be used as opportunity charging for trucks - Manufacturers taking feedback from operators in building better range prediction solutions for electric trucks

4.4. Literature Search Post-Workshop

Based on the input from the workshop, a literature search and review for peer-reviewed scientific articles was carried out. The focus was to find out the use of sociotechnical factors for technology adoption for road freight. A search for "socio-technical" in the title or the subject yielded 8157 English-language peer-reviewed articles. Filtering the ones which also included the word "transport" narrowed the number down to 439 articles. Further shortlisting based on the subject category of "Transport" and "Transport science and technology" reduced the number to 104 peer-reviewed journals. Further filtering was performed based on the below criteria

- Articles with a focus on passenger mobility or other means of transport, like shipping, airlines, or railways were taken out;
- Abstract was read through to see if it covers road freight segment;
- Despite containing the key words, some articles did not have a sociotechnical approach as the main theme, as was verified by going through the abstract;

- Some of the papers were exploratory (covering general history of sociotechnical transitions across multiple domains, including transport) and did not specifically delve into the impact of sociotechnical factors on transport decarbonisation, which was the main focus of the literature search.

Applying the above filters yielded 31 articles in which either road freight or the overall transport or energy segment was covered. They were taken up for a more detailed review, which yielded 11 articles (Table A2 in Appendix A has the details), which covered some way of factoring sociotechnical aspects into technology adoption. The same search process as above with "road freight" instead of "transport" yielded just one relevant article, which was included in the above-mentioned list of 11 articles.

5. Analysis

The road freight industry is a vital component of the global economy, but it also has a significant impact on the environment, particularly through its carbon emissions. Stakeholders in the workshop acknowledged the challenges associated with various technology options available presently for road freight electrification. They also believed that full electrification is possible to achieve by 2050 for the road freight sector. During the discussions, it became evident that the stakeholders and experts recognised that the current setup, which has evolved around diesel engine-based trucks, needs to be replaced with sustainable options. However, there was also a noticeable resistance observed in moving on from the current setup.

The survey results (Figure 3) indicate that the majority (78%) believed that full road freight electrification can be achieved by 2050. Input from the speaker sessions also indicated that individual technology stakeholders believed that the specific technology does have the potential to enable road freight electrification, but interventions beyond technology improvement would be needed to achieve the transition. For example, one speaker from the infrastructure domain suggested that electric roads are capable of the transition to fully electrified road freight, but 60–70% of the costs should be recovered from the end users using tolls and the remaining by taxes from others who benefit. Strong policy support and societal changes were also indicated as prerequisites for the transition to new technology. This suggests that multiple technologies might provide a viable path to transition on their own. But the very same conclusion also leads to the challenge of supporting and investing in multiple technologies, which can create risks for policy makers and truck/component manufacturers.

The views from the floor included the following: we have the requisite (new) technology, but we do not want to necessarily change the way we operate to accommodate limitations or leverage advantages (of the alternative technology); we have a positive business case, but too often, these examples focus on certain technologies and applications (and not the wider global challenge); we need to educate about the benefits of the system change beyond the immediate user (for example, air quality improvements); and policy needs to be strengthened to facilitate a system change (as opposed to a focus on improvement to the present system). Some of the key messages from the workshop and their alignment to the PESTEL framework are shown below in Table 2.

Hence, it was derived that none of the technology options could be adopted without changes to the system. The group realised that to achieve net-zero emissions by 2050, it was crucial to address not just the technological challenges but also the system challenges. So, the group discussed various aspects of the system that might require changes, including infrastructure, policies, user behaviours, and societal factors. This led to the categorisation of system challenges using the PESTEL framework.

Table 2. PESTEL categorisation of key challenges captured during the workshop.

Challenges/Barriers	PESTEL Category
Varying but large infrastructure investment needed for all electrification technologies	Environmental
Current policies amount to only incremental change but not radical	Political
Required degree of system and/or behaviour change	Social
Current metrices for road freight limiting us to current mindset/behaviour/system	Environmental
Grids have not been tested for their required level of interconnectivity, resilience, and flexibility	Technological
While a fully autonomous truck can bring energy efficiencies, there is lack of clarity on the powertrain technology to which the investment should be aligned	Economic
Existing decarbonisation pathways are limited to an existing system; they do not take a system-of-systems approach	Environmental

The first category identified was infrastructure, which includes charging and refuelling infrastructure for electric and hydrogen trucks, along with the necessary power grid upgrades. Various stakeholders approached this category from various angles. Some focussed on the investment in new charging infrastructure, and some talked about expansion of the grid. The overall theme for the system changes around infrastructure was, however, around creating focussed corridors of very reliable energy.

The second category was policies, which encompass regulations and incentives for decarbonising the road freight transport sector. These policies could be at the national, regional, or international levels and would need to be consistent across different jurisdictions. The third category was user behaviours, which refers to the behaviours of freight operators and drivers, who will need to adapt to new technologies and sustainable practices. This includes changes to route planning, loading and unloading, and driving styles to optimise energy efficiency. The fourth category was societal, which includes consumer demand for sustainable products and services, which would incentivise manufacturers and retailers to adopt sustainable practices.

Overall, the workshop highlighted that while technology solutions exist for road freight decarbonisation, there is a need for system changes to achieve complete road freight electrification by 2050. These system changes include infrastructure, policies, user behaviours, and societal changes. The road freight industry will need to collaborate with policy makers, investors, and consumers to address these challenges and transition towards a sustainable future.

6. Discussion

The initial literature findings around challenges associated with road freight electrification were taken for multiple avenues of further corroboration and analysis. Stakeholder input was first taken to validate the challenges and obtain a perspective on potential approaches to address the challenges. The outcomes indicate that an approach beyond technology would be needed to expedite road freight electrification. A literature review conducted thereafter helped to validate and confirm the findings and also highlighted further areas of research around factoring sociotechnical aspects to new technology adoption.

The outcome from the stakeholder engagement indicated that road freight electrification will not be without challenges and that those challenges will be beyond technology. The adoption and subsequent stabilisation of new technology involves system changes. These changes can, however, be understood only if the technological aspects are seen as being related to various nontechnological factors [50]. Such nontechnological factors can invariably involve changes to the system. For example, the adoption of autonomous driving-related technology has been suggested to improve safety and efficiency [51]. However, the adoption of this new technology can possibly be expedited if one of the system aspects around infrastructure is changed, for example, putting digital infrastructure on the roadside to assist Autonomous Vehicles (AVs) for environment cues around the road, widening cycle and pedestrian paths, and setting up physical barriers to stop cyclists and pedestrians from entering autonomous routes. [51]. Another aspect which can impact adoption could be related to sales and reporting requirements, which would need system changes but can expedite the transition. The Advanced Clean Truck (ACT) regulation [52] by the California Air Resource Board (CARB) is one such example where new sales and reporting requirements related to zero-emission trucks will be enforced from 2024 onwards. Because such system changes will come at a cost and an effort, decisions related to the same need to be taken well in advance.

From a road freight perspective, the aspects of "system" as identified from the discussions in the workshop were infrastructure, policies, user behaviours, and the societal setup This aligns with the elements of a sociotechnical system, which results from the alignment of existing technologies, regulations, user patterns, infrastructure, and cultural discourses [53]. Transport itself, hence, is a sociotechnical system consisting of technology, knowledge, artifacts, policies, regulations, markets, cultural meaning, and infrastructure. Any changes to such a system for enabling the transition to a new technology adoption needs a sociotechnical approach in strategic transport planning, forecasting, and decision making [50]. A study by Schwanen et al. [54] also indicated a strong link between climate change mitigation in transport and the theoretical insights from the social sciences. Their analysis indicated that such transitions span across several decades and it involves positive feedback among a broader range of elements and social actors, like lobby organisations, media, and financial agents. Hence, new technologies have to accordingly fit into social norms and beliefs, and such social embedding is considered essential for integration into the existing market.

An important aspect highlighted in this review paper is the need for stakeholder involvement required for the system transition of sociotechnical systems, like transport. Such involvement helps generate foresight, which can further impact the development of policy strategies [55] and thus enable system changes required for the transition. Such involvement also helps identify barriers to transition [56]. The stakeholder engagement identified the need for a sociotechnical approach for the transition. For example, there were sociotechnical elements discussed around questioning the need for next-day delivery (societal), focussing on operational aspects of building the ERS close to the electricity grids (infrastructure), defining new freight operational metrics (policies), and enabling BEV experience to freight to improve adoption (user behaviour), and many more. The literature review post-workshop helped to identify few sociotechnical approaches which have been applied in studies around achieving carbon-efficient transport systems. However, most of them were found to be focussed on passenger transport [31,56]. Brand et al. [57] used a sociotechnical approach for an integrated systems model for building transport electrification scenarios for Scotland. However, their study was focussed on the overall transport segment and not specifically on HGVs.

Few examples from the adjacent segment were, however, found to be useful for potential use in the road freight segment. For example, Pregger et al. [58] embedded a sociotechnical approach for building an exploratory approach-based pathway for the transition of the German energy system to a low-emission one. They used an approach where societal context building was carried out using cross-impact balancing (CIB) methodology and was then combined with technoeconomic energy modelling. A study by Auvinen and Tuominen [50] focussed on the sociotechnical impact of policy making for a 2100-year horizon; however, the study focussed on qualitative aspects of transport planning and did not delve into any quantitative impact on decarbonisation pathway building.

Embedding sociotechnical aspects into transition pathway building would first require identification of the system changes. These changes can be across various PESTEL categories. Table 2 earlier in the report captures some of those changes as identified from the stakeholder workshop. Such changes are being attempted by some governmental organisations. For example, the EU had initially adopted a regulation in 2019 for an emission standard for all new heavy-duty trucks [5]. The regulation also mandates from 2025 a decrease of 15% emissions for new trucks from the reference period (1 July 2019 to 30 June 2020). The EU regulation on mandatory rests for drivers can help to allow charging on average every 4.5 h [5]. The Department for Transport (DfT) in the UK has proposed the end of the sale of all new nonzero emission HGVs by 2040 [10]. The UK government has committed GBP 20 m to develop cost-effective refuelling infrastructure for zero-emission HGVs across the UK [10]. It has also announced the GBP 200 m Zero Emission Road Freight Demonstrator (ZERFD) programme.

A way to embed such system changes into transport models (used for building decarbonisation pathways) using a sociotechnical approach was the key gap observed in the literature review and also in the stakeholder input. This also paves the way for further research in this area. Transition pathways built with this approach will make the journey to net zero faster and effective. As indicated earlier, while other sectors, like passenger transport and energy, have attempted this, something similar needs to be applied for the road freight transport segment as well.

One possible approach could be to utilise methods like CIB as mentioned earlier in the report to identify the sociotechnical aspects. An existing transport decarbonisation model for road freight can then be picked up, and the identified aspects can be used for building pathway scenarios for decarbonisation. This will help create and embed new additional scenarios into the existing models, which can then be used to build faster pathways to net zero.

The research conducted by the authors also has a few limitations though. Given that the electrification technology for road freight is an evolving one, the study performed may not have covered a broad and diverse set of stakeholders and also may not have covered all the relevant topics in depth. For example, inviting vehicle manufacturers from multiple global regions could have brought diverse perspectives to the table. Given that the electrification ecosystem is becoming broader, some of the topics (for example, renewable energy requirements for charging/electricity and grid-related and other utility provider-specific challenges) may not have been covered in depth.

7. Conclusions

The approach taken in this review paper differs from many others. The three-step approach involved stakeholder validation and feedback as the second and key step. Further analysis helped to break down the challenges into different areas using PESTEL categorisation. The literature review undertaken thereafter helped to identify transport as a sociotechnical system. The link was thus established between the system changes required across the PESTEL categories and the need for a sociotechnical approach to embed/adopt those changes. While the sociotechnical nature of the transition was established using the workshop, the literature review post-workshop suggested that there was a gap in the literature when it comes to embedding sociotechnical aspects into building road freight electrification pathways. The review report hence contributes to the existing research by (1) providing an approach to stakeholder engagement in the form of workshop and (2) by providing a potential approach to transport planners and policy makers for embedding sociotechnical aspect into transition scenarios for existing models.

The findings from the report present a very good opportunity for transport planners to leverage their work. Existing transport models, which are currently used for building decarbonisation pathways for road freight, can benefit from the findings of this report. New scenarios can be added to existing models to factor in a sociotechnical approach-led system transition. This can make the existing models more effective and can also expedite the path to net zero for road freight. This can help reduce the investment and policy risks which are presently biased towards the road freight segment when it comes to transport decarbonisation.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Speakers at the workshop.

Role	Organisation	Country/Region
Vehicle systems technology advisor	Research institute	North America
Research associate	Aerospace institute	EU
Director	Research institute	North America
Vehicle systems manger	Government energy department	North America
Program manager	Nongovernmental, nonprofit body focussed on sustainable transport	UK
Business development	OEM for ERS	EU
Program manager	Semigovernment body on sustainable logistics	EU
Product manager	Truck OEM	
System engineer	Power Distribution company	UK
R&D head	OEM for electric truck	EU
VP Products	Sustainable freight mobility solution provider	EU
Professor of industrial engineering	University	EU
CSR	Multinational logistics company	EU
Professor of automotive engineering	University	UK
Senior engineer	Truck OEM	EU
Marketing manager	Electric vehicle charging solution provider	RoW
Lead—Electric Vehicle	Infrastructure and construction services	North America
Research staff	Research institute	North America
Transport and mobility analyst	Research institute	North America

OEM—Original Equipment Manufacturer; EU—European Union; UK—United Kingdom; RoW—Rest of the World.

Table A2. Summary of literature regarding sociotechnical impact on road freight transport planning/pathway.

Title	Author	Publications	Summary
Is the transport system becoming ubiquitous? Sociotechnical road mapping as a tool for integrating the development of transport policies and intelligent transport systems and services in Finland	Tuominen, Anu; Ahlqvist, Toni	Technological forecasting and social change, 2010, Vol. 77 (1), pp. 120–134, DOI: 10.1016/j.techfore.2009.06.001	The paper presents a sociotechnical road-mapping method as a tool to integrate the technology developments better with societal developments and transport policy design. The method is tested with a Finnish case study, which provides three thematic, complementary roadmaps of the potential transport system technology services of the future.
Lifestyle, efficiency, and limits: modelling transport energy and emissions using a sociotechnical approach	Brand, Christian; Anable, Jillian; Morton, Craig	Energy efficiency, 2019, Vol. 12 (1), pp. 187–207, DOI: 10.1007/s12053-018-9678-9	The article presents the development and use of quantitative scenarios using an integrated transport–energy–environment systems model to explore four contrasting futures for Scotland that compare transport-related 'lifestyle' changes and sociocultural factors against a transition pathway focussing on transport electrification and the phasing out of conventionally fuelled vehicles using a sociotechnical approach.
Future transport systems: long-term visions and sociotechnical transitions	Auvinen, Heidi; Tuominen, Anu	European transport research review, 2014, Vol. 6 (3), pp. 343–354, DOI: 10.1007/s12544-014-0135-3	This paper explores how sociotechnical transitions can be anticipated and taken into account in strategic transport planning. Techniques to integrate long-term foresight and understanding of sociotechnical change in the transport system to support long-term transport policy targets are introduced.
A review of sociotechnical energy transition (STET) models	Li, Francis G.N.; Trutnevyte, Evelina; Strachan, Neil	Technological forecasting and social change, 2015, Vol. 100, pp. 290–305, DOI: 10.1016/j.techfore.2015.07.017	This paper provides a taxonomy for a new model category called 'sociotechnical energy transition' (STET) models, used for integrating both quantitative modelling and conceptual sociotechnical transitions.
A sociotechnical model of autonomous vehicle adoption using ranked choice stated preference data	Asmussen, Katherine E.; Mondal, Aupal; Bhat, Chandra R.	Transportation research. Part C, Emerging technologies, 2020, Vol. 121, p. 102835, DOI: 10.1016/j.trc.2020.102835	This paper examines the individual-level AV adoption and timing process, considering the psychosocial factors of driving control, mobility control, safety concerns, and tech savviness. A ranked choice stated preference design is used to elicit responses from Austin-area residents regarding AV adoption. The findings from our analysis are translated to specific policy actions to promote AV adoption and accelerate the adoption time frame.
Linking narratives and energy system modelling in transport scenarios: A participatory perspective from Denmark	Venturini, Giada; Hansen, Meiken; Andersen, Per Dannemand	Energy research and social science, 2019, Vol. 52, pp. 204–220, DOI: 10.1016/j.erss.2019.01.019	The present paper investigates the iterative and participatory applications of driving forces in bridging qualitative and quantitative methods in transport scenarios for the Danish transport sector.

Table A2. *Cont.*

Title	Author	Publications	Summary
Discontinuation of the automobility regime? An integrated approach to multilevel governance	Hoffmann, Sebastian; Weyer, Johannes; Longen, Jessica	Transportation research. Part A, Policy and practice, 2017, Vol. 103, pp. 391–408, DOI: 10.1016/ j.tra.2017.06.016	The paper discusses the discontinuation of incumbent sociotechnical regimes by means of deliberate governance. Comparing actor constellations and policy measures in four different countries (the UK, Germany, France, and the Netherlands) and on the EU level, the paper identifies strategies and measures that have been applied to challenge the automobility regime.
Exploring stability and change in transport systems: combining Delphi and system dynamics approaches	Rees, David; Stephenson, Janet; Hopkins, Debbie; Doering, Adam	Transportation (Dordrecht), 2017, Vol. 44 (4), pp. 789–805, DOI: 10.1007/s11116-016-9677-7	This paper applies qualitative system dynamics modelling to help interpret the results of a Delphi study into global transport transitions, involving 22 international experts in various aspects of transport.
Process supporting strategic decision making in systemic transitions	Auvinen, Heidi; Ruutu, Sampsa; Tuominen, Anu; Ahlqvist, Toni; Oksanen, Juha	Technological forecasting and social change, 2015, Vol. 94, pp. 97–114, DOI: 10.1016/j.techfore.2014.07.011	This paper introduces a process for supporting strategic decision making and policy planning in systemic transitions using the multilevel perspective (MLP) as an underlying theoretical framework and combines various methods and tools from the fields of foresight, impact assessment, simulation modelling, and societal embedding.
A virtual environment for the formulation of policy packages	Taeihagh, Araz; Bañares-Alcántara, René; Givoni, Moshe	Transportation research. Part A, Policy and practice, 2014, Vol. 60, pp. 53–68, DOI: 10.1016/ j.tra.2013.10.017	This paper describes the development of a virtual environment for the exploration and analysis of different configurations of policy measures in order to build policy packages. The paper also considers the challenge of the interdependence and complexity of sociotechnical systems and the availability of a wide variety of policy measures to address policy problems
Moving towards sociotechnical scenarios of the German energy transition—lessons learned from integrated energy scenario building	Pregger, Thomas; Naegler, Tobias; Weimer-Jehle, Wolfgang; Prehofer, Sigrid; Hauser, Wolfgang	Climatic change, 2020, Vol. 162 (4), pp. 1743–1762, DOI: 10.1007/ s10584-019-02598-0	This paper presents an application of a sociotechnical scenario-building method for improving long-term scenarios and strategies for the energy transition in Germany. Developing integrated scenarios on a national level starts with employing the cross-impact balancing (CIB) approach for identifying consistent societal scenarios.

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