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Original citation:

Jha, S, Davies, HC & Pandey, M 2024, 'Establishing the requirements to support improved adoption of alternate technologies for the long-haul road freight decarbonisation', Transportation Planning and Technology, vol. (In-Press), pp. (In-Press). https://doi.org/10.1080/03081060.2024.2311073

DOI 10.1080/03081060.2024.2311073
ISSN 0308-1060
ESSN 1029-0354

Publisher: Taylor and Francis Group

Transportation Planning and Technology

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/gtpt20

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To cite this article: Sourabh Jha, Huw C. Davies & Mukesh Pandey (05 Feb 2024): Establishing the requirements to support improved adoption of alternate technologies for the long-haul road freight decarbonisation, Transportation Planning and Technology, DOI: 10.1080/03081060.2024.2311073

To link to this article: https://doi.org/10.1080/03081060.2024.2311073

TRANSPORTATION PLANNING AND TECHNOLOGY
https://doi.org/10.1080/03081060.2024.2311073

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Establishing the requirements to support improved adoption of alternate technologies for the long-haul road freight decarbonisation

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ABSTRACT

The UK has a target of achieving net-zero carbon emissions by 2050, which will require the decarbonisation of road transport. However, in the long-haul road freight segment, the optimal pathway to achieving net-zero is uncertain. This review paper explores and evaluates existing approaches to building decarbonisation pathways for heavy goods vehicles (HGVs). The search and review methodology, utilising the frameworks SALSA, PRISMA, and PESTEL, found gaps in three main aspects of pathway building. While a number of the studies considered vehicle or energy systems, a few took a broader system-level view. The parameters used for measuring the utility of the alternate technology required to achieve net-zero were not comprehensive. Further, the pathways lacked a socio-technical approach. The findings from the research have been used to provide insights and a conceptual framework that can be used for building a comprehensive model for improving technology adoption for the HGV decarbonisation pathways.

ARTICLE HISTORY
Received 30 December 2022
Accepted 19 January 2024

KEYWORDS
Road freight decarbonisation; heavy goods vehicle emission reduction pathway; socio-technical approach; transport model

1. Introduction

The world is experiencing a rise in global temperature. Intergovernmental Panel on Climate Change, IPCC (2021) report mentioned that, in light of the Paris Agreement's commitment of limiting the global temperature rise to less than 1.5 °C, carbon dioxide (CO_2) emissions, which is the main component of global warming, have to reach net-zero by 2050 to limit the temperature rise to 1.5 °C. The report highlights that the majority of CO_2 emissions (64% ± 15%) is caused by fossil fuel sources, with land transportation being one of the largest contributor sectors. Road-based transport sector accounts for three-quarters of the transport sector CO_2 emissions (International Energy Agency 2022a). Projections from the IEA (International Energy Agency 2002) show a decline in

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emissions of CO_2 for passenger road vehicles by 14% from 3.6 Gt in 2018 to 3.1 Gt by 2030, but for road freight the decline is less acute at 4% from 2.4 to 2.3 Gt. To decarbonise road transport, zero-emission electric motor-powered vehicle technologies are expected to become important (European Environment Agency 2022). The Climate Change Committee (2020) report stated that zero-emission options for HGVs (vehicles with maximum permissible total weight more than 3.5 t, mostly responsible for long-haul road freight) are expected to take longer to achieve widespread market uptake than compared to cars and vans. The long-haul HGVs are a subset of the HGV fleet that cover more than 400 kilometres per day (Connected Places Catapult 2021). 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 (European Environment Agency 2022; Basma, Beys, and Rodríguez 2021)

A report by Strategy& (2020) highlighted that electrification technology options (battery electric, hydrogen fuel cell, and catenary hybrid systems) for long-range heavy-duty vehicles have drawbacks in several areas. The report pointed out disadvantages in criteria such as loading capacity, purchase cost and range. For example, the powertrain weight of a diesel engine is 2200 kg, whereas a battery electric system weighs 4300 kg for the same output of 300 kW. A diesel engine truck has a purchase cost of 79,000 euros, while a battery electric truck costs 192,000 euros and a fuel cell electric truck costs 235,000 euros. Furthermore, the range of electric vehicles falls short when compared to conventional combustion engine trucks. Diesel engines offer a range of 1500–2000 km, while battery electric and fuel cell electric vehicles have a range of 400–800 km. A study by Kast et al. (2017) had explored the viability of hydrogen fuel cell in the US and found that Class 8 long haul trucks (trucks more than 14.96 tonnes of Gross Vehicle Weight) were able to meet only 40% of daily trips of conventional diesel-powered trucks. A report by Government Office for Science (2019) in the UK highlighted the impact that electrification would have upon vehicle payload, which would in turn require an increase in the vehicle fleet size and/or utilisation and would thus lead to higher utilisation of the road network.

The relative efficiencies and costs associated with these different pathways have an impact on the overall energy requirements. Studies by Çabukoglu et al. (2018; 2019) focussed on a data driven bottom-up approach to explore the technical limits to electrification for the truck fleet in Switzerland. They estimated that complete truck electrification would require an additional electricity of 5% (3 tWh/year) for battery electric and 13% (8 tWh/year) for electrolyser produced hydrogen-based fuel cell. They emphasised that realising full electrification would also need investments in dense refuelling infrastructure, high-capacity grid to access charging at home-base, access to day-long charging/refuelling infrastructure and renewable production of hydrogen.

It is clear from the review above that there is, at present, a performance and commercial viability gap between the electric replacement and the incumbent diesel technology. Various operational parameters as well as the well-to-wheel GHG emissions for the battery electric vehicle (BEV) and fuel cell electric vehicle (FCEV) technologies were compared with the incumbent diesel based Internal Combustion engines (ICE) technology. Data was taken from various reports and results were summarised in a spidergraph where the actual values were calibrated to a score between 0 and 10 where a low score indicated better viability. The results are summarised in Figure 1 below.

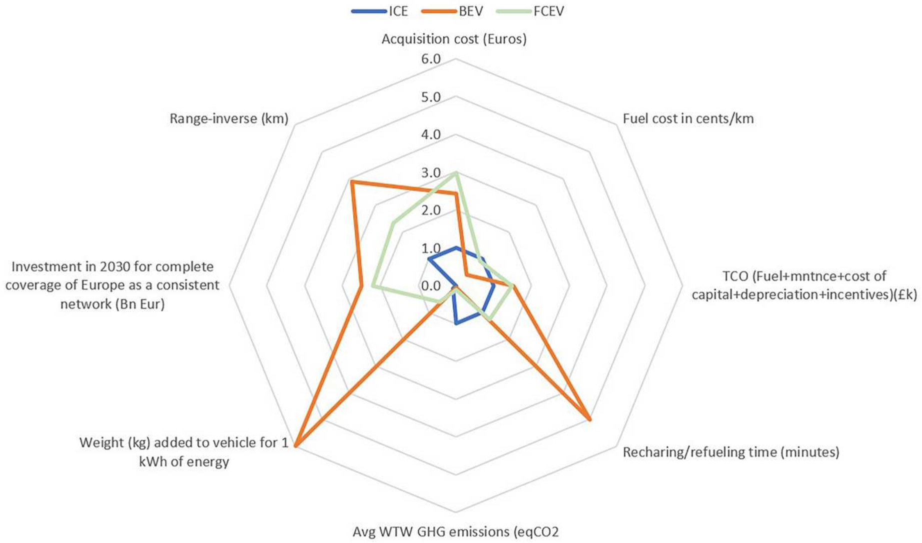


Figure 1. Comparison of Battery Electric Vehicle (BEV), Fuel Cell Electric Vehicle (FCEV) and Internal Combustion Engine (ICE) vehicles. Data has been taken Mojtaba Lajevardi, Axsen, and Crawford (2019, 19–55), Element Energy (2020), Strategy& (2020).

As can be seen in Figure 1, the ICE technology has a better viability, though higher emissions. The emissions for FCEV were assuming the required hydrogen is generated from the local electricity mix (95% hydroelectricity and 5% natural gas) or via the higher carbon intensity feedstock of natural gas via a reforming process.

Given the challenges in the viability of alternative technologies, it is important for transport planners and policymakers to understand the factors which enable and improve the new technology adoption towards decarbonisation of HGVs.

1.1. Theoretical framework

Environmental challenges have created awareness about the need for systemic changes and thus different analytical approaches have been used to study the same (Markard, Raven, and Truffer 2012). It thus becomes important to take a system-level view in studying such transitions to sustainable technologies. Given such transitions involve changes in technology, infrastructure, governance, institutions, social dynamics, culture and knowledge, they could be seen as socio-technical transitions (Geels 2004). Transport has been identified as a socio-technical system. Transition to low or zero emission technologies imply disruption in socio-technical systems (European Environment Agency 2017; 2019). Such disruptions have been analysed by the scholars and a framework around Multi Level Perspective (MLP) has been a dominant one (European Environment Agency 2017; Köhler 2012; Markard, Raven, and Truffer 2012).

MLP was proposed by Geels (2012) as a framework consisting of three layers with the first layer containing niche innovation, the second layer consisting of the existing socio-technical regime and the third layer of the existing landscape. Transitions get initiated by niche innovations breaking into the existing socio-technical regime with further added pressure from the existing landscape. Geels further described, taking the example of automobility in the UK and the Netherlands, how various actors (Industry, Consumers, and Policymakers) create stabilising and destabilising pressures, ultimately enabling or stopping a regime change.

Embedding socio-technical aspects into technology transition have been proposed to improve adoption. A European Environment Agency (2022, 74) report highlighted that while electrification would be the most important technology towards net zero for HGVs, ‘Transition for sustainable mobility will require innovations and changes in social norms, values and lifestyles’. A government report (McKinnon, Milne, and Thirkill 2021) in the UK also highlighted that the role of societal changes has mostly been under-represented in most of the prominent scenario studies. The report pointed out that a techno-economic approach-based model may be challenging to realise as real-world hurdles caused by societal aspects may impact any net-zero solution adoption.

While a system-level model with socio-technical aspects embedded in it may seem to be an effective approach to pathway building, another important factor is the utility provided by the alternate technology which aims to replace the incumbent and create a new regime. Shepherd, Bonsall, and Harrison (2012) used a system-level model to analyse future demand of electric vehicles in the UK and indicated that the uptake of new powertrain technologies depends on them achieving comparable attributes to conventional powertrain and also on supportive policies on supply and demand side. They also noted the usage of choice models to derive consumer utility in the studies involving the uptake of Alternative Fuelled Vehicles (AFVs). In light of the MLP perspective of transition, the concept of utility becomes important. If the actors create an influence such that the utility derived from the alternate technology equals or surpasses the utility derived from the incumbent technology, then it will create a stabilising force for the alternate technology. An initial literature search indicated that socio-technical transitions were used mostly for the passenger transport segment (Fallde and Eklund 2015; Corradi, Sica, and Morone 2023; Geels 2012).

It was also noted that external factors can play an important role in shaping the overall freight demand and hence existing pathways should have means to accommodate those factors. For example, a change in the modal split can impact passenger or freight demand for any specific segment. A move to public transport can impact demand for cars, a change to trains or waterways can impact road freight transport demand. Hence, external factors can help identify the uncertainties in the road freight demand (Aguas and Bachmann 2022).

Integrating all the above aspects to pathway building can help transport planners and policymakers arrive at a more realistic and accurate projection for technology adoption and emissions. Other scholars have conducted reviews on decarbonisation pathways for road freight. These studies have focused on different aspects. Some have conducted quantitative reviews, such as Meyer (2020). Others have compared alternative fuel and powertrain options or reviewed road transport models without specifically focusing on heavy goods vehicles (HGVs), like Shepherd (2014). There have also been reviews that considered various aspects beyond zero-emission technologies across different timelines for road freight, such as the study by Ghisolfi et al. (2022b). However, these reviews mainly focused on well-to-wheel emissions and did not cover lifecycle emissions, as doing so would extend the scope beyond road freight and the associated energy system.

In light of the above background, the current paper attempts to answer the following two research questions:

- Does the literature converge when it comes to a net-zero pathway and technology share projection for HGV decarbonisation?
- How do various approaches for defining HGV decarbonisation pathways differ from each other and are there any gaps in the comprehensiveness of those approaches?

The research aimed to evaluate various approaches taken in the literature for building HGV decarbonisation pathways and looked to identify any gaps, which if addressed, can improve the alternative technology adoption. Hence the following objectives were set out for the literature review.

- Identify the current status and projection of the technology transition for HGVs towards net-zero by 2050
- Validate if the approaches to technology adoption for HGVs had considered and integrated the aspects around the socio-technical approach, system level view, and consumer utility

The literature was systematically searched, reviewed, and analysed using the method described in the next section. The structure of the paper is as follows: Section 2 is the methodology for the review; Section 3 presents the results and observations; Section 4 presents the analysis; section 5 covers a discussion; and the conclusion is presented in section 6.

2. Method

The methodology adopted was as follows. To determine a likely technology mix in 2050, the requirement was to identify the relevant studies published in the literature. It was important to keep the focus on studies and reports focussed on road freight decarbonisation. Another important aspect was to look for views from multiple stakeholders so as any bias can be accounted for. A multi-level search criterion for relevant journal articles 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’, ‘emission reduction’, ‘emission forecast’ and ‘technology forecast’. An Internet search on reports from government, regulatory and semi-autonomous bodies, independent research organisations, climate/environmental organisations and prominent companies in the energy sector was also carried out using the same search strings. While the overall search and sifting methodology was based on PRISMA guidelines (Moher et al. 2009), the review methodology was based on SALSA framework (Grant and Booth 2009).

Reports and articles were quickly reviewed by examining their titles, abstracts, executive summaries, and conclusions. Based on this rapid review, a selection of reports/articles was made. The selection criteria included a focus on road freight, reports published from 2017 onwards, coverage of emission targets and projections, inclusion of a 2050 technology forecast, and a focus on the UK/EU. The focus on the UK/EU markets was driven by their stated objective of achieving net zero emissions by 2050.

However, studies that had a global perspective but included specific references to either the UK or the EU market were also considered. The search was constrained to the last five years to include recent studies in response to emerging global commitments to decarbonise following the Paris Agreement of 2015. The shortlisted articles/reports were taken up for a systematic review. For each eligible study, the forecasted technology mix was extracted, the basis for those forecasts identified and the results tabulated. The tabulated results enabled the identification of technology solutions, the share of technology solutions by study, the difference in technology share across the different studies, and the basis for the forecasts.

The initial reviews yielded studies around the projection of technology mix and emissions but did not throw much light on working behind those projections. The second round of search and review focused on peer-reviewed articles from scientific journals was hence undertaken. Inputs from the earlier search on technology forecasts and the basis for those forecasts were also factored in. Multi-level search criteria were used with the first level covering synonyms of ‘road freight decarbonisation’, and ‘heavy good vehicle emissions’ and the second level containing synonyms of ‘emission reduction pathway’ and ‘decarbonisation model’. Articles were shortlisted using rapid and scoping reviews based on their focus on heavy goods vehicles, the inclusion of any approach to projection building, and the presence of an adoption pathway. The focus was on studies that shared the working details of a model, either as a case study or through the development of the model itself, as long as the outcome was related to decarbonisation pathways for heavy goods vehicles (HGVs). PESTEL approach (Pan, Chen, and Zhan 2019; Yüksel 2012) was used for categorising the adoption factors. PESTEL (Political, Economic, Sociological, Technological, Environmental and Legal) technique was selected among other options of SWOT (Strengths, Weaknesses, Opportunities, Threats), TAM (Technology Acceptance Model), TIMBER (Technology, Infrastructure, Market, Behaviour, Energy, and Regulation) and Porter five forces due to relevance of factors found from similar studies. Approaches like TAM, for example, are very user-centric and will not be able to accommodate external factors (Pal et al. 2018). Other frameworks like SWOT, TAM and TIMBER did not factor in societal factors or are too broad-based for transport. Thematic analysis involving low and high-level abstraction to generate codes and themes from qualitative data (Clarke and Braun 2017) was carried out to understand and compare the key elements of the emission reduction pathways and projection building. The Figure 2 below captures a summary of the overall review and the analysis approach.

3. Results

As can be seen from Figure 2 above, the literature search was focussed on two key themes, one around finding out the HGV emission forecasts across studies and the other around understanding the working behind the adoption pathways for alternative technologies for HGVs.

3.1. Emission forecasts

The initial literature search focussed on the first research question around HGV technology forecast with UK/EU focus identified 40 separate studies. After taking out reports

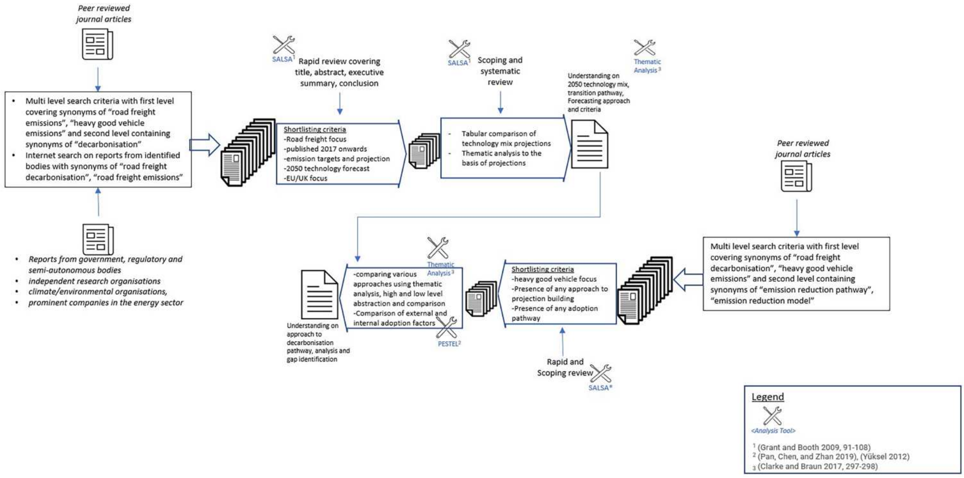


Figure 2. Overall review and analysis approach.

which had shorter horizons than 2050 or were generic to transport and did not cover HGVs specifically, there were 15 reports shortlisted for detailed review as shown in Table 1 below. This included reports like the one from Transport & Energy (Ash, Davies, and Newton 2020) which took a balanced approach where energy requirements were mapped to HGV electrification technologies and accordingly projections were made for the 2050 technology mix.

Of the 15 reports in Table 1, only six of them projected a fully electric technology options for long-haul HGVs for 2050, while remaining others had hybrid, diesel or bio/synthetic fuels also in the fuel mix. Also, for those six reports which projected a fully electric technology option, there was variation on the choice of technology among battery electric, fuel cell electric and catenary electric. Diversity in the technology forecast in Table 1 was reflected in the report by Department for Transport (2022, 56), which highlighted the need for electrification options around the battery, fuel cell, and electric road but made the following statement on the uncertainty of choosing any preferred technology – 'the most cost-effective mix of zero-emission technologies to power HGVs and trains is still unclear'. Further insight was hence sought on the methodology involved behind building such type of projections which involved adoption of new/alternative technologies for HGVs.

3.2. Understanding adoption pathway building

A literature search and review covering research questions around the understanding of technology adoption pathway building yielded 84 articles and reports. Connected Places Catapult's report (2021) examined technology options for HGVs to reach net-zero emissions by 2050. The suggestions were derived from investigations conducted over the past three years and the resulting body of evidence. However, the report did not specifically address the development of technology adoption pathways or emission projections. In certain studies, like the Catapult Energy System (2019), transport models were employed to assist in generating emission projections. A report by Element Energy Limited (2020)

Table 1. 2050 mix and the transition pathway for net-zero for HGVs.

Publisher, year, reference	Region scope	Transition pathway for HGVs	2050 net-zero mix for long-haul HGVs
Transport & Mobility Leuven and IRU 2017	EU	Hybrid	30% of the blend to be second generation biofuel and 40–45% road network charging infrastructure.
Moultak, Lutsey, and Hall 2017	Global (Incl EU specific projections)	None proposed	Plug-in electric, catenary and fuel cell – aided by broader freight sector strategies, including modal shift, logistics improvements, and demand management
Transport & Environment 2018	EU	Increased logistics efficiency and modal shift	FCEV and full electric (battery or e-highways) and synthetic hydrocarbon fuel
Ash, Davies, and Newton 2020	EU	One among Hydrogen, electric and synthetic fuel depending on the scenario, direct electrification for base scenario	Three options were proposed to be feasible. - 100% direct electrification - 50% hydrogen + 50% direct electrification - 50% SHCF + 50% hydrogen
CEPA and Frazer-Nash 2018	UK	Advanced Biofuel (using waste but not crop)	BEV, FCEV, Biofuel
Government Office for Science 2019	UK	Diesel, Gas	BEV, Gas, Diesel
Zemo Partnership 2020	UK	High blend biofuels	Catenary electric, FCEV, hydrogen-based ICE and sustainable diesel and CNG/LBG
Catapult Energy Systems 2019	UK	Natural Gas, plug-in hybrid, high efficiency diesel	BEV, FCEV, Hybrid (Battery, Hydrogen, regen)
Transport & Environment 2020	UK	Modal shift, efficiency measures. Catenary and battery electric cost effective only by late 2020s	Mostly Catenary and BEV
Element Energy Limited 2020	UK	None, Diesel fades by 2040	BEV, FCEV
Climate Change Committee 2020	UK	Efficiency measures (hybridisation, heat recovery, low rolling resistance tyres and use of lighter materials) and biofuels	Plug-in electric, catenary and FCEV
Shell 2021	Global	Natural Gas	BEV, FCEV, Synthetic Fuel, Biodiesel
Connected Places Catapult 2021	UK	None	FCEV and ERS
Department for Transport 2022	UK	None	BEV, ERS, FCEV
European Environment Agency 2022	EU	None	BEV, Catenary

BEV – Battery Electric Vehicle, CEPA – Center for European Policy Analysis, ICE – Internal Combustion Engine, FCEV – Fuel Cell Electric Vehicle, ERS – Electric Road System, TCO – Total Cost of Ownership, IRU – International Road Transport Union.

used a model where factors around operational suitability, Total Cost of Ownership (TCO), vehicle availability, refuelling/charging infrastructure rollout rate and policy support were factored in. The external factors creating multiple adoption trajectories were based on technology and infrastructure readiness. The high-level working of the model was shared in the report. Eighteen such studies were shortlisted for an in-depth review where a similar model-based approach was used. The high-level approach, scope of the model and the external factors impacting adoption considered in those studies are shown in Table 2 below.

All the studies had either specifically or indirectly covered HGVs from the long-haul or intercity freight perspective. For example, Lumbreras et al. (2014) had influencing factors differentiated by mileage and driving mode (rural, urban and highway) for vehicle types (car, buses, light commercial and heavy good vehicles). Similarly, Askin et al. (2015) covered the heavy-duty trucks of class 7 and 8 in the US in scope and referred to their long-haul usage in scope in the Introduction. Further on for the modelling, they used a ton-mile efficiency penalty for any short-haul usage to compare at par with long-haul usage. González Palencia et al. (2020) also narrowed down road freight segment to exclude Light-duty vehicles and referred to long-haul usage in the introduction section of the article.

While most of the studies used some kind model to build emission projections, the models differed a lot in their scope. Also, the factors impacting the adoption were quite varied. Further analysis on all these aspects is covered in the next section.

4. Analysis

While the findings from the initial review confirmed the diversity in the 2050 technology mix forecasts for HGVs. However, this analysis did not provide substantial insights into the underlying mechanisms governing these forecasts. Further review findings, as captured in Table 2 (with supplementary information in Table 1 in Appendix A), yielded some key insights on the model-based approach used for working the forecasts.

The first key insight was around the scope of the models used for pathway building. Some studies focussed on the vehicle as the system (refer to column 'Systems considered' in Table 2) and considered fewer parameters beyond the vehicle. Lajevardi, Axsen, and Crawford (2018, 186–2011) used a vehicle-level physical emission model to estimate CO2 emission. Similarly, there were other emission models like VERSIT, COPERT, MEET, AFLEET, GREET, MOVES, and PHEM which used variables like fuel type, vehicle mass, year built, typical driving behaviour, and sometimes even type of engine and drivetrain characteristics to arrive at vehicle level emission factors (Ligterink, Tavasszy, and de Lange 2012). PHEM (Passenger Car and Heavy-Duty Emission Model) for example is a physical emission model. COPERT (Computer programme to calculate emissions from road transportation) model also estimates emissions for all major air pollutants as well as greenhouse gases produced by various vehicle categories. Similarly, MEET (Methodology for calculating transportation emissions and energy consumption) is used for calculating transportation emissions and energy consumption in heavy-good vehicles, and employs various estimation functions based on speed and predefined parameters for vehicles weighing 3.5–32 tonnes. Though these models can be used build vehicle level emission forecasts, they cannot be used to aggregate vehicle-level outcomes and evaluate the impact of external factors on those forecasts.

The wider scope of models included the energy demand and generation as well besides the vehicle. For example, Palencia et al. (2020) used the Long-range Energy Alternatives Planning system (LEAP) model to find the cost and emission impact of various market diffusion scenarios of alternate powertrains for medium and heavy-duty trucks in Japan. The factors impacting emission and technology projections were around the vehicle (cost of ownership, maintenance, etc) or the energy systems (fuel-specific emissions, cost, etc). Few of the approaches however used models with a wider scope covering vehicles, energy

Table 2. High level details of various studies which had HGV in scope and had used any model for building emission projection for various alternate powertrain and fuel technologies.

Author, year	Approach/model used	Systems considered	External factors causing variation in pathways
Lajevardi, Axsen, and Crawford 2018	Power demand-based CO2 physical emissions model developed using MATLAB	Vehicle	Varied route profiles and payloads
Capros et al. 2012	PRIMES energy system model	Energy Supply and demand systems	Delays in regulation, technology growth/availability and changes in oil price
Ligterink, Tavasszy, and de Lange 2012	Vehicle level mathematical model built on Laurent (polynomial) equation verified using PEMS emissions data	Vehicle	Changes in payload and speed
Lumbreras et al. 2014	Software tool (EmiTRANS)	Vehicle fleet	Policies and measures impacting technology penetration
Mulholland et al. 2018	Mobility Model (MoMo)	Road Freight	Demand, policy
Carrara and Longden 2017	World Induced Technical Change Hybrid (WITCH) model	Road freight, Energy	level of carbon tax, various rates of GDP growth
Catapult Energy Systems 2019	The energy system modelling environment (ESME) and Well to Motion (WtM) model	Energy production and usage	Strictness of regulation, catenary charging availability, level of demand shift (HGV to M/LCV) and level of carbon capture & Storage (CCS) deployment.
Palencia et al. 2020	Long-range Energy Alternatives Planning system (LEAP) and Vehicle Stock turnover model	End use energy system	Assumed dominance of specific technology (FCEV/BEV/HEV) in each scenario
Shafiei et al. 2014	System Dynamics	Energy generation and consumption system for transportation, transportation system (fleet category, stock growth)	Oil price, carbon tax, fuel-supply push and govt incentives
Barisa and Rosa 2018	System Dynamics based DTReM-LV (Dynamic Transport Emission Model for Latvia) model	Energy consumption system, Transport activity system	Policy measures (subsidy and other policies supporting alternative fuel vehicles and technology progress)
Askin et al. 2015	Vehicle choice, stock model, fuel production and energy system model implemented using System Dynamics concept	Fuel production, HGV fleet, Energy source	Oil price and purchase price premium for AFVs, fuel efficiency improvements, fuel tax level
Guerrero de la Peña et al. 2020	System of Systems Engineering (SoSE)	Regional line-haul Freight transportation system	vehicle performance, fuel cost, policy, and infrastructure design parameters variations
Brand, Anable, and Morton 2019a	Transport Energy Air Pollution Model (TEAM)	transport-energy environment system	socio-economic and political developments classified into policy and scenario variables
Shafiei et al. 2017	System Dynamics	Energy supply, prices and consumption, refuelling infrastructure	oil price, carbon tax, vehicle costs and the use of complementary biogas fuel.
Azam et al. 2016	long-range energy alternatives planning (LEAP)	Transport energy consumption	four different policy scenarios supporting adoption of specific fuel type
Plötz et al. 2019	ALADIN (Alternative Automobiles Diffusion and Infrastructure), energy system model PERSEUS-EU	Energy system, Vehicle load profile	Changes in electricity price, fuel price, battery price and CO2 certificate price which impacts energy generation cost,
Bal and Vleugel 2017	Excel based model	Vehicle	Various combinations of diesel/biodiesel and electric drivetrain
Talebian et al. 2018	Custom approach using regression techniques	Transport Energy generation and consumption for all electric trucking	Degree of emission regulation,

systems, and road freight as well. They also considered wider stakeholders and adoption factors accordingly. For example, Pasaoglu et al. (2016) used system dynamics modelling for simulating the future powertrain scenario in the EU light-duty vehicle sector. Various scenarios were created to explore the dynamics of the powertrain transitions under different market and industry variables around oil prices, GDP growth rates, learning rates, purchase subsidies, and EU emission targets. They then arrived at the market share of alternate powertrains (battery electric, hybrid, and fuel cell electric) in 2050 under various scenarios (policy push, market pull, and petroleum persistence). A review paper by Ghisolfi et al. (2022a) indicated in their study that transport models, especially the ones with system-level approaches have been receiving good acceptance in transport research in the recent years.

The second key insight was around the usage of consumer utility attributes in those models. In a literature review of system-level models across transportation, Shepherd (2014) found that many of the alternate fuel vehicle uptake models used a consumer choice model in arriving at the technology adoption. The consumer in this case would be the person or a group taking the purchase decision for the fleet. The fleet could vary from a single truck to large fleet of thousands of trucks. The preference attributes used by a consumer in choosing a technology would depend on the parameters impacting the utility derived from that technology. These consumer preference attributes will thus have a bearing on the technology adoption and thus on the total emissions. Kluschke et al. (2019) highlighted a disregard for consumer preference attributes across studies involving HGV decarbonisation pathway modelling and indicated that the consumer preference attributes play an important role in shaping the demand. Guerrero de la Peña et al. (2020) also highlighted in their study that fleet operational factors around fleet size, miles travelled, utilisation metrics, and the energy costs associated with a new technology adoption are important for HGVs and have been ignored by many literature studies.

Consumer utility-based choice models help to quantify the preferences people apply when making any purchase decision. A refined search for HGV focussed studies that had used a system-level model and also used a consumer choice model yielded eight articles. As can be seen in Table 3 below, when those eight studies were compared for their coverage of consumer preference attributes in the choice models, lots of variations and gaps were observed.

The projected share of various alternative technology options is derived empirically from choice models as was understood from the model working (please refer to column ‘Model processing’ in Table A1 of Appendix A). The technology share thus arrived at is applied to the projected vehicle stock. The emission factors for various technologies are then used to decide the projected emission share of each technology option. External factors influence the future projected value of the preference attributes. For example, a decision to invest in hydrogen refuelling stations can influence the utility derived from fuel cell electric HGVs and can improve their adoption over others. Similarly, financial incentives towards the purchase of new battery electric vehicles can improve their utility. Hence external factors can play a decisive role in the projected utility and thus also influence the emissions associated with the alternative technologies. This was the third key insight generated from the reviews. To gain a further understanding of this, PESTEL categorisation was done to compare all the shortlisted studies on the

Table 3. Consumer preference attributes across studies.

	Shafiei et al. 2014; 127–142	Askin et al. 2015; 1–13	Shafiei et al. 2017; 237–247	Barisa and Rosa 2018, 419–427	Brand, Anable, and Morton 2019a	Guerrero de la Peña et al. 2020; 102354	Greene 2001	Catapult Energy Systems 2019
Vehicle Cost	Y	Y	Y	Y	Y	Y	Y	
Fuel cost	Y		Y	Y				
TCO/ Maintenance-Running cost	Y		Y	Y	Y	Y	Y	Y
Refuelling/ charging availability	Y	Y	Y	Y	Y	Y	Y	
Driving Range	Y		Y		Y		Y	
Payload Capacity						Y	Y	
Vehicle Availability		Y			Y		Y	
Acceleration time/ efficiency						Y	Y	
Refuelling/ charging time		Y			Y	Y		
Hours of Service						Y		

external factors considered in adoption pathway building. The result is summarised in Table 4 below.

The PESTEL categorisation revealed some interesting insights. None of the studies considered the impact of any sociological parameters on the emission pathways. As also indicated by various studies, the role of societal changes had been mostly under-represented in most of the prominent scenario studies (McKinnon, Milne, and Thirkill 2021). Transitions for sustainable mobility will require changes in social norms, values, and lifestyles (European Environment Agency 2022). Hence, while technical, economic, and policy aspects dominated all the approaches, integrating them with sociological aspects was found missing. A socio-technical system results from the alignment of existing technologies, regulations, user patterns, infrastructure, and cultural discourses (Geels 2004). The socio-technical system can be defined as the interaction of physical networks and social networks with both of them following physical and social laws respectively (Van Dam 2009). They consist of deep-structural rules that drive the actions of the actors involved (Turner 1986). The rules are built over time due to shared beliefs, standardised ways of doing things, thumb rules, heuristics, and norms. Transport can hence be considered a socio-technical system consisting of technology, knowledge, artifacts, policies, regulations, markets, cultural meaning, and infrastructure. While there is a need for a system-level approach, it is also important to understand that technological change is related to a range of non-technological factors (Auvinen and Tuominen 2014). The socio-technical approach has been commonly used over past many years for the introduction of new technology (Davis et al. 2014). When considering long-term strategic planning for transport, for example, the adoption and acceptance of new technology, it is therefore apt to adopt a socio-technical approach. If developments in society are excluded when developing policy, society's engagement is lessened. Anable et al. (2012) highlighted that for building

Table 4. PESTEL categorisation of external factors for HGV adoption pathways across studies.

Author, date	Political	Economic	Sociological	Technological	Environmental	Legal	Model Scope
Lajevardi, Axsen, and Crawford 2018				Varied route profiles and payloads			Vehicle
Capros et al. 2012		changes in oil price		technology growth/ availability		Delays in regulation	Energy
Ligterink, Tavasszy, and de Lange 2012				Changes in payload and speed			Vehicle
Lumbreras et al. 2014	Policies and measures						Vehicle
Mulholland et al. 2018	policy				Demand		Energy
Carrara and Longden 2017		level of carbon tax			rates of GDP growth		System
Catapult Energy Systems 2019					level of demand shift (HGV to M/LCV), level of carbon capture & Storage (CCS) deployment, catenary charging availability	Strictness of regulation	Energy
Palencia et al. 2020					share of FCEV/BEV/HEV		Energy
Shafiei et al. 2014	govt incentives, policies around carbon tax	Oil price, carbon tax			fuel-supply push		System
Barisa and Rosa 2018	Policy measures						System
Askin et al. 2015	Policy around fuel tax	Oil price, purchase price premium for AFVs		fuel efficiency improvements			System
Guerrero de la Peña et al. 2020	policy	fuel cost		vehicle performance	infrastructure design parameters variations		System
Brand, Anable, and Morton 2019a					socio-economic and political developments		Energy
Shafiei et al. 2017	policies around carbon tax	oil price, battery cost, vehicle costs		use of complementary biogas fuel.			System
Azam et al. 2016							Energy

(*Continued*)

Table 4. Continued.

Author, date	Political	Economic	Sociological	Technological	Environmental	Legal	Model Scope
	adoption of specific fuel type based on implemented policies						
Author, date	Political	Economic	Sociological	Technological	Environmental	Legal	Model Scope
Plötz et al. 2019		Changes in electricity price, fuel price, battery price and CO2 certificate price					Energy
Bal and Vleugel 2017					Various combinations of diesel/biodiesel and electric drivetrain		Vehicle
Talebian et al. 2018						Degree of emission regulation	Energy

future scenarios involving HGV technology options, we may run the risk of failure if we exclude the multidisciplinary relations between demographic, social, technological, and political developments. A study by Nykvist, Suljada, and Carlsen (2017) also highlighted the need for taking a socio-technical approach to alternative technology adoption for HGVs. Dingil, Rupi, and Esztergár-Kiss (2021) emphasised the use of socio-technical factors for transport planners from a sustainable transport perspective. Hence it will be important for transport planners and policymakers to consider a socio-technical approach as they build adoption pathways for HGVs.

Another point to note from the PESTEL comparison was that the studies which had used a system-level model had broader categories factored in them for the alternate technology adoption. This further corroborates the earlier finding on the need for a system-level model for building adoption pathways.

5. Discussion

A successful transition to net-zero for HGVs would necessitate pathways that are realistic and are based on models which are comprehensive. System-level models have been used for building HGV pathways as can be seen from Table 2 earlier in the report. However, the analysis and comparison revealed gaps in addressing comprehensive consumer preference attributes and in embedding a socio-technical approach to building pathway scenarios. These gaps have been addressed in parts by various researchers. For example, Anderhofstadt and Spinler (2019) used the Delphi methodology which involves taking reliable opinion consensus from a group of experts across two rounds. The report shortlisted 12 scientific papers (from the larger set of 66 papers found to contain purchase decisions for alternate fuel vehicles) and arrived at 34 decision factors specific to purchase of HGVs. The factors were allocated to five categories of costs, socioeconomic factors, environmental factors, daily practicability, and political factors. Such findings can be utilised to arrive at a comprehensive set of consumer preference attributes which can then be applied to the consumer choice models.

Similarly, there are examples from adjacent sectors which can be used for the HGV transportation sector for embedding a socio-technical approach to building pathways. Pregger et al. (2020) embedded a socio-technical approach for building an exploratory approach-based pathway for low emission transition for the energy system for Germany. In their approach the societal context building was done using cross-impact balancing (CIB) methodology and then combined with techno-economic energy modelling. Brand, Anable, and Morton (2019b) used a socio-technical approach in an integrated systems model for building transport electrification scenarios for Scotland. They identified four scenarios from the developed storylines. The scenarios included societal developments around user attitude, lifestyle changes, and consumption behaviour. However, their study was focussed across the overall transport segment but not only on HGVs and it also did not feature a detailed mapping as in the earlier example of the German energy system. The report by Corradi, Sica, and Morone (2023) cited road transport as a socio-technical system and took a system-level view with actors involving consumers, manufacturers, policymakers, and civil society. The study proposed an approach by identifying the three MLP levels and the actors for the socio-technical transition. Their study was however focussed on passenger cars.

Impact of socio-technical aspects on adoption pathways can be understood from examples like platooning and e-commerce. While electrification of HGVs can be achieved using battery, fuel cell, or catenary electric driven trucks, solutions like platooning can bring efficiency improvements and expedite decarbonisation. However, the adoption of platooning can get impacted by various socio-technical aspects. Han, Kawasaki, and Hanaoka (2022) highlighted the benefits of truck platooning but indicated that aspects like discount on tolls encourage more platoonable trucks to join and thus increase the adoption of platooning. Another example of a socio-technical factor could be the next-day delivery option available on e-commerce technology platforms. Research has shown that consumers are willing to wait for longer if the delivery and returns are free (Buldeo Rai, Verlinde, and Macharis 2019). Such potential behaviour changes can have a far-reaching impact on filling some of the technical gaps for electric trucks and thus can improve new technology adoption. Another example can be modal shift. Studies have indicated modal shift as a means for reducing road freight demand and thus reducing costs and emissions (Nocera, Cavallaro, and Irranca Galati 2018). Earlier in the report in Table 1, multiple studies (Transport & Environment 2020; Transport & Environment 2018) have also indicated modal shift as the means to reduce emissions on a pathway to alternate technology adoption. Any changes around demand management and modal shift will need policy interventions, but the adoption of such changes will also need behaviours/societal changes. Hence a socio-technical approach to building pathway can accommodate such measures as well.

The learnings from the review can be applied to the HGV segment. System-level models can be used as the modelling approach. A comprehensive set of consumer preference factors can be identified and integrated to the consumer choice model. External factors can accommodate the socio-technical aspects and hence more realistic pathway scenarios can be developed. The transition pathways thus built would reflect a more realistic technology and emission projections. Modellers, transport planners and policymakers would immensely benefit from the outcomes of such comprehensive models in their decision making. The findings from the literature review thus present an opportunity to propose the conceptual model blocks where the identified gaps can be addressed using the insights generated from the research. While system-level models were found most suitable for building HGV decarbonisation pathways, there were three key steps identified from the model working details (supporting details in Table A1 in Annexure A). Figure 3 below shows those steps and the associated common process blocks.

In Figure 3 above, the areas of identified gaps have been marked in the red circle. Comprehensive preference attributes can be utilised in the circled block for building the consumer choice model as shown against the ‘Allocate the demand’ step. Also, socio-technical aspects can be factored in the last step of ‘Analyse the demand’, where projections for the preference attributes and the impact of the same on the external factors are accommodated. A detailed breakup of relevant blocks thus arrived at is shown as the conceptual model framework in the Figure 4 below.

The framework proposed in Figure 4 above provides a basic, but holistic building blocks for working out decarbonisation pathways for HGVs. The gaps identified from the research have been factored into this framework. While existing research for decarbonisation HGV pathways identified PESTEL based external factors (Table 2), the framework proposes to embed socio-technical approach to the same. For example, existing

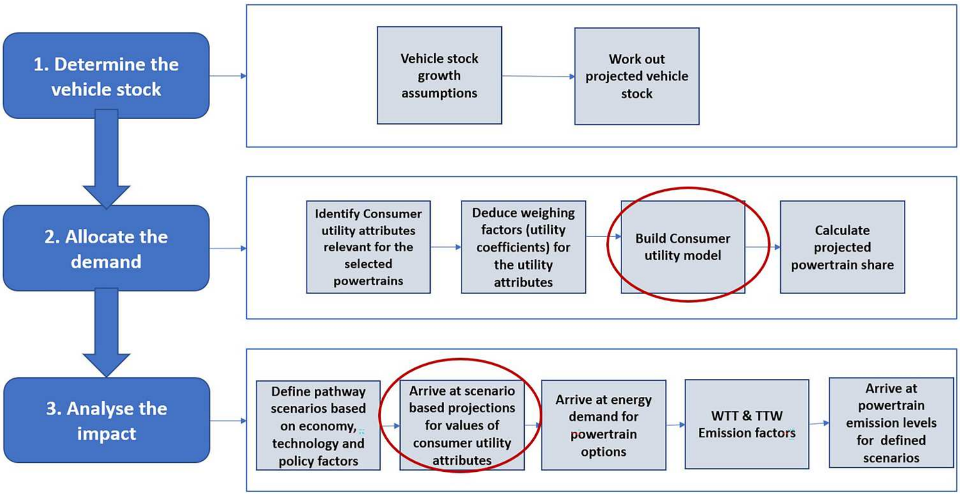
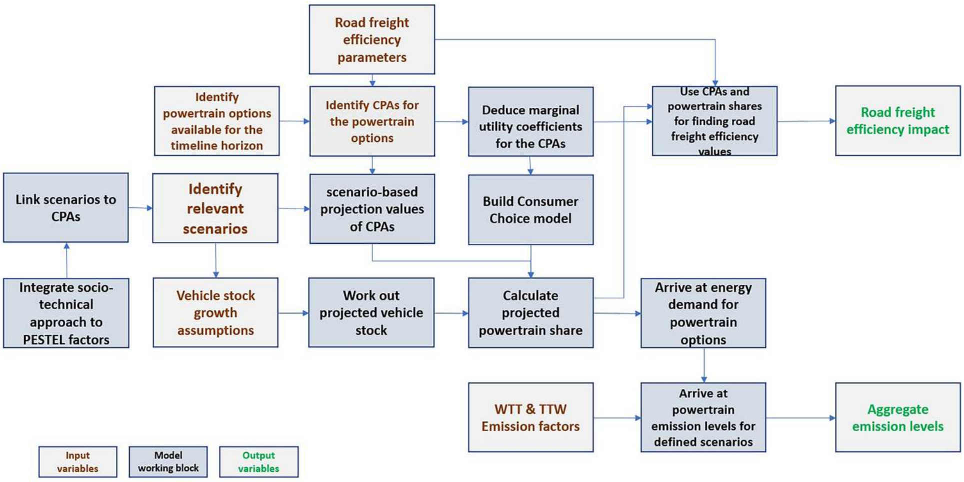


Figure 3. Common process blocks for building decarbonisation pathway.

research points to technology growth or policy impact as existing external factors impacting the pathway, however a user behaviour change (for example, moving out of next-day delivery habit as pointed out earlier in this section) can alter the scenario(s) defined for those factors. Scenario analysis is an important and key part of long-term planning as they help to accommodate for future uncertainty and create internal consistency by taking into consideration the interdependence between demographic, social, technological, economic and political developments (Weimer-Jehle 2006). Hence embedding socio-technical aspect to scenario building will help arrive at a more viable transition pathway. Such scenarios can thus provide a more realistic input to policy makers, researchers, modellers and transport planners.



CPA – Consumer Preference Attribute, PESTEL - Political, Economic, Sociological, Technological, Environmental and Legal, WTT – Well To Wheel, TTW – Tank To Wheel

Figure 4. Process blocks for the holistic framework model.

This framework can be used for embedding qualitative input and arriving at a quantitative output which would be useful for decision-making. The initial part of the framework accommodates external factors (socio-technical approach combined with PESTEL factors) in building the scenario whereas the transport modelling part used a consumer choice model to arrive at quantitative values of emission and road freight efficiency.

The framework proposed however does not prescribe any specific tools or methodologies for identifying the scenarios and linking them to consumer preference attributes. There have been approaches taken up by researchers where qualitative analysis like PESTEL has been followed up by a quantitative analysis. Ortega et al. (2019) talked about Fuzzy cognitive maps (FCM) tool for modelling and analysing interrelations. de Sousa & Castañeda-Ayarza (2022) used a survey approach to assign weight (strength or weakness) to all PESTEL factors which were identified from literature for EV/Hybrid ecosystem in Brazil. Methods like Cross Impact Balancing (CIB) as cited earlier in the report can be used to identify the socio-technical factors by engaging with the system actors. Using CIB technique Pregger et al. (2020) could use the qualitative input from expert opinion and literature review on social context building and convert the same to both qualitative and quantitative future scenario descriptors called Storylines. These Storylines were then related to quantitative scenarios by modelling using a bottom-up energy model. The qualitative factors around impact of culture and society on transition to new technology has been ignored in studies and this can impact the robustness of results of the pathways hence built. The key challenge (which is also a future area of research) is that the premises around such assumptions and their causal relationship to model the parameter are difficult to determine. But the clue can be taken from adjacent sector like Energy where studies using CIB techniques have tried to model the same. A similar approach can also be applied for HGVs using the above proposed framework. This can, however, be a subject of future research by transport modellers.

6. Conclusions

Lack of consensus in technology forecast and the working of decarbonisation pathways for HGVs were investigated in this review report. Analysis and comparison of relevant research literature threw light on the gaps around the lack of system-level models, comprehensiveness of utility attributes, and embedding of socio-technical factors to the adoption pathways. A conceptual framework for building decarbonisation pathways was then proposed, where learnings from other industry/vehicles segments can be used to fill the gaps identified from review.

The findings from this research present a different way of looking at road freight transport decarbonisation from a holistic perspective. Ghisolfi et al. (2022b) had done a literature review of the system-level models for road freight decarbonisation and indicated a lack of comprehensive models. They indicated that in absence of any model equations and empirical rigour in the model, the time horizon perspective of any assessment was not clear. The proposed framework in this report leverages a system-level model and integrates external (socio-technical aligned PESTEL) and internal (preference attributes impacting the utility derived from the alternative technology) adoption factors.

The findings and the conceptual framework proposed in this review report can enable transport planners to capture qualitative insights (socio-technical factors, consumer preference factors) and leverage them for a quantitative output (emission and technology share projection). Such outcomes can be very useful for policymakers and other stakeholders and help them with the key decisions to be taken towards building net-zero adoption pathways for HGVs for 2050.

The research undertaken was limited to a literature search and any field exercise around surveys or expert-led workshops was not conducted. The findings and the proposed framework however present ample research opportunities around building the comprehensive model and applying some of the learning from adjacent segments to the model. For example, a comprehensive preference attributes for HGVs, validated by research and expert opinions, can be embedded using a consumer choice model. Identification of MLP levels and actors specific to the road freight segment can be another research area. Applying approaches like CIB for road freight and integrating them into a comprehensive model built using the proposed framework can also be taken up as a future research work.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Appendix A

Table A1. High level details of transport model used by various studies which had HGV for building emission projection for various alternate powertrain and fuel technologies.

Author, year	Model input	Model processing	Model output
Lajevardi, Axsen, and Crawford 2018	Vehicle parameters (frontal area of vehicle, rolling resistance factor, aerodynamic drag coefficient, and weight), drive cycles data	Vehicle parameters and environment parameters (friction, aerodynamics, acceleration, and gravitational forces) are used to arrive at power demand which further leads to fuel consumption	Fuel consumption rate, CO2 emissions
Capros et al. 2012	Energy demand	Market equilibrium based on energy produced at minimum require cost, consumers deriving maximum utility by choosing the optimum cost option and energy mix being arrived based on cost of clean energy	Amount of energy produced, energy prices
Ligterink, Tavasszy, and de Lange 2012	Payload, velocity, fuel type	Refined Laurent polynomial model with lowest residual variation to arrive at emission per ton of weight	Emission
Lumbreras et al. 2014	Vehicle life curves, vehicle distribution by age, mileage, fuel and maximum weight	Using occupancy rates and load factors, projected vehicles for future years are worked out. Model output was fed to COPERT4 for estimating emissions	Vehicle number and mileages
Mulholland et al. 2018	Road freight stock, activity	Log multivariate linear regression model to project future national trends in road freight activity. Demand and policy driven	Energy consumption, well-to-wheel emissions
Carrara and Longden 2017	GDP, population, resource use, climate policies	Capital and labour are combined with each other and then with energy services to produce output which is consumed by transportation sector. Basis the consumption, cost is calculated. Technology mix is arrived at using cost optimisation	Road freight stock and emission projections

(*Continued*)

Table A1. Continued.

Author, year	Model input	Model processing	Model output
Catapult Energy Systems 2019	Vehicle cost model and projection	Well to Motion (WtM) model was used for developing a prototype Freight model which used TCO based choice model for arriving at technology mix. ESME model then gave an energy system implication and effect of different scenarios based on regulation, catenary charging availability, level of demand shift and carbon capture & Storage (CCS).	Emissions, costs, energy use projections to 2050
Palencia et al. 2020	New vehicle sales, emission factors, fuel consumption, cost of ownership, vehicle survival rate, annual mileage	Powertrain share assumed for various scenarios to arrive at aggregate energy consumption and emissions	Impact of electric drivetrains on CO2 emissions and cost
Shafiei et al. 2014	Vehicle mileage, vehicle purchase and maintenance costs, emission factors, range and economy for various fuels, GDP + population growth (exogenous)	Based on external factors' influenced scenarios, fuel generation is estimated. Vehicle stock is estimated based on GDP. Consumer choice model decided technology mix share in the stock. Total fuel consumption and the emissions are thus arrived at	projections on fuel demand, associated costs, vehicle stock and emissions
Barisa and Rosa 2018	Fuel specific economy and emission factors, annual mileages and utilisation, fuel price, capital costs and maintenance costs	GDP based vehicle stock forecast, choice model (based on cost factors like TCO, inconvenience cost) derived technology distribution, Energy demand modelling based on fuel type requirement and finally CO2 emission modelling based on the amount of fuel and emission factors of fuel types	Vehicle stock projection and emission
Askin et al. 2015	Vehicle stock growth and ton-miles growth, truck scrap rates, vehicle cost projection, penalty cost for range and refuelling limitation, existing refuelling infrastructure distribution, payback period, infrastructure growth rates	The model uses a vehicle sub-model, a fuel production sub-model, and an energy supply sub-model. The sub-models exchange price and demand information. The fuel module calculates the cost and energy source mix of transportation fuels, given fuel demand from the vehicle model and energy source costs from the energy source sub-model	HDV stock and consumption projection by fuel type by 2050
Guerrero de la Peña et al. 2020	Future policies, economic factors, and availability of fuelling and charging infrastructure	Technology mix protected using choice model. Adoption parameters around vehicle performance parameters, fuel costs, economic incentives, and fuelling and charging infrastructure considerations.	Projection for Cumulative CO2 emissions and powertrain adoption
Brand, Anable, and Morton 2019a	Transport and vehicle fleet growth projections based on scenario variables around GDP/capita and population	Transport demand model (TDM) projects demand, vehicle stock model (VSM) allocates demand to vehicle, Direct Energy use and Emissions Model (DEEM)	Travel demand, energy demand, annual and cumulative life cycle emissions, env impacts and external costs

(*Continued*)

Table A1. Continued.

Author, year	Model input	Model processing	Model output
	growths and elasticities for population and income.	helps deduce energy demand, Consumer choice model derives projected technology share. and Life Cycle and Environmental Impacts Model (LCEIM) arrives at emissions.	
Shafiei et al. 2017	energy prices, infrastructure costs, vehicle choice attribute related values (associated costs, range, refuelling availability)	Scenario based technology paths are chosen, for those paths, choice model is used to derive technology share based on attributes of vehicle associated cost, range and refuelling availability. Technology share helps determines fuel demand and associated emissions	Technology mix, fuel demand, emission projections for different scenarios
Azam et al. 2016	Number of registered vehicles, annual mileage, load factor, fuel economy, emission factors	Aims to find energy requirement, environmental impact and their social cost, the model use base year data (2012) and projects till a future year (2040). Activity level, energy intensity and emission factors are used to arrive at consumption	Energy consumption and emission forecast for all scenarios
Plötz et al. 2019	Cost of ownership of different technology (Diesel, BEV, trolly) from driving behaviour, annual mileage, vehicle sales data, freight transport growth projection, projected fuel consumption for diesel trucks	Market penetration of alternate powertrain is used to arrive at energy demand. For HDV, annual mileage and assumed overhead charging infrastructure coverage are used to arrive at power demand. Investment in power generation is deduced from demand. Indirect CO2 emissions is arrived from the energy generation.	Market diffusion of alternative fuel vehicles (HDV, LDV) powered with electricity. Electricity generation with and without trolley trucks (catenary hybrid HDV), GHG emissions for various scenarios
Bal and Vleugel 2017	Route distance, transport mode, engine technology, fuel type, electricity composition (green/grey) and fuel consumption and emission factor tables	Distance and fuel consumption data is used to calculate average fuel consumption for various fuel options. Emission factors are then used to arrive at vehicle level emissions	GHG emissions for predefined route for various biodiesel/ diesel and eclectic combinations
Talebian et al. 2018	vehicle use-intensity (kilometres travelled per vehicle annually), number of new vehicles, GDP/capita and the vehicle stock from 2000 to 2014. Tank-to-wheel and well-to-tank emissions from NRCan database	Analysis was based on GDP projections, and forecasts of electricity and natural gas production and demand. First vehicle stock projection is arrived at and then using fuel GHG emission values, the GHG emission for the freight segment (LDT, MDT, HDT) is arrived at	GHG emissions projections from road freight transport in 2040, energy generation requirement in 2040 to support all electric trucking