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REVIEW ARTICLE

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Modeling the dynamics of freight transport decarbonization: A review and research agenda

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ABSTRACT

The existence of time-bound targets for decarbonization of freight transport raises the need for knowledge of the dynamic behavior of the system. However, little is known about the factors that determine these dynamics, conceptually and empirically. We argue that research is needed to allow substantiated claims about the feasibility of decarbonization policies. We propose a transition theory-inspired framing of the problem, which considers the dynamics of new technologies as alternatives to the established markets, institutions and regulations. We review the relevant freight modeling research literature and develop recommendations for research. While the literature does contain a small set of studies that address the dynamic behavior of the freight system, the relevant phenomena are only partially considered and empirical evidence is scant. We recommend the use of a multi-level dynamic perspective, which includes a long-term view beyond the time horizons considered today. Most importantly, new empirical modeling work is needed to develop valid dynamic models of the relevant decisions taken by all freight transport system stakeholders.

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Decarbonization; dynamic models; freight transport system; logistics

1. Introduction

The freight transport sector is responsible for around 40% of the greenhouse gas emissions of global transport (ITF, 2023). As freight transport demand is strongly tied to economic growth, the business-as-usual prospect is that this share will continue to grow in the future. Spurred by the 2015 Paris agreement, time-limited targets have been set to reduce transport emissions for the transport sector. Europe has made a pledge to arrive at a 90% reduction of emissions in 2050, compared to 1990, and a 55% reduction by 2030 (European Commission, 2021). Current ambitions for carbon reduction in freight transport are insufficient, allowing a 25% growth of emissions between 2024 and 2050, while an 80% reduction would be needed to achieve the 2050 targets. Only high ambition scenarios would help to arrive at the 80% reduction (ITF, 2023). This would involve a strong internalization of external costs to curb demand, and various organizational and technological measures. The 80% goal could only be achieved *if* the necessary measures can be successfully implemented in time. The later the carbon reduction sets in, the more radical the changes will need to be to stay within available carbon budgets. The timing of policies is of critical importance. Figure 1 illustrates alternative decarbonization trajectories depending on policy timing. The graph shows global CO_2 emissions over time under different mitigation scenarios targeting a 2 °C limit. Early policy action enables gradual emission reductions (blue line), while delayed action requires increasingly abrupt transitions (red lines). This demonstrates that postponing freight decarbonization compresses the timeframe for achieving targets, requiring more radical rates of change.

The first and arguably most important study that emphasized the importance of dynamics of sustainability policies was the Club of Rome's report Limits to Growth (Meadows et al., 1972). Although the study was criticized for its lack of empirical validation, it provided numbers to produce a tangible narrative and motivated global leaders to act. One of the key success factors was its focus on the dynamic behavior of the system, i.e. the system's development over time. While one could have assumed that measures will be successful at some point in the future, this was insufficient to understand their impact on the moments in time at which critical thresholds of unsustainability would be exceeded. Inspired by the Club of Rome study and more recent research like Sovacool (2016), we address the issue "how long will it take?" for freight transport decarbonization, with a special focus on the quantitative models needed to predict time-to-decarbonization of policies.

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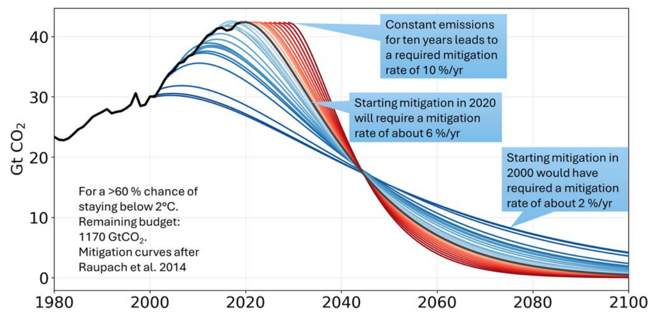

Figure 1. Alternative dynamic decarbonization pathways showing how delayed policy action necessitates increasingly radical emission reduction rates to remain within carbon budgets (Source: Robbie Andrew, under CC license, see https://folk.universitetetioslo.no/roberan/t/global_mitigation_curves.shtml).

We position the paper within the same realm as the Limits to Growth study: to predict the state of the world several decades ahead, an empirically valid predictive model is needed of the freight transport system, spanning a country, a region, or the world, and including all activity from all supply chains that traverse this area. The types of models that can deliver such insights are descriptive in nature as opposed to normative: they show the world as-is (or, more accurately, as would-be in the future), as opposed to as it should be. These models are typically validated empirically by testing their capability to reproduce observed flows. Prediction then happens by developing what-if scenarios for the future, assuming that the main drivers of behavior remain as valid as they were in the base year. We note that, for the development of descriptive models, optimization models may be important—many behavioral principles behind descriptive models rest on notions of optimality (e.g. utility-maximizing boundedly rational behavior of decision makers). Also, optimization models may provide a view into possible behavior of decision-making agents under various assumptions, in isolation or under mutual dependence. Generally, however, behavioral validity of the resulting optimal decisions in these models is not an objective in itself and is seldom evaluated empirically. Therefore, we limit ourselves to those models which aim explicitly at descriptive or predictive empirical validity, for an entire population of agents inside a pre-defined geographical area - often classified also as simulation models—and exclude optimization models from our scope.

In summary, the paper revolves around the question "how to quantitatively predict the dynamics of decarbonization of the freight transport system?" The paper is structured as follows. Section 2 conceptualizes the dynamics of the freight transport system from the perspective of decarbonization objectives. Section 3 focuses on the methods applied to model freight transport system dynamics, building on the existing literature, and identifies gaps in the literature that are relevant for decarbonization policy. Section 4 aggregates these gaps and, from the main topics emerging, forms a research agenda. We conclude the paper in Section 5.

2. Framing the problem: dynamics of freight transport decarbonization

Strategies for the decarbonization of the freight transport system are the following (ALICE, 2019; McKinnon, 2018): (1) reducing demand, (2) shifting modes of transport, (3) improving asset utilization, (4) increasing energy efficiency, and (5) reducing the carbon content of energy. All these changes involve strong system dynamics. Demand reduction is only possible if consumption patterns change over time, not just those of consumers, but also those of the entire manufacturing industry. Organizational changes include changing the mode of transport and adjusting logistics processes through consolidation of flows, so that fewer trucks are needed to move the same amount of freight. The main technological change needed involves using less energy and cleaner energy. Implementing these strategies is not straightforward. Decisions about consumption, logistics organization, and use of technologies are taken by consumers and firms, who have little incentive to adapt their behavior, as mitigation of climate effects does not provide direct business value or cost reduction. These climate effects are external to the market. Much will come down to governments using infrastructural, regulatory, and financial instruments (taxation and subsidies) to nudge decision makers. For institutional and political reasons, such measures take a long time to prepare and implement. Even when implemented, there is a question as to whether they will have the desired effect. While regulatory measures have a direct influence as they concern the output of decisions, infrastructural and financial measures concern inputs and therefore have a less certain impact. An illustrative example is the decades-long subsidy of combined transport in Europe, ruled by the European Court of Auditors as ineffective (European Court of Auditors, 2023). Nassar et al. (2023) show how delayed infrastructure policy can have an impact on reaching modal shift targets. Clearly, policy instruments targeted at change need time to achieve impacts and can also eventually miss the mark.

An external factor that complicates efforts to foresee how change will happen over time is the presence of uncertain and sometimes counterproductive contextual developments (Nassar et al., 2023). Economic growth generally does not play out in the favor of decarbonization targets - although during the Covid-19 pandemic, effects of reduced economic activity on emissions were visible. The energy transition largely develops independently from the transport sector as it depends on all sectors of the economy. It will strongly impact the rate of change for transport, however, as it determines availability and prices of decarbonization technologies. A next important development is digitalization of information in supply chains. One can see the effect of e-commerce platforms that have spurred consumption and fragmented flows by supporting customization of logistics services. Platforms have also had positive effects as electronic freight markets have allowed consolidation of flows, making logistics more efficient. Over the longer term, digitalization will further transform logistics processes as it will promote distributed handling of data (Blockchain) and further consolidation of flows through efficient handling and system-optimized operations (Physical Internet)—see Tavasszy and Quak (2023). The dynamics of the freight system will be strongly affected. Digital data and their automated handling will drive down decision cycle times and even allow decision automation, supported by AI and digital twins. While cyberthreats exist and disturbances in the digital world will propagate more quickly, digitalized logistics also allows more flexibility and robustness, and thus faster response. In the extreme case, logistics execution may become so flexible and responsive that it will obviate the need for planning, removing an entire layer of decisions. Other external factors include geopolitics and population growth—these have a clear relation to freight transport emissions but will generally fall outside the realm of transport policy. As these external factors can have a strong impact and are fraught with uncertainty, we argue that their impact on the dynamics of decarbonization should be understood and considered in transport policy.

The goal of achieving decarbonization within this century requires analysis to address the pathway of change over a timescale well beyond the common horizon for strategic transport forecasts of 25 years. Achieving decarbonization at a scale to meet the target of a 2 °C global temperature rise compared to pre-industrial levels requires not only a very large-scale reduction in GHG emissions, but also a change in freight transport and logistics systems to a "carbon neutral" system, i.e. close to complete removal of GHG emissions. This change is structural and in economic language "non-marginal." Such a radical change in the global freight system involves long-term decisions. A relevant approach is the idea of sustainability transitions (Köhler et al., 2019). Transition theory is an emerging field in science which has framed the problem of the complexity of managing system-level changes, inspired by notions of institutional and evolutionary economics (Köhler et al., 2019). A key understanding from the transitions literature on sustainable innovation is that system change is not linear. Rather, it is a co-evolutionary process between all the elements of the logistics ("socio-technical" in the language of transitions thinking) system. The analytical framework used is the "multi-level perspective on transitions" (Grin et al., 2010). There are three elements: a social environment or "landscape" which changes very slowly and feeds social, political, economic, environmental, etc. pressures into a system (such as freight transport). There is a "regime," the established transport system based on globalized supply chains using fossil fuel energy. This is coming under pressure to decarbonize but has inertia through long-term infrastructure and system investments and an established business model. Alternatives then are invented (alternative fuels or business models such as decentralization of markets or emissions trading schemes) which are initially applied in "niches." These niches are ideas that are tried in particularly favorable social and market contexts. Under favorable conditions, these niches may expand and develop and influence or replace the regime, as illustrated in Figure 2. Such transitions are slow processes, where the development of a niche into a new regime may take 50 years.

Such a transition is not a series of separate phases, but a process where current options are dependent upon previous decisions. The implication of this is that current decisions influence the possible range of future scenarios. In other words, the short, medium, and long terms may be linked, and medium- and long-term analysis must take account of the (non-linear) implications of short-term decisions. The elements of supply chains must be directed toward decarbonized systems and co-evolve with technologies, markets, and demand. This path dependency means that forward-looking analysis must proceed from the current system state, propose possible mechanisms of change, and work through the mechanisms step-by-step into the future. To structure the analysis, it is useful to consider the different types of decisions that would need to be made to achieve a transition pathway to a decarbonized logistics system, considering the timescales for different types of decisions.

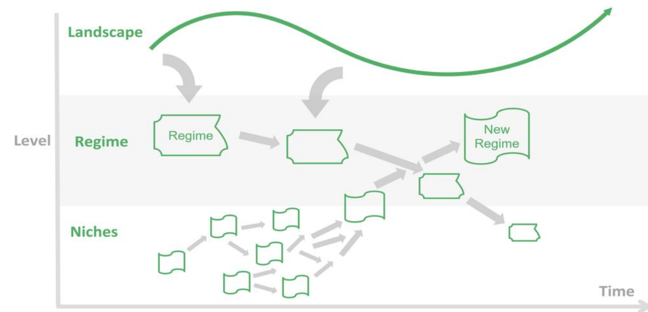

Figure 2. Multi-level perspective of socio-technical transitions such as freight transport, describing how the interplay of innovation niches with prevalent regimes and the societal landscape influences change over time. Figure by authors based on Geels (2002).

Logistics firms take operational decisions in close to real time but can react to shocks such as changes in demand and freight rates due to e.g. accidents (blockage of the Suez Canal), political conflicts (Russia-Ukraine war), climate impacts (droughts, floods, volcanic eruptions) by redeploying resources or changing capacities (e.g. in shipping slow steaming or mothballing fleets). If there are more positive windows of opportunity, it is possible to reconsider investments and delay the retirement of assets. Such processes take place within the current "Regime" (current practices, technologies, and institutional structures, see Grin et al., 2010). This short-term timescale is over the next few years.

In road freight, goods vehicles have an average lifetime of roughly 10 years, and firms must look ahead over a medium term of a 10–15-year period.[1] This is also the timeframe in which environmental policy is developed and enacted. Emissions standards in the EU are defined until 2030/2035. In this timescale, it is possible to react to planned policy measures, e.g. the abandonment of fossil fuels. This will require the adoption of different fuels, which implies new power trains and a new energy infrastructure. The development of vehicles with alternative power trains and the concomitant institutions (certification, safety procedures in refueling, insurance) can be enacted in this time frame. This co-evolution between vehicles, energy infrastructure, and logistics infrastructure, all of which involve strategic

[1]In the EU for example, the road freight fleet had about 4 million vehicles in 2024, and new truck sales of around 360.000 (Eurostat, 2025; ICCT, 2025).

investment decisions in this medium time frame. If investment decisions are made which address all these elements, it is possible for there to be a rapid development, and in particular, uptake of the new technologies and systems.

Beyond the medium term, the long term is the time frame in which the change to a radically different, carbon-neutral system is enacted. This long term involves the working through of strategic investments to cover the whole of global logistics, including the change in logistics structures through digitalization as well as decarbonization. In addition to new fuels and energy infrastructures, it includes changes in the structure of demand (e.g. the production of synthetic food instead of meat, changes in behavior to take account of heat waves or forest fires) and in production (3D printing, open networked logistics systems). This is also the timescale in which societal processes can act or react to changing social, political, and climate environments. New governance structures and institutions can be developed and implemented in society at all geographical and political levels, local, regional, national, international, and global. In terms of understanding system change, historical data indicates that this is of the order of a 50-year timescale of change in economic systems (so-called Kondratiev waves from Freeman & Louçã, 2001) and a possible sustainability transition. In terms of policy action and investment decisions, the understanding of system change as a co-evolutionary process has a vital implication. Like climate change mitigation, short term decisions in a path dependent system determine the long-term outcomes by limiting the range of future choices. These timescales of change, illustrated in Figure 3, show fixed and variable factors at short-term (years), medium-term (10–40 years), and long-term (40+ years) horizons.

We next review the literature on modeling methods for assessing freight transport system change and policy in these three time scales. Our literature search included the following steps. Firstly, we formulated a search string to match the problem statement. The string used was ("freight transport*" AND (decarbon* OR sustain* OR green) AND dynamic AND model* NOT optimization). Based on this, we identified the initial corpus by systematic search on Scopus and Google Scholar. The initial search resulted in 641 entries. Further screening of titles and abstracts, close reading of articles and snowballing led to a final set of 23 papers. This remaining set formed the basis of the below synthesis of models that aim to provide empirically validated descriptive models of the dynamics of freight transport demand.

3. Models of dynamics: what and how

In this paper, the term dynamics refers to the study of the forces acting on a system and the system's temporal evolution. In our case, this includes, e.g. the influence of political or corporate decisions, and the freight transports system's response to them, over time. Practically, this means that there need to be dependent variables which are a function of time, and that the present state of the system needs to be a function of previous states. Timescales can be different and depend on the context and type of the decision. Since this paper focuses on decarbonization of freight transport, timescales spanning from one or a few years to several decades are most relevant.

An important cause for the dynamic behavior of a system is the regular review of decisions taken by the different agents inside the system, with different time horizons. Typically, strategic problems will be addressed once or a few times in the lifetime of a company, concerning, e.g. the objectives, strategy, and structure of the company. Derived from these, investment decisions will return every couple of years, depending on the nature of the assets in question. In a logistics context, these include investments in network structures, real estate, vehicles, or strategic collaborations. Planning and scheduling decisions have a higher review frequency, typically less than a year (monthly, weekly, daily, hourly), depending on the flexibility of the resources considered. Operational decisions include allocation of resources to match momentary demand and supply, in a transport, inventory, or manufacturing context, with decisions being reviewed at very narrow time intervals. A systematic overview of these decisions, 48 in total, was provided by Langevin and Riopel (2005). They concern the following main areas (Table 1).

Given the time scales sketched above from a transition management perspective, most of these decisions will be classified as "short term" as only the strategic planning decisions and large investments will be revisited less frequently than once in a decade. Dynamic models can be developed for each of these sub-decisions in isolation, in relation to other decisions, or within the full logistics context of operational, tactical, and strategic decisions. The decisions under the heading of "*Transport*" in the table above relate to the following:

- Transport modes
- Type of haulage, e.g. own account or third-party
- Transport fleet mix
- Degree of consolidation
- Carriers to hire
- Assignment of customers to vehicles
- Vehicle routing and scheduling
- Vehicle load plans

The frequencies with which these decisions will be renewed vary widely. Although literature is lacking on the subject, the list has been roughly sorted from low to high frequency. While decisions on outsourcing transport or mode of transport are often only taken once in the lifetime of a company, carrier selection can be a process returning every year, vehicle load plans can change daily, and routing decisions can vary by minute.

Below, we summarize the literature about the descriptive modeling (as opposed to prescriptive modeling, focusing on optimization) of freight transport systems, where we note which decisions are considered. Roughly, we find that short- and medium-term model implementations dominate, and the few long-term focused, empirical models are not useful for our purposes as they lack the necessary policy levers.

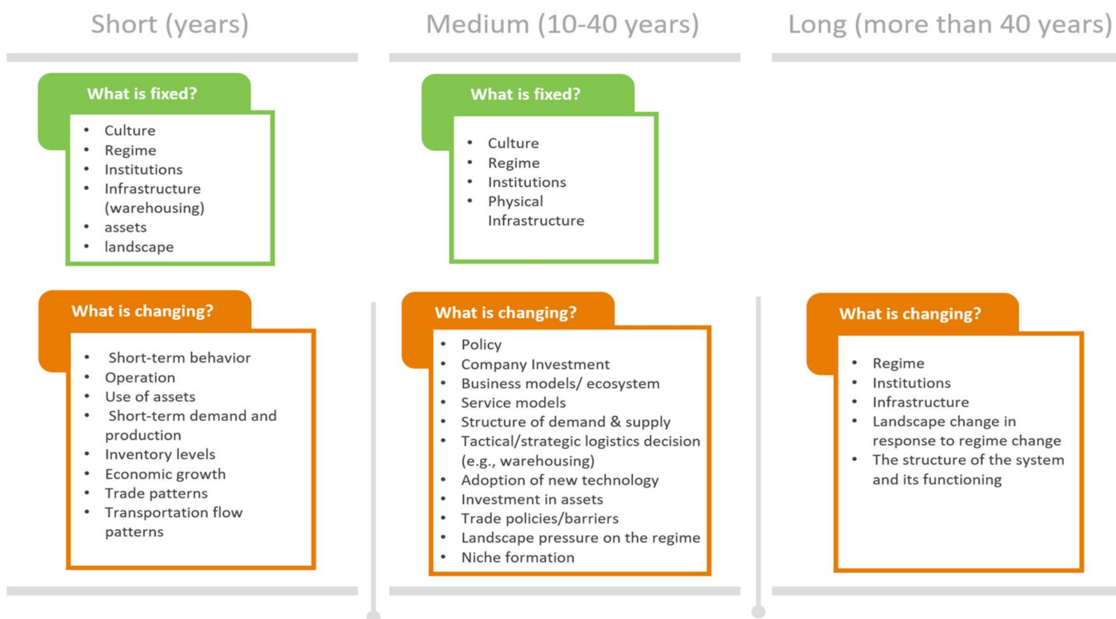

Figure 3. Fixed and variable factors of freight transport system change across short-term, medium-term, and long-term horizons. Figure by authors.

Table 1. Decision areas in logistics (after Langevin & Riopel, 2005).

Decision area	Representative questions
Strategic planning	Which products, customers, service levels?
Physical facility network	Which nodes, network structure, partners?
Communication and information network	Which digital facilities?
Demand forecasting	How to look ahead to minimize lost sales?
Inventory management	How to control stocks, where and when?
Production	When to produce which batches and for whom?
Procurement and supply management	How to source material flows?
Transport	Which organization and means of transport?
Product packaging	Which physical protection, presentation?
Material handling	Which equipment and loads?
Warehousing	How to physically organize storage points?
Order processing	How to record and follow through orders?

3.1. Short-term models

Short-term dynamic models in our context relate to changes that happen within a timeframe in the order of years. As shown above, typical phenomena modeled here include short-term behavioral change driven by operational and tactical decisions, including deployment of assets, changes in production, consumption, trade, and transport decision-making. Non-linear change over time, or higher order dynamics, are due to natural seasons and business cycles, responses to disruptions, and mutually reinforcing or self-dampening processes.

Methods used for short-term freight transport modeling include time-partitioned static models, linear and nonlinear time series models (Li et al., 2018; Lim et al., 2019), higher-order dynamics models (Hutters & Mendel, 2025), and process simulations (Crainic et al., 2018; Dragović et al., 2017). Time-definite and time-series models will provide representations of the system at different points in time, but the structural dependence or causal relation between states will not be explicit, and at most visible through statistical or econometric modeling (Chan et al., 2019; Ke et al., 2024). Important areas in modeling with a rich tradition in description of dynamics of the freight system include volumes and rates in (mostly maritime and air) freight shipping markets (Chan et al., 2019; Ke et al., 2024; Li et al., 2018; Lim et al., 2019) and models of spatial and sectoral interactions (Balster & Friedrich, 2019; Boonpanya & Masui, 2021; Koike & Kawamoto, 2006; Tavasszy et al., 2016; Yu, 2018; Zhu et al., 2020). The former focuses mostly on time-series econometrics, while the latter also supports dynamic input-output and spatial-economic equilibrium modeling. Since the COVID-19 disruption, new research has emerged to understand the dynamics of response to the pandemic (Karam et al., 2022; Loske, 2020; Ng et al., 2022). Higher-order dynamic models of supply chains exist that allow an economic interpretation of supply chain actors and their behavior, which determine endogenous and exogenous dynamics (Mendel). The techniques used here are inspired by dynamic systems control theory and not necessarily constrained to short-term applications - they can also be applied for mid-term economic cycles and long-term technological cycles. Data in these areas for freight transport is typically scant, however. Application of these models using data produced by the other research streams, for example, dynamic input-output models or econometric time series models, could be worthwhile to explore. In simulation models (discrete event, agent-based simulations, or hybrid forms), the structural interactions between agents become explicit in time. The literature is highly method-oriented, with empirical applications used for illustration purposes and relevant for business users as well as public policy makers (Anand et al., 2021; Crainic et al., 2018; Dragović et al., 2017; Nuzzolo et al., 2018).

The above dynamic models are relevant to study how systems develop in an undisturbed situation or respond to disruptions within the existing regimes, i.e. under the existing yearly or multi-year contracts, and existing governance arrangements between actors to respond. Demand, supply, prices, or volumes will be allowed to vary within these models as a result of (explicit or implicit) decisions on consumption, production, trade, inventories, and transport processes. This provides the models with a rich background to predict the short-term dynamic behavior of freight systems. Although they will not address decisions with a lower frequency, they will have an impact on these decisions by predicting changes in the costs of deployment of resources, as well as the flows and stocks of resources in operation. This is important input for the design and timing of longer-term investments in fleets, infrastructures, and supporting organizational arrangements. The short-term models primarily address changes in the modal split of transport and improving asset utilization as a consequence of operational and tactical decisions within the supply chain. In general, they do not address the dynamics of technological change for decarbonization. However, some short-term transport models are used to optimize routing for alternative fuels, given a low carbon technology, especially for battery vehicles. What is limited in these short timescale analyses is a detailed representation of the decision-making processes. These include adapting to market conditions through, e.g. new business models or the adoption of new operating patterns to adapt to the limited range characteristics of low carbon fuels. A part of such decision making is the attitude to new fuel infrastructures and refueling/charging procedures. With respect to the five decarbonization strategies listed by McKinnon (2018), the short-term models primarily target "shifting modes of transport" and "improving asset utilization."

3.2. Medium-term models

Medium-term dynamics models consider changes with time constants of around one or a few decades and include changes related to the landscape's pressure on the regime as well as how niches enter the regime. While the regime, with its cultures, institutions, and physical infrastructure, is assumed to be fixed, medium-term dynamics include the response to changes in policies. The medium term also includes the dynamics of strategic and tactical logistics decisions such as the adoption of new technology, service models, and operational strategies, as well as responses to structural changes in demand and supply. The pace of medium-term dynamics stems from the rate of change of physical capital (vehicles, equipment) and the rate of change of behavior of the actors (adoption of new technologies, modes, and concepts).

In the literature, we mainly find two approaches used for medium-term modeling: the fleet- or mode-centred or the Actor-centered. At the core of the fleet- or mode-centred approach are stocks of vehicles, technical capital, or demand distributed over different modes. Modeling methods such as bottom-up techno-economic fleet-based models (Fridstrøm, 2017; Hao et al., 2015; Mulholland et al., 2018; Xue et al., 2023; Yan et al., 2021), general or partial equilibrium models (Karkatsoulis et al., 2017; Salvucci et al., 2019; Siskos et al., 2018), mode choice modeling (Ferrari, 2014), agent-based modeling (Spangher et al., 2019), and system dynamics (Ghisolfi et al., 2024; Liu et al., 2019; Nassar et al., 2023; Sim, 2017) are used. At each timestep, the stocks are updated. For example, in vehicle stocks, vehicles are depreciated, and new vehicles of different types are added to replace them and to meet an (often) increasing demand. The decisions on which shares of the different vehicle types are to be added (which mode changes are to be realized) are based on different principles, e.g. cost-minimizing or price equilibrium calculations. Different factors, such as policies, taxes, market shares, and the cost and availability of different technologies, influence the changes in the stocks.

The principle is similar for mode shift studies, where the transition between different mode types is modeled at each time step, e.g. using substitution elasticities. In most models, the factors that influence the distribution of new vehicles or modes are provided as exogenously estimated time series (see, e.g. Salvucci et al., 2019; Spangher et al., 2019; Xue et al., 2023; Yan et al., 2021). The input time series are projections based on literature studies and/or historical data, and the current states of the stocks are not taken into account when determining them, which leads to the inputs not being consistent with the development of the stocks (an open loop control of the system). On the other hand, the system dynamics approach has been used for endogenous calculation of (at least some of) the influencing factors (Cagliano et al., 2017; Hu et al., 2020; Raoofi, Mahmoodi, et al., 2024; Shafiei et al., 2018).

In the actor-centered approach, the focus is on the actors' responses to the other actors' decisions and actions. Modeling approaches include evolutionary game theory (Huo et al., 2024), agent-based models (Van Heeswijk et al., 2020), and system dynamics (Bian & Xu, 2024; Melkonyan et al., 2020). In those models, the behavior of several actors, including carriers, shippers, and governments, is explicitly modeled.

There is also a smaller selection of papers that combine the vehicle-centred and Actor-centered approaches. E.g., research by Guerrero et al. (2013) predicts carrier, shipper, and government decisions explicitly while also modeling the vehicle fleet. A few system dynamics studies model the adoption of new vehicles while considering the dynamics of stakeholder decisions (Cagliano et al., 2017; Raoofi, Mahmoodi, et al., 2024; Shafiei et al., 2018).

Regarding applications, the focus of modeling medium-term dynamics in the literature is on the adoption of alternative fuel vehicles and modal shifts. Several studies focus on various freight transport modes at national or continental levels (see, e.g. Notteboom, 2020; Salvucci et al., 2019; Yan et al., 2021), and some also integrate the transport system with the energy system (see, e.g. Karkatsoulis et al., 2017; Shafiei et al., 2018; Siskos et al., 2018). Those models provide holistic insights about the transition rates of the fleets under specific policy conditions. Since the models are very comprehensive, they require large amounts of input data. Only a couple of "policy packages" are studied, and, with a few exceptions, the policies are predetermined and exogenously provided. There is also a selection of models that focus on the road freight sector's adoption of alternative fuels (Cagliano et al., 2017; Guerrero et al., 2013; Mulholland et al., 2018; Raoofi, Mahmoodi, et al., 2024; Xue et al., 2023), "green technologies" (Huo et al., 2024), or the adoption of urban consolidation hubs (Van Heeswijk et al., 2020). Ferrari (2014) and Nassar et al. (2023) explicitly study mode shifts and alternative modes.

There are techno-economic and equilibrium models on the national or continental level that consider freight in general, including all modes (see, e.g. Hao et al., 2015; Karkatsoulis et al., 2017; Siskos et al., 2018; Yan et al., 2021), and provide a holistic view without explicitly modeling the behavior of the different actors. For the more detailed models, there is a clear emphasis on road freight transport and, in particular, toward the adoption of alternative fuel vehicles and fuel-saving technologies. The previous studies clearly show the time delays from policy intervention to the impact on the GHG emissions. For example, Siskos et al. (2018) highlight the importance of actions 2020–2030 to meet the long-term climate goals. In the medium-term dynamics, the fleet turnover rate has a clear influence on the adoption of new technologies. To achieve faster adoption of technologies, retrofitting or vehicle upgrades are needed.

The pace and feasibility of decarbonization pathways also depend critically on dynamics with the energy system, including the alignment of energy availability, infrastructure development rate, and price dynamics. Misalignment between transport and energy systems constraints introduces additional time lags and feedback loops affecting technology adoption. Some integrated models explicitly address these dynamics: Shafiei et al. (2018) couple transport and energy systems to model electricity price feedback on electric vehicle adoption; Karkatsoulis et al. (2017) and Siskos et al. (2018) use PRIMES and GEM-E3T to simulate transport-energy interactions, capturing the impact of infrastructure investment and fuel price evolution on the transition to zero-emission trucks; Salvucci et al. (2019) integrate modal shifts with energy constraints in TIMES-Nordic. Rosenberg et al. (2023) connect a transport demand model, a vehicle stock-flow model, and an energy systems model to investigate the effect of this system on decarbonization timelines. The dynamics of the freight system are driven by the vehicle fleet model of Fridstrøm (2017). Pagnier et al. (2026) link a national freight transport model to an energy system model in an iterative application to produce dynamic scenarios of their co-evolution. The transport model takes an optimization approach but uses empirical parameters to describe dynamics of fleet transitions (Bakker et al., 2025). A further integration with a national freight demand model is recommended. Still, integrated models remain scarce, and the dynamic representation of infrastructure bottlenecks (grid reinforcement, hydrogen networks, port bunkering facilities) is often simplified. Future models should endogenously capture bi-directional dynamics: transport electrification affects electricity prices, demand and grid investment needs, while energy system constraints limit the feasible adoption rates of freight technologies.

In the literature, medium-term models are often run over 30 years or more (to 2050 or longer), which is the time scale where long-term dynamics take effect. This means that the models are run over longer time horizons than the time for which the assumptions hold. In particular, there is a limited representation of system change. This includes vehicles, the associated roads, rails, ports, and other physical infrastructure, refueling infrastructure as well as digitalized control systems for vehicle automation and digitalized logistics concepts. While these aspects are included in some models, we emphasize the lack of models that consider the interactions between these aspects.

As an example, Hao et al. (2015) assume no electrification of heavy road freight transport and run their model until 2050. However, we now know that heavy truck electrification is going on at a large scale. There is still a value in running the models on this long-time scale to validate the long-term dynamic behavior of the model, but the long-term results need to be interpreted with care. For long-term studies, it is also important to include long-term dynamics, as will be discussed below.

The time delays between policy implementation and observed effects are critical for predicting decarbonization trajectories, yet most freight models treat these lags implicitly or inconsistently. Empirical evidence shows that freight system responses to policy measures, such as subsidies for alternative fuels, emissions regulations, or infrastructure investments, incorporate delays due to behavioral inertia, administrative implementation times, and the capital replacement cycle of vehicles and infrastructure. These delays can be represented in quantitative models through delay functions (e.g. first- or higher-order delays in system dynamics) and adaptive adjustment rates that capture gradual behavioral and structural responses. Ferrari (2014) developed a practicable probabilistic model of modal shift with delays given changes in relative costs of modes, which was calibrated on the historical data. Previous work (e.g. Nassar et al., 2023; Raoofi, Huge-Brodin, et al., 2025; Shafiei et al., 2018) demonstrates that capturing the temporal mismatch between intervention and effect can improve the models' relevance for policy timing and sequencing.

Regarding the applications in medium-term modeling for decarbonization, there is a bias toward the adoption of alternative fuels or fuel-saving technologies. However, in the logistics sector, there is a lot of innovation and development within new green logistics concepts (e.g. off-peak deliveries, cargo bikes, and consolidation hubs). It would be relevant to model the adoption of these and their impact on decarbonization on the medium-term time scale. In terms of the five

Table 2. Selected freight transport policy models.

Model	Reference	Model type
Freight transport models at an international level from De Jong et al. (2021)		
HIGH-TOOL	Szimba et al., 2018	Transport flows simulation between EU regions, transport technologies and vehicle stocks
TRANSTOOLS	Jensen et al., 2019	Freight and passenger network assignment
ASTRA family of models	Fermi et al., 2014; TRUST, 2018	System dynamics, IO sectors, transport technologies and flows between EU regions
TRIMODE	Martino et al., 2018	Combined transport, macroeconomy, energy simulation model
Integrated assessment models, including transport climate policy (Jaramillo et al., 2022; Samet et al., 2022)		
PRIMES-TREMOVE	Siskos & Capros, 2014	Dynamic CGE with transport sector and technology details
E3ME	E3ME, 2019	Macro econometric model of the EU, including the transport sector and energy technologies

decarbonization strategies (McKinnon, 2018), the medium-term models primarily address "shifting modes of transport."

3.3. Long run and strategic policy assessment models

Even more than the short and medium changes, it is an even larger challenge to predict system changes that happen over the long term, beyond 40 years in our framework. Here, changes in governance arrangements, institutions, infrastructures, and ultimately landscapes are at stake. Landscape changes were the subject of Kondratieff (1979), who focused on changes in economic-technological systems, including the major waves of the agricultural and industrial revolutions. Grubler (1990) modeled transport infrastructure cycles spanning decades, inspired by Kondratieff's work. The models were built using time series regression, without explanatory factors other than time itself. Recently, explanatory models with a limited number of independent variables were constructed by Van Dorsser (2015) to predict future waterways transport flows, which concerned a shorter time-frame, however, of up to 150 years. There is a clear tradeoff between the breadth of scope of models and their level of detail or explanatory power. The more one focuses on longer-term developments and landscape changes, the less details related to short and mid-term changes seem to matter. At the same time, long-term change is built up of consecutive short-term changes: as the transition theories dictate, short-term changes can accumulate into mid-term and long-term landscape changes. This can only be reproduced if those mechanisms are modeled that produce these changes. Examples of relevant topics are changes in business models of freight transport system actors or entire business ecosystems (Zenezini & Tavasszy, 2022); and changes in consumer lifestyles influenced by technology (Wang et al., 2023). These long-term changes relate to landscape changes as they shape institutions, cultures, and their interactions. The traditional freight modeling research field has yet to discover the array of landscape changes that are relevant, and explore how they can be modeled in detail, conceptually and empirically. Regarding the decarbonization strategies, long-run models have mainly focused on "shifting modes of transport," especially for transport models with long vehicle lifetime (such as maritime), but they also to some extent address "reducing demand" (or at least predicting demand), and "reducing the carbon content of energy," as they can capture the shift to renewable energy sources.

There is a considerable body of literature on freight transport models for policy assessment (Table 2). These are reviewed in detail in Samet et al. (2022), drawing on De Jong et al. (2021) and the IPCC AR 6 (Jaramillo et al., 2022). All these models are dynamic models with different approaches to transport demand, based on CGE sectoral modeling or Input-Output sector structures, combined with a range of transport vehicle technologies and fuels. They are all aggregated models, relying on statistical data for calibration or estimation. They all can represent decarbonization through decreases in emissions per vehicle from new drive-trains and renewable energy sources. However, they do not represent dynamic processes of transition to a new socio-technical system as described above. Furthermore, they do not address the impacts of digitalization at all, and behavioral change is only represented through reactions to changes in prices/costs.

All the above models have further important limitations. Several reviews of freight models (Chow et al., 2010; De Jong et al., 2021; Tavasszy et al., 2012; Wigan & Southworth, 2005) have continued to point out that freight models have a theory of freight transport demand that does not yet consider the impacts of integrated supply chain management. Following on from this argument, the models do not have the capability of representing changes in logistics system organization and market structures. These include smart contracts through digitalized logistics systems enabling paperless supply chains, IOT (Internet of Things) technologies embedding software in system assets for digital data transfer and supply chain optimization, and new system configurations such as synchromodality or the physical internet. A further aspect here is collaborative systems, where different supply chains can interact to consolidate loads, optimize the use of infrastructure and vehicles, and exchange operational data on delays or accidents for trip planning. Also, the models do not allow for new operational methods such as platooning, cargo consolidation services (co-loading), or retiming (choosing the times you make or receive deliveries, collections, and servicing). More generally, the models do not consider the interactions between digitalized logistics systems and decarbonization. This may affect operations, e.g. battery vehicles with limited range requiring new methods for trip planning integrating charging requirements). It will also change management requirements, e.g. for preventive maintenance, emissions reporting, or optimization of terminal operations.

The aspects listed above require a more detailed understanding in terms of their potential impacts on logistics systems than the current (medium- or short-term, i.e. more disaggregated) modeling literature. It is probably not feasible to include all the aspects in an aggregated strategic model. However, some of the current models do have a detailed representation of power train technologies to analyze energy/fuel requirements and emissions. By analogy, future research on digitalization of logistics and transport systems may point to critical areas for transport operations and environmental impacts. The understanding of such areas could enable them to be parameterized and included in aggregated models. Alternatively, new forms of aggregated models could be explored, such as aggregated logistics system models or agent-based model structures applied at the strategic level. Evolutionary models could be used to explore self-ordering networks to develop scenarios for new logistics system structures.

Finally, we address behavior. Although some models mimic dynamic behavior by year-on-year rolling prediction, none of the above can be said to have an empirically valid representation of behavioral mechanisms through time. One can even say this of large-scale system dynamic models that were conceived with time-dependent behavior. Their empirical basis for dynamics is weak (Ghisolfi et al., 2022; Raoofi, Huge-Brodin, et al., 2025). In terms of the use of current simulation technologies, these models do not use ABM (agent-based modeling) approaches to represent the variation of behavior in the populations of agents (consumers and retail demand for improved environmental performance), 3PL providers, cargo owners, or vehicle suppliers in freight transport. This is now possible using modern simulation tools, as well as AI technologies.

3.4. Summary

This section has taken a particular look at dynamics, from a perspective of the very long-term challenge of major societal and technological transitions, like climate change, digitalization, and the energy transition. As these are very long cycles with change horizons of up to a century, the challenges for modeling transport systems lie beyond the typical time windows for forecasts and policy analyses of three decades ahead. Consequently, we need to consider deeper changes in the transport system than we would do otherwise: strategic logistics decisions, institutional changes, and even cultural changes. The short- and medium-term problems will be more in line with the logistics decisions appearing in most freight transport models. Overall, however, in many of these models, dynamics are poorly represented, as simple behavior through time, let alone as higher-order dynamic systems. Time-series models, while empirically well supported by time-series data, rarely describe behavior of agents and have relatively simple explanatory structures. Simulation models, including discrete event-driven models, agent-based modeling, and system dynamics, do consider time explicitly, but generally have a weaker empirical basis.

Considering the five pillars of decarbonization identified by ALICE (2020) and McKinnon (2018), we conclude that in the models, there is a bias toward the pillar "shifting modes of transport," where the adoption of new vehicle technologies is in focus. However, decarbonization strategies within all five pillars would lead to important dynamics. Questions that arise are e.g. What happens with transport demand in the light of 3D printing? How would a shift from oil and coal to renewable energy influence the need for shipping? To utilize all levers for decarbonization freight, future work should address the dynamics of all five decarbonization pillars.

4. Discussion

As shown in the previous section, significant research is needed to support policymaking for the decarbonization of the freight transport system. Below, we view the three requirements listed above and propose directions for research. They are presented top-down, from an overarching, system-of-systems perspective, to the socio-technical system at hand, and down to the narrow freight transport system itself.

1. **Multilevel perspectives:** Long-term modeling is highly important to guide policymaking, but also very challenging. In the long term, the pressure from the landscape as well as the introduction of new niches change the boundary conditions for the regime, and potentially also the system structure. If this is not considered, results from long-term models are questionable. Development of models and approaches to handle this is needed to increase long-term understanding of the system. The long-term dynamics of the transport system are influenced by short-term changes. Similarly, long-term changes, like cultural trends such as circularity, influence short-term dynamics such as daily operation and vehicle routing. Although there are some models targeting this connection between short-, medium-, and long-term connections, it is still an area which needs more attention. At the same time, it is crucial to avoid making the models overly complex, and normal considerations concerning model accuracy and parsimony need to be followed.
2. **Dynamics of socio-technical systems:** Several existing models describe the diffusion of technical systems but cannot capture the long-term changes typical for socio-technical systems. The freight transport system is being severely disrupted by phenomena such as the energy transition and digitalization. Several existing models aim to describe the adoption of alternative fuels and decarbonization, but models of the effects of digitalization are lacking and need to be developed. Digitalization will have a multifaceted impact on the logistics system, and will influence operation (e.g., automation, data-driven operations), business structures

(platforms), as well as the structure of transport demand (Montreuil et al., 2013). Similarly, decarbonization of the transport system depends on long-term energy system transition developments, which challenge logistics with new routing, refueling/recharging, and energy provision infrastructure requirements. Such systems-of-systems approaches recognizing multiple simultaneous transitions are lacking. Such models should include the dynamics of people's behavior, businesses, and society, besides the adoption of the technology.

3. **Empirical research on dynamics of freight systems:** More research is needed to improve our empirical understanding of the dynamics of the future freight transport system. Basic knowledge of time-to-implementation of policy measures, of response times by different sectors of the economy, and political cycles is lacking. Research is needed to describe and validate these dynamic mechanisms, including feedback loops and delays. Studies of the dynamics of historical behavior should be supplemented by models allowing for structural changes. To validate such models, empirical research is needed, and data needs to be collected. This includes not only data from the output variables, such as mode shares, etc., but also data related to behavior of the actors in the system. Once this research is developing, applications to complex decarbonization policies come into view. Recalling the five pillars of decarbonization of McKinnon (2018), we have seen that in current models, there has been a strong bias toward the pillar "shifting modes of transport." Here, we find that the balance is uneven between modes: there is a clear gap for modeling of dynamics for other modes than road transport and inland multi-modal transport. We can recommend, therefore, that this base is broadened. Considering decarbonization strategies within all five pillars would lead to important new dynamics that have not been addressed yet. Questions that arise are e.g. What happens with transport demand in the light of 3D printing? How would a shift from oil and coal to renewable energy influence the need for shipping? To utilize all levers for decarbonization freight, future work should include the dynamics of all five decarbonization pillars.

5. Conclusion

The current literature provides insufficient guidance for a comprehensive modeling of the dynamics of freight transport systems, needed to support decarbonization policies. Several very long-term structural changes are happening simultaneously—energy transition, transport decarbonization, and digitalization. They are entangled and their developments will influence each other. Moreover, the freight transport system is embedded in a larger, societal system, influenced by cultural and social structures, consumption patterns, and lifestyle changes. To build models that support important policymaking to reach decarbonization in time to meet the climate goals, the complex and dynamic nature of the freight transport system needs to be considered, and new types of policy modeling are needed than those available today.

Current freight models ignore important long-term changes and are poor at describing the dynamics of the system. Long-term predictions are currently made with models that only consider medium-term dynamics. Therefore, there is a need to extend the current paradigm of freight transport modeling to also consider the transformation of the societal systems and the system structure in a broader context. Innovation and transition theories can be used as frames. Moreover, connections and consistency between short-, medium-, and long-term dynamics are needed. Several essential new concepts need to be considered in freight transport models, including digitalized logistics systems; platform-based logistics; influence of technologies such as automation and blockchain; changing market structures, business models, and strategies; circular supply chains, the prosumer lifestyles/social structures; behavior of consumers, managers within firms, and decision making within stakeholder systems.

There are several promising modeling techniques to describe and predict dynamic responses, including agent-based modeling, system dynamics, and co-evolutionary models. Applications should go beyond extrapolation of predictions based on historical data and be estimated and validated to capture the dynamics of the freight transport system. The empirical modeling task is daunting. Not only is there a need for additional (dynamic) data, but the proper specification and estimation of these models is also not trivial. Empirically capturing the long-term behavior of the system at large is essential, however, for reliable ex-ante evaluations of decarbonization policies.

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