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A conceptual model

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Dynamics of freight transport decarbonisation: a conceptual model

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ABSTRACT

As part of the global efforts to mitigate climate change, policymakers are designing measures to reduce the carbon emissions of the freight transport system. As global agreements for decarbonisation specify strict time windows, it is important to understand the speed at which the transport system is capable of changing. Our paper proposes a causal loop diagram based on System Dynamics that qualitatively maps the system's causal and dynamic responses to five key decarbonisation strategies. As the main contribution, this conceptual model provided a broad overview of the freight system, formed by subsystems that interact with each other through feedback loops, forming its dynamic behaviour. Through this conceptual modelling effort, we can identify the rebound effects of policies over the whole system, which could defeat the desired decarbonisation results. The model pointed out policies and feedback loops as the dynamic levers to promote freight decarbonisation and influence the system's dynamic responses.

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Freight transport; decarbonisation; low-carbon freight; system dynamics; causal loop diagram

1. Introduction

Climate change is a worldwide concern and the global pressure to decrease greenhouse gas (GHG) emissions is strengthening to reduce negative environmental impacts. According to the Paris Agreement, all parties should put forward a long-term strategy setting out the actions that they will take across the whole economy to contribute to the global goal of limiting the average temperature increase (United Nations, 2015). This means that global emissions should decrease significantly by mid-century, mostly led by developed countries (European Climate Foundation, 2018). In this context, a rising number of countries are targeting net-zero emissions by 2050, which will demand a set of ambitious actions over the next years. Decarbonisation strategies may have quite specific and narrow time windows to take effect, turning this system into a dynamically complex one. Bringing about a 40% reduction in emissions by 2030, for example, requires that passenger electric cars worldwide increase from 2.5% in 2019 to more than 50% in 2030 according to the World Energy Outlook 2020 (International Energy Agency, 2020). While many sectors show decreasing emissions of GHG and passenger transport is moving towards electrification and less CO_2-intensive fuel alternatives, freight transport remains heavily dependent on fossil fuels (Fridell et al., 2019). The transport sector accounted for 7.219 Mt CO_2 of global emissions in 2020, from which freight transport was responsible for about 37% (only heavy trucks accounted for 24%; International Energy Agency, 2021), which is expected to increase due to e-commerce and home delivery. Guérin et al. (2014) stated freight transport as one of the most difficult economic activities to decarbonise, especially because the demand for freight movement is expected to increase, and it will be even harder to reduce its huge dependence on fossil fuels over this period.

Transition pathways to low-carbon freight transport systems combine different measures. McKinnon (2018) proposed five broad strategies to decarbonise freight transportation: (1) reducing the demand for freight; (2) shifting freight to low carbon-intensity modes; (3) optimising vehicle loading; (4) increasing the energy efficiency of freight vehicles; (5) reducing the carbon content of energy used. This is only possible with top-down policies since the freight transport sector represents a market-driven social, technical, and economic system, which depends on many different private and public stakeholders for its change. These stakeholders may strongly differ in their interests, preferences, decisions, and rules of behaviour, which influences the impact of policy options in different contexts (Mease et al., 2018). Policies that intervene in the system may create unanticipated side effects, leading not only to policy resistance, but also to the tendency for interventions to be delayed,

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diluted, or defeated (Meadows, 1982), impacting the evolution of the system. Thus, besides the mechanisms to decarbonise freight transportation, we should also consider the internal dynamics that lead this process, and the time they take to be effective in different scenarios. By viewing the dynamics of the freight transport system from the context of decarbonisation we can analyse how strategies impact each other through dynamic feedback loops and how this could affect the overall speed of change of emissions reduction. Some strategies can have counter-productive rebound effects and reinforce the use of a polluting mode of transport. For example, increasing truck efficiency leads to road transport costs reduction and increase of its use, in addition to reducing emissions. Therefore, a systemic view allows us to analyse the impact of desirable or concurrent effects. It allows policymakers to understand the critical dynamic levers inside the system and to make them aware that their decisions not only impact the final result but also the time that passes until the system is decarbonised.

Given the problem sketched above, the research question that guides this paper is: *how can we conceptually model the complexity and dynamics of the freight transport system's decarbonisation?* In addition to explicitly modelling the mechanisms, we also aim to highlight the dynamic processes of the five decarbonisation strategies described by McKinnon (2018).

We take a systems approach to understand the complexity of this real-world phenomenon, as advocated by Systems Theory and Systems Thinking (Kefalas, 2011; Von Bertalanffy, 1972). The application of Systems Thinking is especially useful when a collaborative approach among leaders and individuals must be fostered (Laszlo, 2012). In general, many static-comparative models have already received good acceptance in transport research over the last years, for travel demand modelling and behavioural analysis. However, in our context, the focus is needed on the dynamic environment and strong interdependencies among decisions made at different points in time. In a Systems Thinking context, System Dynamics (SD) modelling stands out due to its adequacy for investigating the impact of policies and strategies over continuous time taking into account the dynamic complexity of feedback structured systems (Abbas & Bell, 1994; Maalla & Kunsch, 2008; Shepherd, 2014).

1.1. *Scientific contribution*

Our qualitative model is a causal loop diagram that integrates five strategies involved in the decarbonisation of the freight transport sector. It depicts the importance of cause-and-effect relationships for researchers and practitioners. The first innovation of our model is that it provides an overview of the freight transport decarbonisation system. Divided into connected subsystems, this approach provides the qualitative dynamic behaviour of the whole system towards emissions mitigation. This integrated view of the system allows for better coordination of decarbonisation strategies, highlighting the need of collaboration between different stakeholders to manage side effects that could reduce the impacts of decarbonisation policies. Moreover, the model points out dynamic levers of the system related to the decarbonisation objective. These dynamic levers are the main areas of action for policymakers to change the system. In summary, this qualitative analysis contributes to the literature by providing insight into the system of freight transport decarbonisation. As a general qualitative model, it can be applied to any geography, since the assumptions taken to construct this model are not specific to a region. It can act as a basis to develop quantitative and empirical SD models of freight transport decarbonisation.

The paper, from this point onward, is structured as follows. The next section provides a literature review of system dynamics models approaching strategies for freight transport decarbonisation. Following, the qualitative analysis approach section explains the method used and how the different concepts in this approach help to answer the research question. Then we present the causal loop diagrams that describe the system's dynamics. The main feedback loops integrating the dynamics of the proposed model are presented in the discussion section. Finally, we present the conclusions and provide suggestions for further research.

2. System dynamics modelling and freight transport decarbonisation: The state of the art

The SD methodology was developed by Jay W. Forrester (1961), as a basis of explanation to illustrate the effects of decisions in complex, dynamic systems, in which the time functions are emphasised. The specific feature of SD is its non-linear feedback structures. For this reason, the interdependencies between system submodules should be identified and illustrated in an iterative modelling procedure (Thaller et al., 2016a).

1994) discussed and evaluated the strengths and weaknesses of SD concerning its suitability and appropriateness for transportation systems modelling. The authors stated that as transportation problems require integrating forms of knowledge as well as comprise long-term/short-term trade-offs, the SD modelling is well suited for addressing transport problems, especially the strategic studies that are concerned with policy analysis and decision-making. Shepherd (2014) presented a review of SD studies categorising them by area of application in the field of transportation. After an analysis, he provided a summary of insights and recommendations for the future application of the SD approach in this field. At that time, he indicated the lack of research in freight transport and decarbonisation using this modelling approach. After that, some SD models addressed specific strategies of freight decarbonisation or covered a very particular component of the system to reduce emissions as reviewed by Ghisolfi et al. (2022). Table 1 summarises the specific decarbonisation strategies and policies considered in the SD models reviewed by the authors.

The review of Ghisolfi et al. (2022) concludes that previous SD models of freight transport systems were too narrow in their representation to study decarbonisation strategies, especially at a country level. Although the SD literature does address individual decarbonisation measures, there is no model which takes a system-wide perspective to assess by when a given level of decarbonisation could be achieved for the system as a whole, with all measures considered together. This is an important gap since a narrow view of unconnected subsystems prevents identification of the most effective actions and prevents awareness of the dynamic interactions between policy measures during the next decades. Another key concern is the current lack of transparency regarding the mechanisms and temporal dimension of empirical models, including the delay assumptions in key behavioural mechanisms. As the time for decarbonisation measures to take effect is limited, this is an important problem for policy makers.

The current study addresses the research gap reported by Ghisolfi et al. (2022), regarding the lack of a comprehensive model in which several strategies interact and are considered simultaneously. To this

Table 1. SD models for freight transport decarbonisation, strategies, and policies applied.

Decarbonisation strategy	Authors	Policies applied
Reducing freight transport demand	Erdmann et al. (2004) and Hilty et al. (2006)	Investment in new technologies
	Freeman et al. (2015)	Investment in technological efficiency
	Kunze et al. (2016)	Application of higher transport taxes
	Thaller et al. (2016b; Thaller et al., 2017)	Not considered
	Agha et al. (2019)	Increase in fuel prices
	Hidayatno et al. (2019)	Carbon tax internalisation
	Zhang et al. (2019)	Not considered
	Kar and Datta (2020)	Product prices and logistic costs variation
Shifting freight to low carbon-intensity modes	Schade and Schade (2005)	Higher transport prices (taxes); investment in alternative modes
	Han and Hayashi (2008)	Extension of the railway and waterway network and imposition of fuel taxes
	Brito Junior et al. (2011)	Investment in infrastructure capacities and governmental pressure to reduce CO_2 emissions
	Lewis et al. (2014); (2015))	Investment in rail infrastructure
	York et al. (2017)	Increasing investments in the rail network
	Azlan et al. (2019)	Promoting alternative modes, such as railway
	Choi et al. (2019)	Increasing road cost (taxation)
	Dong et al. (2019)	Investment in railway infrastructure
	Liu et al. (2017); 2019a; (2021))	Legal truck weight regulation and investment in railway infrastructure
	Hu et al. (2020)	Different levels of infrastructure investment policy, network scale, and market competitiveness through price adjustments
	Wang et al. (2021)	Increase the use of alternative modes
	Huang et al. (2021)	Increasing carbon taxes and investments in the railway network
Improving vehicle utilisation	Doll et al. (2010)	Internalisation of transport external costs; allowance of heavier trucks
	Aschauer (2013) and Aschauer et al. (2015)	Internalisation of transport external costs, leading to more pressure to consolidate freight
	Oumer et al. (2015)	Shipment consolidation
	Liu and Mu (2015)	Alternative truck weight regulation policies
	Sim (2017)	Not considered
	Melkonyan et al. (2020)	Investments in digital applications for track and trace and to outsource the pickup to consumers
	Hamoudi et al. (2021)	Internalisation of CO_2 emissions tax; different levels of truck capacity utilisation
Increasing energy efficiency	Krail and Kühn (2012)	Taxes on different technologies and emissions levels
	Seitz (2014)	Investments in refuelling infrastructure and R&D technologies
	Seitz and Terzidis (2014)	Investment in refuelling stations and alternative powertrains
	Geng et al. (2017)	Speed reduction, use of shore electricity, engine improvement, and exhaust after-treatment technologies
Promoting new energy sources	Fiorello et al. (2010)	Incentives for fleet renewal, and increases in fossil fuel prices
	Purwanto et al. (2011)	New emission standards, penetration of alternative technologies, increase in fuel efficiency, and fleet renewal; fuel quality; incentives for low-emission cars
	Shafiei et al. (2014)	Oil price variations, alternative fuel availability, and carbon taxes
	Cagliano et al. (2015a); 2015b; 2017)	Subsidies for alternative technologies and investment in refuelling/recharging infrastructure
	Menezes et al. (2017)	Improving fuel efficiency and promoting the use of biofuels
	Haddad et al. (2019)	Not considered
	Barisa and Rosa (2018a; 2018b)	Fossil fuel taxes, subsidies for alternative fuels, investment in refuelling/recharging infrastructure, and mandatory use of biofuels
	Setiawan et al. (2019)	Efficiency improvements, and adoption of electric vehicles
	Rozentale et al. (2020)	Investment in new energy sources
	Zenezini and Marco (2020)	Economic incentives for electric vehicles

Source: Based on Ghisolfi et al. (2022).

end, we model the interdependencies between freight decarbonisation strategies as well as the contribution of different policies to the total emissions from the freight transport sector, including any rebound effects across subsystems.

3. Qualitative analysis approach

The key tool of analysis is the causal loop diagram, which is useful for representing mental models including the feedback structure that determines the dynamic levers of the system (Sterman, 2000). A causal loop diagram consists of a set of nodes and edges, which illustrates how different variables in a system are interrelated. Nodes represent the variables and edges are the links that represent a cause-and-effect relationship between two given variables. The links have polarities that represent a change either in the same or in the opposite direction. If two variables X and Y are connected by a link (cause-effect-relationship) then the polarity indicated by "+", means that variable Y is increasing when X is increasing and decreasing when X is decreasing. On the other side, the polarity indicated by "-", means that variable Y is decreasing when X is increasing and increasing when X is decreasing.

According to Yearworth (2014), the key dynamic concepts that emerge from such diagrams and help to clarify a system's complex behaviour are closed causal loops, identified as either reinforcing (labelled "R" or "+") or balancing (labelled "B" or "-"). A reinforcing loop indicates that a change in one direction is strengthened by increased change, whereas a balancing loop indicates that a change in one direction can be reversed with a change in the opposite direction. Thus, the reinforcing behaviour among the different variables entails an exponential growth in the system, while the balancing feedback leads to a goal-seeking or control behaviour of the system. There are always delays in the feedback within a closed causal loop, which can range from small to large time intervals. The delay is also considered a key dynamic concept as it can make goal-seeking difficult to achieve. If a delay is added to the system, "the main effect is to introduce oscillation in the system which could be: i) damped and eventually lead to convergence on the desired state, or ii) un-damped and lead to a divergence in which the amplitude of the oscillation grows" (Yearworth, 2020, p. 9).

Together, these key dynamic concepts point towards *dynamic levers* in the system that can be used to study its change and to identify promising policy measures. According to Senge (1990), solutions focused on dynamic levers can lead to significant improvements, i.e., the best results do not necessarily come from large-scale interventions but can also come from small and well-focused actions (Roxas et al., 2019). Dynamic levers can be understood as core symptoms, critical variables, points of intervention, tipping points, or simply areas where interventions are deemed most effective, where "a small shift in one thing can produce a big change in everything" (Meadows, 1991, p. 1). Meadows (as cited in Roxas et al., 2019, p. 615) proposed 12 leverage points in a system, which were further categorised into three: "(1) physical elements (i.e., indicators, structures, delays) with the weakest leverage, (2) information and controls (i.e., balancing/reinforcing loops, rules) with medium leverage, and (3) ideas behind the system (i.e., goals) with the strongest leverage". In this sense, dynamic levers can be identified as variables that: (1) are a common cause of multiple effects that can accelerate or decelerate the operation of a system; (2) can be influenced by an intervener, leading the system to major changes; (3) are the root cause characterised by being independent, generating significant and irreversible changes that occur when thresholds have been reached (Roxas et al., 2019).

In the below, we will explore these dynamic levers further, by the identification of the above properties of the system that affect the response time of the freight transport to decarbonisation strategies. The next section describes the model, as built up from the current literature. We first introduce the overall model framework and develop the subsequent parts in separate subsections.

4. A causal loop diagram for freight decarbonisation

In this section, the developed SD model, illustrated by causal loop diagrams, is derived and explained. The model is divided into submodels to support its transparency and traceability. The submodels, represented by coloured arrows in Figure 1, relate to subsystems that correspond with the five decarbonisation strategies: (1) reducing freight transport demand (red arrows), (2) shifting freight to low carbon-intensity modes (green arrows), (3) improving vehicle utilisation (blue arrows), (4) increasing energy efficiency of fleets (purple arrows) and (5) promoting new energy sources (orange arrows). The subsystems are interrelated and influence the output indicator, GHG emissions, placed at the bottom of Figure 1.

Policies are required to deal with freight external costs such as GHG emissions. The variable "strength of policies" is the sum of all policy instruments in the five submodels taking into account the gap between the real and the admissible level of GHG emissions. Based on Stelling (2014), we considered policies distributed in four categories: economic, legal, knowledge-based, and societal instruments. Economic instruments are all about internalising external costs by imposing taxes, charges, fees, tax exemptions,

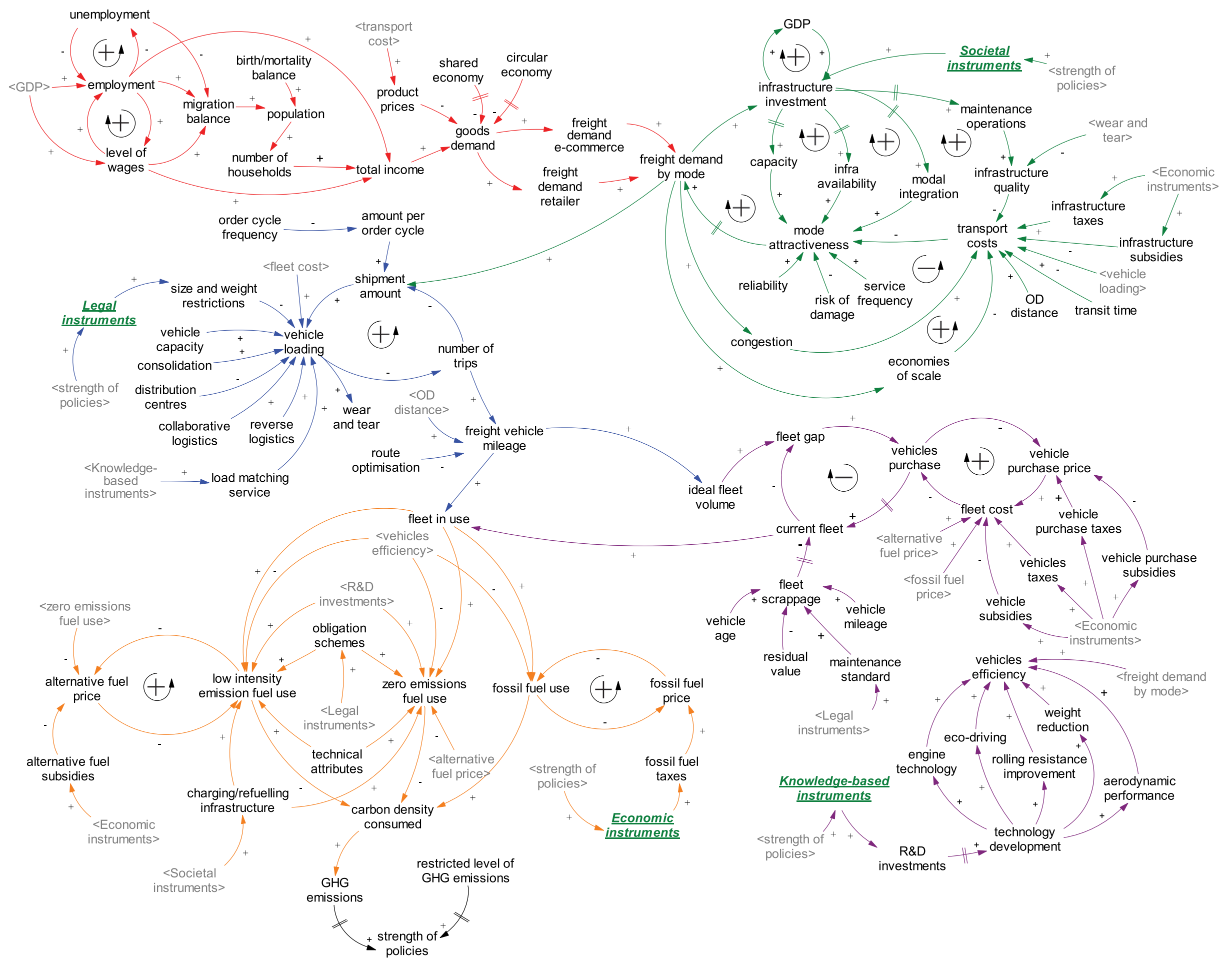

Figure 1. Causal loop diagram for freight transport decarbonisation system.

subsidies, and others. Legal instruments are mandatory rules to enforce some decarbonisation strategies such as truck restrictions (weight, size, time/zone of circulation), fuel composition, and performance-based standards. Knowledge-based instruments can include information spread to increase customer acceptance of other decarbonisation strategies, and Research and Development (R&D) to create new solutions to improve energy efficiency or find alternative energy sources. Finally, societal instruments are related to infrastructure investments to promote the shift from road to less emission-intensive modes, carbon-neutral techniques such as electrical roads, and recharging infrastructure for electrical vehicles. All of these policy instruments are indirectly linked to the "strength of policies" through feedback loops.

Moreover, the "strength of policies" can be more or less rigid according to the established target or admissible level of GHG emissions. It means that policies are dynamic and can be changed, becoming more or less stringent over time as new needs arise, or the level of targeted GHG emissions changes. However, such changes in the "strength of policies" are subject to delays (represented by arrows with hash marks) that result from the decision-making process. Thus, the "strength of policies" is an important dynamic lever to timely achieve the freight decarbonisation goal. The different decarbonisation strategies and their dynamics are discussed in the next corresponding sections, besides the important variables and connections that build the structure of the model.

4.1. Reducing freight transport demand

The first decarbonisation strategy is *Reducing Freight Transport Demand*, which analysis is shown in Figure 2. The population grows by a positive birth and mortality balance on the one hand and by a positive migration balance on the other. Population development also influences the number of households. Moreover, the economic increase guarantees a positive employment development and the level of wages, which leads to a positive income development of private households and disposable income for consumption. The greater disposable income reinforces the freight demand of the private households in total, which is differentiated in freight demand in location bound retail branches and freight demand by e-commerce activities via the internet, as these two forms of consumption generate different last-mile logistics services (Thaller et al., 2016b, 2017).

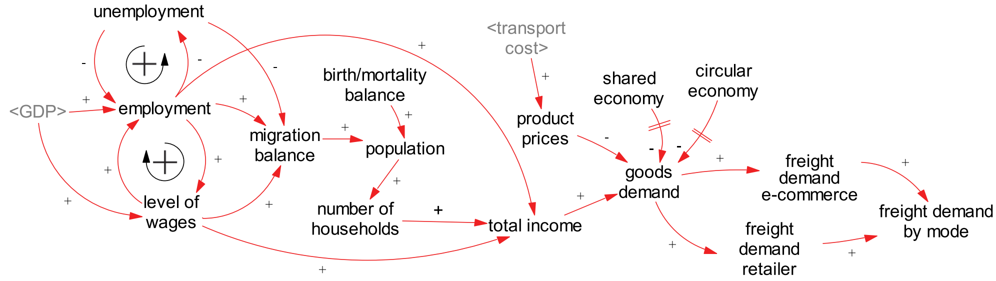

Figure 2. Reducing freight transport demand submodel.

Another factor that influences freight demand is product prices. The prices of the products take into account the transport cost, which in turn, can be influenced by policy instruments like the internalisation of emissions costs. If a price increase can be transferred on to final consumers by the user-pays principle, the impact will depend on the price elasticity of each product category. According to Stelling (2014), if the taxes correspond to full internalisation, the price increase would be substantial.

On the other hand, new consumption concepts such as the sharing economy and the circular economy are positive ways of decoupling GDP from freight transport demand. In a sharing economy, consumers prioritise usage over ownership (Frenken & Schor, 2017), leading to less production, consumption, and, consequently, freight transport demand in the whole supply chain. The circular economy emphasises reuse, remanufacturing, and repair, before recycling and landfill disposal (Korhonen et al., 2018). McKinnon (2018) affirms that such a principle might reduce the level of logistics activities by decreasing the need for the transportation of raw materials or new products. The sharing economy and circular economy are not yet in their maturity stage, however, and may take some time to unfold their impacts.

Another example of the dynamic relationship between consumption patterns and their influence on freight transport demand can be seen in the increase of e-commerce during the COVID-19 outbreak (Arellana et al., 2020; Becdach et al., 2020; Loske, 2020), and freight companies had to adapt to the consumption change.

Regarding the dynamic levers of this submodel, delays are present in changes in population and economic development (GDP), as well as other delays in the adoption of new-economy concepts (e.g., circular economy and sharing economy), and the changes in consumer patterns like e-commerce. All these factors dynamically change over time and impact the level of freight transport demand. Although freight demand reduction contributes to emissions mitigation, the predicted trend is an increase in the coming years, more or less linearly with economic growth. Thus, additional measures will be required to deal with freight transport decarbonisation, especially within restrictive targets such as net-zero emissions.

4.2. *Shifting freight to low carbon-intensity modes*

The second decarbonisation strategy is *Shifting Freight to Low Carbon-Intensity Modes* since each transport mode contributes to fuel consumption with distinct intensities. Many factors influence the mode choice such as volume of goods demand, cost, flexibility, quality and service frequency, reliability, shipment distance, infrastructure conditions, transit time, cargo damage, and others (Holguín-Veras et al., 2021). It is important to consider several factors that influence such a decision to identify dynamic levers. Even when the infrastructure is available, it may not be sufficient to achieve the mode shift goal due to the lack of consensus about operational standards, a failing business-economic rationale, or a conflict of interests between stakeholders (European Commission, 2016). Therefore, considering products that can be carried by different modes, the mode choice depends on many components, as represented in Figure 3.

There are seven feedback loops in this submodel. The first one (at the top of the diagram) shows that infrastructure investments support economic growth and, in turn, an increase in economic development will promote an increase in infrastructure investments. This reinforcement feedback loop may be weak, however, as the transport sector represents a small share of the whole economy (it accounted for about 5% of total Gross Value Added (European Commission, 2021; United States Department of Transportation, 2022)). Besides infrastructure availability, capacity, and modal integration, the investments also assure the maintenance operations over time to recuperate its wear and tear, which contributes to its suitability and quality. As demonstrated by the dominance of road transport, these different types of expenditure and mode attractiveness can end up being self-reinforcing (represented by the four positive feedback loops in the middle of the diagram). The next and only balancing feedback loop of this submodel relates

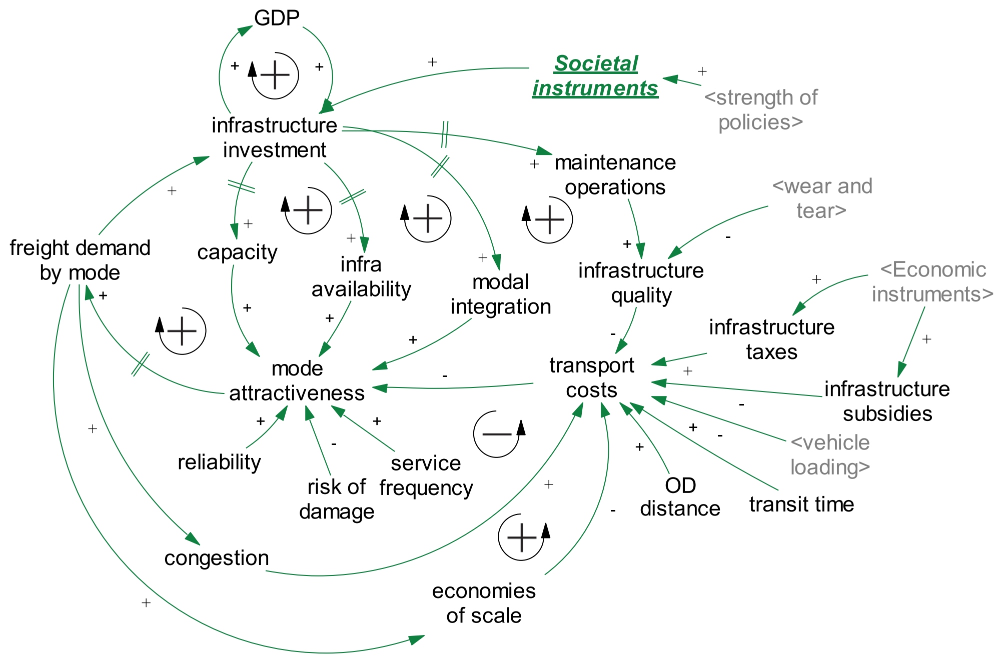

Figure 3. Shifting freight to low carbon-intensity modes submodel.

freight demand by mode, congestion, transport cost, and mode attractiveness, showing the effect of congestion on transport demand. The last reinforcement feedback loop of this submodel (placed at the bottom of the diagram) relates transport cost, mode attractiveness, and freight demand by mode, showing the effects of economies of scale (the more one mode is used, the more attractive it becomes due to costs savings). These behaviours can be used as part of policies to promote low carbon-intensity modes.

Many delays are identified since the implementation of infrastructure is subject to long and infrequent decision processes, and unforeseen circumstances. The main causes for policy-related delays in this phase are postponements in design information, the lengthy duration for approving the project, and inadequate site management. Furthermore, the delay time is also dependent on the type of project undertaken. Maintenance projects generally experience the most severe delays since they are associated with unpredictable and unforeseen site conditions that often require the relocation of utilities and the redirection of traffic flow (Adam et al., 2017).

Economic instruments for internalisation of external costs, such as infrastructure taxes or subsidies could also play a role in the mode choice process. Arencibia et al. (2015) confirmed the benefit of policies in favour of charging for infrastructure use, as the actions with the greatest impact on the deviation of traffic to alternative modes are those that affect the cost of transportation. Conflicts of interest between stakeholders can be raised, once road taxation is not differentiated by commodity transported (Rigot-Müller, 2018), and therefore, such taxes affect manufacturing products with lower values. Additionally, an uneven charging for infrastructure use between modes can benefit one mode over another in terms of operating costs and, consequently, impact their attractiveness and unbalance the use of less polluting modes, as stated by the Community of European Railway and Infrastructure Companies & European Rail Freight Association (2019). Such conflicts are intrinsic to the decision-making process and can delay the mode shift and decarbonisation goals.

Dynamic complexity, and consequently the time delays involved in the mode choice process, first depends on infrastructures as well as their accessibility, which can take significant time to be made available either due to bureaucratic concession or bidden issues, project or operational delays. Therefore, the time to implement this decarbonisation measure may differ significantly between countries where infrastructure is operational or not. Second, the choice of less-polluting modes is challenging even where the infrastructure is already available, considering the mode attractiveness through cost-utility and the delay with which users shift from one transport mode to another. The actual decision to choose a mode of transport lies with companies, where mode attractiveness determines mode utilisation. Delays here can amount to years, if not decades, as companies seldom revisit their choice of mode, if at all. Apart from the low frequency of decision-making, such delays occur due to a lack of readiness to adopt innovations, limited confidence in the future possibilities of new transport modes, difficulties in adapting the logistical organisation, or simple inertia. Ferrari (2014) addressed this problem through dynamic cost functions. The application of his model has shown that different evolutions of modal splits in these places occurred because transport costs evolve as a consequence of the overall freight flow increase, the users' attitudes, and the changes in the transport mode technology and organisation. The interaction between these causes determines the evolution of the transport costs, and thus, along with the users' delay, the evolution of the modal split (Ferrari, 2014).

Holguín-Veras et al. (2021) also argue that the process of freight mode choice is a dynamic system, as its functioning is influenced by the ups and downs of markets as well as by the interactions among the multiple agents involved. The authors estimated discrete choice models to econometrically assess the influence of transit time, freight rate, and generalised cost over the dynamics of mode choice.

In summary, promoting alternative freight modes to trucking will require different efforts such as subsidies, changing companies' preferences and attitudes, enacting faster and more frequent decision-making processes, and understanding needed innovations.

4.3. Improving vehicle utilisation

The third decarbonisation strategy is *Improving Vehicle Utilisation*. Shipping requirements are governed by an operating logistics concept (e.g., Just in Time, Vendor Managed Inventory, Just in Sequence), which influences the order cycle frequency and amount per order cycle (Aschauer, 2013). Figure 4 shows the related variables that form this submodel structure.

Although heavy vehicles consume more fuel than medium and light vehicles, mainly due to their weight (Demir et al., 2011), vehicle loading is inversely related to the number of trips, which means that, as the vehicle load increases, fewer trips are needed to transport a certain amount of load, which reduces costs, fuel consumption, and emissions (Liu et al., 2017). This relationship gives an upward effect on shipment sizes and vehicle loading, forming a reinforcement feedback loop.

Besides shipment sizes and volumes, vehicle loading also depends on vehicle capacity and cargo consolidation, the number of distribution centres, and unavoidable empty runs. McKinnon and Ge (2006) present several reasons and incentives for the decline in empty runs in the United Kingdom, such as outsourcing of haulage operations, multiple destination trips, reverse logistics, and the "digital freight matching" platforms, which usage will increase in the future with the digitalisation of the sector. This new type of platform could support a movement for collaboration in fully open and connected networks as envisioned in the so-called Physical Internet System (Montreuil, 2011). This "hyperconnected" system could result in GHG reductions of up to 45% (Kim et al., 2021), but it may need a long time (estimated 2040) to materialise due to the many changes needed in standards, procedures, and technology (Alliance for Logistics Innovation through Collaboration in Europe, 2020). The asset utilisation can also be improved by local or collaborative procurement by companies (Rezaei et al., 2020), which requires major changes in sourcing practices, or the influence of governments to internalise the external costs of trade. In general, companies will decide more easily to change the sourcing location than to collaborate with other companies, as the latter is not part of their regular decision-making practice. All these factors depend on the frequency with which decisions are taken by the companies regarding the organisation of physical distribution and the deployment of their assets.

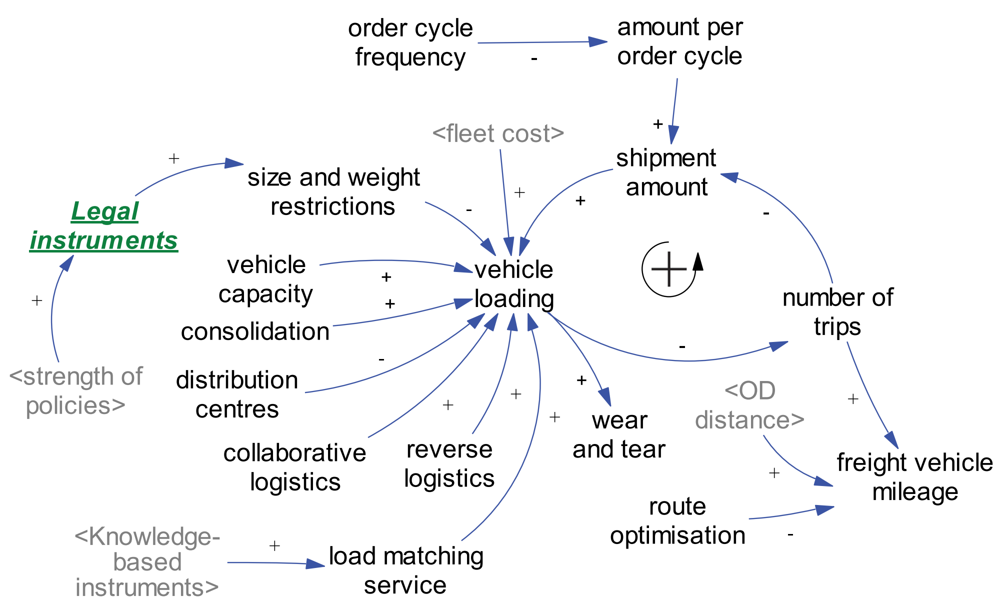

Figure 4. Improving vehicle utilisation submodel.

Size and weight regulations to prevent the overloading of freight vehicles, and to avoid or minimise external costs like accidents and wear and tear, are needed in some countries that heavily rely on roadways and face poor pavement conditions, leading to high logistics and maintenance costs (Liu et al., 2017). On the other hand, the efforts to reduce truck overloading increase transport costs and undermine emissions mitigation due to the increased number of trips.

Beyond the number of trips, freight vehicle mileage is also influenced by the origin and destination distance, and route optimisation. An option to reduce freight vehicle mileage is to involve the collaboration of the end consumer in the fulfilment of the last mile. Halldórsson and Wehner (2020) claim that energy could be saved in last-mile fulfilment when goods are carried as far as possible collectively down in the supply chain in commercial vehicles with high fill rates, and the end consumer should be responsible for only the last part of the last mile.

Like the previous decarbonisation strategies, efficient utilisation of the capacity of the vehicles has the potential to reduce emissions, but not to get rid of them altogether. The time to implement this strategy in the future will depend on how companies change their logistic decisions over time.

4.4. Increasing energy efficiency

The fourth decarbonisation strategy is *Increasing Energy Efficiency* since it impacts the amount of fuel consumed by conventional internal combustion engine (ICE) vehicles. The fuel consumption will depend on the vehicle technologies in use and the driving practices, as demonstrated in the causal loop diagram of Figure 5.

Vehicle technologies that offer potential energy savings are related to weight reduction, aerodynamic drag reduction, rolling resistance, and friction improvements (Folkson, 2014). Some of these can be deployed as retrofit technology on the existing ICE vehicles, which brings an early impact. Powertrain technology includes hybrid engines, battery/plug-in /fuel cell electric vehicles, and biofuel addition (Folkson, 2014). The dynamic of their introduction is unlike that of conventional technology, due to the need to develop infrastructure networks for battery recharging/swapping (Juan et al., 2016), and suitable rechargeable energy storage systems (Pereirinha et al., 2018). The gains of efficiency improvement are observed in the reduction of fuel consumption, present in the next submodel.

The fleet renewal process is another way to promote energy efficiency improvement. The current fleet can be renewed with the adoption of more efficient

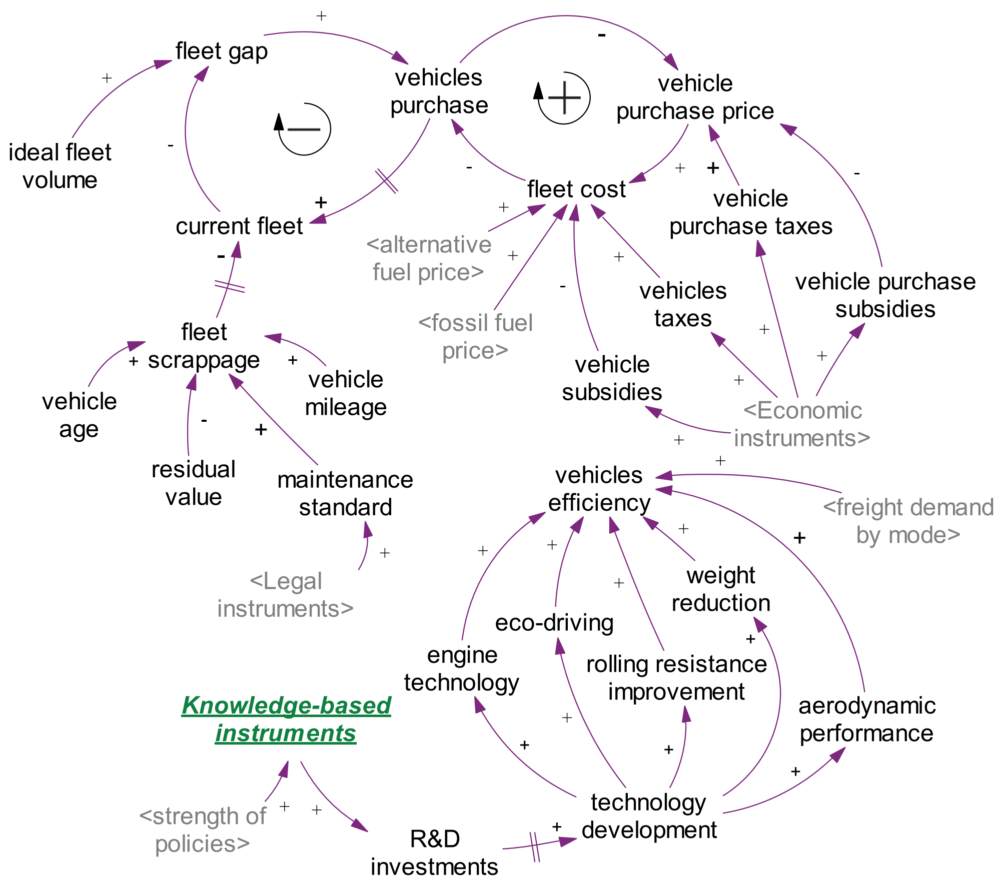

Figure 5. Increasing energy efficiency submodel.

vehicles. The organisational adoption behaviour for new products or technologies takes place in the setting of organisational buying processes, which influences adoption behaviour and the underlying criteria in a process-orientated way (Seitz, 2014), including higher specificity of demand, a higher number of persons involved, a stronger tendency towards rationality and a longer purchase decision process (Webster & Wind, 1972). The market share of conventional or alternative powertrain concepts is a function of an organisation's familiarity, perceived technological attractiveness, and vehicle availability (Seitz & Terzidis, 2014). The vehicle purchase is defined by the fleet gap, that is, the difference between the current fleet and the ideal fleet to attend to the demand, forming a balancing feedback loop. Vehicle purchases also depend on fleet costs and vehicle purchase prices. Technology solutions to improve vehicle efficiency make them more expensive than ICE vehicles. Significant reductions in purchase prices of new technology solutions will be necessary before they make a relevant contribution to total vehicle sales. This is a vicious circle as costs will not reduce until sales increase, and sales will remain low until costs come down (Folkson, 2014), as demonstrated by the reinforcement feedback loop. Subsidies for alternative technologies and taxes for old fleets may be needed to promote the entrance of more efficient vehicles into the market.

The fleet renewal process is also related to the scrappage of old vehicles, which depends on the vehicle's age, mileage, and residual value (Huo & Wang, 2012). While the decision to replace a vehicle with a greener model ultimately rests with the commercial entity that owns or operates the fleet, governments can regulate schemes to encourage the replacement of inefficient vehicles and offer green transport subsidies as dynamic levers to encourage the adoption of the most up-to-date technologies. Another important factor impacting fuel consumption is vehicle state of repair since poorly maintained vehicles consume more fuel (Greene & Façanha, 2019). Legal instruments regulating maintenance frequencies and vehicle taxes differentiated according to environmental and safety performance could also be taken as dynamic levers to increase the standard of the vehicles, induce fleet renewal and hence decrease emissions (Stelling, 2014).

The urgent need to promote the entry of new technology vehicles into the market results from the renewal process that generally takes a long time, considering vehicle economic lifetimes from 6 to more than 20 years (European Automobile Manufacturers Association, 2021). Progress towards renewing fleets has been uneven across countries, with developed nations adopting the cleanest Euro VI equivalent standards, while most developing countries still operate pre-Euro class vehicles (Miller & Jin, 2018). Developing countries face challenges in the fleet electrification process such as the development of battery charging networks, grid capacity, and affordability of vehicles. The import market of used ICE trucks from Europe and North America at cheaper prices tends to discourage developing countries to switch to low-carbon vehicles. Moreover, the longer life of low carbon trucks tends to delay their export as used vehicles, and the scarcity of raw materials and reliance on recycling will discourage the export of used batteries and fuel cells (McKinnon, 2020), making the process of decarbonising freight even more challenging for developing countries.

The delays related to technology development indicate a slow cycle and new alternative technologies will likely take decades to develop. The USA, Japan, and China dominate R&D funding for key climate technologies (United Nations Framework Convention on Climate Change, 2017) while developing countries lag in non-renewables innovation. Depending on the availability of technologies across borders, this aspect may impact the global dynamics of the implementation of decarbonisation policies.

The dynamic components of this submodel are the current fleet, vehicle purchase, and fleet scrappage. The reinforcing feedback loop between vehicles purchase and their prices shows that new technologies will not get into the market without incentives for users' acceptance and will not even be produced without a promising market outlook for vehicle manufacturers. It may take 5–15 years, in some cases longer (European Automobile Manufacturers Association, 2021), before innovations can penetrate the market, which means that the effects on the climate will take at least this long to materialise. To deal with all presented delays, implementing specific dynamic levers such as policies for fleet renewal are needed.

4.5. Promoting new energy sources

The fifth decarbonisation strategy is *Promoting New Energy Sources*, and alternative fuels with low carbon density to mitigate emissions. We considered alternative fuels those zero emissions such as electrification and hydrogen, as well as low-intensity emissions fuel, such as biofuels. Figure 6 shows the variables considered in this submodel.

The adoption of one type of fuel over another depends on (1) financial attributes (vehicle purchase price, fuel price, and efficiency); (2) technical attributes (driving range, recharging time, performance, brand, diversity, and warranty); (3) infrastructure attributes (charging/refuelling infrastructure availability); and (4) policy attributes (reducing purchase price, purchase tax, annual tax, and toll; Liao et al., 2017). The two reinforcement feedback loops show that

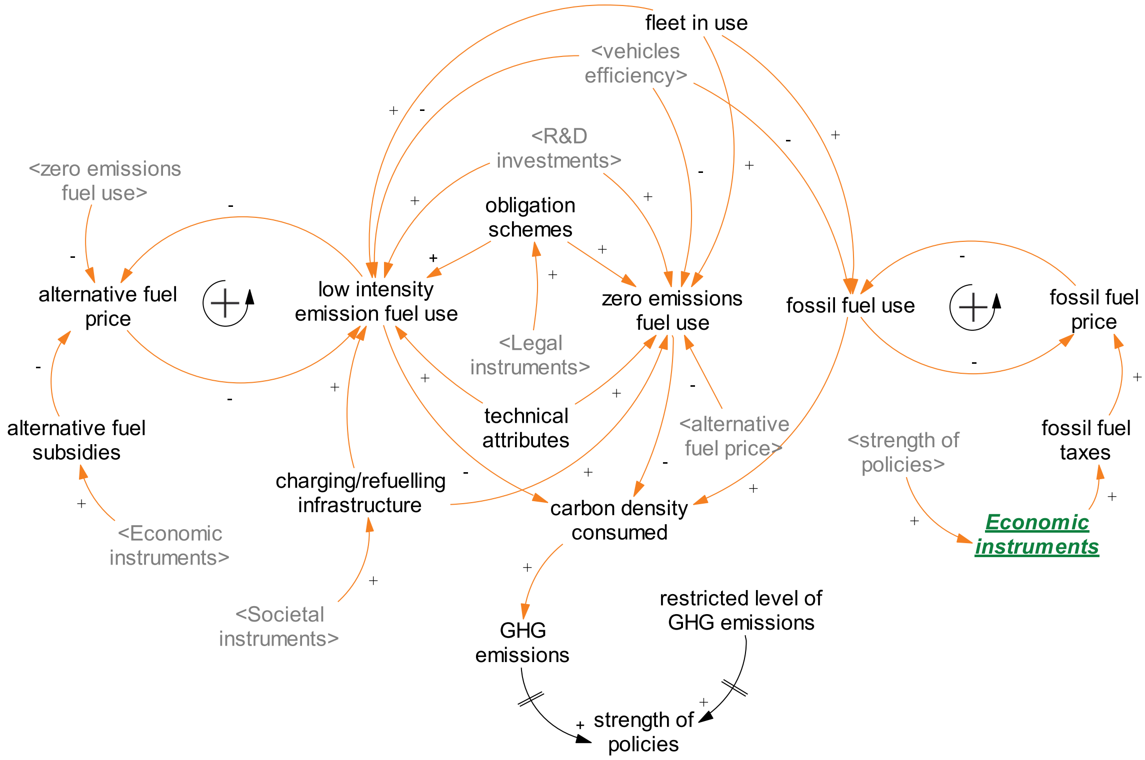

Figure 6. Promoting new energy sources submodel.

prices of both fossil and alternative fuels have to be considered as they compete and influence the adoption of one over another. Moreover, the gradual availability of charging or refuelling service points is a key factor for successful alternative fuel adoption over time.

Fuel price depends on production or import costs, and transport may compete with other sectors, bringing implications for alternative energy supply systems. For example, the rise in oil prices led to a sharp increase in biofuel production. However, some commodities can be used either as food, feed or to make biofuels. Therefore, food versus fuel is the dilemma regarding the risk of diverting farmland or crops for liquid biofuel production to detriment of the food supply on a global scale (Demirbas, 2011). The greater the alternative fuels subsidies and their demand, the greater will be its competitiveness for energy resources in other sectors (Mansson, 2016), which brings a complex dynamic among the stakeholders involved, affecting the adoption of biofuels over time. A similar thing happens to hydrogen, for which the transport sector seems to be less interesting than the heavy industry market. Even when green hydrogen production costs turn to be more competitive by 2030, according to the International Renewable Energy Agency (International Renewable Energy Agency, 2020), there will be competition between these sectors, driving up the price of hydrogen for transport. Such decades-long transition programmes should take these dynamics into account and make them transparent for the transport sector.

Fuel taxation for fossil fuels or subsidies for alternative fuels may stimulate the adoption of renewables. Raising diesel prices can be an effective approach when aiming to speed up alternative fuel market diffusion (Capros et al., 2016). Legal instruments are also dynamic levers to promote the alternative fuels penetration rate into the market such as the obligation schemes or blending targets, e.g., to include a certain percentage of biodiesel in fuels (Stattman et al., 2013). Folkson (2014) highlights the compatibility of renewable liquid fuels with current technologies as a benefit. Teixeira et al. (2020) discuss preferences for business-as-usual fuels over more environmentally friendly options. Liquid alternative fuels can be deployed faster than technologies that require heavy investments in technology and infrastructure. However, biofuels will not be enough to meet emission reduction targets and there is an additional need for alternative electrified powertrains with noteworthy emission reduction potentials (Plötz et al., 2019). In other words, accelerating the adoption of low or zero-carbon technologies is essential to achieving deep system decarbonisation. Many factors influence their adoption, such as users' preferences, positive experiences of other companies, and payback time (Boer et al., 2013). High costs, limited range, long recharging times, and a lack of adequate fast-charging networks are some of the drawbacks still related to cleaner technologies. A slow entrance into the market of new technologies hinders the option to purchase modern second-hand vehicles, and the barrier of their high costs will remain until this secondary market is available. It is probably for this reason that adoption has only started in countries with generous subsidy schemes. In addition, the climate mitigating effect of these vehicles will only be effectuated once green energy sources become available at the scale needed. The modelling of these processes into the decades ahead could help to optimise the subsidy policies.

5. Discussion

Based on the proposed conceptual dynamic model for freight transport decarbonisation, in this section, we discuss the feedback loops between the submodels that integrate the dynamics of the system. An important aspect of the proposed model worthy to highlight is that the submodels of each decarbonisation strategy are interconnected, through shadow variables, forming feedback loops that are not directly visualised. This approach is important to show the conflicts and affinities that can exist between the different decarbonisation strategies since many efforts are required to decarbonise the freight sector, and interventions can result in side effects not understood when implementing each strategy individually. The feedback loops that integrate the proposed model are presented in Figure 7.

The first four indirect feedback loops identified between the submodels describe the rebound effect of more efficient freight transport, leading to transport cost reductions, lower products prices, and thereby increased demand, due to the effect of cost elasticity of road transport performance (Ferrari, 2016; Jong et al., 2010), which reinforces efficiency due to economies of scale. Transport efficiency is expressed in terms of better vehicle utilisation, freight demand by mode, vehicle efficiency, and fuel prices, dynamically linking the related decarbonisation strategies over time.

The first feedback loop shows that the increase in vehicle loading reduces transport cost, influencing product prices, goods demand, freight demand by mode, shipment amount, and vehicle loading in a reinforcing loop.

(i) vehicle loading $\rightarrow^{-}$ transport cost $\rightarrow^{+}$ product prices $\rightarrow^{-}$ goods demand $\rightarrow^{+}$ freight demand by mode $\rightarrow^{+}$ shipment amount $\rightarrow^{+}$ vehicle loading (reinforcing loop).

The second feedback loop represents the dynamics of vehicle efficiency gains, reducing fuel use, and influencing fuel price, fleet costs, vehicle loading, transport costs, product price, goods demand, and freight demand by mode, leading to a reinforcement of vehicle efficiency.

(ii) vehicles efficiency $\rightarrow^{-}$ fuel use $\rightarrow^{-}$ fuel price $\rightarrow^{+}$ fleet cost $\rightarrow^{+}$ vehicle loading $\rightarrow^{-}$ transport cost $\rightarrow^{+}$ products price $\rightarrow^{-}$ goods demand $\rightarrow^{+}$ freight demand by mode $\rightarrow^{+}$ vehicles efficiency (reinforcing loop).

The third feedback loop indicates that both fossil fuel and alternative fuel prices increase the fleet cost

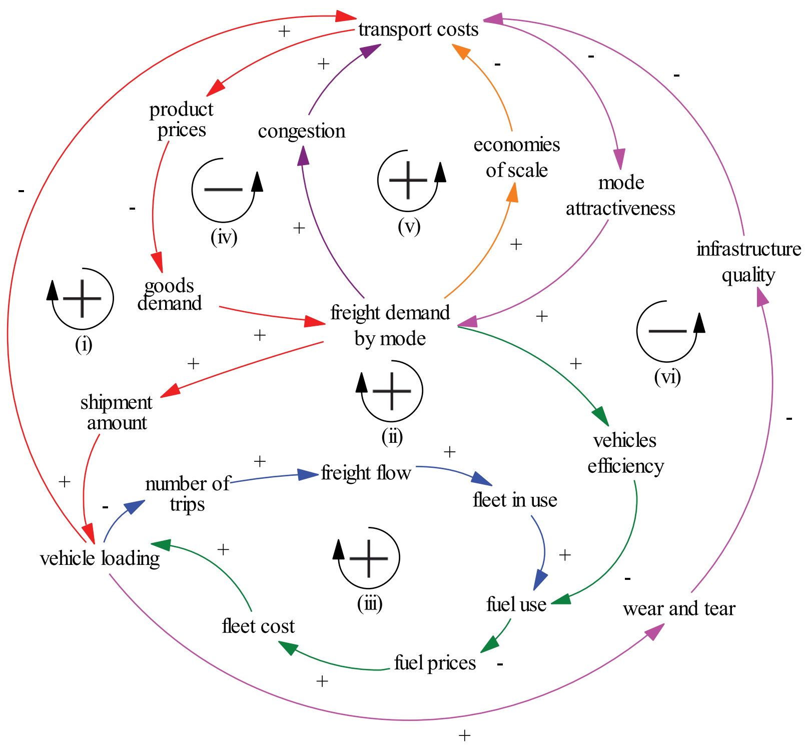

Figure 7. Feedback loops between the submodels of freight transport decarbonisation system.

that induces better vehicle utilisation, influencing transport costs, products price, goods demand, freight demand by mode, shipment amount, vehicle loading, number of trips, freight vehicle mileage, the fleet in use, and fuel use, leading to a reinforcing loop of fuel prices.

(iii) fuel price $\rightarrow^{+}$ fleet cost $\rightarrow^{+}$ vehicle loading $\rightarrow^{-}$ transport cost $\rightarrow^{+}$ products price $\rightarrow^{-}$ goods demand $\rightarrow^{+}$ freight demand by mode $\rightarrow^{+}$ shipment amount $\rightarrow^{+}$ vehicle loading $\rightarrow^{-}$ number of trips $\rightarrow^{+}$ freight vehicle mileage $\rightarrow^{+}$ fleet in use $\rightarrow^{+}$ fuel use $\rightarrow^{-}$ fuel price (reinforcing loop).

The fourth feedback loop shows that the freight demand by mode also influences congestion, transport cost, product price, goods demand, and freight demand by mode. Especially for roadways, the increase in demand can lead to congestion given the limited capacity of roads, discouraging the use of this transport mode.

(iv) freight demand by mode $\rightarrow^{+}$ congestion $\rightarrow^{+}$ transport cost $\rightarrow^{+}$ products price $\rightarrow^{-}$ goods demand $\rightarrow^{+}$ freight demand by mode (balancing loop).

The fifth feedback loop relates freight demand by mode, economies of scale, transport costs, product prices, goods demand, and freight demand by mode. This loop is especially important for alternative modes (railways and waterways) as the increase in freight flow and service frequency play an important role in the reinforcement of their use due to economies of scale.

(v) freight demand by mode $\rightarrow^{+}$ economies of scale $\rightarrow^{-}$ transport cost $\rightarrow^{+}$ products price $\rightarrow^{-}$ goods demand $\rightarrow^{+}$ freight demand by mode (reinforcing loop).

These five feedback loops are particularly important for the first stage of decarbonisation, as efficiency improvements are interesting, not only because of their environmental benefits but also because they are economically profitable. As the efforts to reduce CO_2 emissions become more expensive, the transport costs will not be reduced anymore (or will even increase). Therefore, dynamic levers should be combined to reduce the rebound effect of efficiency gains on the freight transport demand to mitigate emissions.

The sixth and last feedback loop shows that the vehicle loading is directly related to the wear and tear of the infrastructure used. Then, wear and tear influences infrastructure quality, transport costs, mode attractiveness, freight demand by mode, shipment amount and finally returning the effect to vehicle loading in a balancing feedback loop.

(vi) vehicle loading $\rightarrow^{+}$ wear and tear $\rightarrow^{-}$ infrastructure quality $\rightarrow^{-}$ transport costs $\rightarrow^{-}$ mode attractiveness $\rightarrow^{+}$ freight demand by mode $\rightarrow^{+}$ shipment amount $\rightarrow^{+}$ vehicle loading (balancing loop).

Since wear and tear mostly affect the roadway mode, this feedback loop indicates that increasing truck loading undermines pavement conditions and the attractiveness of roadways. The effect of this loop on roadway use will depend on many other factors outside the loop. Moreover, this effect is considered negligible for railways and waterways.

In summarising, our dynamic causal loop diagram contributes to understanding how complex patterns of freight decarbonisation are as an endogenous consequence of the structure of a system ruled by multiple non-linear feedbacks, and allowing for strategy and policy analysis. The broad boundary model we proposed captures several of the most important feedbacks governing the behaviour between the freight demand patterns, choice of transport modes, utilisation of vehicle capacity, fleet efficiency improvement, and alternative fuels diffusion. Although no quantitative results are provided at this stage, this comprehensive view of the freight decarbonisation system, provided by the qualitative model, underscores the importance of applying a set of policies rather than isolated actions. For example, it would not be enough just to promote policies to encourage low-carbon technologies, but it is also necessary to impose restrictive policies on internal combustion vehicles so that the environmental and economic advantages are reinforced in a combined way. Another example that highlights this aspect is the rebound effect of road transport efficiency increase, which end up reducing costs and increasing demand. In this sense, it is important to have demand management policies, so that the rebound effect does not eliminate the environmental advantages obtained by increasing efficiency.

6. Conclusions

In this paper, a causal loop diagram for studying the dynamics to decarbonise the freight transport system has been developed. The contributions of this model can be summarised as follows:

- The model provided an overview of the freight transport system. This approach shows that the system is not composed of isolated subsystems, but that they interact with each other, providing the dynamic behaviour of the whole system;

- The model linked five decarbonisation strategies, showing the dynamics and feedback loops between their main components to evidence that these strategies affect each other in a reinforcing or balancing way;
- The model pointed out the dynamic levers as policies to promote or stimulate decarbonisation, which should be the focus of policymakers; and
- The model provides an integration of distinct decarbonisation strategies subsystems allowing more in-depth studies and filling a gap identified in the literature, which collaborates with the developments in this academic field.

The main dynamic levers identified in the proposed causal loop diagram are directly and indirectly related to policies' implementation and divided into economic, legal, social, and knowledge-based instruments, such as taxes or subsidies, R&D, information, and maturation of new technologies, infrastructure investments for alternative modes or more efficient vehicle and fuel adoption. Besides the decarbonisation strategies and specific policies within each strategy, acting as leveraging points, the identified feedback loops are also dynamic levers that show how the whole system is connected. It shows to policymakers the possible indirect side effects of their policies that could defeat the desired results. All of these dynamic levers take part in the system's change over time, affecting the freight transport demand, the infrastructure used, the fleet technology, and how its use is optimised.

Although full decarbonisation might only be achieved with a radical technological change, the presented strategies all contribute towards freight transport decarbonisation. Given the magnitude of the emissions reduction required over the next few decades, decarbonisation must be approached systematically, exploiting all the opportunities. In this sense, the proposed model contributes to showing the big picture of the system with its feedback loops and dynamic levers which are critical to achieving the desired results.

This qualitative analysis contributes to the literature with insights about the dynamics of implementation of decarbonisation strategies that can delay or speed up the system's change over time due to the behaviour of exponential growth or balancing feedback loops (polarities are an important result of our work). However, we recognise that with the current work it is not possible yet to set priorities for policies, a quantitative model simulating their impacts within the system is required.

For further research, this causal loop diagram should be converted into an empirical quantitative model, and scenarios should be simulated considering uncertainties about technology, policies, lobby practice, regulatory pressure, and market acceptance. As a key factor for new technologies adoption, the market acceptance, as well as the organisational buying process and the behaviour analysis, should be further investigated for a more reliable and holistic understanding of the market penetration of alternative powertrain concepts in the market of heavy commercial vehicles.

As a general qualitative model, it can be applied to any geography, since the assumptions taken to construct the model are not specific to a region. However, as the contexts of countries or regions differ, these should be considered in the quantitative approach to show the effect of decarbonisation strategies implemented in distinct realities. For example, besides mandatory regulations, some complementary policy instruments, implemented voluntarily, have emerged in some countries to encourage sustainable freight practices, such as the SmartWay programme in North America (Bynum et al., 2018), the China Green Freight Initiative in Asia (Liu et al., 2019b), the Lean and Green programme in Europe (Kaledinova et al., 2015), and the "FRET21" in France (Touratier-Muller & Ortas, 2021). However, other countries differ from this reality. In India, Kumar (2021) underlines a lack of coordination between freight logistics organisations and public entities. In Brazil, apart from the use of enforcement legislation, Froio and Bezerra (2021) point out the difficulties of involving shippers in sustainable freight projects, while other policies such as increasing the use of biofuels can be more easily explored due to the production facilities in this country. All these context specificities should be considered.

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