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System-level impacts of electrification on the road freight transport system: a dynamic approach

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Abstract

Purpose – Electrification is a promising solution for decarbonising the road freight transport system, but it is challenging to understand its impact on the system. The purpose of this research is to provide a system-level understanding of how electrification impacts the road freight transport system. The goal is to develop a model that illustrates the system and its dynamics, emphasising the importance of understanding these dynamics in order to comprehend the effects of electrification.

Design/methodology/approach – The main methodological contribution of the study is the combination of the multi-layer model with system dynamics methodology. A mixed methods approach is used, including group model building, impact analysis, and literature analysis.

Findings – The study presents a conceptual multi-layer dynamic model, illustrating the complex causal relationships between variables in the different layers and how electrification impacts the system. It distinguishes between direct and induced impacts, along with potential policy interventions. Moreover, two causal loop diagrams (CLDs) provide practical insights: one explores factors influencing electric truck attractiveness, and the other illustrates the trade-off between battery size and fast charging infrastructure for electric trucks.

Originality/value – The study provides stakeholders, particularly policymakers, with a system-level understanding of the different impacts of electrification and their ripple effects. This understanding is crucial for making strategic decisions and steering the transition towards a sustainable road freight transport system.

Keywords Road freight transport system, Logistics, Electrification, Electric trucks, System-level effects, System thinking, System dynamics, Causal loop diagram

Paper type Research paper

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1. Introduction

Road freight transportation is responsible for more than 7% of total CO_2 emissions worldwide and is expected to grow to 16% in 2050 (McKinnon, 2018). To achieve sustainability goals, a transition to fossil-free road freight transport is required (McKinnon, 2018), and electrification is expected to be a key solution.

The electrification of road freight transport requires significant changes in the current system, involving a multitude of actors who will need to adjust their behaviour and decision-making. This shift will involve changes in energy provision, the transformation of vehicles, the development of energy infrastructure, and new digital services. Moreover, the limited range and need for recharging during operation will change the rules for transport planning. Transport systems typically involve a range of actors, such as vehicle manufacturers, transport service providers, and transport buyers (Gutierrez and Huge-Brodin, 2022), but electrification adds new actors to the list, such as electricity and infrastructure providers and software developers. The electrification of freight transport thus proposes monumental complexities, where the performance of the system still needs to be assessed beforehand in order to make strategic decisions. This reflects on the actors described above but certainly also on the policymakers, who are setting the rules of the game of electrifying transportation.

The challenge of strategic decision-making is further emphasised by the fact that electrification of the road freight transport system involves several dynamics. One example is the "chicken-and-egg" dynamics problem between market adoption of electric trucks (e-trucks) and charging infrastructure expansion. Simply put, the adoption of e-trucks requires a sufficient network of charging stations, but the incentives for building charging infrastructure are low if there are no trucks that can use them. This raises the question of how to effectively balance the increased number of e-trucks with the expansion of charging infrastructure. Finding a solution requires coordination between the needs of truck manufacturers, infrastructure providers, and policymakers.

Therefore, it is crucial to have a system-level understanding of the impact of electrification on the road freight transport system. This transition involves changes in various components that are interconnected and cannot be considered separately. A change in one component leads to changes in other components and the entire system (Browne *et al.*, 2022). Additionally, different involved actors have their own agendas, and it is challenging to align these agendas together. Moreover, policymakers do not occupy a privileged position outside the system (a "cockpit") from which they can manipulate the transportation system (Geels, 2012). Instead, they are part of the system and bound by their dependence on other actors. Thus, the lack of a centralised leadership or governance structure within the transportation system makes it difficult to effectively manage the required changes.

In general, up until now, most research into the electrification of freight transport has been centred on technological aspects (Gillström *et al.*, 2024). Studies of the complex system at a higher system level, including actors, have so far been mostly absent. Nonetheless, many projects have recently started to address the actors' situation, for example, within the research programme Triple F, funded by the Swedish Transport Administration (Triple, 2023). However, these studies are typically focused on narrow parts of the freight transport system, such as the transport provision chain and the connection between truck manufacturers and their customers, the hauliers. The overarching system level has only been sparsely addressed; hence, this study seeks to contribute to the system-level knowledge of how different actions or decisions affect the system as a whole.

To accomplish this, we utilised a system dynamics (SD) methodology, which is useful for modelling the dynamics of complex systems and incorporating diverse stakeholder perspectives. We engaged experts to develop an SD model to describe the dynamics of electrifying the freight transport system. To structure our findings, we adopted the multi-layer model presented by Wandel *et al.* (1992) and developed by Browne *et al.* (2022), consisting of three system layers (supply chain, transportation, and infrastructure layers) and two connecting markets (market for transportation services and traffic market). This well-established model is widely used in the literature to analyse the freight transport system across various layers, particularly the infrastructure layer, which is critical for the transition to electrification.

Combining the multi-layer model with SD methodology, we develop a conceptual dynamic model on which the direct and induced impacts of electrification, along with potential policy interventions, are mapped. The paper is organised as follows: Section 2 reviews literature, Section 3 outlines methodology, Section 4 presents results, Section 5 discusses findings, and Section 6 concludes the paper.

2. Literature overview

There is a growing body of research on the potential impacts of electrification on the road freight transport system. We organised this literature using the multi-layer model (Wandel *et al.*, 1992; Browne *et al.*, 2022) categorising each study based on the specific layer it investigates. The references provided here should be viewed as examples rather than an exhaustive list. Subsequently, we explored studies that adopt a holistic system-level approach, considering all layers. Table 1 offers a structured overview of research across these layers, highlighting research gaps and clarifying the contribution of our study to the field.

Within the *infrastructure layer*, some studies investigate the required infrastructure for transitioning to e-trucks, such as the spatial distribution of charging infrastructure (Sauter *et al.*, 2021; Speth *et al.*, 2022) and power demand and grid impact (Shoman *et al.*, 2023; Zhu *et al.*, 2020). Tong *et al.* (2021) link e-trucks, charging infrastructure, and the power grid to estimate the health and climate benefits of full electric truck adoption.

Aspects covered	References
Supply chain layer demand and supply chain, structural decisions	Gillström *et al.* (2024), Gutierrez and Huge-Brodin (2022)
Market for transportation services battery size impacts on payload capacity	Magnusson and Berggren (2018), Morganti and Browne (2018)
Transportation layer energy consumption, carbon intensity and emissions	Gao *et al.* (2017), Gustafsson *et al.* (2021)
Traffic market financial and economic aspects, battery sizes, routing challenges, and charging strategies	Al-Hanahi *et al.* (2022), Basma *et al.* (2021), Noll *et al.* (2022), Nykvist and Olsson (2021), Parviziomran and Bergqvist (2023), Raeesi and Zografos (2022)
Infrastructure layer location of charging infrastructure, power demand and grid impact	Sauter *et al.* (2021), Shoman *et al.* (2023), Speth *et al.* (2022), Tong *et al.* (2021), Zhu *et al.* (2020)
Static system-level overview considering different layers and couplings between activities and resources	Browne *et al.* (2022), Langevin and Riopel (2005), McKinnon (2018), Wandel *et al.* (1992)
Dynamic system-level overview considering freight transport in general by using system dynamics, but not considering electrification specifically	Ghisolfi *et al.* (2022a, b)
Dynamic system-level overview focused on the impact of electrification within the freight transport system considering different layers and the dynamics between them, as well as the specific impact of electrification at the system-level	Current study

Source(s): Table by authors

Table 1. Summary of existing research on electrification impacts across multi-layer models, highlighting gaps addressed by this study

Several studies have focused on the impacts of electrification on the vehicle's operation to fulfil a transport task, i.e. within the *traffic market* and *transportation layer*. These studies primarily focus on the financial aspects, estimating the effects of electrification on the total cost of ownership for various scenarios (e.g. Basma *et al.*, 2021; Noll *et al.*, 2022; Parviziomran and Bergqvist, 2023). Other research efforts have delved into operational factors such as battery sizes (Nykvist and Olsson, 2021); routing challenges (Raeesi and Zografos, 2022); charging strategies (Al-Hanahi *et al.*, 2022); energy consumption (Gao *et al.*, 2017); and carbon intensity and emissions (Gustafsson *et al.*, 2021).

Few studies focus on the *market for transport services* and *supply chain*, the top two layers. In particular, the demand side, which is related to the supply chain layer, is seldom present in the literature on freight transport electrification (Gutierrez and Huge-Brodin, 2022). Gillström *et al.* (2024) also identify a research gap in the study of structural decisions within the supply chain, particularly focusing on collaboration and role changes among various actors. Furthermore, only a few studies explore how battery size affects payload capacity, which directly impacts the logistics system (Magnusson and Berggren, 2018; Morganti and Browne, 2018).

These previous studies typically focus on effects within one layer or interconnections between two layers (most often *transportation layer* and *traffic market*) or consider one aspect only (e.g. the optimal location of charging infrastructure). While these studies are highly relevant and are required to increase understanding of the impacts of electrification on road freight transport, to make long-term strategic decisions, they need to be complemented with a holistic, system-level understanding.

Few studies adopt a holistic approach to analysing the freight transport system in general, without specifically focusing on electrification. Wandel *et al.* (1992) introduce a multi-layer model, and Browne *et al.* (2022) draw on this multi-layer model and discuss couplings between activities and resources in the layers. In particular, Browne *et al.* (2022) call for more research on system-level understanding, suggesting that a deeper understanding of the couplings between system components could enhance policy-making and innovation strategies. McKinnon (2018) describes how different features of the logistics system can affect its environmental performance. Langevin and Riopel (2005) map out 48 critical logistics decisions, emphasising their interconnectedness and the impact of each decision on others within the logistics system. However, electrification is not specifically addressed in these studies. Furthermore, these studies do not thoroughly investigate complex dynamics between different layers, despite mentioning the importance of understanding interactions across system layers.

To assess the impact of electrification on the freight transport system, it is crucial to understand the system's dynamics and how changes caused by electrification ripple through it. SD is one appropriate method for understanding and describing these complex dynamics (Sterman, 2000). Shepherd (2014) provides an overview of the application of SD in transportation and notices that this approach is particularly effective for system-level modelling of the relationships among various actors within the system. Some studies use SD to explore the diffusion of alternative fuel vehicles in passenger transport (Keith *et al.*, 2020; Struben and Sterman, 2008), while others specifically target electric passenger vehicle adoption (Feng *et al.*, 2019; Gómez Vilchez *et al.*, 2020). Fewer studies have used SD to assess freight vehicle adoption (Bian and Xu, 2024; Shafiei *et al.*, 2018). However, these studies mainly focused on the *infrastructure layer* and *traffic market* rather than a holistic system-level perspective.

In a more recent overview, Ghisolfi *et al.* (2022a) present a literature review of SD models targeting freight transport decarbonisation, noting that only three out of fifty articles address electrification and highlight a shortfall in system-level studies. In a related work, Ghisolfi *et al.* (2022b) present a conceptual SD model based on the five decarbonisation policy instruments outlined by McKinnon (2018). This model does not explicitly study electrification, but it considers electrification as one of several alternative fuels; thus, it does not take the particular complexities and consequences of electrification into account.

Building on existing literature, this study aims to address the identified gap by focusing specifically on the effects of electrification and examining the dynamics of the freight transport system. By providing a system-level understanding, this study serves as a foundation for researchers to pursue further research on the topic and to enhance the existing knowledge base. Table 1 provides an overview of the existing literature and illustrates how our research contributes to filling this gap.

3. Methodology

Systems thinking is a theoretical anchor that focuses on understanding entire systems and their interactions rather than isolating individual components, which is useful for studying complex dynamic systems (Ramage and Shipp, 2009). The freight transport system is one such system, involving multiple stakeholders such as shippers, hauliers, infrastructure providers, and regulators, making system thinking particularly relevant to our study (Shepherd, 2014).

To apply systems thinking, we use system dynamics and, in particular, CLDs as a methodological tool. CLDs qualitatively map cause-and-effect relationships and identify feedback loops, reinforcing loops that amplify changes and balancing loops that maintain system stability (Sterman, 2000). Feedback loops explain how a change in one variable affects other variables and feeds back to the initial variable (Sterman, 2000).

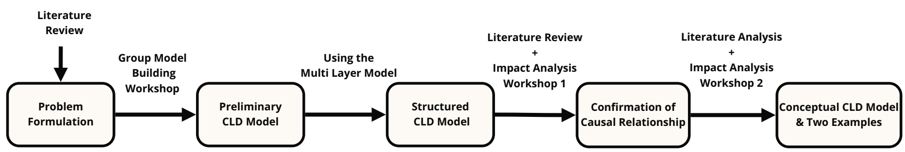
This study utilises CLDs to explore the interactions among variables and stakeholders, revealing how changes in one variable can create ripple effects throughout the system. We used a mixed-methods approach, including group model building, impact analysis, and literature analysis, to gather qualitative data and develop our SD models (Luna-Reyes and Andersen, 2003). This process, depicted in Figure 1 and elaborated in the following subsections, involved the participation of 28 experts.

3.1 Group model building workshop

As the first step, a Group Model Building (GMB) workshop was convened with 13 experts from public authorities, industry, and academia. GMB is a participatory approach within SD methodology, where stakeholders collaborate to create a dynamic model of a complex system to understand the underlying causes and feedback loops that drive system behaviour (Hovmand, 2014; Wilkerson *et al.*, 2020).

During the workshop, participants were introduced to SD modelling and problem formulation, which originated from a general literature review. Four main activities were carried out: *hopes and fears*, *variable elicitation*, *graphs over time*, and *initiating a causal loop diagram* (see Andersen and Richardson, 1997; Luna-Reyes *et al.*, 2006 for descriptions of the activities). The workshop utilised Miro for collaborative content creation, and Zoom for main sessions and breakout room activities.

Each group developed a CLD, which was then refined into a preliminary CLD through iterative analysis and discussion among the authors. Table S1 and Figure S1 in the Supplementary Materials present the workshop agenda and an example output. It should be noted that the



Source(s): Figure by authors

Figure 1. Methodological process of the research, a mixed approach of group model building, impact analysis, and literature analysis

workshop explored the effects of automation, electrification, and digitalization on transportation, with the authors specifically extracting insights on electrification's impact on freight transportation for this study.

3.2 Using the multi-layer model to structure the model

The preliminary CLD developed during the GMB workshop was complex, with many interlinked variables and feedback loops. To structure these findings, we utilised the multi-layer model (Wandel *et al.*, 1992; Browne *et al.*, 2022). Applying this model to the preliminary CLD offered a structured view of how electrification impacts the road freight transport system, including the interactions between various layers and stakeholders.

3.3 Literature review and first impact analysis workshop

The third step involved conducting a literature review to identify and confirm variables and causal relationships in the structured CLD. Subsequently, a group of seven experts from the public authorities, industry, and academia conducted the first impact analysis workshop to verify the structured CLD and analyse the impact of electrification on the different layers of the freight transport system. Figure S2 in the Supplementary Materials shows a sample output from the workshop. This step helped to validate the variables and causal relationships identified in the previous steps and ensure that the model was grounded in literature and approved by the expert group.

3.4 Literature analysis and second impact analysis workshop

In the final step, a detailed literature analysis was carried out to refine and validate variables and causal relationships in the model. Additionally, two example CLDs were developed to capture the real-world dynamics of the impact of electrification across different layers. During this step, eight experts from academia, all engaged in electrification and freight transport projects, convened for the second impact analysis workshop. This workshop served as a platform for sharing insights and knowledge regarding the potential impacts of electrification on the system. Figure S3 in the Supplementary Materials shows a sample output from the workshop. The discussions among these experts, who had already conducted numerous interviews and in-depth discussions on the topic, aimed to extract and combine their collective knowledge. The result from this workshop was condensed into the potential impacts of electrification on the road freight transport system, classifying them as direct or induced, inspired by Milakis *et al.* (2017).

3.5 Quality of the research process

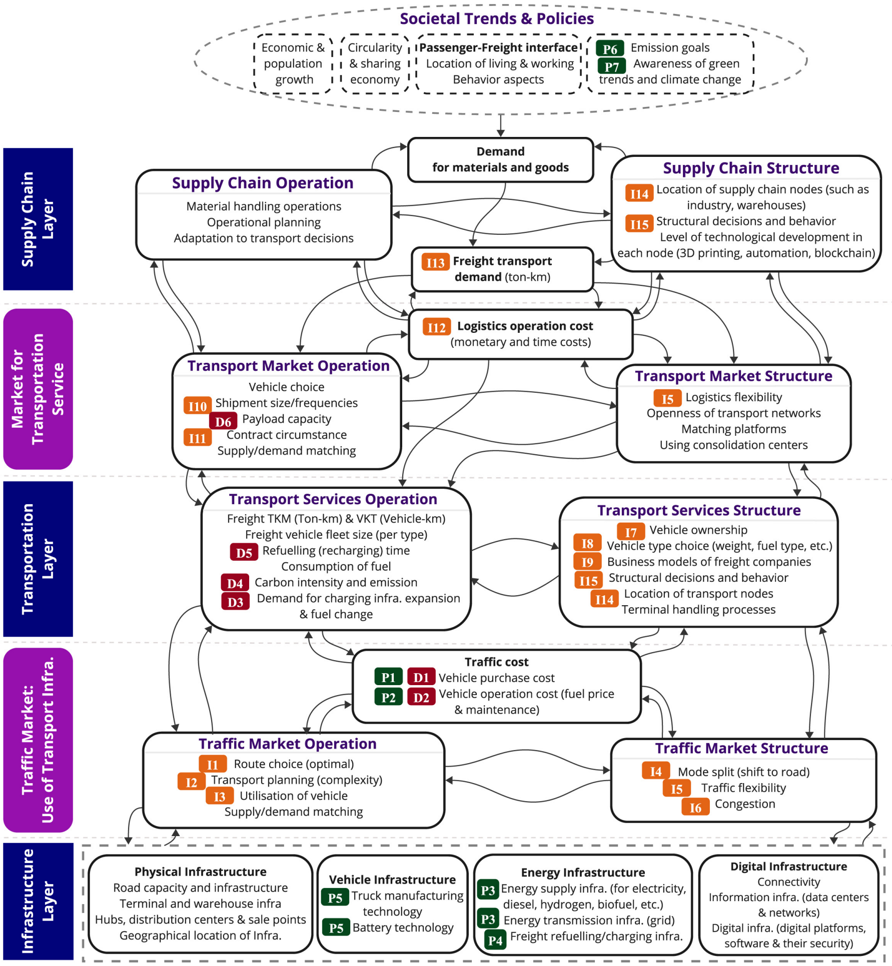
Sterman (2000) outlines key considerations that should be satisfactorily addressed to gain confidence in a SD model: (1) *Defining purpose and model boundaries:* The model's purpose is established during the problem formulation phase by literature reviews and internal author sessions. Model boundaries are defined in the GMB workshop through the variable elicitation activity. (2) *Structure of the model based on real-world decision-making:* The model's structure is based on real-world data from academic literature, expert groups, and the authors' knowledge by conducting a GMB workshop, two impact analysis workshops, several internal author sessions, and a detailed literature review. (3) *Documentation, reproducible process, and result:* The entire research process, from design to analysis, is meticulously documented to ensure transparency and facilitate future research. The reproducibility aspect is, however, fluid in this case: as development and knowledge on freight transport electrification are fast-moving, future research following the same process may alter some results.

4. Results

This section presents the study results: The conceptual multi-layer dynamic model visualises the complex causal relationships and illustrates how electrification impacts the system. Two example CLDs exemplify the dynamics between factors influencing e-truck attractiveness and battery size selection.

4.1 Conceptual multi-layer dynamic model

The conceptual multi-layered dynamic model is presented in Figure 2. First, we discuss the dynamics of the road freight transport system in general and subsequently explore how electrification will impact the system. The model comprises three system layers: the *supply*



Note(s): Three different impacts are shown using colour codes: red for the direct impact of electrification (D1-D6), orange for the induced impact of electrification (I1-I15), and green for potential policy intervention (P1-P7)

Source(s): Figure by authors

Figure 2. An overview of the conceptual multi-layer dynamic model, highlighting the separation of operational and structural variables in different layers

chain layer, wherein materials are produced, bought, and sold; the *transportation layer,* wherein transportation takes place; and the *infrastructure layer,* which contains the roads and the infrastructure. Between these layers, there are two connecting markets: the *market for transportation services*, where transport demand meets supply, and the *traffic market,* where transportation uses the infrastructure.

There are several dynamics both within and between the layers. To shed light on dynamics within the layers, the variables are categorised into *"operation"* and *"structure"* categories, inspired by Aronsson and Huge Brodin (2006). Operational variables are important for day-to-day decision-making and short-term planning, while structural variables refer to strategic decisions that have a long-term impact on the system. There are also dynamics between the different variables within each category, but they are not explicitly illustrated for simplicity. It should be noted that Figure 2 is not a complete or definitive list of all relevant variables; rather, it is intended to provide some example variables to illustrate the broader picture of the system and its dynamics. Furthermore, the direct and induced impacts of electrification, along with potential policy interventions, are mapped on the model to illustrate how electrification influences various layers and how these changes diffuse throughout the system.

4.1.1 Dynamics of the road freight transport system in general. The "*supply chain layer*" represents freight transport demand in tonne-kilometres, which is derived from the need for companies to move materials and goods. In the dashed oval at the top of Figure 2, "societal trends and policies" represent broader external factors that could impact the system. These include economic and population growth, circularity, the sharing economy, passenger living and working locations, behavioural patterns, and climate-related policies. These landscape factors influence the supply chain and the demand for materials and goods.

The structural variables in the supply chain layer include the location of supply chain nodes (e.g. industrial sites, warehouses), structural decisions and behaviours, and the level of technology development (e.g. 3D printing, automation, and blockchain). The operational variables refer to activities such as material handling operations, operational planning, and adaptation to transport decisions. There is a dynamic relationship between the supply chain structure and operation variables, which both impact the demand for materials and goods. This, in turn, affects freight transport demand.

The "*market for transportation service*" is the interface where supply and demand for transportation services are matched. Logistics operation cost (monetary and time cost) is a key variable in the market that affects and is affected by freight demand and supply chain structure and operation. The interactions between transport buyers (e.g. goods owners and shippers) and transport service providers (e.g. freight companies, forwarders, and hauliers) in this market influence several transport and logistic decisions in both operational and structural aspects.

Operational aspects involve vehicle selection, shipment size, frequency of freight trips, payload capacity, contract circumstances, and matching transportation supply and demand. Structural variables encompass investments in logistics flexibility and the willingness to adapt to logistic solutions like transport networks, matching platforms, and consolidation centres. These structural factors indicate how actors can collaborate and benefit from the sharing economy. Within this layer, there is a dynamic relationship between logistics operation costs and both operational and structural variables.

The "*transportation layer*" is where the actual transportation takes place. Structural variables include vehicle ownership, type selection (e.g. weight and fuel type), freight companies' business models and decisions, node locations, and terminal handling processes. Operationally, variables include executed freight tonne kilometres, vehicle kilometres, fuel consumption, carbon intensity, emissions, demand for charging infrastructure, and refuelling/recharging time. There is a dynamic relationship between the transport service structure and operation variables, which both impact the traffic cost.

The “*traffic market (use of transport infrastructure)*” is where supply and demand for transportation infrastructure are matched. In the traffic market, the key variable is traffic cost, which includes vehicle purchase and operation costs. Operational variables encompass route selection, vehicle utilisation, transport and charging planning, and matching infrastructure supply and demand. Meanwhile, structural variables involve long-term decisions related to mode split, traffic flexibility, and congestion. There is a causal relationship between the operational and structural variables in the traffic market, with both influencing and being influenced by traffic costs.

The “*infrastructure layer*” can be divided into four main categories: (1) physical infrastructure, which includes roads, terminals, warehouses, hubs, distribution centres, and sales points; (2) vehicle infrastructure, which includes truck manufacturing and battery technologies; (3) energy infrastructure, which includes energy supply, transmission, and refuelling/recharging infrastructure; and (4) digital infrastructure, which includes all the necessary digital tools to connect vehicles and infrastructure and optimise their use, covering connectivity, information, and digital infrastructures.

4.1.2 Impact of electrification on the road freight transport system. During the workshops with the experts, a number of potential impacts of electrification on the road freight transport system were identified. Some of the impacts are “*direct*” consequences of electrification, such as the increased vehicle purchase cost, which is related to the e-truck and its purchase. Other impacts are “induced,” resulting from a ripple effect of direct impacts, and are related to the use of e-trucks, such as potential changes in routing to take charging needs into consideration. The impacts of electrification identified during the workshops are presented in Table 2, where they are also classified as direct and induced. Furthermore, the table also includes a set of potential policy interventions identified during the workshops. Many of the impacts have also previously been identified in the literature, and in those cases, references are provided in Table S2 in the Supplementary Materials. The intention is not to provide an exhaustive or precise list but rather to differentiate between various impacts and emphasise the importance of understanding the system’s dynamics to comprehend the effects of electrification. The impacts and policy interventions are mapped into the conceptual model in Figure 2.

4.2 Examples of the impact of electrification on the freight transport system

In this section, two example CLDs are developed to highlight the complex dynamics of the electrification impact on the road freight transport system. The direction of influence between two variables is indicated by a colour code, where green means influence in the same direction and red means influence in the opposite direction. The variables in the example CLDs are organised into the five system domains, and variables are appropriately placed in their corresponding layers.

4.2.1 Example 1, exploring the complexity of factors influencing the attractiveness of e-trucks. The first example CLD explores factors influencing e-truck attractiveness and their interconnected feedback loops, as shown in Figure 3. Table S3 in the Supplementary Materials provides details on the loops and dynamics of various variables.

In the reinforcing loop of “*awareness (R1)*,” as e-truck market share increases, technology awareness rises, which in turn increases e-truck attractiveness and leads to further market share. This loop is related to the diffusion model of new technologies, encompassing the influences of word of mouth, marketing, and social exposure (Rogers *et al.*, 2014; Sterman, 2000). The “*access to charging (B1)*” loop counterbalances this growth: with an increase in e-truck market share, the demand for e-truck charging rises, creating a market gap for e-truck charging infrastructures. This gap diminishes the attractiveness of e-trucks, consequently reducing their market share. To bridge the e-truck charging station gap, the “*investment in*

No.	Possible impact of electrification	Direction	Comments
	Direct Impact		
D1	Vehicle purchase cost	+	E-trucks, including batteries, are expected to be more expensive than their diesel counterparts.
D2	Vehicle operation cost (fuel per km & maintenance)	−	E-trucks are anticipated to have lower vehicle operational costs, including fuel per kilometre and maintenance.
D3	Demand for charging infrastructure expansion and fuel change	+	To operate e-trucks, a new charging network and electricity in the transport sector are necessary.
D4	Carbon intensity and emissions	−	E-trucks have lower emissions. Note that in the early stages of electrification adoption, emissions may rise due to emissions from infrastructure construction.
D5	Refuelling/recharging time	+	Recharging times for e-trucks are longer and more frequent compared to refuelling times for diesel trucks.
D6	Payload capacity	−	The weight of the battery reduces the payload capacity of e-trucks in weight-constrained applications
	Induced Impact		
I1	Route choice (optimal)	−	Detours might be needed to access charging points.
I2	Transport planning (complexity)	+	Charging planning leads to greater complexity in transport planning by fleet managers.
I3	Utilisation of vehicle	?	High purchase costs and reduced load capacity require higher e-truck utilisation rates for compensation. However, the time spent searching for a charging spot and waiting at stations may decrease the utilisation rate. Additionally, reduced noise emissions enable nighttime e-truck deliveries, potentially boosting their utilisation rates.
I4	Mode split (shift to road)	?	Adopting e-trucks might reduce total ownership costs and increase shifting from rail and marine transport to trucks for greater flexibility, profitability, and customer satisfaction.
I5	Traffic and logistics flexibility	−	Traffic flexibility is limited due to the complexities of charging and transport planning. Moreover, logistics flexibility is constrained by reduced load capacity.
I6	Congestion	+	Increased detours, charging queues, and additional trips (due to reduced payload capacity) can lead to more congestion in the system.
I7	Vehicle ownership	−	High purchase costs and uncertainty about residual value may lead to a shift to financial or operational leasing business models, and reduced vehicle ownership.
I8	Vehicle type choice (e.g. weight, fuel type)	?	In the initial phase of e-truck adoption, there are fewer options available to choose from.
I9	Business models of freight companies (complexity)	+	Freight companies will need to adjust their business models to accommodate e-trucks and complex charging planning, potentially requiring new income streams and new collaborations and partnerships.
I10	Shipment frequencies	+	Reduced payload might lead to decreased average shipment size and increased shipment frequencies.
I11	Contract circumstance	?	Contracts between transport buyers and freight companies should have longer durations to enable freight companies to make investments in e-trucks. Who should bear the additional costs incurred during the first phase of adoption: the shipper, the freight company, or the customer?
I12	Logistics operation cost (monetary and time costs)	+	Logistics operation costs may increase due to: i) reduced load capacity, resulting in more frequent shipments. ii) longer charging times, leading to less productive driving time. iii) potential detours to reach charging points

Table 2.
The direct and induced impacts of electrification on the road freight transport system, along with potential policy interventions

(*continued*)

I13	Freight transport demand (ton-km)	?	The impact of electrification on freight transport demand (induced demand) is uncertain, mainly because the total cost effect is uncertain.
I14	Location of nodes (supply chain and transportation layers)	?	Strategic location decisions for nodes in both the supply chain and transportation layers should consider accessibility to the grid and electricity network. Moreover, these nodes should be equipped with multiple charging infrastructures.
I15	Structural decisions and behaviour (supply chain and transportation layers)	?	For instance, beyond national and global emission targets, many companies, in both transport buyers and freight companies, set their internal emission goals, motivating the transition to e-trucks. These emission goals are defined mostly by transport buyers, which are larger companies with more financial resources compared to smaller, low-margin freight companies.
	Policy intervention		
P1	Vehicle purchase cost		Government incentives to reduce e-truck purchase costs.
P2	Price of fuel (electricity, diesel)		Government policies involve subsidising electricity prices to reduce the operational costs of e-trucks and taxing diesel fuel to make e-trucks more attractive.
P3	Energy supply and transmission infrastructure		Government investment in constructing renewable electricity power plants and upgrading the electricity grid network
P4	Freight refuelling/ charging infrastructure		Government incentives for charging station construction.
P5	Truck manufacturing and battery technology		Government investment in supporting innovations within e-trucks and battery technologies
P6	Emission goals		Governments, both at the national and international levels, are setting emission goals to motivate the adoption of fossil-free transport.
P7	Awareness of green trends and climate change		Investment in programmes aimed at educating customers, freight companies, and shippers about climate change and the importance of considering the climate impact of their activities

Note(s): Directions are denoted by: "+" for positive/increase, "–" for negative/decrease, and "?" for uncertain/limited evidence or no clear direction for change. Refer to Figure 2 for the positions of impacts and policy interventions
Source(s): Table by authors

Table 2.

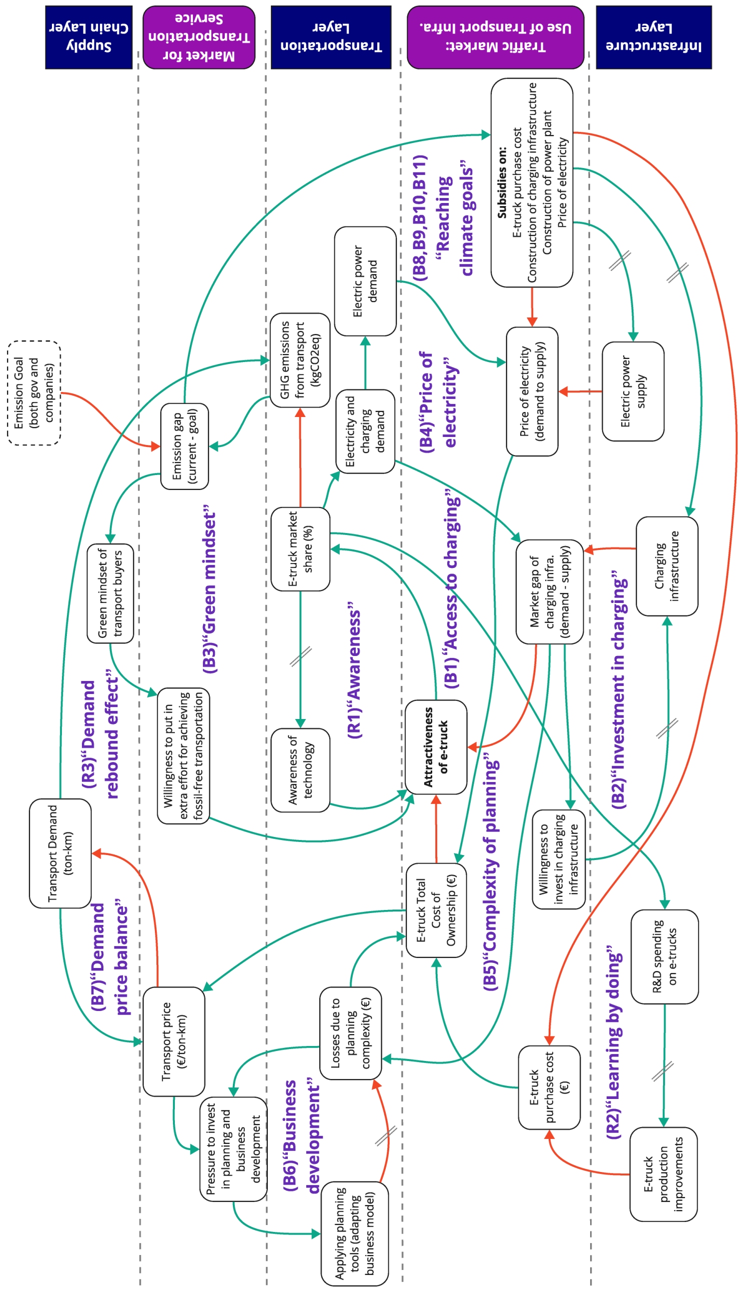
charging (B2)" loop comes into play: the market gap and potential profitability of charging stations prompt increased investment, leading to the construction of more stations with a time delay and closing the market gap.

Moreover, the transition to e-trucks is motivated by the emission gap (the difference between current emissions and the goal of emissions by both government and private companies), as shown in the "*green mindset (B3)*" loop: This gap motivates transportation companies to increase their efforts towards fossil-free transportation, increasing e-truck attractiveness, and closing the emission gap.

In the "*price of electricity (B4)*" loop, as the attractiveness and market share of e-trucks grow, so does the demand for electric power, causing a surge in electricity prices. This, in turn, increases the total cost of ownership for e-trucks, diminishing their attractiveness.

Furthermore, in the "*learning by doing (R2)*" loop, as the attractiveness and market share of e-trucks increase, there will be more budget for research and development in manufacturing companies. This, with a time delay, results in improved e-truck production and thus lower e-truck purchase costs, which increase e-truck attractiveness.

E-trucks introduce complexity in the planning (and performance) of transport missions, as illustrated by the "*complexity of planning (B5)*" loop. Growing e-truck attractiveness and market share lead to increased gaps in charging infrastructure, causing financial losses due to charging planning challenges and a decline in attractiveness. The "*business development*



Note(s): Green arrows indicate same-direction influence, and red arrows indicate opposite-direction influence. The loops are indicated with their names, and each loop is identified as either a reinforcing loop (R) or a balancing loop (B). Two vertical lines (||) on the arrows show a delay in the model

Source(s): Figure by authors

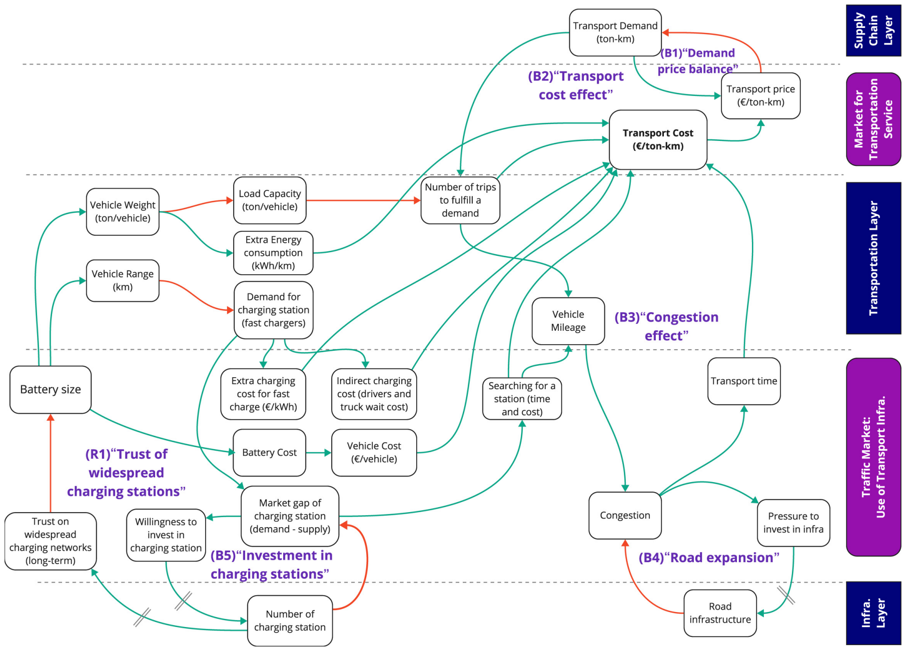
Figure 3.
A CLD model of the dynamics of the factors influencing e-truck attractiveness

(B6)" loop seeks to reduce these losses by investing in advanced planning tools and business solutions. These investments, with a time delay, decrease complexity-related losses, making e-trucks more attractive.

The "*demand price balance (B7)*" loop reflects a general demand-price relationship: cheaper transportation boosts demand, causing higher transportation prices (De Jong *et al.*, 2010). The "*demand rebound effect (R3)*" loop reveals a rebound effect in transportation (see Hymel *et al.*, 2010). The emission gap prompts government investment in e-trucks (e.g. subsidies on purchase cost and electricity price). These policies reduce e-truck costs by lowering transportation prices and stimulating higher total transport demand, ultimately resulting in increased emissions. In essence, attempts to reduce e-truck transportation costs may inadvertently raise transport demand and emissions.

There are four loops capturing policymakers' interventions to leverage e-trucks for "*reaching climate goals (B8–B11)*." When e-truck attractiveness and market share are low, higher emissions motivate policymakers to enhance e-truck attractiveness through subsidies on: (1) e-truck purchase costs, reducing e-truck total costs, and boosting attractiveness. (2) charging station construction, reducing the market gap for chargers with a time delay, and increasing e-truck attractiveness. (3) power plant production, leading to delayed increases in electricity supply, lowering electricity prices, affecting e-truck total costs, and enhancing attractiveness. (4) the price of electricity to decrease e-truck total costs, thereby increasing their attractiveness.

4.2.2 Example 2, a dynamic trade-off between battery size and fast charging infrastructure for e-trucks. The trade-off between e-truck battery size and building a widespread network of fast charging infrastructure is an important question for both industry and academia. Although seeking the optimal trade-off for a given transport task seems tempting, the involved feedback loops make this optimisation challenging. Figure 4 depicts the causal loop



Source(s): Figure by authors

Figure 4.
A CLD model of the dynamics of the trade-off between truck battery size and fast charging infrastructure

diagram of the example, and Table S4 in the Supplementary Materials details the loops and dynamics of various variables.

The battery is a key and expensive component of e-trucks (Basma *et al.*, 2021), so a larger battery leads to higher battery and vehicle purchase costs, which leads to a higher transport cost per tonne-kilometre. Moreover, a larger battery increases the vehicle's weight, which has dual consequences (Magnusson and Berggren, 2018; Nykvist and Olsson, 2021). First, it reduces the load capacity per vehicle, necessitating more trips to fulfil demand and increasing transportation costs. Second, heavier trucks consume more energy, which also increases transport costs.

A smaller battery, on the other hand, reduces the vehicle's range, necessitating more frequent charging at en-route fast charging stations. Fast charging is usually more expensive than depo or destination charging, resulting in additional charging costs. Additionally, with a small battery, charging during a shift may become necessary, incurring indirect costs for drivers and trucks awaiting charging (Parviziomran and Bergqvist, 2023). Moreover, the search for charging stations, especially with a high charging gap, entails additional costs and time. More driving to find a station increases vehicle mileage and congestion in the transportation system, which in turn increases transport time and cost. However, opting for larger batteries can reduce the demand for fast charging and its associated costs, demonstrating a trade-off between battery size and fast charging station development.

Figure 4 outlines several loops capturing the dynamics of the model. The "*demand price balance (B1)*" loop reveals a general demand-price relationship, similar to the one in the prior CLD example. Concurrently, the "*transport cost effect (B2)*" loop illustrates how transport costs are balanced through the demand mechanism: A decrease in transport costs and prices results in an increase in demand, leading to more freight trips to fulfil that demand, which in turn increases transport costs. Moreover, the "*congestion effect (B3)*" loop describes how transport costs are balanced through the congestion mechanism: A decrease in transportation costs and prices induces higher demand and increased trip frequency. This surge in freight trips increases vehicle mileage and congestion, subsequently raising transport time and costs.

The "*road expansion (B4)*" loop reveals the interplay between congestion levels and the pressure to invest in new road infrastructure. This investment, with a time delay, yields expanded road networks and decreased traffic congestion (see Sterman, 2000). Moreover, similar to the prior example, the "*investment in charging stations (B5)*" loop strives to address the market gap in charging infrastructure. The broader the gap in charging station availability, the greater the incentive to invest in and construct new stations to bridge the gap. There is a time delay between investment and infrastructure availability.

The loop "*trust of widespread charging stations (R1)*" reveals a long-term dynamic: If the battery size is small initially, many fast chargers will need to be built to meet the demand, leading to the construction of a widespread network of charging stations and long-term trust in the charging network. As a result, the battery size could remain small. Conversely, if the battery size is large initially, there is no need to build as many fast charging stations, resulting in less trust in the charging network and the continued use of large batteries. This kind of dynamic, in which initial conditions have a persistent influence on the outcome, is known as path dependency behaviour (Barnes *et al.*, 2004).

5. Discussion

5.1 Impact of electrification on the road freight transport system

Assessing the impact of electrification on the road freight transport system requires an understanding of the dynamics from a system-level perspective. Isolated technical or financial analyses, such as comparing the total cost of ownership between electric and diesel trucks, are useful but only reflect limited actors' perspectives. To gain deeper insights, we need a transition from linear thinking to system thinking, viewing freight transportation as a complex, dynamic system. Previous literature highlights the need for this approach: McKinnon (2018), in his analytical framework for green logistics, mapped the interrelationships of various parameters to measure environmental impacts; Langevin and Riopel (2005) demonstrated the interconnectedness of 48 logistics decisions, highlighting system complexity; and Browne *et al.* (2022) called for frameworks to analyse intricate interactions and facilitate systemic change. Our research complements these previous studies by providing a conceptual dynamic model to enhance the understanding of freight transport system dynamics and, in particular, the influence of electrification.

As illustrated in Figure 2, the conceptual dynamic model shows that variables (and therefore actors) in all different layers are affected by electrification. There are a few direct impacts and many induced impacts. It is critical for different actors, including policymakers, to understand various dynamics within the system in order to understand induced impacts much better and faster. Direct impacts mostly enter the system at the transportation layer and traffic market and then cause induced impacts throughout the whole system. Policy interventions mainly happen in the infrastructure layer and traffic market. This figure, despite its complexity, provides valuable insights into the different drivers of the system and their ripple effects. It is important to acknowledge that reality and its dynamics are far more intricate and that several direct and induced impacts will affect the same actor at the same time or with a still unknown temporal delay. Therefore, employing system thinking and complex modelling becomes essential to enhancing the understanding of the system.

The two example CLDs provide practical insights into the model's application and potential value. They illustrate how electrification triggers various feedback loops: many are balancing, helping the system achieve equilibrium, while a few are reinforcing, pushing the system to change. Additionally, these examples demonstrate how findings from previous studies are interconnected, such as those on the total cost of ownership (Basma *et al.*, 2021; Noll *et al.*, 2022; Parviziomran and Bergqvist, 2023), charging strategies (Al-Hanahi *et al.*, 2022), and battery sizing (Nykvist and Olsson, 2021). This highlights the CLD's usefulness in connecting research from diverse perspectives, including technical, business, and strategic. Furthermore, by clarifying the consequences of changes, the examples enhance understanding of the system's complexity, as highlighted by Browne *et al.* (2022).

The study's conceptual model, exploring the impact of electrification on the road freight transport system, can be viewed through the lens of the Multi-Level Perspective (MLP) of transition theory (Geels, 2012). The MLP theoretical framework includes three levels: regimes, niches, and landscapes. The regime consists of the existing road freight transport system and its related dynamics, which are characterised by diesel trucks, existing infrastructure, policies, market structures, and user practices. Electrification is a niche technology attempting to break into the regime. This involves adopting new technologies (such as e-trucks), transforming infrastructure (such as charging stations), adjusting policies (such as incentives), evolving market structures (including shifts in supply chains and logistics), and changing user and industry practices. The landscape includes broader societal trends, policies, environmental concerns, and economic factors that create pressure on the current regime. For example, increased awareness of climate change and governmental climate policies can create a conducive environment for the electrification of road freight transport.

5.2 Policy analysis

Electrification has multifaceted impacts on the road freight transport system, and the role of policymakers is pivotal in steering it towards sustainability. Policy changes ripple throughout the system, highlighting the necessity of a system-level perspective to evaluate their broader implications. To illustrate various potential policy interventions within the system, we use the first example CLD, as depicted in Figure 5. Green arrows indicate potential policy interventions, interconnected with corresponding policies in Table 2.

As depicted in Figure 5, there are several potential policy interventions. P1) "Subsidies on e-truck purchase cost" will decrease e-truck total cost of ownership (TCO) and make e-trucks more attractive. P2) "Subsidies on the price of electricity" will lower electricity prices and e-truck operational costs, lowering TCO and increasing attractiveness. However, diesel price taxes could raise diesel truck operating costs, making e-trucks a better alternative. P3) "Subsidies on the construction of power plants" could increase electric power supply, lower electricity prices, and lower the TCO of e-trucks, making them more attractive. P4) "Subsidies on the construction of charging infrastructures" would bridge the charging infrastructure gap and make e-trucks more attractive. P5) "Fund on vehicle technology maturity" boosts e-truck production technologies and lowers their purchase cost and TCO, making them more attractive. P6) "Changing emission goals" refers to addressing environmental concerns by setting a range of emission goals for the transportation sector. Examples include the EU's "Fit for 55" legislative package and Sweden's 2045 carbon neutrality goal (European Commission, 2021; Regeringen, 2017). Stricter targets may boost e-truck adoption. P7) "Investment in awareness programmes" could impact the green mindset of transport buyers and freight companies, motivating them to make extra efforts towards sustainable transport.

We acknowledge the complexity of policy design within this system. Our research aims not to prescribe specific policies but to highlight potential interventions and demonstrate the dynamic nature of policy impacts. For instance, "fund on vehicle technology maturity" could lower vehicle purchase cost, reducing the need for "subsidies on e-truck purchase cost."

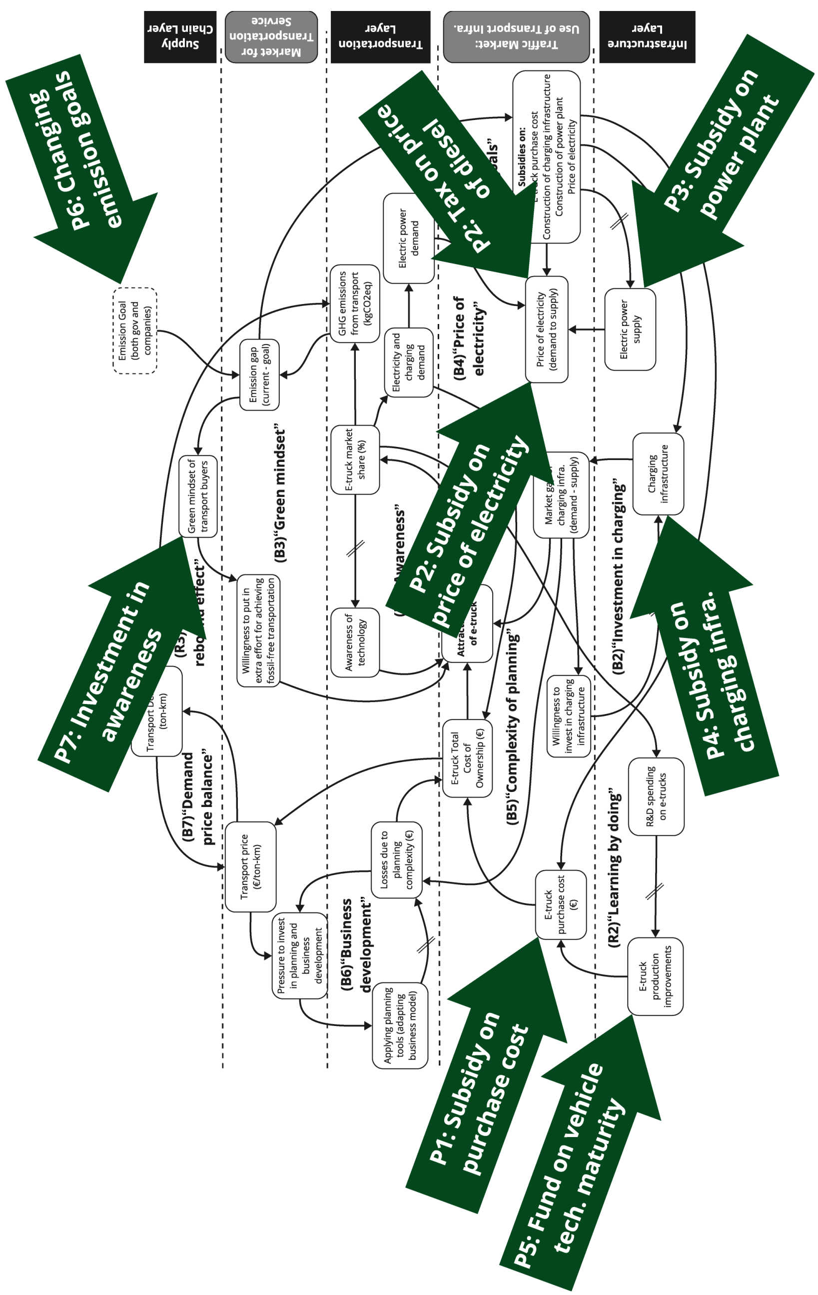
Furthermore, understanding the dynamics of the system is crucial for formulating effective policies, especially given the long-term and delayed nature of policy interventions. Recognising system delays, i.e. delays between the cause (e.g. the decision to invest in charging infrastructure) and the effect (e.g. charging infrastructure is ready to be used), is essential for informed decision-making. The system also faces several "chicken-and-egg" problems, like the relationship between e-truck adoption and charging infrastructure, as discussed in the introduction, or the interplay between transport demand and costs. These interconnected dynamics mean there is no obvious starting point for initiating change. Therefore, it is essential to align various policies effectively to guide the system toward sustainability.

5.3 Limitations and future work

The aim of the conceptual model and examples presented here is to provide a holistic picture and fundamental understanding of the system's dynamics. However, taking a holistic perspective means that some of the details are lost in the modelling process. Therefore, it is essential to complement this work with more detailed studies to further develop and clarify the causal relationships within the overall model. The model developed here is conceptual, and the findings serve as a starting point for further exploration and should not be used for analysis without further validation.

Furthermore, our research explores a future-oriented system that has not yet been implemented on a large scale, resulting in limited numerical data. Therefore, qualitative data and conceptual modelling are essential for hypothesising the system's dynamics and potential behaviours. While we acknowledge the limitations due to the lack of numerical data for validating our model, we believe that our conceptual approach contributes with important system understanding and provides a framework for future investigations when numerical data become available.

The results clearly demonstrate how the transition to electric freight transport raises new questions and trade-offs that must be carefully considered. However, the model presented



Note(s): Green arrows indicate potential policy interventions
Source(s): Figure by authors

Figure 5.
Exploring policy interventions within the example CLD of the factors influencing e-truck attractiveness

here is indeed a simplification, and there are many other variables that could be included. Moreover, the effect of electrification on the freight transport system is subject to a significant degree of uncertainty. This uncertainty extends to questions about how electrification will influence various variables within the system, the ripple effects of these changes, and the actions taken by policymakers in response. In future studies, it is essential to consider and account for these uncertainties.

The conceptual model and presented CLDs do not specify the strength or dominance of different loops. Additionally, the system involves several time delays. To further explore and understand the dynamics of the system, a quantitative system dynamics model could be highly beneficial. This can be facilitated by conducting further workshops with stakeholders to provide quantitative evaluations of different scenarios and compare the effects of various decisions and policies.

6. Conclusion

Understanding the impact of electrification on freight transport systems is complex and challenging. By combining the multi-layer model with a system thinking and dynamics approach, we developed a conceptual dynamic model and two example CLDs. The study highlights the importance of having a system-level understanding to comprehend the impact of electrification on the system.

The main takeaways of the study are: (1) The conceptual dynamic model identifies dynamic relationships within each layer (structure and operation variables) and between layers of the system. (2) Differentiating between direct and induced impacts of electrification, the model explores how these impacts change variables (and therefore influence actors) in the different layers. (3) Identification of potential policy interventions offers insights into how policymakers can strategically influence the system. (4) Example CLDs provide practical insights, addressing specific questions on factors influencing electrified transport attractiveness and the trade-off between battery size and fast charging infrastructure for e-trucks. (5) This study shows SD, and in particular, CLD is a useful method for demonstrating the dynamics and ripple effect through the system.

The main academic contribution of this study is the integration of a dynamic perspective into the well-established multi-layer model (Wandel *et al.*, 1992; Browne *et al.*, 2022). We developed a conceptual model that connects various qualitative and quantitative studies on the impacts of electrification to provide a holistic picture of the system. This conceptual model could be the backbone for further mathematical models and invite future research into the system's dynamics. By bridging the traditional gap between qualitative and quantitative research, our approach links both soft and hard variables essential for understanding the electrification transition. In practice, our findings support more structured system-level discussions and allow stakeholders, particularly policymakers, to make more informed decisions towards a sustainable road freight transport system.

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Supplementary Material

The supplementary material for this article can be found online.

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