Exploring dynamic interdependencies during electrification transformation: From a freight hauler perspective

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Executive Summary
The article explores freight haulers' decision-making challenges when adopting battery-electric heavy-duty trucks (BETs). Freight haulers must balance operational, financial, and technical factors, such as purchase costs, payload losses, charging infrastructure, and contract structures, to stay profitable during the transition to zero-emission transport. The study identifies key parameters and feedback loops that influence investment decisions using interviews, stakeholder workshops, and system dynamics modeling. Two significant challenges emerge: comparing BETs with diesel trucks and managing the trade-offs between depot and public charging options. The study highlights that coordinated stakeholder actions, stable business models, and trust in charging infrastructure are critical to support freight haulers in adopting BETs.

Keywords: consumer behavior, trends of e-mobility, heavy duty electric vehicles, public policy, charging business models article.

1 Introduction

The road transportation sector is rapidly transitioning towards electrification to reduce greenhouse gas emissions and promote long-term sustainability [1][2][17]. Battery-electric heavy trucks (BETs) are expected to play a significant role in decarbonizing freight transport [3][4]. Nevertheless, the electrification of heavy-duty road freight faces persistent challenges, as reflected by BET sales, which currently remain close to 1% within the European Union [5].

To better understand the barriers to BET adoption, this study focuses on the forestry transport sector, which accounts for nearly 20% of Swedish road transport [58]. Insights from this sector can support stakeholders — including original equipment manufacturers (OEMs), transport buyers, logistics service providers (LSPs), freight haulers, refueling infrastructure providers, and policymakers — in planning coordinated strategies rather than isolated actions [6][58]. A system-wide perspective is crucial to accelerate the uptake of BETs across the freight transport ecosystem [35].

Despite increasing efforts, a critical gap remains understanding which operational, financial, and socio-technical parameters freight hauling companies prioritize when deciding whether to invest in BETs [20]. Furthermore, the trade-offs between these parameters and the causal relationships among them remain largely unexplored. Electrifying freight fleets is not simply replacing diesel trucks with electric ones; it requires a systemic approach considering the complex interdependencies among factors such as payload capacity, vehicle range, battery cost, access to charging infrastructure, contract durations, and expected profitability. Uncertainties related to

infrastructure availability, policy incentives, and evolving business models further complicate haulers' investment decisions [35][3][41].
Previous research has examined areas such as cost modeling [50], energy performance [9], and policy design [35]. However, the dynamic relationships between decision-making parameters — especially from the freight hauler's perspective — have received little attention. Thus the purpose of this study is to identifying and prioritize key parameters influencing BET investment decisions in the forestry sector. Insights from freight haulers and practitioners help to explore the causal relationships between these parameters. We also discuss how these key parameters change over time, leading to decision-making trade-offs for freight haulers.

2 Methodology

This study adopted a systems thinking and system dynamics (SD) approach to investigate the complex interactions among decision-making parameters influencing freight haulers' adoption of battery-electric heavy-duty trucks (BETs) [8][16]. SD was selected as the method choice as it assists in determining interdependencies, identifying feedback loops, and visualizing potential trade-offs within the decision-making parameters prioritized by freight haulers before investing in BETs. Fig. 1. outlines the methodological process.

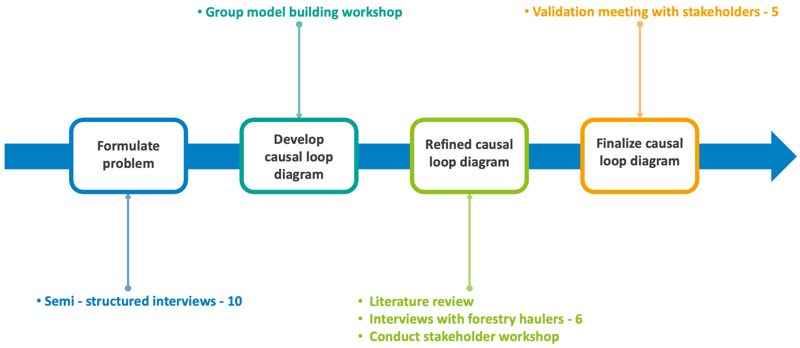

Figure 1: Methodological process of the research, a mixed method approach

The research began with the problem formulation step by reviewing BET adoption trends across Sweden, focusing particularly on the challenges encountered by freight haulers during the transition to zero-emission vehicles. To refine the problem statement and formulate research questions, ten semi-structured interviews were conducted with stakeholders from the transport sector, including OEMs, transport buyers, logistics service providers (LSPs), and freight haulers.
Interviewees represented diverse operational contexts — from intermodal transport and mining to waste collection and long-haul logistics — with fleet sizes ranging from 25 to 700 trucks and operating distances between 60 and 500 kilometers. Despite the respondents operational and topographical location differences, common barriers emerged across all interviews. These insights provided a foundational understanding of the transport system structure and raised the need to hold a subsequent causal loop diagram (CLD) development process to visualize it.
To deepen the understanding of the system and the potential decision-making parameters and interdependencies, a Group Model Building (GMB) workshop was conducted with five experts in transport systems, logistics, system thinking, and transition mapping. Participants included academic researchers, industry professionals, and doctoral students. GMB served as a participatory method to elicit system structure, surface hidden assumptions, and foster shared understanding among stakeholders [55][56][57].
During the GMB workshop, key parameters influencing BET adoption were collaboratively identified from a freight hauler's perspective, and their behaviors over time were discussed. Causal relationships among parameters were mapped, leading to the construction of a preliminary CLD that captured feedback loops, decision trade-offs, and system boundaries from a freight hauler's perspective. The insights from the GMB guided the scoping of the subsequent literature review and stakeholder interviews, which aimed to showcase parameters that might be critical to electric truck adoption decisions by freight haulers.
Relevant studies were retrieved using Scopus, with keywords including "logistic service provider," "freight carrier," "battery-electric truck," "fleet management," and "charging infrastructure." Simultaneously, six additional interviews were carried out with transport planners, sustainability managers, and forestry freight haulers, further enriching the understanding of adoption parameters. Parameters identified through the literature

review (presented in Table 1) and interviews (detailed in Appendix A) were consolidated into a comprehensive list.
Subsequently, a stakeholder workshop was organized (Comprising of thirty people), engaging practitioners from OEMs, transport buyers, logistics service providers (LSPs), freight haulers, academic researchers, and refueling station operators within the forestry transport sector. The workshop aimed to rank and prioritize parameters from the perspective of freight haulers. Participants reviewed the consolidated list of parameters, including definitions and descriptions (Appendix A), and were asked to select the three parameters they considered most critical to BET investment decisions. Their selections were recorded, contributing directly to the formulation of a dynamic hypothesis and the refinement of the preliminary CLD.

Table 1: Electric truck adoption: hauler-centric parameters from literature review

Parameter	Source
Operational driving range	[20], [21], [24], [30], [51]
Vehicle utilization	[20], [21], [23], [3]
Battery pack price	[20], [25], [3], [51]
Revenue model	[22], [26], [31], [3], [51]
Planning/ management tool	[21], [20], [32], [41]
Opportunity charging	[20], [21], [23], [3], [52]
Charging power	[20], [21], [27], [3]
State of charge of battery	[20], [22], [33], [3]
Driver cost	[20], [21], [22], [34]
Driving speed	[21], [23], [30], [53]
Ambient temperature	[21], [34], [54]
Driver competence training	[21], [28], [32]
Collaboration/knowledge sharing	[20], [23], [29]

The final CLD was constructed by taking insights from the GMB workshop, stakeholder interviews, and voting results. Validation meetings were conducted with five industry practitioners who were new to this study, that included managing directors, transport planners, and business development managers, to verify the model's usefulness and remove potential biases. The interview feedback confirmed that the CLD developed represents the parameters freight haulers should consider before investing in BETs.
The methodological process was participatory and iterative, ensuring the system model developed, and subsequent trade-off decisions reflect real-world challenges freight haulers face during the electrification transition.

3 Results

This section presents the main findings, structured into three sub-sections: (1) insights from stakeholder interviews, (2) key parameters influencing BET investment decisions from a freight hauler perspective, and (3) a causal loop diagram illustrating the causal relationships among these parameters and revealing the emerging trade-offs.

3.1 Interview with stakeholders

Interviews with ten stakeholders conducted in 2023 revealed several common challenges in the transition towards battery-electric heavy-duty trucks (BETs). These included the limited availability of public charging infrastructure, reduced payload capacity compared to diesel trucks, increased complexity in planning transport tasks, and the higher purchase cost of BETs. Drivers within the hauling companies raised concerns regarding range anxiety, the need to drive at reduced speeds to extend vehicle range, and the lack of specific driver training to handle BET-related operational issues.
In 2024, six additional interviews were conducted with managing directors, transport planners, sustainability managers of LSP companies, owners and planners of forestry transport hauling companies, and quality managers

from Swedish forestry land-owning organizations. A primary concern identified was the lack of charging stations, especially at critical loading and unloading points. As one forestry transport coordinator explained:
"Driving range anxiety, unavailability of on-road charging stations, grid limitations..."
While forestry haulers acknowledged that the purchase cost of BETs is becoming comparable to diesel trucks, they emphasized that payload losses arising from heavier powertrain components remain a critical challenge. Many companies noted that, although they are willing to pay CO_2 taxes, they prefer to continue operating diesel fleets until they have secured sufficiently long-term contracts to make BET investments financially viable. As one participant observed:
"Transport price is essential for a transport buyer while undergoing this technological transition."
The challenges faced by forestry haulers were often more complex due to their operating environment. Participants highlighted difficulties such as poor road conditions, unexpected loading delays deep within forests, and the limited effectiveness of current planning tools for route and driver scheduling. According to the flow coordinator from the LSP:
"Prominent factors affecting transport demand are weather, driving distances, road maintenance or closures, and driver market uncertainty."
Additionally, freight haulers emphasized the need for BETs to match the operational reliability of diesel trucks. One owner and driver clearly stated:
"We need reliable vehicles similar to the diesel V8 while undergoing this transition toward ZEVs."
Furthermore, haulers called for greater business support from OEMs, including:
"Reliable prognosis for operational cost, public charging options, and suggestions for new business models from an OEM to guide us in this uncertain technological transition."
One freight hauling company highlighted the importance of prioritizing depot charging over public infrastructure. They explained:
"Presently, we see the use of public charging infrastructure costs us at least three times more than at our depot, where we receive industrial rates for charging. This affects our electrifiable driving range of battery electric trucks, leading to picking trucks with larger battery sizes."
The insight highlighted that the high public charging cost impacts operational expenses and influences vehicle battery size selection. The freight haulers are leaning towards BETs with larger batteries to reduce dependencies on public networks. In addition to concerns around charging availability and cost, some haulers raised issues about the investments needed for depot charging infrastructure. As one freight hauler explained:
"Investment in depot charging infrastructure costs us at least three times more than the present battery electric vehicle price."
Another insight that came from a freight hauler's transport planner, who pointed out the financial sensitivity of electric truck operations:
"In many operations that flow through our calculations, we can see battery electric vehicles yield better cost margins than diesel ones. However, it is sensitive to where we charge our vehicles during operations."
Furthermore, the economic vulnerability of freight haulers was highlighted by a forestry hauler, who stressed the risks posed by thin profit margins:
"We operate with very low profit margins, not more than four percent; if the transport buyers cannot support us with longer contracts and higher prices for the transport tasks, the transition looks difficult to survive."
This comment underscores the freight haulers' need for supportive contracting structures and stable revenues to manage the risks of adopting new vehicle technologies.

To successfully adopt BETs, the haulers stressed the following key aspects:

- Securing longer-term transport contracts,
- Receiving better incentives from policymakers,
- Developing a mixed fleet strategy incorporating battery-electric and other zero-emission solutions,
- Gaining guidance from OEMs on profitability and new ways of operating.

These insights directly informed the identification of the main decision-making parameters from the interviews (see Fig. 5. in Appendix A).

3.2 Electric truck adoption parameters: Prioritization workshop

After the interviews and literature review, a workshop was held with important transport system stakeholders to find out which parameters are most important for freight haulers when deciding whether to invest in battery-electric heavy-duty trucks (BETs). Participants included people from original equipment manufacturers (OEMs), transport buyers, logistics service providers (LSPs), freight haulers, academic researchers, and refueling station operators, with a focus on the forestry transport sector.

At the workshop, participants were shown a list of key parameters identified earlier through research and interviews (see Appendix A). Each parameter had a short explanation to make sure everyone understood them the same way. Participants were then asked to choose the three parameters they thought were the most important for freight haulers to decide about BET investment after reading the problem statement, as showcased in Fig. 6. in Appendix A. Their votes were recorded and are presented in Fig. 5. in Appendix A.

The parameters that got the most votes were:

- **Vehicle purchase cost**,
- **Payload losses**,
- **Operational driving range**,
- **Vehicle utilization**,
- **Operational cost**,
- **Charging cost**,
- **Battery pack price** and
- **Revenue model**.

The vehicle purchase cost, along with the battery pack price, formed the primary concern of freight haulers because the purchase cost of BETs is at least three times higher than that of diesel trucks [59]. Within the purchase cost of BETs, more than one-third comes from the size of the battery pack chosen for operations [50] [59] [60]. The choice of battery size is closely linked to the charging strategy [36], which influences the overall charging cost. Having a larger battery pack (with charging mainly at the depot) or a smaller battery pack (combined with cheaper public charging) seems viable to compete with diesel refueling costs [59] [61].

Payload losses caused by the heavier powertrain components in BETs also affect the ownership cost of the trucks [59]. Although the operational costs — including driver wages, vehicle maintenance, road tolls, insurance, taxes, and other miscellaneous expenses — are lower for BETs than diesel trucks, the lack of sufficient charging infrastructure leads to indirect costs. These costs occur when drivers and goods experience waiting times during charging time [59] [61].

Operational driving range and vehicle utilization are essential for haulers as they help determine operational flexibility and the electrifiable distance they can cover. Lastly, the revenue model — which influences contract length and sets the transport price from transport buyers — affects hauler profitability. The key parameters voted by the freight haulers when planning the shift from diesel to BETs through this workshop are connected to the total operating economy (TOE), which consists of ownership costs and revenue components.

Even though the interviews and literature review helped find important parameters, the workshop was used to confirm the results in a broader group of actors.

3.3 Causal loop diagrams – feedback dynamics and interdependencies in BET adoption

The causal loop diagrams (CLDs) are an important tool in system dynamics for visualizing the feedback relationships that drive system behavior. They show how different variables are connected, using arrows to indicate cause-and-effect links and symbols to show whether relationships are reinforcing or balancing.

The modeling team (*comprising the first and third authors*) started by working on the initial CLD during the group model building (GMB) workshop. Interviews and voting results from forestry transport system stakeholders were then used to improve the model, focusing on the parameters most important for freight haulers when deciding whether to invest in BETs. This led to the formulation of a *dynamic hypothesis*, as shown in Fig. 2. In system dynamics, a dynamic hypothesis explains how feedback loops and system structures create behavior patterns over time, providing the foundation for building and testing models.

In Fig. 2, two main dynamic competitions exist. The first competition happens between the parameters influencing freight haulers' decisions to invest in BETs. The second competition is between the two charging options — public charging versus depot charging — and how each affects parameters that influence freight haulers' decisions to invest in BETs. In the scope of this study, the key parameters that influence freight haulers' decisions to invest in battery-electric heavy-duty trucks (BETs) are identified as vehicle purchase cost, payload losses, operational driving range, vehicle utilization, operational cost, charging cost, battery pack price, and revenue model.

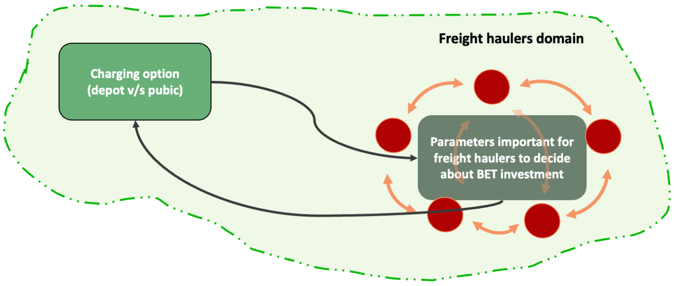

Figure 2: The dynamic hypothesis gives an overview of two competitions: Parameters important for selection of BETs over diesel and the effect of charging options (depot v/s public) on these parameters

Fig. 3. presents the causal loop diagram (CLD) built from the key parameters that influence freight haulers' decisions to invest in battery-electric heavy-duty trucks (BETs). The CLD was developed iteratively by the modeling team, with five validation meetings held with stakeholders to help confirm and refine the causal relationships between the parameters. Insights from the interviews and literature review showed that freight haulers prefer trucks with larger battery sizes and tend to favor depot charging over public charging. The first CLD model shown in Fig. 3. illustrates the way freight haulers plan their electrification journey with the key parameters that influence their decisions to invest in BETs.

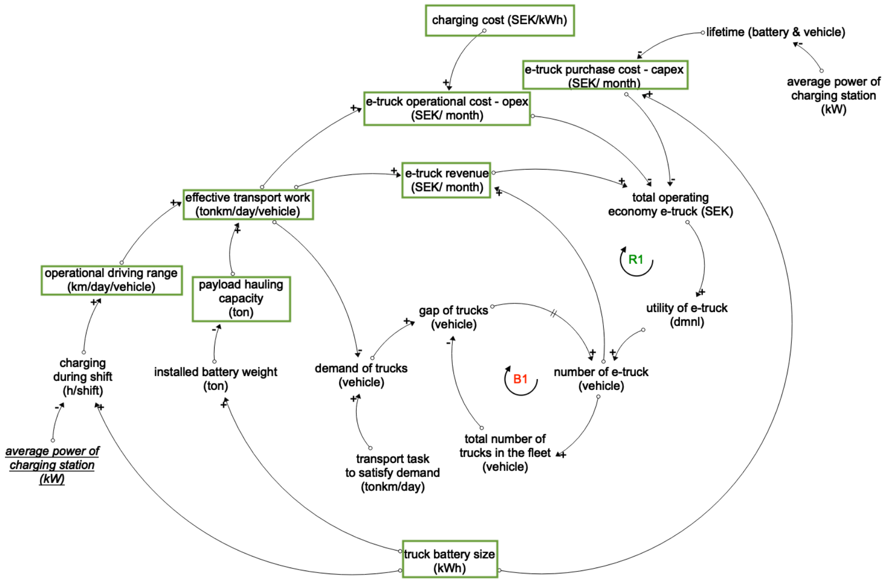

Figure 3: Causal loop diagram representing the interdependencies between the voted electric truck adoption parameters from the stakeholder workshop (Highlighted with green boxes)

The feedback loops are labeled as **R** or **B** in Fig. 3. and 4; the loop parameters are listed in Table 2. In the diagrams, **R** represents reinforcing feedback loops that strengthen and amplify changes in the same direction (similar to a snowball rolling downhill). In contrast, **B** represents balancing feedback loops that counteract changes, helping to stabilize the system and move it towards a particular goal [8].
The **'e-truck fleet scaling – B1'** loop is a balancing loop that replenishes the total number of trucks in the fleet based on the gap created between truck demand and available trucks. This gap depends on the transport tasks assigned to haulers and the amount of transport work they can perform with their current fleet.
The **'revenue-driven growth – R1'** loop is a reinforcing loop that matches what freight haulers raised during the interviews. If haulers receive longer, stable contracts and higher transport prices from transport buyers for operating BETs, their total operating economy improves. This increases the utility of e-trucks, making BETs more attractive and encouraging further investment in electric trucks.
The second major dynamic captured in Fig. 4. shows the *competition between public and depot charging* options. The blue parameters and links represent the impact of public charging infrastructure on the key parameters

(*shown in green boxes*) that influence BET investment decisions. The CLD in Fig. 4. highlights a finding from the interviews: charging cost, operational planning, and overall profitability are affected by how haulers choose between the depot and public charging options. Although haulers indicated a preference for trucks with larger batteries and depot charging, they must also balance the benefits and costs of using public charging, as this choice influences multiple parameters through several feedback loops.

The **'battery-size – share of public station dynamics – R2'** loop suggests that increasing the share of public charging stations can allow haulers to avoid buying oversized batteries, lowering truck purchase costs and making public charging more attractive, which then drives the development of even more public stations [35].

The **'e-truck – charging scaling – R3'** loop shows that more BET investments create a demand for charging stations. As infrastructure gaps are filled (with a delay), the availability of stations increases the utility of BETs and encourages further adoption.

The **'e-truck electrifiable range growth – R4'** loop aligns with haulers' need to expand their operational range. More charging stations mean better coverage [35], giving haulers greater flexibility in planning routes and operating their fleets with BETs.

The **'public charging – e-truck fleet sizing – R5'** and **'ease of operational cost for e-truck – R8'** loops support R4 by showing that a better public charging network reduces detour and queuing times. This improved coverage and trust in the network helps haulers manage more transport tasks without expanding their fleet size.

The **'indirect costs – public charging – R6'** loop reinforces R5 by showing that reduced detour and queuing time lowers operational costs. This improves profitability, making BETs more attractive and supporting the need for more public charging stations.

The **'word of mouth – public charging – R7'** loop explains that as haulers trust public charging more [39] [40], the attractiveness of using these stations increases, driving further investment in public charging infrastructure.

As indicated by the interviews, there are also downsides to having a public charging network, which the freight haulers currently weigh carefully.

The **'public charging cost dynamics – B2'** loop shows that the extra costs of using public chargers add to operational expenses [35], lowering profits and potentially reducing BET investments.

The **'charging power dynamics – B3'** loop highlights that having public charging within the total network leads to higher average charging power. The use of higher-power charging affects battery life [3], leading to future battery replacement costs. This makes haulers cautious about investing in BETs.

Finally, the **'limits to growth with public charging – B4'** loop shows that if the number of e-trucks grows faster than the charging network, temporary shortages and longer waiting times could occur. The hauler's revenue earned decreases, leading to the discouragement of investments in BETs.

The feedback loops explain the complex challenges and trade-offs freight haulers must navigate when investing in battery-electric trucks.

Table 2: Explaining the dynamics of variables in different loops of the CLD model (From Fig. 3 and 4). *R for reinforcing loops* and *B for balancing loops*. *Green arrows* for the same direction impact and *red arrows* for the opposite direction impact

Loop name	R / B	Dynamics of variables
"e-truck fleet scaling"	B1	number of e-truck → total number of trucks in the fleet → gap of trucks → number of e-truck
"revenue-driven growth"	R1	number of e-truck → e-truck revenue → total operating economy e-truck → utility of e-truck→ number of e-truck
"battery size - share of public station dynamics"	R2	share of public charging stations → truck battery size → savings for e-truck purchase cost - capex → potential cost saving using public charging → utility of public charging infrastructure → public charging → share of public charging stations
"e-truck - charging scaling"	R3	number of e-truck → demand for charging stations → gap of charging stations → availability of charging stations → utility of e-truck → number of e-truck
"e-truck electrifiable range growth"	R4	number of e-truck → demand for charging stations → gap of charging stations → public charging → share of public charging stations → share of electrifiable transport mission → utility of e-truck → number of e-truck

"public charging cost dynamics"	B2	share of public charging stations → extra charging cost for public stations → charging cost → e-truck operational cost - opex → total operating economy e-truck → utility of e-truck → number of e-truck → demand for charging stations → gap of charging stations → public charging → share of public charging stations
"charging power dynamics"	B3	share of public charging stations → average power of charging station → lifetime (battery & vehicle) → e-truck purchase cost - capex → total operating economy e-truck → utility of e-truck → number of e-trucks → demand for charging stations → gap of charging stations → public charging → share of public charging stations
"public charging - e-truck fleet sizing"	R5	share of public charging stations → trustable public charging network → detour and queuing time → effective transport work → demand of trucks → gap of trucks → number of e-trucks → demand for charging stations → gap of charging stations → public charging → share of public charging stations
"indirect costs - public charging"	R6	share of public charging stations → trustable public charging network → detour and queuing time → indirect cost (waiting time for driver and goods) → e-truck operational cost - capex → total operating economy e-truck → utility of e-truck → number of e-trucks → demand for charging station → gap of charging stations → public charging → share of public charging station
"word of mouth - public charging"	R7	share of public charging stations → trustable public charging network → utility of public charging infrastructure → public charging → share of public charging stations
"limits to growth with public charging"	B4	share of public charging stations → trustable public charging network → detour and queuing time → effective transport work → e-truck revenue → total operating economy e-truck → utility of e-truck → number of e-trucks → demand for charging stations → gap of charging stations → public charging → share of public charging stations
"ease of operational cost for e-truck"	R8	share of public charging stations → trustable public charging network → detour and queuing time → effective transport work → e-truck operational cost - opex → total operating economy e-truck → utility of e-truck → number of e-trucks → demand for charging stations → gap of charging stations → public charging → share of public charging stations

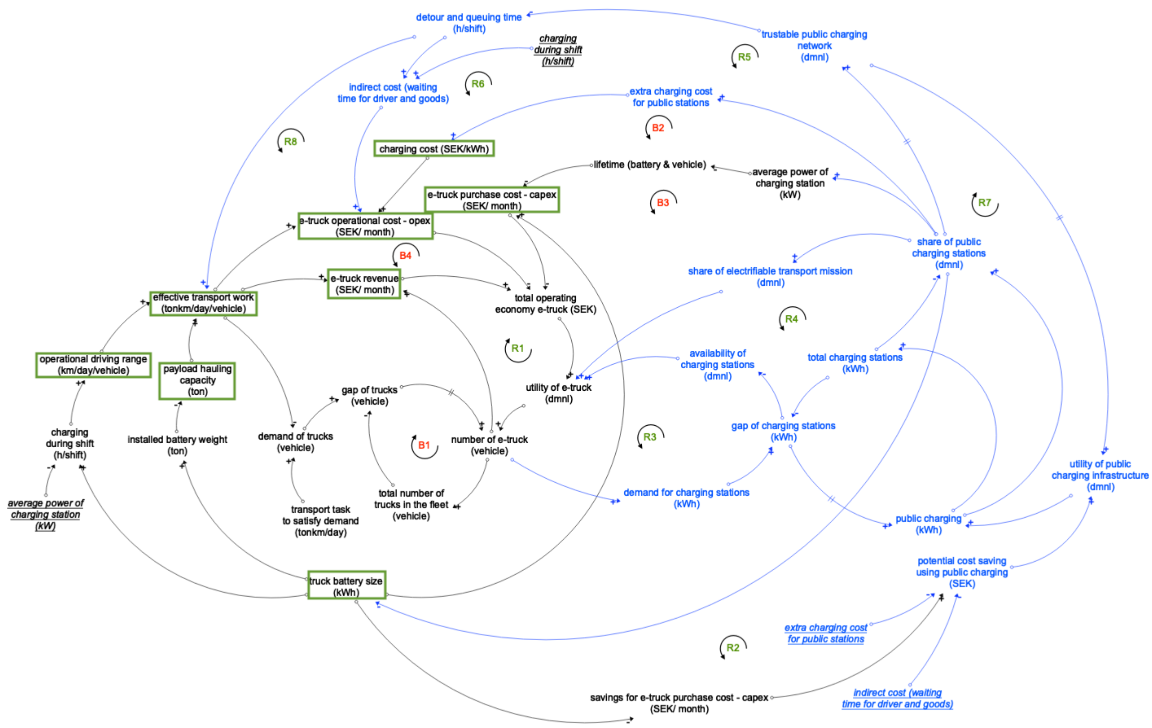

Figure 4: Causal loop diagram representing the interdependencies between the voted electric truck adoption parameters from the stakeholder workshop (Highlighted with green boxes), GMB, and validation interviews for the CLD

4 Discussion

The primary aim of this study was to explore the dynamic interdependencies in the form of feedback loops and decision-making trade-offs faced by freight haulers when considering the adoption of battery-electric heavy-duty trucks (BETs).

From the interviews performed in 2023 and 2024, several challenges for adopting BETs emerged, and many remained persistent over time. The haulers mentioned that the limited availability of public charging infrastructure on highways and their loading and unloading areas limit their electrifiable operational area. Furthermore, the loss of payload carrying capacity and higher purchase cost compared to their diesel trucks are hindering the adoption of BET. In both years, haulers highlighted that the uncertainty around contract length and support for higher transport pricing by transport buyers makes investing in BETs difficult. Although haulers from the forestry transport sector interviewed in 2024 acknowledged that BET purchase prices are becoming more comparable to diesel trucks, they stressed that payload losses, new operational business model and a lack of reliable charging options continue to dominate their decision-making.

The findings show that a complex combination of factors shapes freight haulers' decisions to adopt BETs. Key parameters identified through interviews, the stakeholder workshop, and the group model-building process include vehicle purchase cost, payload losses, operational driving range, vehicle utilization, operational cost, charging cost, battery pack price, and revenue models. These parameters do not operate independently; they are linked through feedback loops that either reinforce or balance the attractiveness of BET adoption. In particular, two dynamic competitions emerged as central to understanding haulers' behavior:

- First the competition between BETs and diesel trucks, where haulers weigh operational and financial trade-offs such as vehicle cost, range limitations, and profitability under current transport contracts.
- Second, is the competition between public and depot charging options, which influences operational planning flexibility and long-term cost structures.

The causal loop diagrams developed in this study highlight that supportive infrastructure, trade-offs between business model parameters, and coordinated stakeholder actions drive the transition toward BETs.

One pattern observed is the '*accidental adversaries*' where freight haulers and public charging providers aim to support the transition to zero-emission freight transport [46]. However, haulers are reluctant to invest in BETs without sufficient public charging infrastructure, while charging providers depend on BET adoption to justify building more stations. This hesitation on both sides can weaken the business case for BETs. If public charging prices increase to maintain profitability for charging operators, it may further discourage hauler investments, creating a cycle where both sides unintentionally slow the transition.

Another emerging pattern is '*shifting the burden*' within which haulers begin the BET investment of trucks with larger battery sizes and rely on depot charging for operations. However, they also need to start utilizing and trusting the public charging network for it to develop and grow. The haulers then can find the right balance of utilizing both charging infrastructures rather than over-reliance on one [47] [48].

This study mainly focused on the forestry transport sector in Sweden, so the results might not fully apply to other transport sectors or countries. The generalization of the results should, therefore, be approached with caution. The CLDs were based on a small number of interviews and workshops, which means the findings could be influenced by the views of the people who took part. Also, the study mainly looked at battery-electric trucks and did not explore other technologies like hydrogen trucks.

5 Recommendations and further research

The following are the key recommendations from this study:

- **Coordinated efforts among the freight haulers:**

The transition towards electrification requires a joint market effort, where multiple haulers are willing to invest in BETs. A single hauler, or even a small group, cannot generate enough momentum for widespread adoption.

- **Helping freight haulers with a better understanding of business models:**

Freight haulers need research-driven support to understand transport contract lengths better, set fair transport prices, and manage total operational costs based on the dynamic feedback loops identified in the system representation. This support is important to help haulers start investing in BETs while maintaining profitability.

- **Balancing public and depot charging is challenging:**

Based on their transport operations, haulers need research-based advice on how to balance the use of public and depot charging stations. Finding the right mix is important to keep their operations flexible and their businesses profitable.

The next step within the framework of this study starts by developing a mathematical simulation model [8]. The mathematical model will assist in testing different scenarios like changes in charging cost, battery price, adding government subsidies, and other policy interventions [42] [43]. The effect of scenarios will be mapped to the adoption of e-trucks. A second group model-building workshop will be held with logistic service providers and haulers (having different truck fleet sizes). The step will further strengthen the existing causal loop diagrams. Once the model reaches good usefulness and maturity, it will be expanded to other zero-emission vehicles like fuel-cell and hydrogen internal combustion technology [49][50].

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Authors contributions

V. Shenoy conceptualized the study, developed the methodology and models, conducted interviews and the stakeholder workshop, performed data analysis, and led the writing of the manuscript. A. Pernestål contributed to the conceptualization and validation of the models. Z. Raoofi contributed to the methodology and CLD modeling, model validation, and co-wrote the introduction section. C. Nyquist Magnusson contributed to the stakeholder workshop. J. Mårtensson contributed to the conceptualization. All authors reviewed and approved the final manuscript.

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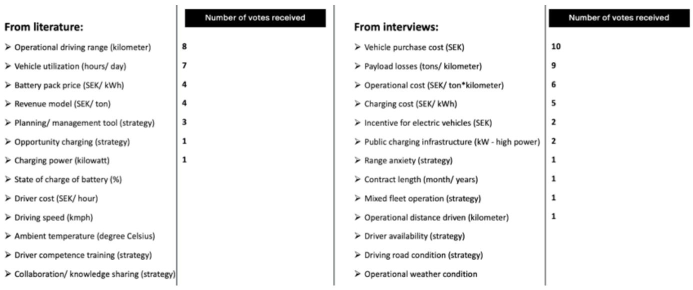
Appendix A

Parameter	Short description
Operational driving range	The range that the vehicle provides with one charging event (kilometer)
Vehicle utilization	Measure of vehicle usage for transport tasks (hours/ day)
Battery pack price	Cost of the battery pack installed in the vehicle (SEK/ kWh)
Revenue model	The way in which transport task is being paid, bound by the contract terms (SEK/ ton)
Planning/ management tool	Route planning, transport task allocation, and fleet management dashboard
Opportunity charging	Charging the battery when having a downtime (loading/ unloading)
Charging power	The power available to charge the vehicle (kilowatt)
State of charge of battery	Usable battery capacity limit regulated by the Original Equipment Manufacturer (percentage of installed battery capacity)
Driver cost	The driver's contract cost (SEK/ hour)
Driving speed	The speed the vehicle maintains during the operations (kmph)
Ambient temperature	The vehicles operating surrounding temperature (degree Celsius)
Driver competence training	Educating and training the drivers to handle new vehicle configurations
Collaboration/ knowledge sharing	Sharing lessons learned, collaborating with other stakeholder within the transport ecosystem
Vehicle purchase cost	The upfront vehicle purchase cost when owning the truck (SEK)
Payload losses	The amount of payload carrying capacity lost for increased powertrain weight (Battery) (tons/ kilometer)
Operational cost	The amount of operational cost to the haulers for doing a transport task (SEK/ ton*kilometer)
Charging cost	The cost paid for utilizing a public charging infrastructure for charging (SEK/ kWh)
Incentive for electric vehicles	Subsidies or reduce the upfront cost of owning an electric vehicle
Public charging infrastructure	Availability of high-power public charging infrastructure at specific intervals on route
Range anxiety	Concern that the battery electric vehicle will run out of battery charge before reaching a charging station, leading to vehicle off-road
Contract length	The type and length of contact between the logistic service provider, transport hauler, and transport buyer
Mixed fleet operation	The operational fleet comprises diesel, battery, and fuel-cell vehicles
Operational distance driven	The amount of distance driven by the vehicle per year (kilometer)
Driver availability	The driver market resource and competence availability
Driving road condition	The conditions in which the vehicle is operated like highway, urban, forestry, or mixed road conditions forestry, or mixed road conditions
Operational weather condition	The conditions in which the vehicle is operated are summer, winter, rainy or snowy.



From literature:	Number of votes received	From interviews:	Number of votes received
➢ Operational driving range (kilometer)	8	➢ Vehicle purchase cost (SEK)	10
➢ Vehicle utilization (hours/ day)	7	➢ Payload losses (tons/ kilometer)	9
➢ Battery pack price (SEK/ kWh)	4	➢ Operational cost (SEK/ ton*kilometer)	6
➢ Revenue model (SEK/ ton)	4	➢ Charging cost (SEK/ kWh)	5
➢ Planning/ management tool (strategy)	3	➢ Incentive for electric vehicles (SEK)	2
➢ Opportunity charging (strategy)	1	➢ Public charging infrastructure (kW - high power)	2
➢ Charging power (kilowatt)	1	➢ Range anxiety (strategy)	1
➢ State of charge of battery (%)		➢ Contract length (month/ years)	1
➢ Driver cost (SEK/ hour)		➢ Mixed fleet operation (strategy)	1
➢ Driving speed (kmph)		➢ Operational distance driven (kilometer)	1
➢ Ambient temperature (degree Celsius)		➢ Driver availability (strategy)	
➢ Driver competence training (strategy)		➢ Driving road condition (strategy)	
➢ Collaboration/ knowledge sharing (strategy)		➢ Operational weather condition	

Figure 5: Result from the workshop with forestry transport system stakeholders to identify parameters important for freight haulers to decide about BET investment

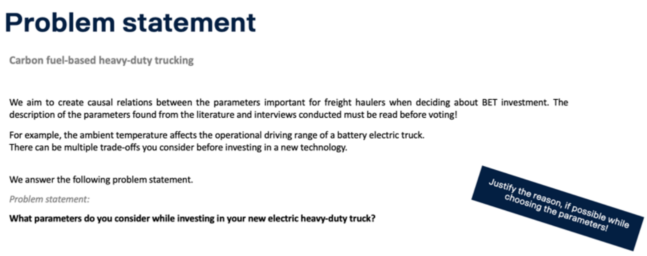


Figure 6: Problem statement presented at the workshop with forestry transport system stakeholders to identify parameters important for freight haulers to decide about BET investment

Presenter Biography

Vivek Venkatesh Shenoy is an industrial PhD student (From Scania CV AB, Sweden) affiliated with the Integrated Transport Research Lab at KTH Royal Institute of Technology. His research focuses on understanding the transition toward sustainable zero-emission heavy-duty truck alternatives by simulating and optimizing vehicle fleets. He holds a master's degree in the field of vehicle engineering.