Decarbonising the UK heavy goods vehicle sector: modelling long-term adoption dynamics of battery-electric and hydrogen fuel cell trucks

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1. Introduction

The United Kingdom (UK) has committed to achieving net-zero greenhouse gas emissions by 2050 and to reducing economy-wide emissions by 68% by 2030 under its Nationally Determined Contribution to the Paris Agreement [1]. The transport sector remains the largest contributor to domestic carbon dioxide emissions, accounting for approximately 30% of total UK emissions in 2024 [2], with heavy goods vehicles (HGVs) representing one of the most difficult subsectors to decarbonise due to their high energy demand, long operating ranges, and stringent reliability requirements. In response, the UK government has mandated that all new HGVs sold must be zero-emission by 2040, where "zero-emission" is defined as vehicles without an internal combustion engine or with emissions below specified thresholds for freight or passenger transport [3]. Within this regulatory framework, the UK government has adopted a technology-neutral policy stance, recognising battery-electric vehicles and hydrogen fuel cell electric vehicles as viable zero-emission propulsion pathways.

Despite these commitments, the uptake of zero-emission HGVs remains limited. Fleet operators face substantial uncertainties related to vehicle cost, operational performance, refuelling or charging availability, and long-term infrastructure provision, all of which influence investment decisions in a sector characterised by thin margins and long asset lifetimes [4]. As a result, understanding how technological development, infrastructure deployment, and policy interventions interact dynamically over time to shape adoption trajectories is critical for delivering the UK's freight decarbonisation objectives.

This study investigates the long-term adoption of zero-emission HGVs in the UK freight sector, with particular attention to the dynamic interaction between competing battery-electric and hydrogen fuel cell technologies.

2. Research questions

What factors influence the adoption of zero-emission HGVs in the UK freight sector, and how do technological, organisational, infrastructural, and policy factors interact dynamically over time? This overarching question is supported by the following sub-questions:

- What are the key underlying mechanisms and central feedback loops shaping freight operators' decisions to adopt zero-emission HGVs?
- What are the implications of these underlying system structures for the future evolution of the UK HGV market under a business-as-usual scenario and under alternative policy interventions aimed at accelerating transport sector decarbonisation?

3. Aims and objectives

The aim of this study is to examine the long-term adoption dynamics of zero-emission HGVs in the UK freight sector by developing a behaviourally grounded system dynamics (SD) modelling framework that captures the interaction between technological development, infrastructure provision, organisational decision-making, and policy intervention. In particular, the research seeks to understand how competition between battery-electric and hydrogen fuel cell HGV technologies evolve over time and influence the decarbonisation trajectory of the UK freight system. To achieve this aim, the study pursues the following objectives:

- To identify and conceptualise the key technological, organisational, infrastructural, and policy factors influencing zero-emission HGV adoption in the UK freight sector.

- To represent competition between battery-electric and hydrogen fuel cell HGVs within a novel SD model that captures the central feedback mechanisms and endogenous interactions shaping fleet operators' adoption behaviour.
- To formalise and quantify the dynamic hypothesis within the model, which will be parametrised and calibrated using a combination of primary and secondary data.
- To conduct structural and behavioural model validation and explore how different system structures and feedback loops influence long-term market evolution under a well-developed scenario framework.
- To analyse the model results and derive policy-relevant insights to support the decarbonisation of the UK freight sector.

4. Literature review

Research on the adoption of zero-emission HGVs has expanded rapidly in recent years, reflecting growing policy and industry interest in freight decarbonisation. Much of the empirical literature has relied on stated-preference surveys and discrete choice modelling to quantify fleet operators' preferences for alternative powertrains, offering valuable insights into attribute trade-offs and heterogeneity in decision-making [5,6]. However, conventional discrete choice models are typically static and do not capture how adoption patterns evolve endogenously over time in response to infrastructure deployment, technology maturity, or policy feedback. To address this limitation, simulation-based approaches, particularly SD has been applied to model long-term vehicle diffusion and infrastructure interactions [7].

While SD models have been widely used to study passenger vehicle transitions, their application to the HGV sector remains limited. Existing SD-based freight studies often focus on a single zero-emission technology [8] or rely on simplified exogenous adoption trajectories [9], thereby underrepresenting competition between battery-electric and hydrogen fuel cell HGVs and the behavioural complexity of fleet decision-making. Previous system-level modelling studies provide valuable insights into interactions between energy systems, technology development, and infrastructure deployment; however, their representation of heavy-duty vehicle adoption relies on exogenous assumptions regarding technology maturity and omits behavioural factors such as technology awareness, limiting direct applicability to the UK context [10].

Overall, there is a paucity of UK-specific studies that integrate parametrised technological maturity, and behavioural choice modelling with dynamic system-level feedback to analyse long-term zero-emission HGV adoption. This study addresses this gap by combining SD with an endogenous, behaviourally grounded adoption mechanism to examine competing zero-emission freight adoption under alternative policy and infrastructure scenarios.

5. Theoretical framework

The transition to zero-emission HGVs in the freight sector can be understood as a complex socio-technical change process shaped by organisational decision-making, technological development, infrastructure availability, and policy intervention. Freight vehicle adoption occurs primarily in a business-to-business context, where purchasing decisions are influenced by operational performance, cost considerations, and risk perceptions rather than individual consumer preferences [11]. Such transitions are further characterised by feedback-driven diffusion processes, whereby early adoption influences technology awareness, infrastructure investment, and subsequent uptake. SD provides an appropriate theoretical lens through the principles of systems for analysing these interactions, as it enables representation of endogenous feedback loops, non-linear behaviour, and path dependence in long-term technology transitions [12,13].

6. Research design

This study employs a SD modelling approach to analyse long-term zero-emission HGV adoption in the UK freight sector, explicitly representing competition between battery-electric and hydrogen fuel cell technologies. The model captures feedback-driven interactions between fleet adoption, perceived utility, infrastructure availability, technology development, and policy support, allowing adoption trajectories to emerge endogenously. Fleet operators' adoption decisions are represented through a behaviourally grounded choice mechanism in which perceived utility depends on factors including cost, vehicle range, refuelling or charging time, infrastructure availability, and technology awareness. The framework is applied to explore adoption dynamics under a business-as-usual scenario and alternative policy intervention scenarios aligned with the UK's zero-emission HGV mandate.

7. Relevance of study

The decarbonisation of the UK freight sector presents significant challenges due to long vehicle lifetimes, high capital costs, and strong dependence on supporting infrastructure. Policymakers face uncertainty regarding the timing, scale, and coordination of investments required to support competing zero-emission technologies, while freight operators must make strategic decisions under conditions of technological and regulatory uncertainty. By explicitly modelling the dynamic interaction between vehicle adoption, infrastructure deployment, and policy intervention, this study provides insights into the conditions under which zero-emission HGV uptake can be accelerated without creating technology lock-in or stranded infrastructure assets. The findings are relevant to policymakers designing technology-neutral support mechanisms, infrastructure investment programmes, and interim targets aligned with the UK's 2040 zero-emission HGV mandate. More broadly, the modelling framework offers a decision-support tool for industry stakeholders seeking to assess long-term transition pathways and manage risk in the shift toward zero-emission freight transport.

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