Engineering Science and Technology, an International Journal 80 (2026) 102442

Contents lists available at ScienceDirect

Engineering Science and Technology, an International Journal

journal homepage: www.elsevier.com/locate/jestch

Evaluating market-based interventions for heavy-duty zero-emission truck adoption under consumer heterogeneity☆

Zhenyu Tan [a,*], Gbemi Oluleye [a,b,c]

[a] Centre for Environmental Policy, Imperial College London, SW7 2AZ, United Kingdom
[b] Sargent Centre for Process Systems Engineering, Imperial College London, SW7 2AZ, United Kingdom
[c] Grantham Institute – Climate Change and the Environment, Imperial College London, SW7 2AZ, United Kingdom

ARTICLE INFO

Keywords:
Heavy-duty trucks
Market-based interventions
Zero-emission trucks
Agent-based modelling
Perceived risk
Innovation diffusion theory
Total cost of ownership

ABSTRACT

This research aims to assess the effects of different market-based interventions on accelerating the adoption of heavy-duty zero-emission trucks (ZETs). A novel agent-based model is developed and applied to simulate heterogeneous consumer choices across three heavy-duty truck segments, namely 49 t tractor-trailers, 31 t dump trucks, and 18 t straight trucks, while accounting for perceived risks. The analysis also considers three powertrain options: internal combustion engine trucks, battery electric trucks, and hydrogen fuel cell trucks. The assessment covers 56 policy scenarios, including hydrogen subsidies, purchase subsidies, electricity subsidies, operational subsidies, diesel taxes, and various combinations of these interventions. The results indicate that while subsidies are effective in promoting ZET adoption, they are costly; however, diesel taxation can help finance these measures. Therefore, policy combinations appear to be more effective. The analysis further shows that the effectiveness of interventions may diminish over time and that better alignment between specific policy instruments and truck types may improve policy efficiency. The simulation also reveals competition between different ZET technologies, which may lead to policy inefficiencies. This research contributes to the literature by demonstrating the impacts of market-based interventions on adoption behaviour beyond total cost of ownership calculations.

1. Introduction

The last four decades have witnessed economic development across major economies. For example, China's GDP has increased by approximately 100 times compared to its level in 1980, while the GDPs of India, the United States, Mexico, and Australia have grown by around 20 times, 10 times, 9 times, and 11 times, respectively [1]. Other countries as illustrated in Fig. 1 have also experienced at least a threefold increase in GDP. From an economic perspective, such rapid growth implies substantial increases in both inputs and outputs. These large volumes of inputs and outputs need to be transported to locations where they are produced, processed, or consumed, meaning that intensified production activities require strong freight transport capacity. This relationship is reflected in the evolution of road freight activity in the example countries, as shown in Fig. 2. Road freight activity is closely associated with economic development, particularly in China, India, and Mexico, where it has increased by approximately 20 times, 16 times, and 2.5 times, respectively [2]. The scale of road freight activities is projected to continue rising alongside increasing production in the foreseeable future.

This growth imposes a substantial environmental burden, as the freight sector remains heavily reliant on diesel fuel, particularly in the heavy-duty segment. Freight activities can generally be categorised into heavy-duty and medium- and light-duty operations. The classification thresholds used in different countries or by different organisations vary; for example, 12 tons in China [3], 15 tons in the U.S. [4], and 15 tons by IEA [5]. To avoid ambiguity and ensure consistency, this study defines heavy-duty road freight activities as those involving trucks with a gross vehicle weight above 12 tons. Those trucks performing heavy-duty tasks are referred to as heavy-duty trucks (HDT). Currently, most HDTs in the

Abbreviations: ABM, Agent-based Model; ZET, Zero-emission Truck; ICET, Internal Combustion Engine Truck; BET, Battery Electric Truck; HFCT, Hydrogen Fuel Cell Truck; TCO, Total Cost of Ownership; HRS, Hydrogen Refuelling Station; BAU, Business-as-Usual; GHG, Greenhouse Gases; OPEX, Operational Expenditure.

☆ This article is part of a special issue entitled: 'JESTCH_SWEDES 2025' published in Engineering Science and Technology, an International Journal.

* Corresponding author.
E-mail addresses: z.tan23@imperial.ac.uk (Z. Tan), o.oluleye@imperial.ac.uk (G. Oluleye).

https://doi.org/10.1016/j.jestch.2026.102442

Available online 15 June 2026
2215-0986/© 2026 The Author(s). Published by Elsevier B.V. on behalf of Karabuk University. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

freight sector are diesel trucks [6], which are major contributors to climate change and air pollution. To be specific, HDTs account for more than 25% of the CO_2 emissions from the European road transport sector despite representing about 2.5% of the vehicle fleet [7]; in the U.S., HDTs are responsible for about 23% of total greenhouse gas (GHG) emissions from the transportation sector while constituting only a small portion of the vehicle fleet [8,9]. In China, HDTs account for less than 3% of the vehicle population but contribute as much as 52.4% of PM emissions from road transport [10]. Such disproportionate emissions pose a severe challenge to sustainable development and highlight the urgent need to transition HDTs towards alternative fuels.

Currently, two types of zero-emission trucks (ZETs) are available for road freight applications: battery electric trucks (BET) and hydrogen fuel cell trucks (HFCT) [11]. BETs and HFCTs can achieve lower emissions than diesel trucks [12]. On the positive side, BETs are quiet in operation and exhibit high well-to-wheel efficiency, meaning that less energy is lost between energy generation and propulsion at the wheels [13]. On the other hand, charging batteries takes a long time, which can be several hours even when fast charging is used [6]. Battery swapping has recently emerged as an alternative approach that can reduce recharging time. Nevertheless, BETs still have a payload penalty, because batteries are much heavier than a full diesel tank, meaning BETs can carry less cargo weight. Their limited onboard energy storage also constrains driving range. HFCTs are essentially hybrid vehicles in which a fuel cell converts hydrogen into electricity to charge an onboard battery, which then powers the electric drivetrain. This process generates only water vapour as exhaust while also operating quietly. Since hydrogen has a high energy density, HFCTs do not suffer from substantial payload penalties. The hydrogen stored on board can easily provide a driving range comparable to that of diesel trucks [11]. In addition, hydrogen refuelling also takes just several minutes. Although both ZETs are technically available, their market penetration remains low. BETs represent about 3% of truck sales in China and 1.5% in Europe, while the global stock of HFCTs was only around 7,000 vehicles in 2022.

One major barrier to the low market penetration of ZETs is their high total cost of ownership (TCO). The current purchase price of a battery electric HDT is about two to three times that of a comparable diesel truck, while hydrogen fuel cell HDTs are priced even higher [6,14]. Although BETs exhibit high efficiency and benefit from relatively low fuel prices, which creates advantages in terms of lower operational expenditure [15], their TCO still remains high. BETs have already achieved a lower TCO than diesel trucks in certain applications in China, whereas this cost advantage has not yet materialised in most other regions [6]. HFCTs rely on more expensive hydrogen fuel, resulting in higher operational costs and a further increase in their TCO [15]. Another barrier is the lack of refuelling and recharging stations. Most BET operators today rely on overnight depot charging, but the availability of enroute fast-charging infrastructure is essential for minimising disruptions to freight operations. However, fast-charging networks for HDTs are still at an early stage of development [6]. Similarly, hydrogen refuelling stations (HRS) are scarce. The number of operational HRS was around 1,300 worldwide at the end of 2024 [6]. Moreover, the limited deployment of HFCTs reduces incentives for private investors to expand HRS, while the lack of HRS further suppresses market demand for HFCTs [16]. This is known as the chicken and egg conundrum. Some other barriers, such as the limited driving range of BETs, the relatively low technological readiness of HFCTs in real-world freight operations, reluctance to adopt new technologies and payload penalties, are also highlighted by existing literature [11].

To generate demand-pull for ZETs, market-based interventions are required to close the TCO gap and create a cost advantage for ZETs. Therefore, this study aims to assess the impacts of market-based interventions on ZET adoption behaviours. Market-based interventions refer to policy approaches in which governments use market mechanisms, such as prices, taxes, subsidies, or tradable permits, to influence behaviours rather than relying on direct regulations or mandates. The focus on market-based interventions does not mean these interventions are necessarily more important than other interventions, for example, ensuring the accessibility to stable hydrogen supply. Rather, this work just adopts one analytical perspective for addressing the "chicken-and-egg" conundrum by assessing how market-based interventions can accelerate the adoption of ZETs.

The remainder of this paper is organised as follows. Section 2 reviews the literature on the adoption of ZETs and identifies research gaps. Section 3 introduces how this research was conducted, including the modelling approach and data sources, and Section 4 presents and discusses the results, explores their implications for policy design, and highlights important considerations when interpreting the findings. Section 5 concludes the paper by summarising the main insights, outlining policy implications, and suggesting directions for future research.

2. Literature review

Numerous studies have examined the cost trajectories of zero-emission HDTs and the associated need for supportive policy

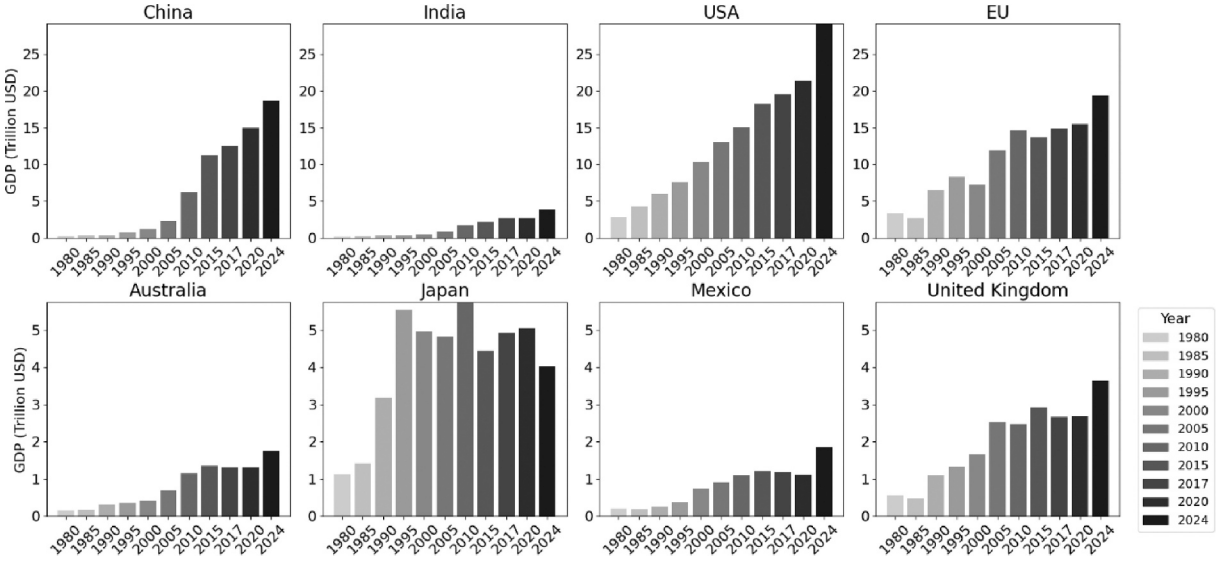


Fig. 1. GDP in some major economies.

interventions. Sharpe and Basma [17] reviewed the literature on the capital costs of HDTs and found that ZETs were typically two to three times more expensive than diesel trucks. They also studied a specific type of HDT, the zero-emission tractor-trailers, and analysed projected cost reductions in North America and Europe between 2020 and 2030. They concluded that BETs could experience a reduction by about 40% in capital cost by 2030, while HFCTs may experience a more modest reduction of about 23%. Extending the analysis beyond capital costs, Burke et al. [18] explored TCO projections and investigated the economic viability of various types of ZETs, including medium- and heavy-duty vehicles, and short- and long-haul applications, in the U.S. from 2020 to 2040. Their results showed that BETs may become cost-competitive by 2030, whereas HFCTs may only achieve cost competitiveness slightly beyond 2030 and only if the hydrogen price halves. Similarly, Xue et al. [19] conducted a TCO analysis of various types of ZETs in China. Their results indicated that ZETs for mid- and long-haul applications are unlikely to become cost-competitive until around 2035, underscoring the importance of technological innovation and market-based interventions in narrowing the TCO gap between diesel and zero-emission alternatives. Many other studies covering the major truck market, such as India [20] and Australia [21], have obtained a similar trend in cost projection. However, these projected cost reductions depend on sufficient demand-pull effects to enable economies of scale. Without market-based interventions to stimulate such demand-pull effects, the TCO of ZETs may remain higher than that of diesel trucks over the coming decade and today's high cost continues to suppress market demand.

Several studies have investigated the impacts of market-based interventions on the TCO of heavy-duty zero-emission trucks. ICCT [22] examined the impact of purchase subsidies and carbon taxes on the TCO of heavy-duty zero-emission dump trucks in Guangdong Province, China. Their findings suggested that, under business-as-usual conditions, ZETs would not achieve TCO parity with diesel trucks until around 2030. However, with policy support, cost parity could be reached as early as 2023 for BETs and 2026 for HFCTs. Using a similar method, ICCT [23] assessed the impact of purchase subsidies and tax exemptions on battery electric tractor-trailers in Tangshan City, China. Their results showed that such interventions could reduce the TCO by about 35% relative to diesel alternatives and thus create cost advantages for BETs. In another Chinese study, ICCT [24] examined TCOs across various truck powertrains and use cases and concluded that, with a comprehensive policy mix including road toll exemptions, carbon taxes, purchase subsidies, and hydrogen fuel subsidies, HFCTs could potentially achieve cost parity around 2025. While these studies focus on Chinese cases, some research in other major truck markets has also obtained similar results to justify the potential of market-based interventions. A European study by ICCT [25] examined the effects of purchase subsidies, toll exemptions, hydrogen fuel subsidies, and carbon pricing. The study found that hydrogen subsidies were the primary driver for achieving cost parity by 2030, as purchase costs were expected to converge more closely with those of diesel trucks. In a North American study, Larson et al. [26] analysed the effects of carbon taxes on the TCO of ZETs and showed that carbon taxes enhanced the cost advantage of BETs. On the other hand, if grey hydrogen was used, carbon taxes alone were not enough to create a cost advantage for HFCTs. Overall, these studies provide evidence that market-based interventions can significantly improve the economic viability of ZETs.

However, the aforementioned studies do not explore how market-intervention induced changes in the TCO affect adoption and diffusion dynamics. The adoption of ZETs is also constrained by factors such as limited availability of recharging and refuelling, perceived risks, the impacts of recharging time on business operation, and reluctance to invest in new technologies. These uncertainties and adverse consequences are conceptualised as perceived risks in Bauer's theory of perceived risk (1960). They generate intangible costs, which are monetised non-financial factors, and influence vehicle purchasing decisions [11]. Such perceived risks have been examined in empirical studies. For example, Thilina and Gunawardane [27], Hu et al. [28], and Karunanayake and Samarasinghe [29] studied consumer hesitation towards adopting electric vehicles and found perceived risk was negatively related to willingness to buy electric vehicles. These findings suggest that incorporating perceived risks allows for a more comprehensive assessment of the true economic costs faced by consumers when comparing ZETs with diesel trucks [11,30–33]. Moreover, potential adopters are heterogeneous in their preferences and perceptions, leading them to assign different levels of intangible cost to the same truck option. While ZETs may attract early adopters who perceive lower risks and assign smaller intangible costs, the same TCO may not be considered sufficiently cost-effective by the broader population of potential adopters [30,34]. This aligns with the theory of the diffusion of innovations, where consumers have different resistance to innovations, from very low to very high, according to socio-demographic characteristics [35]. Early adopters tend to assign lower perceived risks, whereas late adopters impose higher intangible costs when evaluating new technologies [36]. Taken together, these insights indicate that perceived risks shape adoption decisions, and that improving economic viability

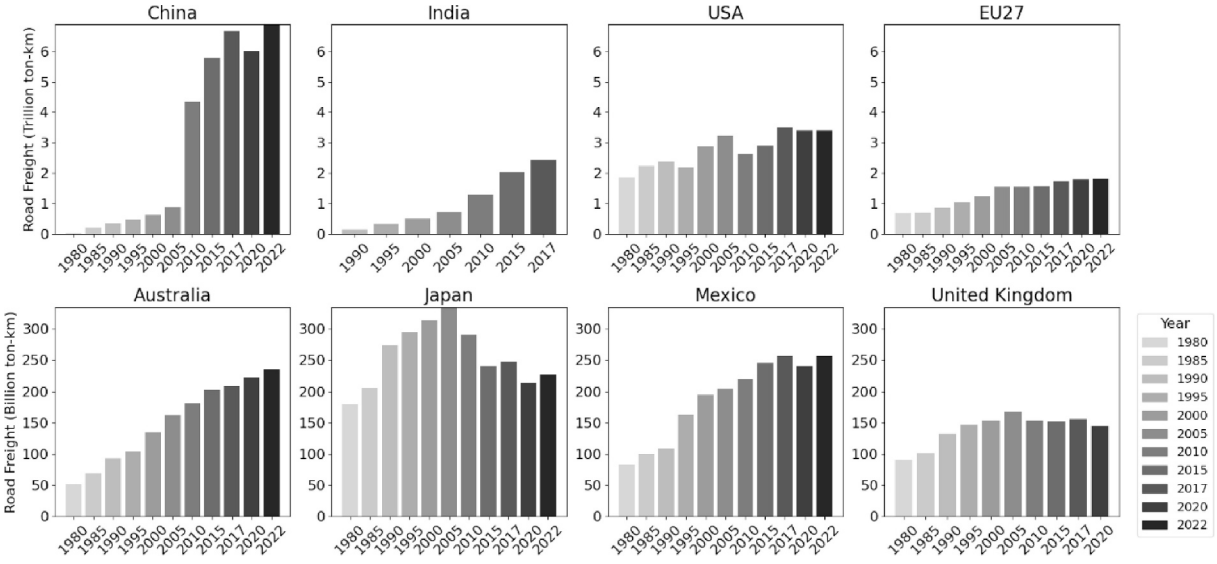


Fig. 2. Road freight activity in some major economies.

through market interventions can help compensate for these perceived risks, thereby enhancing the likelihood of widespread adoption.

In recent studies investigating the diffusion of ZETs, adoption behaviours have often been assumed to be homogeneous and primarily determined by TCO. For example, Zheng et al. [37] employed an agent-based model to simulate truck purchasing behaviours under scenarios with and without hydrogen subsidies. They concluded that without policy intervention, HFCTs would struggle to attract consumers. Their model assumed all buyers are homogeneous, which is not the case in a real truck purchasing scenario. Similarly, Teng et al. [38] analysed the policy effects using a system dynamics model and found that hydrogen subsidies and purchase taxes could increase HFCT adoption. Zhu et al. [39] also applied a system dynamics model to assess how purchase subsidies affect HFCT adoption. However, the aggregate nature of system dynamics modelling requires buyers to be represented as a homogeneous group, limiting the ability to capture behavioural heterogeneity or to examine how different types of buyers may respond differently to policy interventions. In an evolutionary game theory simulation study, Yin et al. [40] evaluated the intervention effects and concluded that without addressing the high cost of hydrogen and bottlenecks in refuelling infrastructure, HFCT penetration targets would be difficult to achieve. Their method assumed consumers shared the same probability of choosing HFCTs and could only obtain adoption probability under different scenarios.

In contrast, a smaller number of studies have explicitly considered heterogeneity and intangible costs in adoption analysis. Axsen et al. [31] applied choice observations to calibrate intangible costs and a market share equation for light-duty vehicles and concluded that purchase subsidy, diesel taxes, and carbon taxes could increase the market share of hybrid electric vehicle and reduce 2030 GHG intensity by about 16.6 to 22.8% relative to a scenario without interventions. Another study by McCollum et al. [32] found that strategies aimed at reducing consumers' perceived risks could complement carbon pricing and accelerate a low-carbon transition. In a broader policy context, Vass [34] examined interventions in the electricity and transport sectors and found that only a sufficiently strong carbon price could substantially increase the market share of low-emission vehicles. Focusing on the truck market, Miller et al. [36] concluded that reducing perceived risks could increase future ZET market share, but they did not investigate market-based interventions. Hammond et al. [41] also exclusively studied the freight-sector and assessed the impacts of carbon taxes, purchase subsidies, and other non-market-based interventions on GHG emissions up to 2050. They concluded that only a mix of interventions had a higher potential to increase ZET market share and reduce GHG emissions. Despite explicitly acknowledging heterogeneity, these studies primarily represented heterogeneity at an aggregate market level by specifying the extent to which relative cost differences translate into market shares. In other words, their estimations only captured the overall concentration of consumer choices. Therefore, consumers' heterogeneous perceptions of new technologies and prices were not explicitly reflected.

In conclusion, several gaps can be identified. First, studies examining the economic viability of ZETs outnumber those that explicitly examine adoption and diffusion, so there is a need to enrich the discussion about how policies translate into accelerated market penetration of ZETs. Second, although incorporating intangible costs is essential for a comprehensive analysis of adoption behaviour, existing academic research in this area remains limited. Third, while some studies account for market heterogeneity, market responses are typically represented as aggregate reactions to cost differences, rather than individual heterogeneity. Fourth, most of the literature overlooks government expenditures associated with policy interventions and thus has weak insights into the fiscal implications. Additionally, the extent to which policy effectiveness is shaped by competition between different powertrain technologies (e.g., diesel, electric, hydrogen) remains insufficiently understood. Therefore, to bridge the gaps, this research examines how market-based interventions affect the total cost of ownership (TCO) and, in turn, ZET adoption while accounting for fiscal burdens and interactions between competing powertrain technologies. The novelty lies in its integration of innovation adoption theories, its implications for policy design and its methodological contribution through the development of a bottom-up evaluation model introduced in the next section.

3. Methodology

3.1. Agent based model development

To account for the heterogeneity among buyers in market adoption, this research employs an agent-based model (ABM). ABM is particularly well-suited to simulating systems where diverse agents interact within a dynamic environment, and where individual behaviours influence overall outcomes. Unlike system dynamics models, which typically require assumptions about aggregate or average behaviours, ABM allows the modelling of individual decision-making processes without presuming homogeneity among consumers [42]. This makes it an appropriate choice for exploring how different types of truck buyers respond to market-based interventions. In this study, buyer heterogeneity is captured by assigning buyers different levels of innovativeness following the diffusion of innovation framework [35]. This approach is learnt from the ABM work by Zsifkovits and Günther [43], who simulated passenger car purchasing behaviours based on buyers' individual adoption tendencies. The ABM model was constructed in *NetLogo*, and it simulates the diffusion of ZETs, both with and without policy interventions, over the period from 2020 to 2050. The model comprises five types of agents (Fig. 3).

The first agent is the government, which introduces and manages policy interventions. Equation (1) estimates the government's net fiscal impact of the interventions by subtracting tax income from total subsidy expenditures.

$$GovNetExp = SubExp - TaxIncome \tag{1}$$

The other two groups of agents are a manufacturer and trucks. The manufacturer is responsible for improving vehicle technologies, accumulating production experience which influences fuel economy and vehicle prices, producing and supplying trucks. Trucks are categorised into three powertrain types, namely ICET, BET, and HFCT, and are applied across three segments, namely 49-ton tractor-trailer, 31-ton dump trucks, and 18-ton straight trucks. The rest of the paper will use the weight classes to represent each segment. The manufacturer is assumed to have unlimited production capacity to satisfy all buyer demand and to recycle any unsold trucks at the end of each year, so only newly produced vehicles are sold annually. This assumption enables a

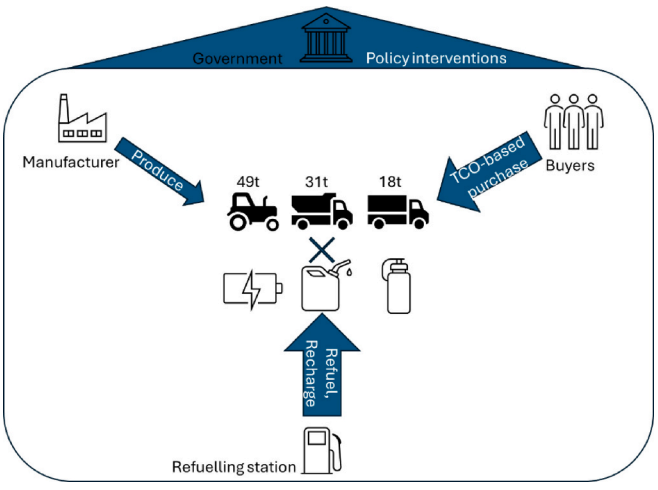


Fig. 3. Overview of the agents.

focus on the demand side and the investigation into market-based interventions. The manufacturer and trucks' behaviours are modelled using Eqs. (2) to (10). Eqs. (2) and (3) capture the temporal evolution of key parameters, namely truck purchase price and fuel economy for each truck type k (ICET, BET, and HFCT), reflecting projected improvements or trends up to 2050. Eqs. (4) and (5) calculate the salvage value of a truck and how its salvage rate changes over time. Eqs. (6) and (7) determine the discounted lifetime fuel cost and maintenance cost, respectively, based on annual mileage, fuel use (both full-load and unladen), and a discount factor. Eq. (8) derives the discounted salvage value, while Eq. (9) computes the discount factor used in cost calculations. Eq. (10) integrates all these components, including subsidies and taxes, to calculate the TCO of each truck type.

$$TP_{k,t} = TP_{k,t-1} \times \left(1 - TPCR_{k,t}\right) \tag{2}$$

$$FE_{k,t} = FE_{k,t-1} \times \left(1 - FECR_{k,t}\right) \tag{3}$$

$$RV_{k,t} = TP_{k,t} \times ResidualR_{k,t} \tag{4}$$

$$ResidualR_{k,t} = ResidualR_{k,t-1} + ResidualCR \tag{5}$$

$$DFC_{k,t} = \left(FE_{k,t} \times M \times FLP + FE_{k,t} \times (1 - USave) \times M \times (1 - FLP)\right) \times FP_{k,t} \times DF \tag{6}$$

$$DMain_k = Main \times M \times DF \tag{7}$$

$$DRV_{k,t} = RV_{k,t}/(1 + r)^5 \tag{8}$$

$$DF = 1/(1 + r)^t \tag{9}$$

$$TCO_{k,t} = TP_{k,t} - Sub + Tax - DRV_{k,t} + DFC_{k,t} + DMain_k \tag{10}$$

Truck price *TP* and fuel economy *FE* change over time according to their respective changing rates, *TPCR* and *FECR*, respectively. *DRV* and *RV* represent discounted residual value and residual value, respectively. *RV* is a percentage (*ResidualR*) of the purchase price, and the percentage changes over time at a rate determined by *ResidualCR*. *DFC* is the discounted fuel cost. *FLP* is the percentage of full-load mileage (*M*), and *USave* is the fuel saving when unladen. *DMain* is the discounted maintenance cost. *DF* is the discounted factor.

The fourth agent is the refuelling station, which supplies fuel to trucks and develops fuel production technologies. Fuel prices (*FP*) change over time according to a changing rate (*FPCR*), as Eq. (11) shows. Their location and distribution are not investigated in this model, but the model reflects the abundance of diesel refuelling stations and the lack of recharging and hydrogen refuelling services by introducing risk, which is explained in the buyers' behaviours.

$$FP_{k,t} = FP_{k,t-1} \times \left(1 - FPCR_{k,t}\right) \tag{11}$$

Finally, the fifth group of agents are buyers, who respond to varying TCOs and policy incentives, purchase trucks and use refuelling services. Their decisions are based on perceived risk theory proposed by Bauer [44]. According to this theory, consumers have resistance towards buying ZETs, so they require risk compensation to switch from ICETs to ZETs. Truck buyers are concerned about the recharging and refuelling reliability, the constraint of range, safety, charging time, and other potential impacts on the operation, and thus, they have resistance to adopting ZETs, and they need risk compensation to address their resistance. In other words, they will only buy a ZET when the cost advantage is large enough after considering their perceived risk. The more resistance a buyer has, the more risk compensation the buyer requires. This forms the theoretical basis of the buyers' behavioural rules in the model. Buyers calculate costs while considering the corresponding perceived risk, as Eq. (12) shows. Buyers are assumed to perceive the same level of risk of BETs and HFCTs, as the impact of different components of the risks is not quantified and ranked in the existing literature, and ICETs have no such risk. $RCM_{k,i}$ is a risk compensation multiplier of the buyer i regarding truck type k. The multiplier is based on buyers' innovativeness and resistance to ZETs [43], and it is calculated as Eq. (13). The multiplier is a simplified way to define intangible costs when those risks have no specific rules to monetise. This research assumes there are 400 buyers within each truck segment, and they only buy trucks within their corresponding segment. Their innovativeness follows the distribution according to the diffusion of innovation theory [35], so among the buyers, 2.5% are innovators, 13.5% are early adopters, 34% are early majorities, 34% are late majorities, and 16% are laggards. Buyers in each category have different resistance towards ZETs. Resistance values are randomly assigned to the buyers within a certain range defined for each group of buyers. The ranges are ascending according to the innovativeness levels, and they are (0, 0.025), (0.025, 0.16), (0.16, 0.5), (0.5, 0.84), (0.84, 1). The innovators have the least resistance to adopting ZETs, and the laggards have the most resistance. Buyers' heterogeneity is reflected in Eq. (13), which adjusts the TCO based on each buyer's level of innovativeness and resistance towards ZETs.

$$AdjustedTCO_{k,t,i} = RCM_{k,i} \times TCO_{k,t} \tag{12}$$

$$RCM_{k,i} = 1 + (1 - Innovativeness_i) \times Resistance_i \tag{13}$$

$$P_k = (1/AdjustedTCO_k)/\left(\Sigma_{k=1}^{3}(1/AdjustedTCO_k)\right) \tag{14}$$

Buyers are assumed to only make decisions based on a 5-year adjusted TCO, and this model only analyses from a first-owner perspective. The 5-year ownership horizon is chosen as the existing literature does (such as [24,26], and [25]), and most trucks have about a 5-year first life before reselling and scrappage in Europe and China [25] and [23]. In addition, current battery and fuel cell durability permits at least 5 years of operation and therefore, no replacement is needed [24] and [25]. Thus, a 5-year horizon is a reasonable starting point for this research. Also, buyers' decisions are assumed to follow an inverse proportional probability function, as Eq. (14) shows. This functional form is chosen for the following reasons. First, it is a simplified discrete choice model [45] which uses a random utility function and has been used in empirical studies of product choices. Second, compared with the random utility function, it does not require choice observations, which are not easily accessible, to define a utility function. Third, it is a monotonic decreasing function, so it reflects that more expensive trucks have a lower probability of being bought, which follows the law of demand. Fourth, this functional form has two reasonable elasticity properties. The elasticity is monotonically decreasing as a standard discrete choice model does. As the cost advantage increases, the penetration of a powertrain technology slows down. The other property is that the elasticity is mild and enables a smooth evolution of the adoption. In contrast, a random utility function only results in a drastic change due to the exponential function expression when the TCO is the only variable. Fifth, this function is a micro expression of those macro market shares in previous literature. This function derives the adoption probability of each type of truck, and the probability is used in the buyers' decision process, as shown in Fig. 4. Buyers first calculate their adjusted TCO of different trucks. Then, when one or more ZETs become cheaper than the ICET, buyers consider both the lower-cost ZETs and the ICET as available options in order to reflect hesitation towards adopting new technologies. Next, buyers have a probability of removing the ICET from the option set. This probability depends on buyers' resistance. Specifically, when a randomly generated number is greater than the buyers' resistance level, they only consider ZETs. Therefore, the less resistance they have, the more likely they do not consider ICET as an option. The last behaviour rule is that each buyer agent buys one truck every year. It is easier to understand that the agents in a year are not identical to the ones in other years, so the number of buyer agents represents the scale of the market each year. This setting avoids any distraction associated with

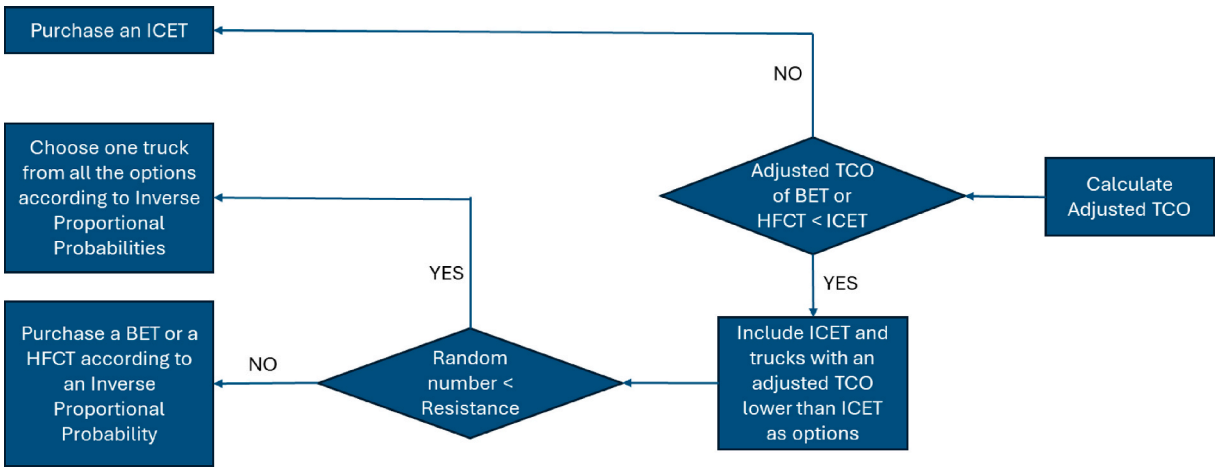


Fig. 4. Buyers' decision process.

fleet turnover, business operation or macro economy and enables the focus on market competition among those powertrain technologies.

3.2. Data and assumptions

The data used in this research were collected and adapted from eight existing studies [18,22,24,25,37,38,46,47]. These sources include academic articles published in high-impact journals (such as International Journal of Hydrogen Energy – IF 8.3, Transportation Research Part D – IF 7.7) and reports produced by the International Council on Clean Transportation, an influential research organisation. The collected data are of high quality, and consequently, other sources, including field investigations and prototype analyses, are not considered. Moreover, this research uses average data in those selected studies and conducts a sensitivity analysis by varying key parameter inputs within their observed ranges in the literature to enhance the robustness of the research results. In addition, this research extends existing work in these papers to a more market-induced diffusion modelling framework. The data sources cover China, Europe, and the US. Since China is leading the penetration of ZETs, having more Chinese studies in the reference data set is acceptable. Table 1 shows all values for the variables, and where the sources are not specified in the table, the values of those variables are average values derived from the literature listed above. The average values imply that the results and implications from this research are generic and apply to all possible regions where ZETs are a feasible alternative. The maximum and minimum ranges are shown in Table 2.

Freight activities are assumed to cover 76% of the annual kilometre travel, following Zheng et al. [37], as a truck can be unladen. When trucks are unladen, they are assumed to have 38% saving in fuel economy according to the average value in Zheng et al. [37] and ICCT [25]. The residual values were calculated using a depreciation method or a percentage of the original price in those studies. Considering the development of battery and fuel cell technologies and their recycle technologies, a changing residual value is more reasonable. ICETs are assumed to have a stable 30% of residual value, and BETs and HFCTs are assumed to have 15% salvage values in 2020 and have a 2% increasing rate in this decade, which will slow down afterwards [24,25]. The annual mileage was assumed to be 100, 90, and 50 thousand km, which are reasonable for Tractor-trailers, Straight Trucks, and Dump trucks, respectively [24,25,37,38]. This research uniformly assumes a 10-year life duration for the simplicity of modelling since the life of trucks is also in different formats, such as the maximum life duration and the maximum travel mileage. The difference between the TCO horizon and the lifetime is to enable the second-hand usage of trucks in the market, though this is not analysed in this research.

3.3. Scenario design

56 scenarios were designed around 14 categories of market-based interventions as summarised in Table 3.

3.4. Sensitivity analysis

After all preliminary results of the scenario analysis were obtained, a sensitivity analysis was conducted by varying the inputs of selected variables like (1) the innovativeness distribution, the variation of which can indicate the impact of buyers' resistance, (2) HFCT prices and, (3) hydrogen prices. Their variation can reflect the impact of prices, while these prices also vary in different geographical contexts. The other two variables are (4) the changing rate of the HFCT prices and (5) the hydrogen price. The potential results can indicate the potential market penetration in the optimistic and pessimistic future. Another variable, (6) discount rate, is to provide a different analysis, while different governments and buyers have different perspectives about the future. The last variable, (7) the considered duration of ownership, can provide more information for truck owners who have different ownership cycles. We also conducted an additional sensitivity analysis in which resistance to BETs was reduced by half to show how it affects our results and if our conclusions still survive. All these analyses can enhance the robustness of the model and the results.

4. Results and discussion

4.1. Business-as-usual case without market-interventions

In the BAU case, the TCO gap of tractor-trailers between an ICET and an HFCT is slightly more than 390 thousand USD, and the TCO gaps of dump trucks and straight trucks are about 180 thousand and 170 thousand USD, respectively, in 2020 (Fig. 5). The tipping point of tractor-trailers is 2041, and dump trucks and straight trucks are around 2037. The model's cost estimation aligns with cost projections [24,25]. The simulation also shows all weight classes of BETs achieve cost parity before 2030 as predicted in existing literature (such as [18,19]). The first adoption of ZETs is found in the same year as the tipping point is reached, but the adoption is limited within the innovator group, who have less resistance. In other words, the adopters perceive less risk of recharging/refuelling difficulty, impact on their business, or difficulty of use, and are willing to adopt ZETs. However, the market will still be dominated by ICETs. By 2050, the market share of fuel cell tractor-trailers is less than 10%, and the market share of FC dump trucks and FC straight trucks is about 25%, indicating relatively slow diffusion of HFCTs. The market share of battery electric tractor-trailers is about 40%

Table 1
Model inputs.

Truck Types	Truck price (,000 USD)	Truck price decrease rate by 2030	Truck price decrease rate by 2040	Truck price decrease rate by 2050	Residual rate	Residual value increase rate by 2030	Residual value increase rate by 2040	Residual value increase rate by 2050	Full-load fuel economy/100 km	Fuel economy decrease rate by 2030	Fuel economy decrease rate by 2040	Fuel economy decrease rate by 2050
ICET 49 t	81	−1%	−0.5%	−0.3%	30%	0%	0%	0%	35 L	4%	2%	1%
ICET 31 t	51								39 L	4%	2%	1%
ICET 18 t	19								26 L	3%	1%	0%
BET 49 t	243	5%	2%	1%	15%	2%	1%	0%	137kWh	4%	2%	1%
BET 31 t	160								131kWh	3%	1%	0%
BET 18 t	125								76kWh	3%	1%	0%
HFCT 49 t	354	7%	2%	1%	15%	2%	1%	0%	8.73 kg	5%	3%	2%
HFCT 31 t	187								8.9 kg	5%	3%	2%
HFCT 18 t	169								4.5 kg	5%	3%	2%
Sources			Assumed	Assumed	[24,25]	Assumed	Assumed	Assumed			Assumed	Assumed
Truck Types	**Unladen fuel economy save**	**Fuel price (USD/unit)**	**Fuel price decrease rate by 2030**	**Fuel price decrease rate by 2040**	**Fuel price decrease rate by 2050**	**Annual mileage (,000 km)**	**Maintenance cost (USD/km)**	**Discount Rate**	**Full load percentage**	**life duration (year)**		
ICET 49 t	38%	0.97	0%	0%	0%	100	0.0415	8%	76%	10		
ICET 31 t						50						
ICET 18 t						90						
BET 49 t		0.14	0%	0%	0%	100	0.0303					
BET 31 t						50						
BET 18 t						90						
HFCT 49 t		8.33	4%	2%	1%	100	0.0317					
HFCT 31 t						50						
HFCT 18 t						90						
Sources	[25,37]			Assumed	Assumed		[24]		[25]	Assumed		

Table 2
Parameter ranges in the literature.

Truck Types	Truck price (,000 USD)	Truck price decrease rate	Residual rate	Residual value increase rate	Full-load fuel economy (L, kWh or kg)/100 km	Fuel economy decrease rate by 2030	Unladen fuel economy save	Fuel price (USD)	Fuel price decrease rate by 2030	Annual mileage (,000 km)	Maintenance cost (USD/km)	Discount Rate	Full load percentage	life duration (year)
Max														
ICET 49 t	138	−3%	30%	–	39	5%	40%	1.11	−5%	150	–	10%	–	15
ICET 31 t	56	−4%	30%	–	40	5%		1.11	−5%	80	–			
ICET 18 t	25	−4%	30%	–	31	4%		1.11	−5%	125	–			
BET 49 t	316	6%	27%	–	164	4%		0.18	0	150	–			
BET 31 t	167	6%	27%	–	165	4%		0.18	0	80	–			
BET 18 t	163	6%	27%	–	91	4%		0.18	0	125	–			
HFCT 49 t	375	10%	27%	5%	9	5%		11.67	5%	150	–			
HFCT 31 t	278	10%	27%	5%	12	5%		11.67	5%	80	–			
HFCT 18 t	208	10%	27%	5%	6.35	5%		11.67	5%	125	–			
Min														
ICET 49 t	47	4%	30%	–	33	3%	24%	0.90	0	65	–	6%	–	5
ICET 31 t	46	4%	30%	–	38.2	4%		0.90	0	25	–			
ICET 18 t	15	3%	30%	–	22	3%		0.90	0	53	–			
BET 49 t	194	4%	15%	–	116	3%		0.11	0	65	–			
BET 31 t	153	4%	15%	–	97.8	3%		0.11	0	25	–			
BET 18 t	100	4%	15%	–	64.6	3%		0.11	0	53	–			
HFCT 49 t	333	5%	0	1%	8.46	5%		4.86	2.4%	65	–			
HFCT 31 t	125	5%	0	1%	5.86	5%		4.86	2.4%	25	–			
HFCT 18 t	129	6%	0	1%	3.83	5%		4.86	2.4%	53	–			

*: "-"represents data unavailable.

Table 3
Scenarios and their explanations.

Categories	No.	Scenarios	Further Information
No Interventions	1	**BAU**	Business-as-usual and no intervention
Fixed Hydrogen Subsidies	2	**FH-2**	2 USD per kg of hydrogen
	3	**FH-3**	3 USD per kg of hydrogen
	4	**FH-4**	4 USD per kg of hydrogen
Variable Hydrogen Subsidies	5	**VH-50%**	50% hydrogen price is paid by the government
	6	**VH-75%**	75% hydrogen price is paid by the government
	7	**VH-90%**	90% hydrogen price is paid by the government
Fixed Purchase Subsidies	8	**FP-10 k**	10,000 USD purchase subsidy
	9	**FP-20 k**	20,000 USD purchase subsidy
	10	**FP-30 k**	30,000 USD purchase subsidy
	11	**FP-50 k**	50,000 USD purchase subsidy
	12	**FP-80 k**	80,000 USD purchase subsidy
	13	**FP-100 k**	100,000 USD purchase subsidy
	14	**FP-120 k**	120,000 USD purchase subsidy
Variable Purchase Subsidies	15	**VP-10%**	10% of the HFCT price is paid by the government
	16	**VP-20%**	20% of the HFCT price is paid by the government
	17	**VP-30%**	30% of the HFCT price is paid by the government
	18	**VP-50%**	50% of the HFCT price is paid by the government
	19	**VP-60%**	60% of the HFCT price is paid by the government
Diesel Taxes	20	**T-20%**	A tax that increases the diesel price by 20%
	21	**T-50%**	A tax that increases the diesel price by 50%
	22	**T-80%**	A tax that increases the diesel price by 80%
Operation Subsidies	23	**O-2 k**	2,000 USD to HFCT owners every year in the first 5 years of ownership
	24	**O-3 k**	3,000 USD to HFCT owners every year in the first 5 years of ownership
	25	**O-4 k**	4,000 USD to HFCT owners every year in the first 5 years of ownership
	26	**O-5 k**	5,000 USD to HFCT owners every year in the first 5 years of ownership
	27	**O-10 k**	10,000 USD to HFCT owners every year in the first 5 years of ownership
	28	**O-15 k**	15,000 USD to HFCT owners every year in the first 5 years of ownership
	29	**O-20 k**	20,000 USD to HFCT owners every year in the first 5 years of ownership
	30	**O-25 k**	25,000 USD to HFCT owners every year in the first 5 years of ownership
Combinations of Subsidies and Taxes with Low Capacity	31	**FH-2 + T-20%**	Combinations of the above interventions
	32	**VH-50%+ T-20%**	
	33	**FP-10 k + T-20%**	
	34	**VP-10 k + T-20%**	
	35	**O-2 k + T-20%**	
Combinations of Subsidies and Taxes with Medium Capacity	36	**FH-3 + T-50%**	
	37	**VH-75%+ T-50%**	
	38	**FP-50 k + T-50%**	
	39	**VP-30%+ T-50%**	
	40	**O-5 k + T-50%**	
Combinations of Subsidies and Taxes with High Capacity	41	**FH-4 + T-80%**	
	42	**VH-90%+ T-80%**	
	43	**FP-100 k + T-80%**	
	44	**VP-60%+ T-80%**	
	45	**O-10 k + T-80%**	
Combination of Various Subsidies and A Tax	46	**C4**	Combinations of VH-50%, VP-10%, O-2 k, and T-50%
Variable Electricity and Hydrogen Subsidies	47	**BHVE-50%**	50% of energy costs of ZETs are paid by the government
	48	**BHVE-75%**	75% of energy costs of ZETs are paid by the government
	49	**BHVE-90%**	90% of energy costs of ZETs are paid by the government
Variable BET and HFCT Purchase Subsidies	50	**BHVP-10%**	10% of the truck price of ZETs is paid by the government
	51	**BHVP-20%**	20% of the truck price of ZETs is paid by the government
	52	**BHVP-30%**	30% of the truck price of ZETs is paid by the government
	53	**BHVP-60%**	60% of the truck price of ZETs is paid by the government
Operation Subsidies for BETs and HFCTs	54	**BHO-2 k**	2,000 USD to ZET owners every year in the first 5 years of ownership
	55	**BHO-5 k**	5,000 USD to ZET owners every year in the first 5 years of ownership
	56	**BHO-10 k**	10,000 USD to ZET owners every year in the first 5 years of ownership

due to a larger cost advantage, and the share of battery electric dump trucks and straight trucks is similar to their fuel cell counterparts at about 25%. The TCOs of ZETs are not reduced enough to attract buyers with more resistance to battery electric and fuel cell technologies, so the adoption rates each year of all three types of ICETs remains about 50%. The limited cost advantages and the high perceived risks hinder the ZET diffusion, and the growth of the cumulative adoption of HFCTs is slow; in comparison, the number of BETs increases faster (Fig. 5). This result indicates that without further interventions to enhance the cost advantage and reduce perceived risk, widespread diffusion of ZETs may remain difficult to achieve. Notably, the simulation also shows a slight decline in the number of BETs when HFCTs start being adopted. In late 2040, the evolution of TCOs of BETs is stabilised, and the TCOs of HFCTs keep decreasing; some ZET share just shifts from BETs to HFCTs without generating additional decarbonisation benefits. The reduction in BET market share and the cumulative number provide evidence of the competition between ZETs. These competition dynamics have also been documented in the existing literature (such as [36,41]).

4.2. Impact of single market-based interventions

In this section, the impact of subsidies and taxes is investigated individually. Subsidies bring forward the first adoption of HFCTs, accelerate the penetration of HFCTs, and increase the market share of HFCTs by 2050 (Table 4). Some interventions have limited influence on the diffusion. For example, FP-10 k (Fig. 6) brings the first adoption of tractor-trailer 2 years earlier and the first adoption of dump trucks and straight trucks three years earlier. It also increases the market share of

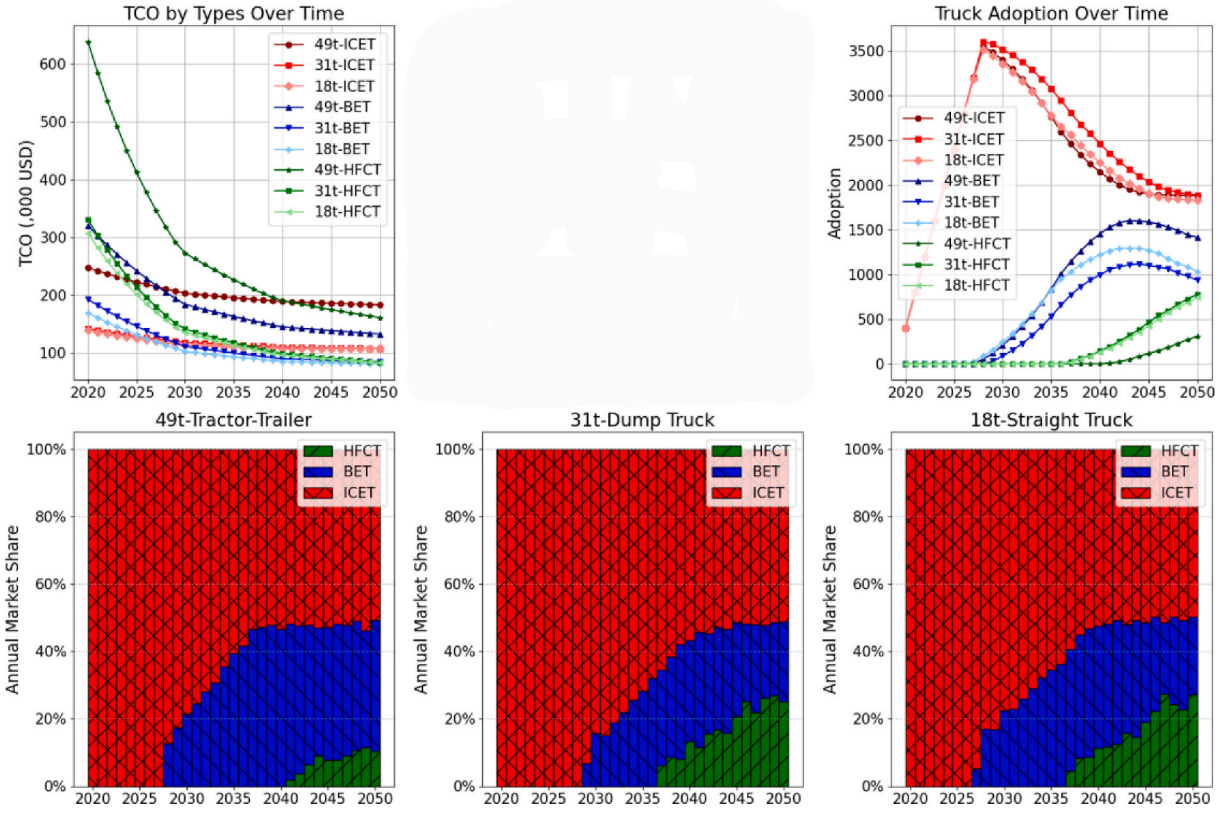


Fig. 5. Truck TCO and adoption under the BAU scenario.

Table 4
Simulation results for single market-based interventions.

Scenarios	The Year of the First Adoption			The Year of HFCTs Market Share Overtakes ICET Market Share in A Year			The Year of HFCTs Stock Overtakes ICET Stock			Total Government Net Expenditure by 2050 (,000 USD)	The ICET Market Share in 2050			The HFCT Market Share in 2050		
	49 t	31 t	18 t	49 t	31 t	18 t	49 t	31 t	18 t		49 t	31 t	18 t	49 t	31 t	18 t
BAU	2041	2037	2037	–*	–	–	–	–	–		51%	51%	50%	11%	25%	27%
FH-2	2034	2030	2030	–	–	–	–	–	–	108,584	49%	34%	33%	24%	48%	45%
FH-3	2030	2029	2029	2047	2038	2041	–	2042	2046	275,583	30%	21%	26%	44%	57%	59%
FH-4	2029	2027	2027	2038	2034	2036	2043	2037	2040	579,891	25%	9%	13%	53%	70%	70%
VH-50%	2032	2029	2029	–	2048	2045	–	–	2050	145,012	49%	34%	30%	23%	47%	49%
VH-75%	2028	2027	2027	2047	2037	2038	–	2045	2046	420,410	34%	24%	22%	38%	58%	59%
VH-90%	2027	2025	2025	2039	2031	2034	2042	2035	2037	715,827	26%	15%	18%	56%	67%	63%
FP-10 k	2039	2034	2034	–	–	–	–	–	–	36,640	51%	40%	40%	18%	36%	40%
FP-20 k	2037	2031	2031	–	2044	2043	–	2048	2047	121,400	49%	27%	19%	21%	55%	58%
FP-30 k	2036	2030	2029	–	2039	2038	–	2042	2042	268,170	45%	11%	15%	31%	71%	66%
FP-50 k	2033	2028	2028	2046	2032	2032	2050	2037	2036	686,700	24%	6%	9%	57%	80%	78%
FP-80 k	2030	2026	2025	2038	2028	2028	2041	2033	2032	1,628,800	9%	2%	1%	71%	97%	98%
FP-100 k	2029	2025	2025	2034	2027	2026	2038	2031	2031	2,398,200	8%	0%	0%	76%	100%	100%
FP-120 k	2028	2025	2025	2031	2026	2025	2036	2030	2030	3,114,480	6%	0%	0%	83%	100%	100%
VP-10%	2038	2035	2035	–	–	–	–	–	–	24,040	56%	49%	52%	17%	27%	31%
VP-20%	2036	2032	2032	–	2049	2050	–	–	–	77,501	55%	36%	38%	20%	47%	41%
VP-30%	2033	2030	2030	2050	2042	2044	–	2046	2047	190,693	35%	27%	23%	41%	53%	57%
VP-50%	2029	2027	2027	2039	2035	2036	2043	2038	2039	601,150	17%	11%	12%	57%	73%	68%
VP-60%	2028	2026	2026	2036	2032	2033	2039	2035	2037	923,769	9%	13%	11%	73%	72%	71%
T-20%	2038	2034	2032	–	–	–	–	–	–	−669,170	42%	55%	36%	22%	23%	30%
T-50%	2033	2030	2028	2049	2049	2037	2050	–	2042	−528,177	23%	31%	19%	24%	38%	35%
T-80%	2029	2028	2026	2042	2038	2029	2044	2042	2035	−593,970	14%	19%	8%	31%	43%	48%
O-2 k	2039	2034	2034	–	–	2050	–	–	–	28,706	52%	38%	34%	16%	37%	42%
O-3 k	2038	2032	2032	–	2048	2048	–	–	–	53,520	49%	31%	30%	18%	46%	49%
O-4 k	2037	2031	2031	–	2043	2044	–	2047	2048	100,192	49%	24%	23%	24%	54%	57%
O-5 k	2036	2030	2030	–	2040	2039	–	2044	2043	162,115	49%	17%	13%	24%	64%	64%
O-10 k	2033	2028	2027	2045	2033	2032	2049	2037	2036	615,250	21%	8%	7%	54%	79%	77%
O-15 k	2030	2026	2026	2039	2029	2028	2043	2033	2033	1,300,770	11%	3%	2%	70%	93%	94%
O-20 k	2029	2025	2025	2034	2027	2026	2038	2031	2031	2,170,160	8%	0%	0%	75%	100%	100%
O-25 k	2028	2025	2025	2030	2025	2025	2036	2030	2030	3,004,550	6%	0%	0%	84%	100%	100%

*"-"HFCTs do not overtake ICETs.

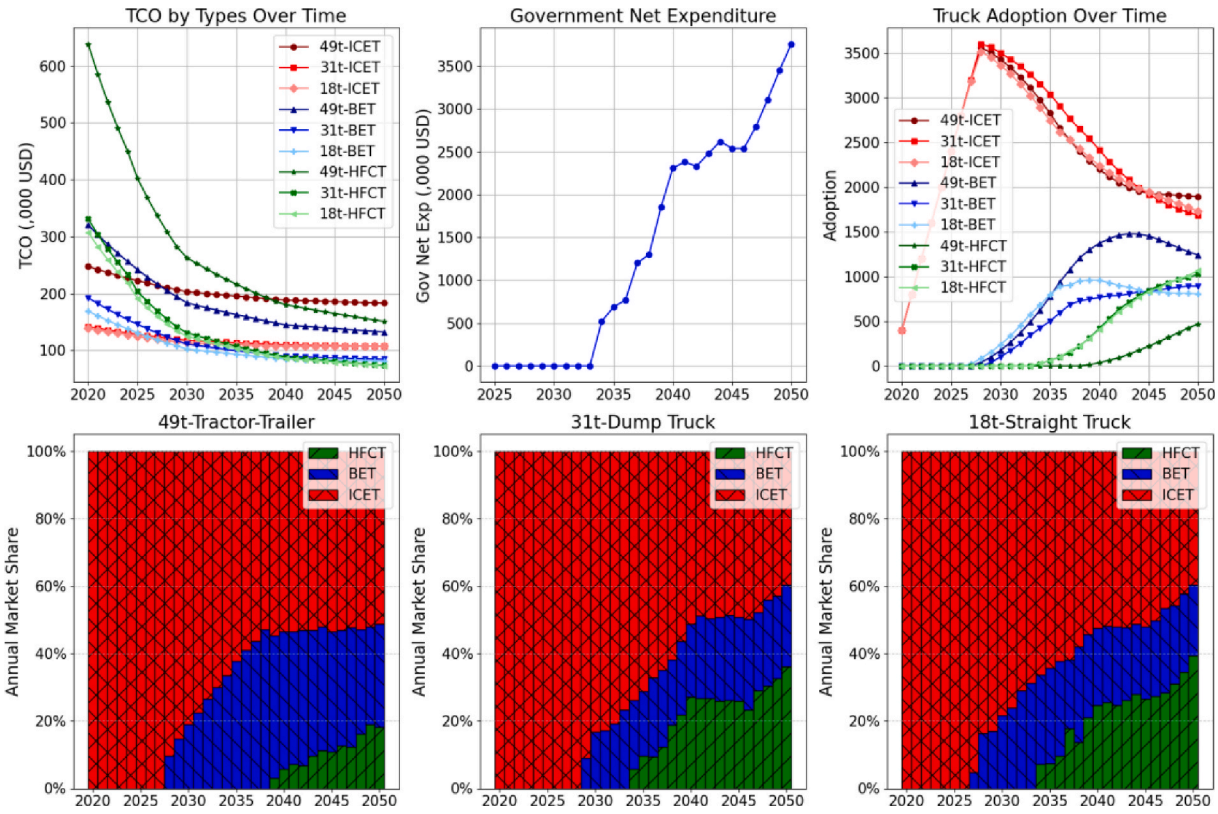


Fig. 6. Truck TCO and adoption under the FP-10 k scenario.

the three types of HFCTs in 2050. In contrast, O-20 k (Fig. 7) brings the adoption of HFCTs to the late 2020s, and 75% of tractor-trailer sales will be HFCTs, and all dump trucks and straight trucks are HFCTs. These effects have corresponding financial burdens on the government

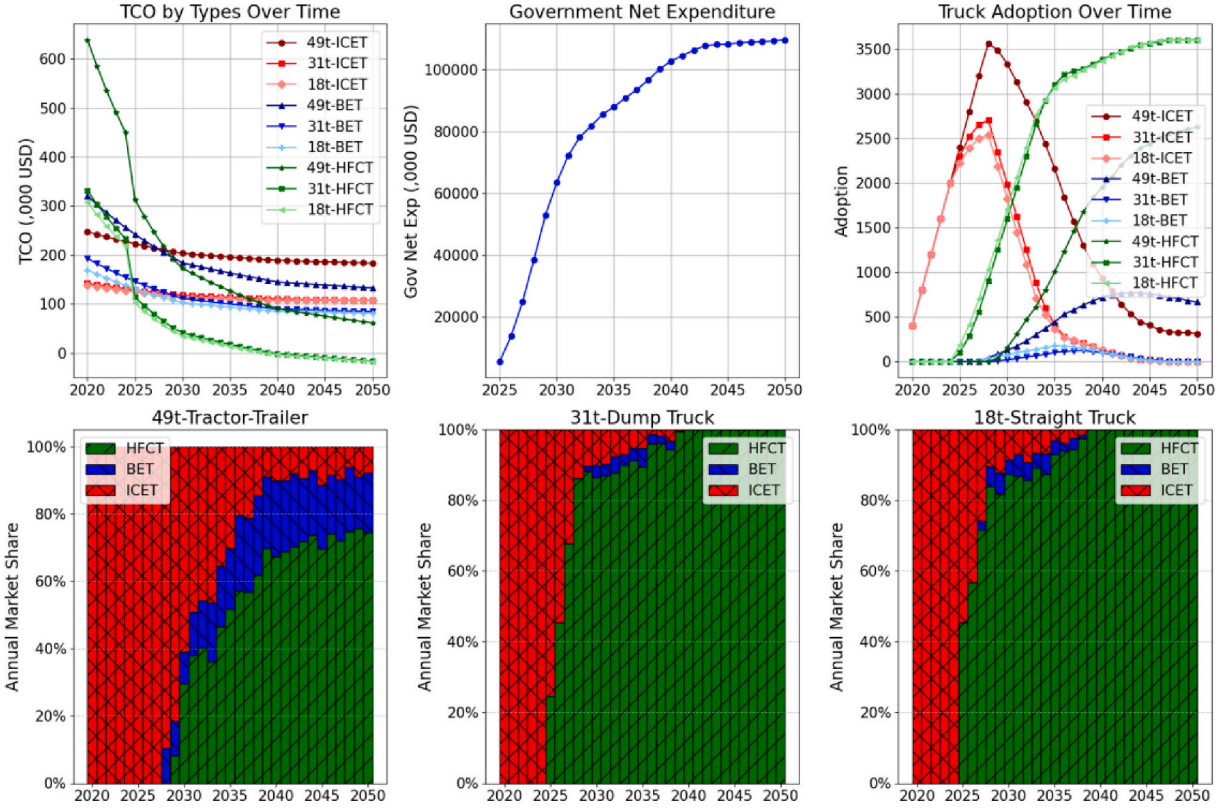


Fig. 7. Truck TCO and adoption under the O-20 k scenario.

because stronger interventions require higher government expenditure. Some interventions impose relatively low fiscal costs but produce only marginal effects. For example, VP-10% costs about 24 million USD in total by 2050 but cannot help HFCTs overtake ICET in terms of market share and cumulative adoptions. In contrast, FP-120 k generates exceptionally high government expenditure, exceeding 3 trillion USD, although it is capable of driving the truck market towards near net-zero adoption. The large expenditure implies the infeasibility of those high subsidies because such expenditure would be difficult for governments to sustain, given a limiting budget. As a reference, the UK government only grants about 874 million USD in total to support the adoption of electric cars from 2025 to 2030 [48], and China, which has the largest fleet, offered about 1.4 trillion USD to subsidise low-emission vehicles in 2025 [49]. These results contribute to the existing literature, much of which overlooks the government expenditures associated with policy interventions. As a result, these findings provide valuable policy insights into fiscal feasibility of interventions and policy design. Overall, these findings and discussions indicate that subsidies are effective but create a huge financial burden necessitating the use of taxes to help finance the subsidies.

Diesel taxes increase the TCO of ICETs, enabling ZETs to achieve cost advantage earlier. The market share of ICETs each year reduces, with this share being taken by ZETs. Also, the cumulative adoption of ZETs increases. For example, under the T-80% scenario (Fig. 8), as BETs become the cheapest in terms of TCO after 2025, their adoptions accelerate, and by 2033, BETs have the most stock in each segment. In contrast, HFCTs have a higher initial TCO, and they achieve the cost advantage later. By 2050, HFCTs have more cumulative adoption than ICETs. ICET market share is squeezed to less than 20%, and particularly, ICE straight trucks take less than 10%. In comparison, the T-20% scenario has a weaker impact. A 20% diesel price increase does not accelerate the diffusion of ZETs effectively, and ICETs continue to dominate the truck market by 2050. In addition, under T-50% scenario, the tax squeezes ICET market share, but it is still more than 20%. These results indicate that a weak diesel tax has little impact on the diffusion of ZETs and the decarbonisation of the freight sector. This finding reinforces Vass' conclusion (2016) that only a sufficiently strong carbon price could substantially increase the market share of low-emission vehicles. In terms of the financial effects of taxes, the results show that the diesel tax paid by owners of ICETs generate fiscal revenue and thus alleviates the financial burden of the government. Under the T-20%, T-50% and T-80% scenarios, cumulative tax revenue reach about 670 million USD, 530 million USD, and 600 million USD by 2050, respectively. Notably, as the tax increases, ICET market share reduces, but the tax revenue does not always increase. It implies that there exists a non-linear relationship between tax levels and tax revenue. When an ICET owner needs to pay more tax, fewer buyers will buy ICET, and thus tax revenue may ultimately reduce. Given that much of the existing literature (such as [31,32]) and tends to overlook government budget and expenditure and the relationship between the tax revenue and policy effects is ambiguous, this finding implies the importance of balancing tax intensity with policy impacts. As the revenue is always positive, the taxes are an important source to support the government's spending on subsidies. Therefore, it is worth examining if the combination of subsidies and taxes can benefit the ZET adoption and balance the cost burden (Section 4.4).

The above results indicate that to enhance the effect of interventions, the government can increase subsidies or the tax on diesel. However, the simulations also reveal diminishing marginal effects in the diffusion process. Current literature only shows that interventions are important to increase economic viability but has not been able to uncover this diminishing effect. In the FP, VP, and O market intervention scenarios, the curves of HFCT market share against cumulative government expenditure are concave as intervention values increase (Fig. 9). The same increase in the subsidy expenditure does not attract the same number of HFCT buyers. It indicates increasing the intensity of subsidies reduces policy efficiency, which means it is harder to incentivise buyers with stronger resistance. Thus, it is necessary to combine with other

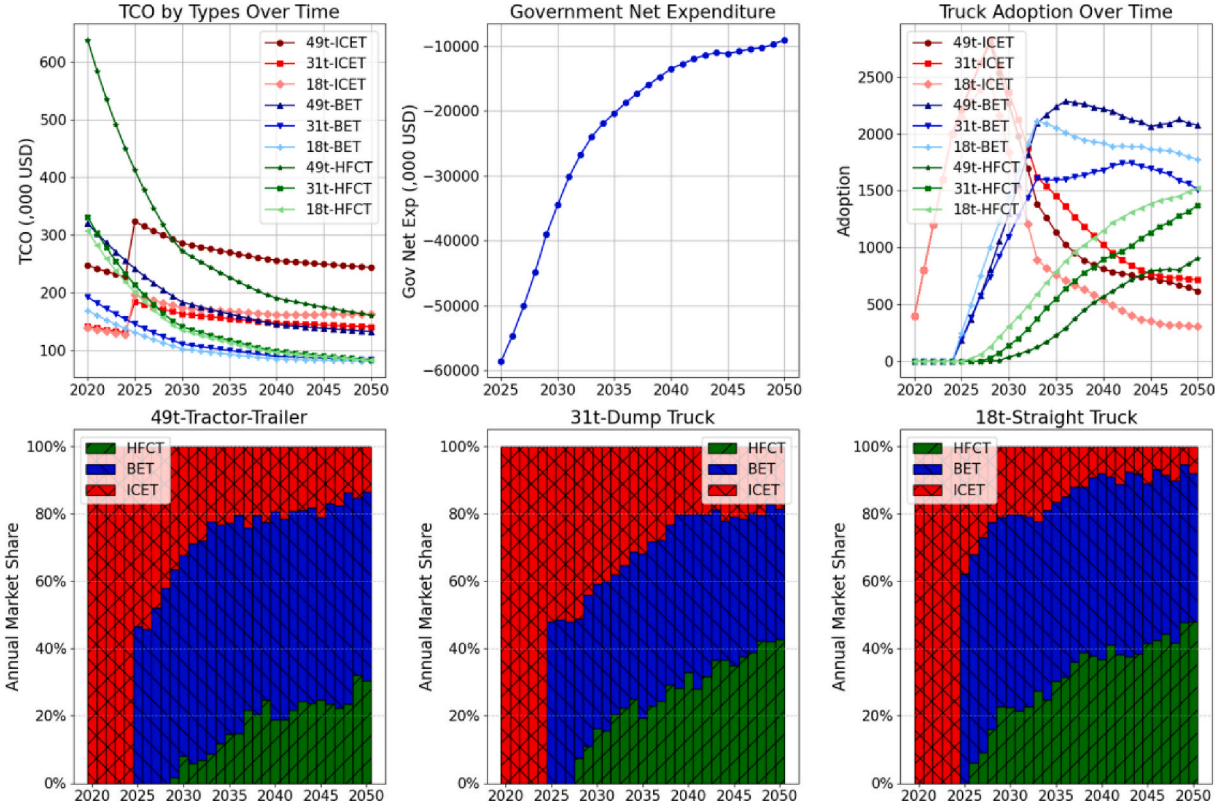


Fig. 8. Truck TCO and adoption under the T-80% scenario.

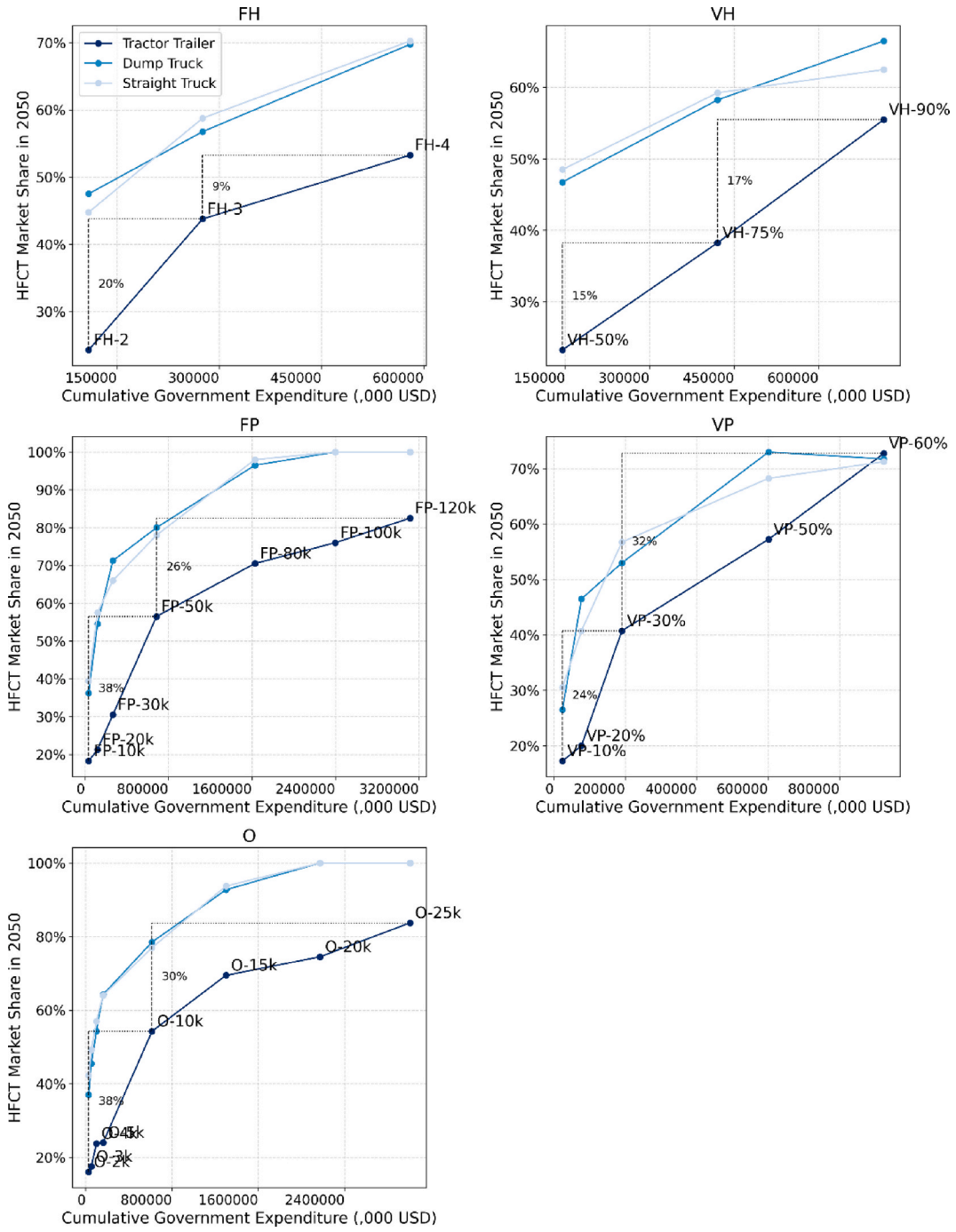


Fig. 9. Diminishing effects of subsidies.

market-based interventions, like taxes, which will be explained in section 4.4. A diminishing effect is also observed those tax scenarios (Fig. 10). A diesel tax creates cost advantages for ZETs, so it is easier to demonstrate the diminishing effect through the ICET market share. The change from T-20% to T-50% reduces 20% of the ICET market share, whereas the change from T-50% to T-80% only squeezes 9% more. It indicates that some buyers would still choose ICETs even though the disincentives are significantly large. It implies that to better support the ZET transition, the disincentives should be applied together with some other interventions, such as a mandate banning ICETs or increasing the usefulness and compatibility of ZETs.

The effects of market-based interventions differ across truck segments. Fuel cell tractor-trailers require stronger subsidies to reach the same penetration level as the other lighter trucks without interventions, because fuel cell tractor-trailers have a larger cost disadvantage by 2030. Second, increasing FH, VH, and VP subsidies has weaker diminishing effects on tractor-trailers, and thus, tractor-trailers catch up with the lighter trucks regarding market share when subsidy intensity increases. These subsidies have a greater impact on the TCO of tractor-trailers because tractor-trailers consume more hydrogen. In contrast, FP and O subsidies have the same impact on all HFCTs. Third, diesel taxes have the strongest impact on straight trucks and the weakest impact on dump trucks. This is because diesel taxes increase the OPEX of an ICET, and the OPEX of a straight truck represents about 80% of the TCO, while the OPEX of a dump truck represents about half of the TCO when there is no intervention. These differences imply that an efficient

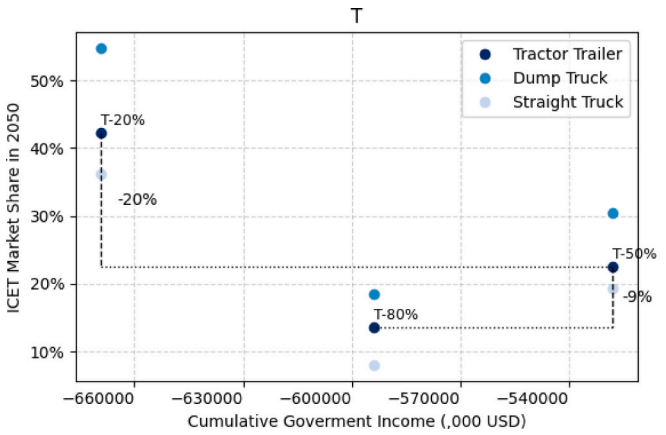


Fig. 10. Diminishing effects of diesel taxation.

policy design should take the usage characteristics into account.

The last comparison is between different types of subsidies. The results show that no single subsidy consistently outperforms the others, and each type of subsidy has different advantages. For example, VH subsidies forward the first adoption of HFCTs earlier than other subsidies (Fig. 11), with the VH curve takes the left and bottom position in the figure. It is because VH subsidies provide greater financial support to HFCT owners during the early stages of diffusion, when hydrogen prices remain relatively high. Also, a comparison between VP and FP subsidy scenarios indicates that VP subsidies exert a stronger influence on early adoption when government expenditure levels are similar. These indicate that variable subsidies may be more effective in stimulating early adoption. From the criterion of penetration, FP and O subsidies contribute to a higher HFCT market share in 2050. In Fig. 12, the HFCT market share by truck type is mapped against the cumulative government expenditure in each segment, and FP and O subsidies take the left and upper positions. It means they are relatively more efficient, enabling the government to spend less but achieve more HFCT adoptions.

4.3. Impact of combining market-based interventions

This sub-section provides evidence that combinations of subsidies and taxes have better effects than a single intervention when net expenditures are similar. A summary of the policy combinations is shown in Table 5. The policy combinations bring the first adoption earlier and increase HFCT market share more effectively than a single intervention does. Under the low intensity scenarios, fuel cell straight trucks have more cumulative adoptions than their ICET counterpart across all policy combination scenarios, while this is not the case in the single subsidy scenarios, except for the combination of VP-10%+T-20%. This finding aligns with the conclusion of Hammond et al. [41] that a mix of interventions had a higher potential to increase ZET market share and reduce GHG emissions. Among the low intensity combinations, VH and FH subsidies combined with a tax, can also help fuel cell dump trucks gain more cumulative stock than their ICET counterpart, and the total government net expenditures are −460 million and −420 million USD. All the low-intensity policy combinations cannot make fuel cell tractor-trailers dominate the market. All the medium combinations help the cumulative adoption of fuel cell tractor-trailers overtake the ICETs, and the combination of VH-75%+T-50% can make fuel cell tractor-trailers the dominating type by 2038. All the medium combinations can help fuel cell dump trucks and straight trucks become a dominating type in the late 2030s. When increasing the combinations to high intensity, all three types of HFCTs can be the dominating types in the market before 2037. These results suggest that combinations of subsidies and taxes reduce the financial burden of the government and accelerate decarbonisation of the freight sector and can make policies self-sustainable.

The simulation results also show that combining several subsidies with a diesel tax has a better effect. Under the C-4 scenario, those subsidies and the tax make the TCO of fuel cell dump trucks and straight trucks the lowest, and these two types of trucks start to diffuse in the market from 2025. The combinations also help fuel cell tractor-trailers quickly achieve a cost advantage compared to their ICET counterpart after 2027. The market share of lighter HFCTs in 2050 is about 70% and the market share of fuel cell tractor-trailers is about 53% and it is similar to that under the VH-4 and VP-50% scenarios, which are extreme. Notably, the government net expenditure of this policy combination is less than a quarter of that in the FH-4 or VP-50% scenarios, and all stakeholders in the truck market are involved in this policy mix. The truck producer, the refuelling station and the HFCT buyers receive subsidies, and the government collects taxes, but the joint effect of these interventions has a better effect than subsidising one stakeholder. It implies that it is beneficial for the government to issue a policy mix to incentivise a joint effort to accelerate the diffusion of HFCTs.

4.4. The impact of subsidising both BETs and HFCTs

In the previous scenarios, only HFCTs were subsidised. When interventions for both ZETs are applied, the results show that there are more early BET adoptions before 2035 (Fig. 13). This is because BETs achieve a lower TCO after 2025, and the subsidies enhance their attractiveness to the buyers. However, the TCOs of HFCTs approach those of BETs over time, so the cost advantage of BETs diminishes, and HFCTs take some market share from BETs. Therefore, the benefit of the parallel interventions diminishes, and the efficiency reduces over time. By 2050, under the BHVE-90% scenario, the ICET market share in each segment from light to heavy is 10%, 14%, 11%, which is just 15%, 1%, and 8% less than that under the VH 90% scenario, but the same cost can reduce more ICETs according to Table 6. This large inefficiency is also witnessed in all parallel intervention cases. This cost inefficiency is again because of the competition between ZETs. These results indicate that continuously subsidising both ZETs from 2025 to 2050 may lead to relatively high fiscal costs. This cost-efficiency evaluation is not discussed in the existing literature, for example, Hammond et al. [41], as

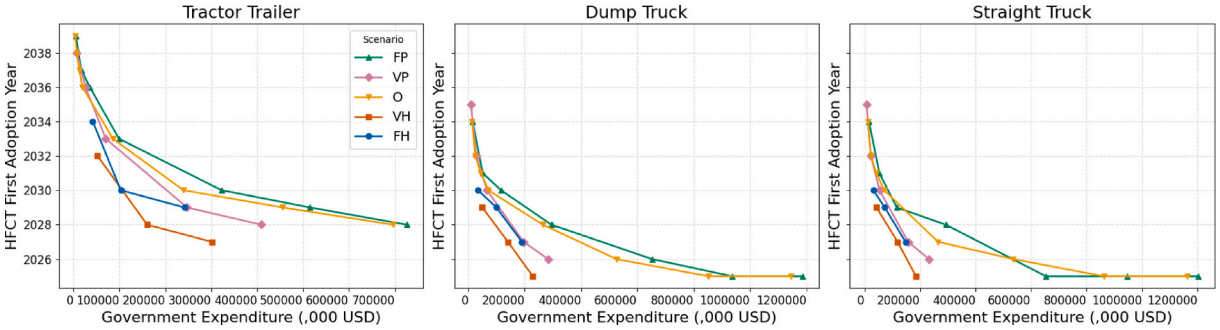


Fig. 11. HFCT First adoption year vs government expenditure by truck type.

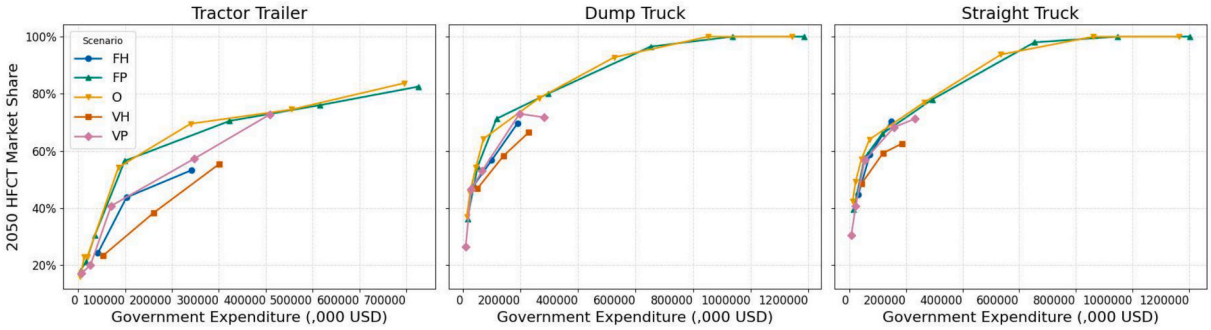


Fig. 12. HFCT market share vs government expenditure by truck type.

Table 5
Simulation results for combinations of market-based interventions.

Scenarios	The Year of the First Adoption			The Year of HFCTs Market Share Overtakes ICET Market Share in A Year			The Year of HFCTs Stock Overtakes ICET Stock			Total Government Net Expenditure by 2050 (,000 USD)	The ICET Market Share in 2050			The HFCT Market Share in 2050		
	49 t	31 t	18 t	49 t	31 t	18 t	49 t	31 t	18 t		49 t	31 t	18 t		49 t	31 t
FH-2 + T-20%	2031	2029	2028	–	2043	2041	–	2047	2045	−464,143	37%	27%	22%	33%	52%	51%
VH-50%+T-20%	2029	2028	2027	–	2040	2040	–	2045	2044	−419,968	33%	29%	24%	33%	49%	48%
FP-10 k + T-20%	2036	2031	2030	–	2049	2045	–	–	2050	−612,336	39%	33%	27%	24%	43%	46%
VP-10 k + T-20%	2035	2031	2030	–	2050	2048	–	–	–	−619,078	41%	36%	28%	23%	37%	39%
O-2 k + T-20%	2036	2031	2030	–	2047	2045	–	–	2049	−600,538	37%	30%	23%	22%	48%	53%
FH-3 + T-50%	2027	2026	2025	2037	2033	2032	2041	2037	2036	−622,468	11%	10%	8%	51%	63%	55%
VH-75%+T-50%	2025	2025	2025	2034	2030	2029	2038	2033	2033	−325,730	14%	9%	8%	51%	61%	55%
FP-50 k + T-50%	2029	2026	2025	2038	2029	2029	2042	2034	2033	−161,898	11%	6%	6%	56%	71%	70%
VP-30%+T-50%	2028	2027	2025	2039	2036	2034	2043	2040	2038	−829,729	18%	11%	11%	40%	61%	54%
O-5 k + T-50%	2030	2027	2026	2044	2035	2032	2048	2039	2036	−852,999	24%	9%	7%	37%	66%	56%
FH-4 + T-80%	2025	2025	2025	2029	2028	2027	2034	2033	2032	−302,151	7%	7%	5%	54%	64%	54%
VH-90%+T-80%	2025	2025	2025	2027	2026	2025	2032	2032	2031	83,787	6%	6%	9%	53%	64%	52%
FP-100 k + T-80%	2025	2025	2025	2029	2025	2025	2034	2030	2030	356,702	5%	0%	0%	73%	100%	100%
VP-60%+T-80%	2025	2025	2025	2028	2027	2026	2033	2032	2032	70,141	6%	9%	8%	59%	66%	60%
O-10 k + T-80%	2027	2025	2025	2033	2029	2028	2037	2033	2032	−399,430	11%	5%	4%	51%	75%	67%
C-4	2027	2025	2025	2038	2031	2031	2043	2035	2035	127,744	19%	11%	9%	53%	68%	70%

their focus was on whether policy interventions achieve decarbonisation targets rather than evaluating the comparative cost efficiency of detailed policy design. Moreover, even under scenarios involving exceptionally high levels of government expenditure on both ZET technologies, some laggards continue to prefer ICETs. This suggests that additional interventions beyond financial incentives may be necessary to encourage laggards to adopt ZETs. For example, reducing buyers' resistance towards ZETs could reduce the ICET market share under the same intervention. This is justified in the sensitivity analysis below.

4.5. *Sensitivity analysis for the combined market-based interventions*

Most of the sensitivity analyses were conducted under the C4 scenario. The parameter variations are summarised in Table 7, and the corresponding results are summarised in Table 8. In addition, three scenarios were selected to examine the effects of reducing BET resistance by half to show if the findings about the inefficiency of parallel policy still survives. These results are shown in Table 9.

When varying the innovativeness, the normal distribution of innovativeness in the theory [35] remains unchanged, instead, the proportions of buyers within each adopter category were adjusted (Table 7). Under the less innovative scenario, more buyers may perceive greater incompatibility with ZETs, for example, due to limited refuelling and recharging infrastructures, and therefore require larger compensation. Consequently, the policies become less effective, and the penetration slows down. In contrast, under the more innovative scenario, the buyers may realise the usefulness or may experience more convenient refuelling and recharging services, making them more willing to adopt ZETs. The results indicate that the overall perceived risk level affects the policy effect, and when the context becomes more compatible for ZETs, for example, in regions with stronger ZET-supportive infrastructure and institutions, the policy interventions will be more effective, and there

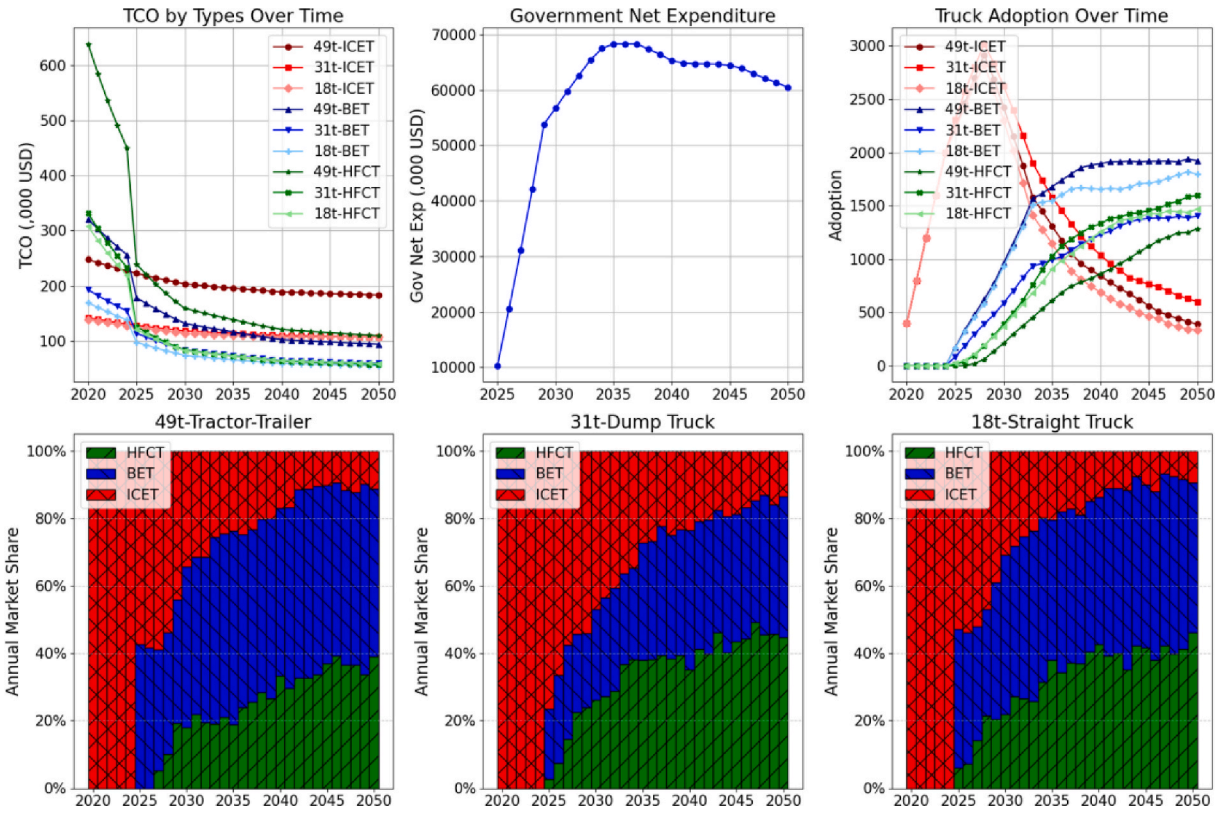


Fig. 13. Results of the BHVE-90% parallel policy scenario.

Table 6
Simulation results of parallel policy scenario.

Scenarios	The Year of the First Adoption			The Year of HFCTs Market Share Overtakes ICET Market Share in A Year			The Year of HFCTs Stock Overtakes ICET Stock			Total Government Net Expenditure by 2050 (,000 USD)	The ICET market share in 2050			The HFCT market share in 2050		
	49 t	31 t	18 t	49 t	31 t	18 t	49 t	31 t	18 t		49 t	31 t	18 t	49 t	31 t	18 t
BHVE-50%	2032	2029	2029	–	2050	2046	–	–	2049	622,479	26%	31%	23%	23%	38%	33%
BHVE-75%	2028	2027	2027	2044	2039	2036	2045	2043	2040	1,146,294	16%	22%	16%	32%	39%	41%
BHVE-90%	2027	2025	2025	2037	2033	2032	2040	2038	2037	1,507,726	11%	14%	10%	39%	45%	46%
BHVP-10%	2038	2034	2034	–	–	–	–	–	–	122,728	37%	46%	48%	20%	26%	25%
BHVP-20%	2036	2032	2032	2048	2045	2049	–	2050	–	330,702	21%	30%	33%	21%	38%	35%
BHVP-30%	2033	2030	2030	2046	2039	2042	2047	2046	2044	597,557	15%	22%	22%	29%	37%	34%
BHVP-60%	2028	2026	2026	2030	2029	2029	2035	2033	2034	1,640,546	5%	9%	6%	46%	45%	47%
BHO-2 k	2039	2034	2034	–	–	–	–	–	–	120,114	36%	42%	37%	20%	29%	29%
BHO-5 k	2036	2030	2030	2048	2039	2039	–	2043	2042	456,130	22%	12%	7%	24%	47%	43%
BHO-10 k	2033	2028	2027	2039	2030	2029	2043	2035	2034	1,210,470	11%	4%	5%	36%	46%	44%

would be fewer ICET adopters in 2050. This finding implies the benefit of reducing buyers' resistance towards ZETs and aligns with previous studies (such as [32,36]). The results further suggest that relying on a single market-based intervention to reduce perceived risks and improve economic viability may not be the most effective strategy, whereas broader policy packages can more effectively accelerate freight-sector. decarbonisation.

The results also show that a lower hydrogen price or a lower HFCT price accelerate HFCT diffusion, although they are associated with higher government expenditures. Increasing the HFCT price changing rate further accelerates adoption. A higher discount rate reduces the weight of operation cost, which is cheaper for HFCT in the future, and thus reduces the cost advantage of HFCTs. Similarly, a shorter ownership horizon reduces the cost advantages of ZETs. The high discount rate and the long ownership horizon that a buyer applies to calculate the TCO hinder HFCT penetration and reduce the policy effectiveness.

The simulation results obtained under the assumption that resistance towards BETs is half that of HFCT further support the finding and implications about parallel policies. As expected, across the three scenarios listed in Table 9, BETs gain more market share than in the baseline cases where resistance towards BETs and HFCTs is identical. To achieve the same ICET share reduction, less HFCT subsidies would be required. In

Table 7
Variables and their values in the sensitivity analysis.

Variables	Change	Values				
Distribution		Innovator	Early adopter	Early majority	Late majority	Laggard
	Less Innovative	0.5%	6.0%	28.0%	45.0%	23.5%
	Original Model	2.5%	13.5%	34.0%	34.0%	16.0%
	More Innovative	4.5%	19.0%	45.0%	25.0%	6.5%
HFCT Price		Tractor trailer	Dump Truck	Straight Truck		
	Cheaper	283	150	135		
	Original Model	354	187	169		
	More Expensive	425	224	203		
HFCT Changing Rate		by 2030	by 2040	by 2050		
	Slower	4%	1%	0.5%		
	Original Model	7%	2%	1%		
	Faster	10%	3%	1.5%		
H2 Price	Lower	6.66				
	Original Model	8.33				
	Higher	10.00				
H2 Changing Rate		by 2030	by 2040	by 2050		
	Slower	2%	1%	0.50%		
	Original Model	4%	2%	1%		
	Faster	6%	3%	1.50%		
Discount Rate	Smaller	6%				
	Original Model	8%				
	Larger	10%				
Ownership Period	Shorter	3				
	Original Model	5				
	Longer	10				

Table 8
Selected results from the sensitivity analysis.

Scenario	Compared to the Original C4 Scenario						
	Total Government Net Expenditure by 2050 (,000 USD)	**ICET Market Share in 2050**			**HFCT Market Share in 2050**		
		49 t	31 t	18 t	49 t	31 t	18 t
Less Innovative	−130,018	7%	3%	3%	0%	7%	−3%
More Innovative	146,891	−7%	−3%	0%	−2%	0%	−5%
Cheaper HFCT	297,187	−8%	−1%	−2%	11%	6%	−2%
More Expensive HFCT	−226,229	6%	3%	3%	−8%	−3%	−8%
Slower HFCT Price Changing	−491,091	21%	24%	17%	−30%	−30%	−28%
Faster HFCT Price Changing	357,234	−11%	−2%	−1%	15%	10%	0%
Cheaper Hydrogen	79,813	−5%	−2%	−1%	9%	4%	2%
More Expensive Hydrogen	−61,018	5%	2%	2%	−7%	−2%	−7%
Slower Hydrogen Price Changing	−115,063	9%	−1%	1%	−8%	2%	−6%
Faster Hydrogen Price Changing	41,695	−9%	−1%	2%	7%	2%	−5%
Small Discount Rate	44,421	−2%	−1%	1%	1%	1%	−8%
Large Discount Rate	−18,231	1%	0%	1%	0%	2%	−6%
Shorter Ownership	−335,581	9%	5%	12%	−6%	−4%	−14%
Longer Ownership	426,204	−11%	−1%	−5%	9%	0%	−12%

Table 9
Selected results from the scenarios with reduced BET resistance.

Scenario	Total Government Net Expenditure by 2050 (,000 USD)	ICET Market Share in 2050			BET Market Share in 2050			HFCT Market Share in 2050		
		49 t	31 t	18 t	49 t	31 t	18 t	49 t	31 t	18 t
VH-90%	645,652	16%	13%	14%	43%	25%	29%	41%	63%	57%
BHVE-90%	1,826,033	8%	9%	9%	56%	44%	48%	36%	48%	43%
O-15 k	1,215,555	9%	3%	2%	32%	8%	6%	59%	90%	93%

addition, providing energy subsidies to BETs further increases BET market share. However, the analysis also identifies that there exists at least one HFCT subsidy scenario, for example, O-15 k, not only reducing ICET market share to levels below those observed under the BHVE-90% scenario but also requiring less subsidy expenditure. Therefore, the model reinforces the conclusion that parallel policies have efficiency loss due to the competition between ZETs.

4.6. Limitations

Whilst a robust methodology was developed to examine how market-based interventions accelerate the adoption and diffusion of ZETs, there are some limitations, especially in the model inputs. Those inputs, such as the price of trucks, hydrogen price, and advancements in fuel economy, follow projections in the existing literature but may differ from future real-world developments. Furthermore, even though the learning rate is endogenous, it only captures the relationship between the quantity of trucks or hydrogen demand and their prices. However, in reality, fuel cells and hydrogen are used in other sectors, and thus, a more comprehensive endogenous learning mechanism would need to account for total cross-sectoral demand. Another limitation is the simplification of the impact of all risks or intangible costs using a

multiplier to keep the model tractable. Hence, we are not able to explicitly determine which factors contribute to buyers' resistance or how that resistance might be reduced in practice. To obtain more detailed insights into decision-making processes, future research should include additional factors as variables in the model. In addition, the buyers are assumed to perceive the same risk level of BETs and HFCTs due to the lack of quantification of different risk factors. However, the results of this research are strong reference for policymaking as they are easily adaptable to real contexts. For example, if people's overall resistance to BETs is less than HFCTs, BETs may have a greater advantage, and thus, stronger interventions would be required to achieve equivalent HFCT penetration, as demonstrated in the sensitivity analysis. Future studies are suggested to quantify the risk compensation for different ZETs to fill the literature gap.

5. Conclusions and future work

This research develops and applies a novel ABM to evaluate the adoption and diffusion potential of market-based interventions for ZETs. A new addition to the literature is the incorporation of for intangible costs within a heterogeneous buyer market, alongside consideration of government budget implications. The model simulates the competition among ICETs, BETs, and HFCTs across the 49-ton, 31-ton, and 18-ton segments over the period from 2020 to 2050. A total of 56 policy scenarios are examined, including hydrogen subsidies, purchase subsidies, electricity subsidies, operational subsidies, diesel taxes, and various combinations thereof. The model results suggest the necessity of market-based interventions, given the substantial cost disadvantages faced by ZETs in the near term and the significant risk compensation required by buyers in the longer term. The simulations further suggest that competition between BETs and HFCTs may reduce overall policy efficiency. While subsidies are shown to be effective in promoting ZET market penetration, they may consistently impose a high fiscal burden on governments, potentially constraining their feasibility. Accordingly, the analysis suggests that diesel taxes could play a crucial role in financing subsidies and alleviating overall fiscal pressure. The comparisons between interventions indicate firstly, that their effectiveness in promoting ZET adoption may diminish over time; and secondly, that they may have different effects on different truck segments because of variations in usage characteristics and cost structures; and lastly, that each type of subsidy may offer different advantages in supporting ZET adoption. The analysis on policy combinations indicates that they could not only accelerate decarbonisation of the freight sector and reduce the financial burden on the government but also mitigate the impact of the diminishing effect. The analysis of parallel subsidies on both ZETs suggests that the competition between ZETs reduces the policy effect, which results in inefficiency. Finally, the analysis highlights the critical role of perceived risks. When buyers exhibit less resistance towards ZETs, those interventions may be more effective.

This research and the results can derive the following policy implications. First, it would be costly and inefficient to keep increasing the intensity of interventions to enhance the policy impact. Since a combination of interventions implies a better effect than a single intervention, policymakers may benefit from considering policy mixes. Second, subsidies may impose a heavy fiscal burden, and taxes could help finance the subsidy spending, potentially enabling more financially sustainable policy frameworks. Third, as truck segments exhibit different operational characteristics, policymakers could design dedicated policies for each truck segment to maximise policy efficiency. Fourth, if the government is not going to prioritise one of the ZET technology pathway, it would be beneficial to have other complementary interventions to persuade ZET adoption. Fifth, different stakeholders in the freight sector may benefit from adopting a whole-system perspective and coordinating efforts to address barriers arising from both tangible costs and perceived risks. Even though the model, policy implications and the trends from the results are robust, the numerical results should be interpreted with caution due to limitations in the model's input data. Future studies could explore interventions beyond market-based mechanisms, consider different sources of perceived risks and determine different risk levels for alternative ZET technologies within specific contextual settings. Such research could complement the findings of this study and further support the decarbonisation of the heavy-duty freight sector.

CRediT authorship contribution statement

Zhenyu Tan: Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gbemi Oluleye:** Writing – review & editing, Validation, Supervision, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] World Bank (2025) *GDP (current US$)*. Available from: https://data.worldbank.org/indicator/NY.GDP.MKTP.CD.

[2] OECD (2025) *Annual Freight Transport*. Available from: https://data-explorer.oecd.org/vis?lc=en&df[ds]=dsDisseminateFinalDMZ&df[id]=DSD_TRENDS%40DF_TRENDSFREIGHT&df[ag]=OECD.ITF&df[vs]=1.0&dq=.A.....&pd=%2C&to[TIME_PERIOD]=false&vw=ov.

[3] NTCRTMS. (2019) *Motor Vehicle Classification for Road Traffic Management (GA 802-2019)*. http://jjzd.yiyang.gov.cn/uploadfiles/202405/20240528154450751 52.pdf.

[4] ICCT (2024a) *Race to Zero: Zero-emission bus and truck market in the United States (January –June 2024)*. https://theicct.org/wp-content/uploads/2024/12/ID-272-%E2%80%93-US-R2Z-Q2_spotlight_final.pdf.

[5] IEA (2024) *Global EV Outlook 2024*. Paris https://www.iea.org/reports/global-ev-outlook-2024.

[6] IEA (2025) *Global EV Outlook 2025*. Paris https://www.iea.org/reports/global-ev-outlook-2024.

[7] P.G. Alves, J.P. Vale, L. Nybo, A.D. Flouris, T.S. Mayor, Sustainable solutions for reducing air-conditioning costs and tailpipe emissions from heavy-duty transportation across Europe, Int. J. Sustain. Transp. 17 (6) (2022) 711–725.

[8] O. Stryhunivska, B. Zwolińska, R. Giel, The Management of Harmful Emissions from Heavy-Duty Transport Towards Sustainable Development, Sustainability. 16 (24) (2024).

[9] B. Sen, T. Ercan, O. Tatari, Q.P. Zheng, Robust Pareto optimal approach to sustainable heavy-duty truck fleet composition, Resources, Conservation and Recycling. 146 (2019) 502–513.

[10] S. Cheng, B. Zhang, P. Peng, F. Lu, Health and economic benefits of heavy-duty diesel truck emission control policies in Beijing, Environ. Int. 179 (2023) 108152.

[11] V. Aryanpur, F. Rogan, Decarbonising road freight transport: the role of zero-emission trucks and intangible costs, Sci. Rep. 14 (1) (2024) 2113.

[12] Z. Wang, S. Acha, M. Bird, N. Sunny, M.E.J. Stettler, B. Wu, N. Shah, A total cost of ownership analysis of zero emission powertrain solutions for the heavy goods vehicle sector, Journal of Cleaner Production. 434 (2024).

[13] P. Aguilar, B. Groß, Battery electric vehicles and fuel cell electric vehicles, an analysis of alternative powertrains as a mean to decarbonise the transport sector, Sustainable Energy Technol. Assess. 53 (2022).

[14] ICCT (2025) *DELIVERING AFFORDABILITY The Emerging Cost advantage of Battery Electric Heavy-Duty Trucks and U.S. Policy Strategies to Unlock Their Full Economic Potential*. https://energyinnovation.org/wp-content/uploads/Delivering-Affordability-Emerging-Cost-Advantages-of-Battery-Electric-Heavy-Duty-Trucks.pdf.

[15] I. Staffell, D. Scamman, A. Velazquez Abad, P. Balcombe, P.E. Dodds, P. Ekins, N. Shah, K.R. Ward, The role of hydrogen and fuel cells in the global energy system, Energy & Environmental Science. 12 (2) (2019) 463–491.

[16] Deng, H., Yang, B., Chow, M.-Y., Yao, G., Chen, C. & Guan, X. (2023) Hydrogen Supply Infrastructure Network Planning Approach towards Chicken-egg Conundrum. *arXiv preprint arXiv:2308.06958*.

[17] B. Sharpe, H. Basma, A meta-study of purchase costs for zero-emission trucks. https://theicct.org/publication/purchase-cost-ze-trucks-feb22/.

[18] Burke, A. F., Zhao, J., Miller, M. R., Sinha, A. & Fulton, L. M. (2023) Projections of the costs of medium- and heavy-duty battery-electric and fuel cell vehicles (2020-2040) and related economic issues. *Energy for Sustainable Development*. 77.

[19] X. Xue, Z. Yan, D.N. Prada, G. Jia, S.S. Popuri, R. Vijayagopal, Y. Li, R.L. Sari, C. Liu, X. He, A.A. Amer, Life Cycle Economic and Environmental Assessment for Emerging Heavy-Duty Truck Powertrain Technologies in China: a Comparative Study of Battery Electric, fuel Cell Electric, and Hydrogen Combustion Engine Trucks, Environ Sci Technol. 59 (4) (2025) 2018–2030.

[20] ICCT (2024b) *Total cost of ownership parity between battery electric trucks and diesel trucks in India*. https://theicct.org/wp-content/uploads/2024/08/ID-183-%E2%80%93-TCO-HDV_report_final.pdf.
[21] FENEX (2025) *Green Hydrogen for Road Transport in Western Australia*. https://www.fenex.org.au/project/green-hydrogen-for-road-transport-in-western-australia-21-rp2-0094/.
[22] ICCT (2023a) *Case Studies on Zero-Emission Trucks: Market Overview and Policy Recommendations in Guangdong Province*. https://theicct.org/wp-content/uploads/2023/11/ID-73-%E2%80%93-CN-Guangdong_final.pdf.
[23] ICCT (2023b) *Actual Driving Performance of Electric Semi-Trailer Tractors in China*. https://theicct.org/wp-content/uploads/2023/11/Tangshen-case-study-report-A4-CN-v5.pdf.
[24] ICCT (2021) *TOTAL COST OF OWNERSHIP FOR HEAVY TRUCKS IN CHINA: BATTERY-ELECTRIC, FUEL CELL ELECTRIC, AND DIESEL TRUCKS*. https://theicct.org/wp-content/uploads/2021/12/ze-hdvs-china-tco-EN-nov21.pdf.
[25] ICCT (2022) *FUEL- CELL HYDROGEN LONG -HAUL TRUCKS IN EUROPE: A TOTAL COST OF OWNERSHIP ANALYSIS*. https://theicct.org/wp-content/uploads/2022/09/eu-hvs-fuels-evs-fuel-cell-hdvs-europe-sep22.pdf.
[26] P.D. Larson, R.V. Parsons, D. Kalluri, Zero-Emission Heavy-Duty, Long-Haul Trucking: Obstacles and Opportunities for Logistics in North America, Logistics. 8 (3) (2024).
[27] D. Thilina, N. Gunawardane, The effect of perceived risk on the purchase intention of electric vehicles: an extension to the technology acceptance model, International Journal of Electric and Hybrid Vehicles. 11 (1) (2019) 73–84.
[28] X. Hu, R. Zhou, S. Wang, L. Gao, Z. Zhu, Consumers' value perception and intention to purchase electric vehicles: a benefit-risk analysis, Research in Transportation Business & Management. 49 (2023).
[29] T. Karunanayake, D. Samarasinghe, The effect of Perceived Risk on the Purchase Intention of Alternative fuel Vehicles, Sri Lankan Journal of Management. 23 (2) (2018).
[30] N. Rivers, M. Jaccard, Combining top-down and bottom-up approaches to energy-economy modeling using discrete choice methods, The Energy Journal. 26 (1) (2005) 83–106.
[31] J. Axsen, D.C. Mountain, M. Jaccard, Combining stated and revealed choice research to simulate the neighbor effect: the case of hybrid-electric vehicles, Resour. Energy Econ. 31 (3) (2009) 221–238.
[32] D.L. McCollum, C. Wilson, M. Bevione, S. Carrara, O.Y. Edelenbosch, J. Emmerling, C. Guivarch, P. Karkatsoulis, I. Keppo, V. Krey, Z. Lin, E.Ó. Broin, L. Paroussos, H. Pettifor, K. Ramea, K. Riahi, F. Sano, B.S. Rodriguez, D.P. van Vuuren, Interaction of consumer preferences and climate policies in the global transition to low-carbon vehicles, Nature Energy. 3 (8) (2018) 664–673.
[33] X. Hao, S. Ou, Z. Lin, X. He, J. Bouchard, H. Wang, L. Li, Evaluating the current perceived cost of ownership for buses and trucks in China, Energy (2022) 254.
[34] Vass, T. M. (2016) Trading off political acceptability and economic efficiency: Policy options for reducing Canada's electricity and transportation emissions.
[35] E.M. Rogers, *Diffusion of Innovations*, 5th ed., Free Press, New York, NY 10020, 2003.
[36] Miller, M., Wang, Q. & Fulton, L. (2017) Truck Choice Modeling: Understanding California's Transition to Zero-Emission Vehicle Trucks Taking into Account Truck Technologies, Costs, and Fleet Decision Behavior.
[37] Y. Zheng, D. Hou, Y. Liu, Y. Zhou, J. Xiao, Complex system analysis of the implications of hydrogen fuel cell trucks in China's road freight transportation, International Journal of Hydrogen Energy. 60 (2024) 1449–1461.
[38] F. Teng, Q. Zhang, S. Chen, G. Wang, Z. Huang, L. Wang, Comprehensive effects of policy mixes on the diffusion of heavy-duty hydrogen fuel cell electric trucks in China considering technology learning, Energy Policy. 185 (2024).
[39] M. Zhu, P. Dong, Y. Ju, J. Li, L. Ran, Effects of government subsidies on heavy-duty hydrogen fuel cell truck penetration: a scenario-based system dynamics model, Energy Policy. 183 (2023).
[40] T. Yin, S. Chen, G. Wang, Y. Tan, F. Teng, Q. Zhang, Can subsidy policies achieve fuel cell logistics vehicle (FCLV) promotion targets? evidence from the beijing-tianjin-hebei fuel cell vehicle demonstration city cluster in China, Energy. 311 (2024).
[41] W. Hammond, J. Axsen, E. Kjeang, How to slash greenhouse gas emissions in the freight sector: Policy insights from a technology-adoption model of Canada, Energy Policy. 137 (2020).
[42] W. Rand, R.T. Rust, Agent-based modeling in marketing: guidelines for rigor, International Journal of Research in Marketing. 28 (3) (2011) 181–193.
[43] M. Zsifkovits, M. Günther, Simulating resistances in innovation diffusion over multiple generations: an agent-based approach for fuel-cell vehicles, Central European Journal of Operations Research. 23 (2) (2015) 501–522.
[44] Bauer, R. A. (1960) Consumer behavior as risk taking, Proceedings of the 43rd National Conference of the American Marketing Assocation, June 15, 16, 17, Chicago, Illinois, 1960, American Marketing Association.
[45] D. McFadden, The choice theory approach to market research, Marketing Science. 5 (4) (1986) 275–297.
[46] J. Yan, J. Zhao, Willingness to pay for heavy-duty hydrogen fuel cell trucks and factors affecting the purchase choices in China, International Journal of Hydrogen Energy. 47 (58) (2022) 24619–24634.
[47] Xu, F., Crawford, C., Feng, Y., Lin, Z. & Li, S. (2023) Environment-economic analysis of diesel, hybrid electric, plug-in hybrid electric trucks in China. *Transportation Research Part D: Transport and Environment*. 117.
[48] DfT (2025) *Discount of up to £3,750 on electric cars set to slash costs for thousands*. https://www.gov.uk/government/news/discount-of-up-to-3750-on-electric-cars-set-to-slash-costs-for-thousands [Accessed 24 February 2026].
[49] SINA Finance (2024) *The Ministry of Finance has released the 2025 New Energy Vehicle Subsidy Notice! The total amount is nearly 10 billion yuan! What percentage does your city account for?* https://finance.sina.com.cn/roll/2024-11-22/doc-incwxnsk3907888.shtml [Accessed 24 February 2026].