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Cost and Emission Performance of Blue and Grey Hydrogen as Diesel Alternatives in Fuel Cell Trucks

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ABSTRACT

This study examines the cost and emission performance of blue and grey hydrogen as alternatives to diesel in hydrogen fuel cell trucks in the Gulf–Europe corridor. Specifically, it evaluates the feasibility of using hydrogen-powered trucks (H-trucks), fuelled by blue or grey hydrogen, as sustainable alternatives to conventional diesel trucks (D-trucks). To evaluate hydrogen fuel over diesel fuel, the study first develops bi-objective integer linear programming (ILP) models and performs Pareto optimality analysis to trade-off costs and emissions for both H-trucks and D-trucks over the 1200-kilometre (km) corridor. Second, it determines superior cost and emission boundaries for H-trucks, quantifying the emission and cost reductions achieved by H-trucks relative to D-trucks. Third, it determines the optimal fleet composition for H-trucks, including a mix of light-duty trucks (LDTs), medium-duty trucks (MDTs) and heavy-duty trucks (HDTs). The findings indicate that blue hydrogen stands out as a viable diesel alternative with a superior emission boundary of 1.5–4.5 kg-CO_2 (kilogram-carbon dioxide)/kg-H_2 (kilogram-hydrogen) and a cost boundary of \$1.1-3.0/kg. Compared to D-trucks, blue H-trucks can reduce emissions by up to 3.28 times (327.76%) and costs by up to 23.54% in the Gulf–Europe corridor. For scenarios with lower or upper emission and cost limits, HDTs are recommended to minimise costs, while MDTs are preferred to reduce emissions. These results support the adoption of blue H-trucks as a cleaner and more cost-effective option, advocating for a shift towards hydrogen-based transportation to enhance environmental sustainability and economic efficiency.

1 | Introduction

With recent progress in the global adoption of hydrogen fuel cell vehicles (HFCVs), there have been numerous advancements in hydrogen production pathways, especially in blue and grey hydrogen [1–5]. Green hydrogen relies on electrolyser technologies and renewable electricity in its production pathways, resulting in higher production costs compared to blue and grey hydrogen [6, 7]. Blue hydrogen, produced from CH_4 with carbon capture and storage (CCS), captures up to 95% of CO_2 emissions [8, 9], making it a cleaner alternative compared to traditional fossil fuels [10–12]. Grey hydrogen, though still reliant on fossil fuels, has benefited from more efficient steam methane reforming (SMR) processes [13, 14], reducing the overall carbon footprint of production. These advancements have accelerated the use of hydrogen in heavy transportation sectors, such as trucks and trains. Hydrogen-powered trucks (H-trucks) are being deployed in Europe, the United States (U.S.) and China, offering a lower-emission alternative to diesel vehicles [4, 11, 15]. Additionally, hydrogen-powered trains are increasingly being adopted in countries like Germany and the UK [15–18], offering a low-

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emission alternative on routes where electrification is not economically viable. As the Gulf Cooperation Council (GCC) countries advance in hydrogen production and infrastructure development [6], there is significant potential for deploying HFCVs in the Gulf–Europe corridor [6, 19]. Such deployment would not only demonstrate the technical and economic feasibility of large-scale hydrogen transport but also serve as a pioneering example for accelerating HFCV adoption in the GCC countries [19, 20].

Many studies have extensively analysed emission and cost reductions in hydrogen vehicles compared to diesel and electric alternatives [7, 21–23]. A key research gap remains in identifying the specific emission and cost thresholds at which H-trucks, particularly those fuelled by blue and grey hydrogen, can outperform diesel trucks (D-trucks) in terms of both environmental and economic performance. Most existing literature [21, 24–26] provides generalised comparisons but lacks detailed boundary analysis that considers varying hydrogen production pathways and their impact on long-haul freight transport. Moreover, it remains unclear which categories of H-trucks (light-duty trucks [LDTs], medium-duties trucks MDTs or heavy-duty trucks [HDTs]) offer the greatest potential for reducing emissions and minimising transportation costs under varying operational scenarios. These gaps constrain the ability of policymakers and logistics planners to make well-informed decisions regarding hydrogen adoption in freight transport systems. Motivated by these gaps, this research develops bi-objective integer linear programming (ILP) models focused on the Gulf–Europe corridor, aiming to identify optimal cost and emission thresholds, evaluate trade-offs and determine the most effective vehicle categories for sustainable freight operations. The solution method and findings of this study address the following research questions (RQs):

1. What are the emission and cost thresholds for both blue and grey hydrogen, up to which H-trucks achieve emission reductions and cost savings over D-trucks?
2. To what extent do H-trucks offer reductions in costs and emissions compared to D-trucks?
3. What is the optimal mix of H-trucks for the Gulf–Europe corridor to achieve the lowest possible costs and emissions?

To address the above RQs, we quantify CO_2 emissions associated with both blue and grey hydrogen production pathways, as well as emissions from D-trucks. Specifically, it considers carbon emissions from blue hydrogen production via CH_4 with CCS, and grey hydrogen production from CH_4 without CCS. The CO_2 emissions required to power an H-truck over a given distance differ significantly from those of a D-truck covering the same distance. Similarly, the costs associated with hydrogen production differ from those of diesel procurement. Therefore, we calculate and compare the costs of hydrogen production with diesel costs. To achieve this, we first develop bi-objective ILP models to determine both cost and emissions along the Gulf–Europe corridor for H-trucks and D-trucks, considering both lower and upper bounds. Each truck type is assigned a daily transport demand of Q tons, constrained by their respective fuel limits: F_{lh} (limit of hydrogen fuel) for H-trucks and F_{ld} (limit of diesel fuel) for D-trucks. Second, we compare the cost and emissions outputs of H-trucks and D-trucks to identify trade-off points that highlight the performance boundaries where H-trucks are superior. Based on these points, we quantify the reductions in both cost and emissions achieved by H-trucks compared to D-trucks. Third, we determine the optimal fleet composition of H-trucks along the corridor, identifying the required numbers of LDTs, MDTs and HDTs needed to minimise both cost and emissions. The findings of this study contribute to both academic literature and practical decision-making by offering a quantitative, optimisation-based assessment of hydrogen adoption. The key contributions are as follows:

- The study introduces bi-objective ILP models that evaluate trade-offs between cost and CO_2 emissions for both hydrogen-powered (blue and grey) and diesel-powered trucks. This framework enables the identification of Pareto-optimal solutions over a 1200 km corridor, providing robust thresholds to support sustainable fuel decisions.
- The study determines the optimal fleet composition of hydrogen trucks, LDTs, MDTs and HDTs, to meet freight demand while minimising cost and emissions. The results offer actionable guidance for policymakers and logistics planners in adopting hydrogen-based freight solutions.

The novelty of this study lies in its integrated evaluation of cost and emission performance for blue and grey hydrogen as alternative fuels to diesel. While existing research often focuses on hydrogen applications in isolated national contexts or specific vehicle types, this study uniquely addresses the cross-regional logistics challenge by modelling a realistic 1200 km international corridor. It advances the literature by developing bi-objective ILP models that simultaneously minimise cost and CO_2 emissions, offering a detailed trade-off analysis between hydrogen- and diesel-powered freight. Unlike previous studies that examine hydrogen feasibility in qualitative or single-objective terms, this article provides quantifiable performance boundaries, identifying cost ($1.1–3.0/kg) and emission (1.5–4.5 kg-CO_2/kg-H_2) thresholds under which hydrogen trucks become competitive. Furthermore, the study contributes a novel approach to optimal fleet sizing by determining the required mix of light-, medium- and heavy-duty hydrogen trucks to meet daily demand constraints while minimising environmental and economic impacts. This holistic, data-driven framework is particularly relevant for GCC countries, offering policy-relevant insights to guide infrastructure investment and sustainable freight transitions in emerging hydrogen economies.

The remainder of the article is organised as follows: Section 2 provides an overview of recent studies and research gaps. Section 3 offers a thorough overview of the Gulf–Europe transportation project, explaining its objectives and significance and presenting a detailed problem statement. Section 4 describes the research methodology, offering a step-by-step explanation of the procedures involved. In Section 5, we present the findings with a thorough analysis of the results. Last, Section 6 concludes by discussing the environmental and economic advantages of transitioning to hydrogen-based transportation. Finally, it suggests future research directions.

2 | Related Studies and Research Gaps

This section reviews recent advancements in hydrogen production pathways and fuel cell technologies, compares the emissions

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and costs of H-trucks and D-trucks, and identifies existing research gaps.

2.1 | Advancements in Blue and Grey Hydrogen Production Pathways

Recent advancements in hydrogen production technologies have significantly improved the viability of hydrogen as a clean fuel. Among the main hydrogen production pathways, grey and blue hydrogen are currently the most commercially mature and scalable [27, 28]. Grey hydrogen is produced through SMR without carbon capture, making it carbon-intensive, while blue hydrogen incorporates CCS into the SMR process to mitigate CO_2 emissions [9, 28, 29].

Technological advancements in CCS have significantly enhanced the viability of blue hydrogen by improving CO_2 capture efficiency and reducing the energy penalties traditionally associated with the process [8, 9, 27, 30]. These improvements have made blue hydrogen an increasingly attractive near- to mid-term solution for decarbonising energy systems, especially in hard-to-abate sectors such as heavy transport and industry. Research by Howarth and Jacobson [30], Khan et al. [31], and Ueckerdt et al. [32] shows that, when CCS technologies achieve optimised capture rates above 90%, blue hydrogen can reduce lifecycle greenhouse gas (GHG) emissions by more than 50% compared to grey hydrogen, which lacks any form of carbon capture. In addition to emissions reductions, blue hydrogen offers practical advantages due to its compatibility with existing natural gas infrastructure, including pipelines, storage systems and reforming facilities [8, 31, 33]. This compatibility reduces the need for extensive new investments, making it a more economically feasible option in the short to medium term [34–36]. Furthermore, blue hydrogen leverages existing natural gas infrastructure and is supported by growing political and financial momentum in regions like the GCC, which holds vast methane reserves and suitable geological formations for carbon storage [6, 19]. Despite these improvements, key uncertainties persist. Emission intensities of blue hydrogen vary widely depending on the methane leakage rates, CCS technology used and energy source for reforming [9, 29, 37]. Similarly, production costs are sensitive to natural gas prices, CCS investment, and economies of scale [34, 38, 39]. As Martins et al. [1], Khan [40] and Durakovic et al. [41] note, current literature lacks a unified framework to quantify the thresholds at which blue or grey hydrogen becomes cost-competitive with diesel while offering environmental benefits. This limit informed decision-making for transport applications [42–44].

2.2 | Advancements in HFCVs

Several prominent hydrogen fuel cell trucks have recently emerged, reflecting the industry's push towards sustainable transportation. Nikola Corporation's Nikola Tre Fuel Cell Electric Vehicle (FCEV) is designed for long-haul transportation, offering a 500 mile range and a quick 20 min refuelling time. This vehicle is specifically engineered to meet the demands of commercial trucking applications, providing efficiency and reliability for long-distance travel [45, 46]. The Nikola Tre FCEV is shown in Figure 1a. Toyota, in partnership with Kenworth, developed the T680 FCEV, optimised for port operations with a 300 mile range [48], while Hyundai's XCIENT Fuel Cell features a 180-kW system and a 250-mile range, aimed at global zero-emission logistics [49]. Volvo Trucks [50] is working on the FH Hydrogen Fuel Cell Truck, a prototype targeting long-distance transport with a 620 mile range and 15 min refuelling.

Additionally, Honda has unveiled its Hydrogen Semi Concept, which is equipped with a 240 kW fuel-cell system and offers a 400 mile range. This marks Honda's potential entry into the hydrogen truck market, showing a significant step towards clean long-haul transportation. The vehicle's capabilities are designed to meet the demands of freight logistics while reducing carbon emissions [47], as shown in Figure 1b. Together, these innovations underscore the industry's commitment to hydrogen technology, highlighting benefits such as extended range and reduced refuelling times compared to battery–electric alternatives, paving the way for decarbonising freight transportation.

2.3 | Comparison Between H-Trucks With D-Trucks

H-trucks offer a promising solution for decarbonising freight transport, particularly for long-haul operations where battery–electric trucks often face limitations related to driving range, payload capacity and lengthy charging durations [51, 52]. H-trucks produce zero tailpipe CO_2 emissions, and their

(a) (b)

FIGURE 1 | Hydrogen FCEVs developed by (a) Nikola–Nikola Tre [46]; and (b) Honda–Honda Class 8 [47].

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overall environmental benefit can be substantial when fuelled by low-carbon hydrogen, especially from blue or green sources [27, 30]. Compared to conventional D-trucks, H-trucks have the potential to reduce both GHG emissions and urban air pollution [26, 53]. However, the actual environmental and economic performance of H-trucks depends on several interrelated factors. One of the most critical factors is the hydrogen production pathway [6, 54], whether grey, blue or green, as each exhibits significant variation in both carbon intensity and production cost [7, 13, 31, 55]. Beyond production, various operational parameters, including vehicle fuel economy, payload capacity, route characteristics, ambient conditions, driving behaviour and trip frequency, have a significant impact on lifecycle emissions, fuel consumption and the total cost of ownership, ultimately determining the environmental and economic competitiveness of hydrogen-based transport systems [21, 56–59].

2.4 | Research Gaps

Existing studies widely recognise the environmental benefits of hydrogen-powered vehicles, particularly their potential to significantly reduce or eliminate tailpipe emissions [1, 13, 60]. However, many of these assessments are based on average or static estimates for cost and emissions [26, 38, 54], which cannot accurately represent real-world conditions. Variations in hydrogen production pathways [6, 8, 10, 54], fuel types and purity levels [13, 55], vehicle operating conditions, load factors and driving cycles [21, 61] can substantially influence both cost efficiency and emission performance across different transport scenarios. For example, grey hydrogen, produced via SMR without carbon capture [9, 31], is generally cheaper but can result in lifecycle GHG emissions that are equal to or even greater than those of D-trucks once upstream emissions are considered [62–64]. In contrast, blue hydrogen, which incorporates CCS, can significantly lower emissions, yet its production remains more expensive due to additional infrastructure and energy requirements [27, 31, 37]. A limited number of studies, including those by Kapetanović et al. [17], Rout et al. [21], Kennington [23] and Muñoz et al. [26], have attempted partial comparisons of cost and emissions between hydrogen and D-trucks. However, these studies generally fall short of identifying the precise operational and economic thresholds, such as variations in fuel efficiency, transport distance, payload capacity and hydrogen price, at which H-trucks can outperform D-trucks. Moreover, they often overlook real-world logistical constraints that critically influence the competitiveness and scalability of hydrogen trucking systems [6, 65]. Furthermore, the current literature rarely considers detailed fleet-size comparisons across truck types, including LDTs, MDTs and HDTs. Differences in gross vehicle weight (GVW) and payload significantly influence fuel use [66], cost per kilometre [67] and emission intensity [66], yet such heterogeneity is often overlooked. This gap reduces the applicability of existing research for effective policy-making and strategic investment decisions.

Addressing these gaps, this study uses a bi-objective ILP model to quantify the cost and emission profiles of H-trucks versus D-trucks over a 1200 km corridor. It identifies the specific thresholds at which hydrogen becomes favourable, assesses the influence of vehicle type, and evaluates the optimal fleet mix. In doing so, it provides a more nuanced and actionable understanding of when and how hydrogen-powered trucking can outperform diesel in both environmental and economic terms.

3 | Overview of the Gulf–Europe Corridor, Potential of Adopting HFCVs and Problem Description

3.1 | Corridor Overview

In a move to advance regional connectivity, Qatar, Iraq, Turkey and the United Arab Emirates (UAE) signed a Memorandum of Understanding (MoU) on April 22, 2024, to launch the Gulf–Europe transportation initiative, commonly known as the Iraq Development Road Project. The agreement outlines a phased implementation plan starting in 2024 and projected for completion by 2050. The primary goal of this initiative is to enhance regional transportation infrastructure and streamline trade and logistics between the Gulf and European regions [6, 19]. Iraq and Turkey serve as key transit countries, forming a vital link within this emerging multimodal corridor, as illustrated in Figure 2a. A core component of the project involves the construction of ~1200 km (745 miles) of integrated railway and highway infrastructure. This development aims to improve the efficiency, speed and capacity of cross-border freight transportation. The main routes are marked in red, originating from Kuwait, Saudi Arabia, Qatar, Bahrain, the UAE and Oman, traversing Iraq and ultimately connecting to Turkey [68, 69].

The MoU also outlines plans for developing Iraq's Al-Faw Port in Basra, which is intended to serve as a major regional trade gateway and will be directly linked to Turkey via an integrated transport network [69, 70]. A key component of the corridor is a railway line starting in Basra and extending northward to the Turkish border, paralleled by a highway designed to support large-scale road-based freight transport, as shown in Figure 2b. This infrastructure passes through several major Iraqi cities, enhancing both domestic and international connectivity, with solid black lines indicating roadways and dashed lines representing railway tracks.

3.2 | Potential of Adopting HFCVs in the Gulf–Europe Corridor

The Gulf–Europe corridor presents strong potential for adopting HFCVs, particularly in the context of long-haul freight transport. Drawing insights from initiatives in the U.S., such as the Los Angeles–San Francisco corridor and the Houston–Los Angeles corridor, it is evident that HFCVs can effectively support zero-emission goals while maintaining operational efficiency across vast distances [20, 65, 71, 72]. These U.S.-based projects are supported by substantial investments in hydrogen infrastructure and refuelling stations, enabling the deployment of hydrogen-powered heavy-duty trucks over distances exceeding 2000 km. Similarly, the Gulf–Europe corridor spans 1200 km and connects major industrial hubs across the Gulf, Iraq, Turkey and Europe. This makes it a promising option for the deployment of HFCVs, particularly for reducing GHG emissions from diesel-based freight. The corridor's strategic importance and multimodal logistics setup, featuring road, rail and maritime connectivity, provides an ideal foundation for introducing a clean energy transition in road freight [65, 73]. The barriers to HFCV adoption have been

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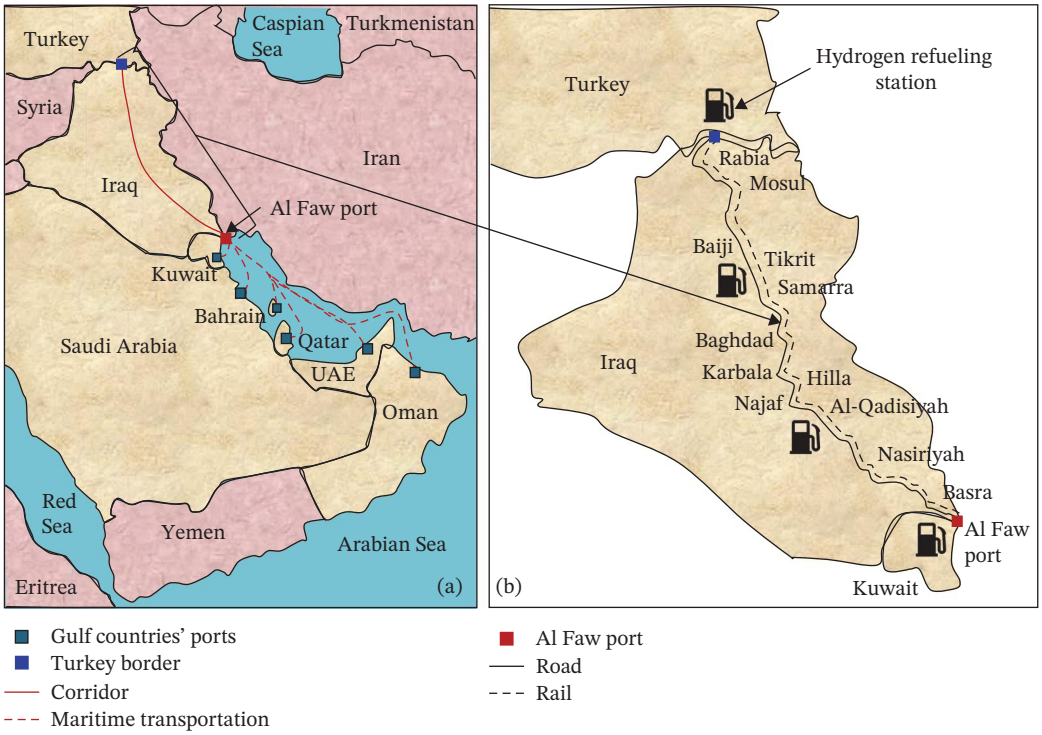

FIGURE 2 | The Gulf–Europe corridor connects (a) the Gulf countries with European countries and (b) major Iraqi cities along a route extending from Al-Faw Port to the Turkish border (reproduced from [19, 20]).

examined by Rahman et al. [20], while Rahman and Baldacci [72] designed a hydrogen refuelling station model determining the required number of dispensers, their utilisation, refuelling times, queue sizes and hydrogen stock levels necessary to accommodate stochastic vehicle inflows for this corridor.

Moreover, the Gulf countries possess substantial hydrogen production capacity [6], particularly blue and green hydrogen, which can support fuel supply across the corridor. If supported by coordinated investment in refuelling infrastructure, regulatory harmonisation and cross-border collaboration, the adoption of HFCVs could significantly advance the region's climate goals [65, 73]. Overall, leveraging HFCVs along this corridor could promote environmental sustainability, enhance energy security and position the Gulf–Europe route as a model for clean logistics development.

3.3 | Problem Description

Natural gas (CH_4) plays a significant role in the global energy supply, accounting for 22.8%, as shown in Figure 3a. The Middle East countries hold vast natural gas reserves, with Qatar being

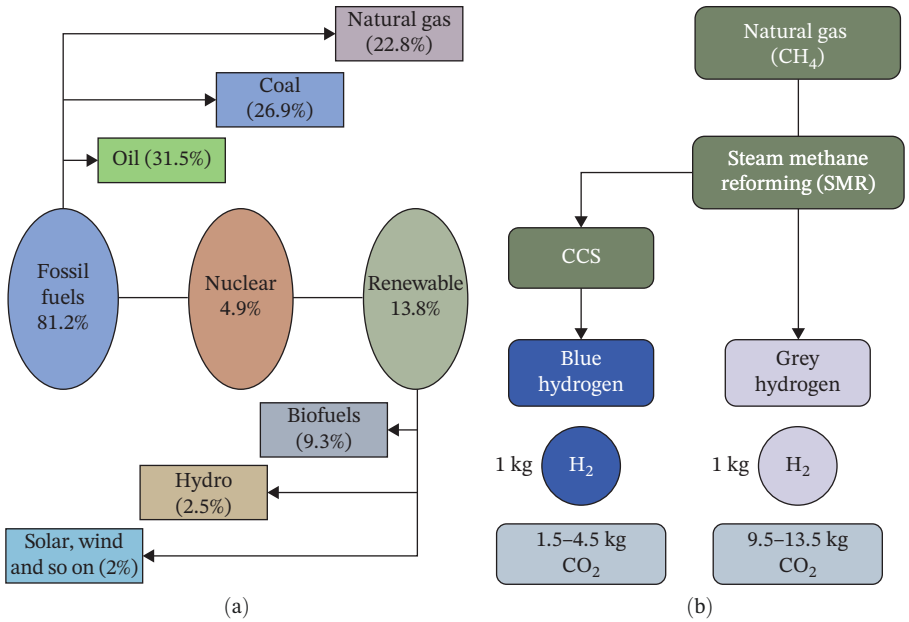

FIGURE 3 | (a) Share of global energy supply (Source: Ishaq et al. [74]), and (b) CO_2 emissions from grey and blue hydrogen production using CH_4 pathways (Source: Boretti [54]; Yu et al. [55]).

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the third-largest holder at 12.5%. This abundant resource presents a significant opportunity for countries in the region to transition to H-trucks in this corridor by 2050. Figure 3b shows two hydrogen production pathways using CH_4. Blue hydrogen, produced through SMR combined with CCS, emits 1.5–4.5 kg of CO_2 per kg of H_2 produced. In contrast, grey hydrogen, which relies solely on SMR, results in higher emissions, producing 9.5–13.5 kg-CO_2. From Table 1, the fuel economy of H-trucks, we find that their minimum emissions are 0.0428, 0.075 and 0.1578 kg-CO_2/kg-H_2. km for LDTs, MDTs and HDTs, respectively. These values are significantly lower than the emissions from D-trucks. However, the maximum emissions from H-trucks, which are 0.3875, 0.675 and 1.4210 kg-CO_2/kg-H_2. km, are slightly higher than the upper bound emissions of D-trucks.

Moreover, H-trucks demonstrate 1.5–3.5 times better fuel economy compared to D-trucks. For instance, diesel LDTs achieve a fuel economy of 8–12 km/L, whereas hydrogen LDTs attain 30–40 km/kg, which is nearly 3.5 times higher. Despite the superior fuel economy, hydrogen production pathways require more costs than the cost of diesel fuel. Producing blue hydrogen costs approximately \$1.1–3.2 per kg [31, 55, 75], while grey hydrogen is slightly cheaper, ranging from \$0.8–2.3 per kg [31, 55, 75, 76]. In comparison, diesel costs only \$0.6–1.2 per litre in Middle Eastern countries, including Iraq and Turkey. This makes blue hydrogen about two-three times more expensive, and grey hydrogen 1.5–2 times more costly than diesel. Based on the above data, H-trucks can reduce emissions by ~50% and achieve a fuel economy that is 1.5–3.5 times greater than D-trucks. This raises critical questions: how much can H-trucks reduce emissions and lower costs compared to D-trucks along the 1200 km Gulf–Europe corridor? Additionally, what would constitute the optimal fleet composition—including LDTs, MDTs and HDTs—to simultaneously minimise emissions and costs?

4 | Research Methods

To address the RQs in this study, we employ a structured methodology that systematically outlines each step in detail, as described below.

4.1 | Comparison of Fuel Economies, Emissions and Travel Costs: H-Trucks vs. D-Trucks

4.1.1 | Comparison of Fuel Economies

Various-sized trucks exhibit varying fuel economies and emission rates, as shown in Table 1. For example, hydrogen LDTs can travel ~30–40 km per kg of hydrogen, while MDTs achieve around 15–25 km, and HDTs typically range between 7 and 12 km [56, 60]. We averaged the fuel economies to 35 km for LDTs, 20 km for MDTs and 9.5 km for HDTs.

In comparison, diesel LDTs, MDTs and HDTs can travel an average of 10 km, 6.5 km and 4 km per litre of diesel, respectively. Their broader ranges are between 8–12 km for LDTs, 5–8 km for MDTs and 3–5 km for HDTs [60]. These values vary based on factors like vehicle design, load, driving conditions and the efficiency of the trucks [66].

4.1.2 | Comparison of Emissions and Travel Costs

Table 2 presents the lower and upper bounds of emissions associated with blue hydrogen and grey hydrogen. The production emissions are allocated on a per km basis by dividing the emissions by the fuel efficiency of each truck type. For instance, emissions from blue hydrogen production range between 1.5 and 4.5 kg-CO_2/kg-H_2, as shown in Figure 3b. By dividing these emissions by the fuel economy of LDTs, we calculate that the emission per km of transportation is 0.0428 kg-CO_2/km ($\frac{1.5\,\text{kg-CO}_2\text{/kg-H}_2}{35\,\text{km/kg-H}_2}$) for the lower bound and 0.1285 kg-CO_2/km for the upper bound. Similarly, grey hydrogen, which has a higher emission intensity during production, produces emissions in the range of 9.5–13.5 kg-CO_2/kg-H_2, as shown in Figure 3b. Applying the same procedure of dividing by the fuel economy, the per-km emission is calculated to be 0.2714 kg-CO_2/km for the lower bound and 0.3857 kg-CO_2/km for the upper bound. The same calculation procedure is applied to MDTs and HDTs in determining their respective emissions in transportation.

Table 3 outlines the lower and upper bounds of both hydrogen production costs. The costs are expressed on a per-km basis by dividing those by the fuel economy of each type of truck. For example, the production cost for blue hydrogen ranges between \$1.1 and \$3.2 per kg-H_2. When those are divided by the fuel economy of LDTs, the resulting fuel cost is calculated to be \$0.0314/km ($\frac{1.1\,\$/\text{kg-H}_2}{35\,\text{km/kg-H}_2}$) for the lower bound and \$0.0914/km for the upper bound. Similarly, grey hydrogen, with a production cost range of \$0.8 to \$2.3 per kg-H_2, results in per-km fuel costs of \$0.0228/km for the lower bound and \$0.0657/km for the upper bound. This calculation process is consistently applied to MDTs and HDTs to determine their respective per km fuel costs in transportation.

Table 4 also presents the lower and upper bounds for emissions and costs associated with D-trucks. Emissions from diesel consumption range between 2.6 and 2.7 kg-CO_2/L. These values are then translated into emissions per km for different truck types: LDTs, MDTs and HDTs. For LDTs, the emissions per km range from 0.26 to 0.27 kg-CO_2/km ($\frac{2.7\,\text{kg-CO}_2\text{/L}}{10\,\text{km/L}}$), while for MDTs, the emissions range between 0.40 and 0.415 kg-CO_2/km. HDTs produce slightly higher emissions, ranging from 0.65 to 0.675 kg-CO_2/km. Table 4 also provides cost data, starting with diesel fuel

TABLE 1 | Fuel economy and emission rates of D-trucks and H-trucks.

	Fuel economy		Emission rates	
Truck types	**H-trucks (km/kg)**	**D-trucks (km/L)**	**H-trucks (kg-CO_2/kg-H_2. km)**	**D-trucks (kg-CO_2/km)**
LDTs	30–40	8–12	0.0428–0.3857	0.190–0.250
MDTs	15–25	5–8	0.0750–0.6750	0.300–0.550
HDTs	7–12	3–5	0.1578–1.4210	0.600–0.800

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TABLE 2 | Emission boundaries of H-trucks.

Blue hydrogen					Grey hydrogen				
Emission boundary	Production emissions ($kg\text{-}CO_2/kg\text{-}H_2$)	Transportation emissions ($kg\text{-}CO_2/km$)			Emission boundary	Production emissions ($kg\text{-}CO_2/kg\text{-}H_2$)	Transportation emissions ($kg\text{-}CO_2/km$)		
		LDT	MDT	HDT			LDT	MDT	HDT
Lower bound	1.5	0.0428	0.075	0.1578	Lower bound	9.5	0.2714	0.475	1
Upper bound	4.5	0.1285	0.225	0.4736	Upper bound	13.5	0.3857	0.675	1.421

TABLE 3 | Fuel cost boundaries of H-trucks.

Blue hydrogen					Grey hydrogen				
Cost boundary	Production costs ($/kg-$H_2$)	Fuel (hydrogen) costs ($/km)			Cost boundary	Production costs ($/kg-$H_2$)	Fuel (hydrogen) costs ($/km)		
		LDT	MDT	HDT			LDT	MDT	HDT
Lower bound	1.1	0.0314	0.055	0.1158	Lower bound	0.8	0.0228	0.04	0.0842
Upper bound	3.2	0.0914	0.16	0.3368	Upper bound	2.3	0.0657	0.115	0.2421

TABLE 4 | Emission and cost boundaries of D-trucks.

		Transportation emissions ($kg\text{-}CO_2/km$)					Fuel (diesel) costs ($/km)		
Emission boundary	Diesel emissions ($kg\text{-}CO_2/L$)	LDT	MDT	HDT	Cost boundary	Diesel costs ($/L)	LDT	MDT	HDT
Lower bound	2.6	0.26	0.40	0.65	Lower bound	0.6	0.06	0.0923	0.15
Upper bound	2.7	0.27	0.415	0.675	Upper bound	1.2	0.12	0.1846	0.3

costs, which range from \$0.6 to \$1.2 per litre across Gulf countries, Iraq and Turkey. This further broke down into fuel costs for each truck type. For LDTs, fuel costs range from \$0.06 to \$0.12/km ($\frac{1.2\$/L}{10\,km/L}$); for MDTs, from \$0.0923 to \$0.1846/km; and for HDTs, from \$0.15 to \$0.3/km.

4.2 | Evaluating Hydrogen and Diesel Fuels

To evaluate hydrogen and diesel fuels in terms of emissions and cost minimisation, we develop mathematical models for H-trucks and D-trucks. These models calculate the fuel consumption and transportation costs required for each truck type along the corridor. The details of those models are provided in the following sections, along with model considerations. Additionally, the parameters and decision variables used in the models are described in Table 5.

4.2.1 | Development of Mathematical Models to Determine Costs and Emissions From Both H-Trucks and D-Trucks

4.2.1.1 | Models' Considerations and Assumptions. In mathematical modelling, the following assumptions and considerations were made: (1) We considered the same load capacity for both H-trucks and D-trucks across all categories: LDT, MDT and HDT. (2) We did not account for variations in fuel economy across vehicles due to their varying GVW [66, 67], and therefore, we disregarded the impact of GVW on fuel consumption. (3) We have only considered the emission of CO_2. Other pollutants, such as particulate matter (PM), carbon monoxide (CO), unburned hydrocarbons (HC) and sulphur dioxide (SO_2), have not been included in our analysis. (4) Since a hydrogen supply chain and logistics network has not yet been established in Iraq and the Gulf countries, this aspect was not considered in the study.

4.2.1.2 | Models' Description. To compare costs and emissions from H-trucks and D-trucks over a given distance (d) and for a specific demand quantity (Q), we develop bi-objective ILP mathematical models. Equations (1)–(5) represent the model for blue H-trucks, Equations (6)–(10) for grey H-trucks and Equations (11)–(15) for D-trucks. Equations (1), (6) and (11) correspond to Objective 1, which focuses on minimising emissions, while Equations (2), (7) and (12) correspond to Objective 2, which aims to minimise costs for blue, grey and diesel-powered trucks, respectively. Equations (3), (8), and (13) indicate that both H-trucks and D-trucks will transport at least quantity Q. Equations (4) and (9) indicate the blue and grey H-trucks' fuel

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TABLE 5 | Descriptions of the parameters.

Parameters for blue H-trucks	
E^i_{bl}, E^i_{bm}, E^i_{bh}	Emission rates (kg-CO_2/km) of an LDT, MDT and HDT, respectively
C^i_{fbl}, C^i_{fbm}, C^i_{fbh}	Fuel costs ($/km) of an LDT, MDT and HDT, respectively
C^i_b, E^i_b	Cost function and emission function, respectively
Decision variables	
$b_l, b_m, b_h \in Z_+$	Number of LDT, MDT and HDT, respectively
Parameters for grey H-trucks	
E^i_{gl}, E^i_{gm}, E^i_{gh}	Emission rates (kg-CO_2/km) of an LDT, MDT and HDT, respectively
C^i_{fgl}, C^i_{fgm}, C^i_{fgh}	Fuel costs ($/km) of an LDT, MDT and HDT, respectively
C^i_g, E^i_g	Cost function and emission function, respectively
Decision variables	
$g_l, g_m, g_h \in Z_+$	Number of LDT, MDT and HDT, respectively
Common parameters for both blue and grey H-trucks	
f_{hl}, f_{hm}, f_{hh}	Fuel economy (km/kg-H_2) of an LDT, MDT and HDT, respectively
F_{lh}	Fuel limit (kg-H_2)
Parameters for D-trucks	
E^i_{dl}, E^i_{dm}, E^i_{dh}	Emission rates (kg-CO_2/km) of an LDT, MDT and HDT, respectively
C^i_{fdl}, C^i_{fdm}, C^i_{fdh}	Fuel costs ($/km) of an LDT, MDT and HDT, respectively
f_{dl}, f_{dm}, f_{dh}	Fuel economy (km/L) of an LDT, MDT and HDT, respectively
C^i_d, E^i_d	Cost function and emission function, respectively
F_{ld}	Fuel limit (L)
Decision variables	
$d_l, d_m, d_h \in Z_+$	Number of LDT, MDT and HDT, respectively
Common parameters	
Q	Daily demand quantity (ton)
d	Travel distance across the corridor (km)
V_l, V_m, V_h	Capacity (ton) of an LDT, MDT and HDT, respectively
C_{xl}, C_{xm}, C_{xh}	Additional/extra costs associated with an LDT, MDT and HDT, respectively
$i = l, u$, where l denotes the lower bound and u the upper bound.	

consumption will not exceed the specified quantity, F_{lh}; similarly, Equation (14) limits the fuel consumption of D-trucks to the specified quantity, F_{ld}. Finally, Equations (5), (10) and (15) represent the decision variables that will calculate the required number of blue H-trucks, grey H-trucks and D-trucks, respectively.

4.3 | Mathematical Model for Blue H-Trucks

$$\text{Objective 1: Minimize emission, } E^i_b = \left(E^i_{bl}b_l + E^i_{bm}b_m + E^i_{bh}b_h\right)d, \tag{1}$$

$$\text{Objective 2: Minimize cost, } C^i_b = \left(C^i_{fbl}b_l + C^i_{fbm}b_m + C^i_{fbh}b_h\right)d + \left(C_{xl}b_l + C_{xm}b_m + C_{xh}b_h\right), \tag{2}$$

$$\text{Subject to } V_l b_l + V_m b_m + V_h b_h \geq Q, \tag{3}$$

$$\left(\frac{d}{f_{hl}}\right)b_l + \left(\frac{d}{f_{hm}}\right)b_m + \left(\frac{d}{f_{hh}}\right)b_h \leq F_{lh}, \tag{4}$$

$$b_l, b_m, b_h \in Z_+. \tag{5}$$

4.4 | Mathematical Model for Grey H-Trucks

$$\text{Objective 1: Minimize emission, } E^i_g = \left(E^i_{gl}g_l + E^i_{gm}g_m + E^i_{gh}g_h\right)d, \tag{6}$$

$$\text{Objective 2: Minimize cost, } C^i_g = \left(C^i_{fgl}g_l + C^i_{fgm}g_m + C^i_{fgh}g_h\right)d + \left(C_{xl}g_l + C_{xm}g_m + C_{xh}g_h\right), \tag{7}$$

$$\text{Subject to} V_l g_l + V_m g_m + V_h g_h \geq Q, \tag{8}$$

$$\left(\frac{d}{f_{hl}}\right)g_l + \left(\frac{d}{f_{hm}}\right)g_m + \left(\frac{d}{f_{hh}}\right)g_h \leq F_{lh}, \tag{9}$$

$$g_l, g_m, g_h \in Z_+. \tag{10}$$

4.5 | Mathematical Model for D-Trucks

$$\text{Objective 1: Minimize emission, } E^i_d = \left(E^i_{dl}d_l + E^i_{dm}d_m + E^i_{dh}d_h\right)d, \tag{11}$$

$$\text{Objective 2: Minimize cost, } C^i_d = \left(C^i_{fdl}d_l + C^i_{fdm}d_m + C^i_{fdh}d_h\right)d + \left(C_{xl}d_l + C_{xm}d_m + C_{xh}d_h\right), \tag{12}$$

$$\text{Subject to } V_l d_l + V_m d_m + V_h d_h \geq Q, \tag{13}$$

$$\left(\frac{d}{f_{dl}}\right)d_l + \left(\frac{d}{f_{dm}}\right)d_m + \left(\frac{d}{f_{dh}}\right)d_h \leq F_{ld}, \tag{14}$$

$$d_l, d_m, d_h \in Z_+, \tag{15}$$

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5 | Results and Discussion

5.1 | Pareto Optimality Analysis to Determine Cost Boundaries, Emission Boundaries and Optimal Fleet Sizes for the Transportation of Q Tons Goods Along the Corridor

To determine cost boundaries and emission boundaries for both H-trucks and D-trucks, we performed a Pareto optimality analysis on the data presented in Tables 2–4. For this analysis, we consider a daily demand of $Q = 30{,}000$ tons of goods and a fuel limit of $F_{lh} = 252,631.58$ kg-H_2 for H-trucks and $F_{ld} = 720,000$ L diesel for D-trucks. In the first step, we calculate the minimum emissions required to transport Q tons of goods using Objective 1 (Equations (1), (6) and (11) across three types of trucks. In the next steps, we determine the minimum costs using Objective 2 (Equations (2), (7) and (12), incorporating Objective 1 as a constraint, as detailed in the appendix. Detailed calculations for the lower bound of blue H-trucks and D-trucks are presented in sections A1 and A2, respectively.

The lower bound for blue H-trucks is determined using Equations (1)–(5), resulting in an optimal trade-off with total costs and emissions minimised to $C_b^l = 1{,}877{,}920$, $E_b^l = 378{,}720$ and a fleet of $b_l = 0$, $b_m = 0$, and $b_h = 2000$. Figure 4a illustrates the emission–cost trade-off for the lower bound of blue H-trucks over a transportation distance of 1200 km. Similarly, the trade-off for the upper bound of blue H-trucks is illustrated in Figure 4b. Using the same approach, we apply Equations (6)–(10) for grey H-trucks and Equations (11)–(15) for D-trucks. The trade-offs for the lower and upper bounds of grey H-trucks are shown in Figure 4c,d, respectively, while Figure 4e,f display the corresponding trade-offs for D-trucks. A summary of cost and emission boundaries and their optimal fleet sizes is provided in Table 6.

5.2 | Emission Comparison and Trade-Off: H-Trucks vs. D-Trucks

Figure 5 presents a detailed breakdown of emission bounds for transportation in the corridor, comparing between H-trucks and D-trucks. In Figure 5a, the *X*-axis represents the emission bounds for blue hydrogen production, ranging from 1.5 to 4.5 kg-CO_2 per kg-H_2, while the *Y*-axis depicts the emissions from blue H-trucks for 1200 km, which range from ~378,720 to 810,000 kg-CO_2. This range reflects the possible variations in emissions in transportation for the 2000 HDTs or 3000 MDTs due to differing hydrogen production processes. Figure 5b illustrates the emission bounds for grey H-trucks. For the transportation of 3000 MDTs, emissions are significantly higher than those of blue H-trucks, ranging from ~1,710,000 to 2,430,000 kg-CO_2 for hydrogen production emissions between 9.5 and 13.5 kg-CO_2 per kg-H_2. This emphasises the considerably higher emissions associated with grey hydrogen production compared to blue hydrogen. Similarly, Figure 5c illustrates the emission bounds for diesel-powered 2000 HDTs. The emission range for D-trucks is narrower, spanning from 1,560,000 to 1,620,000 kg-CO_2, for diesel emission rates between 2.6 and 2.7 kg-CO_2 per litre. This relatively small range suggests that emissions from D-trucks are relatively consistent.

Figure 5d combines H-trucks and D-trucks, providing a comparative view among them. This marks the 'superior zone,' where

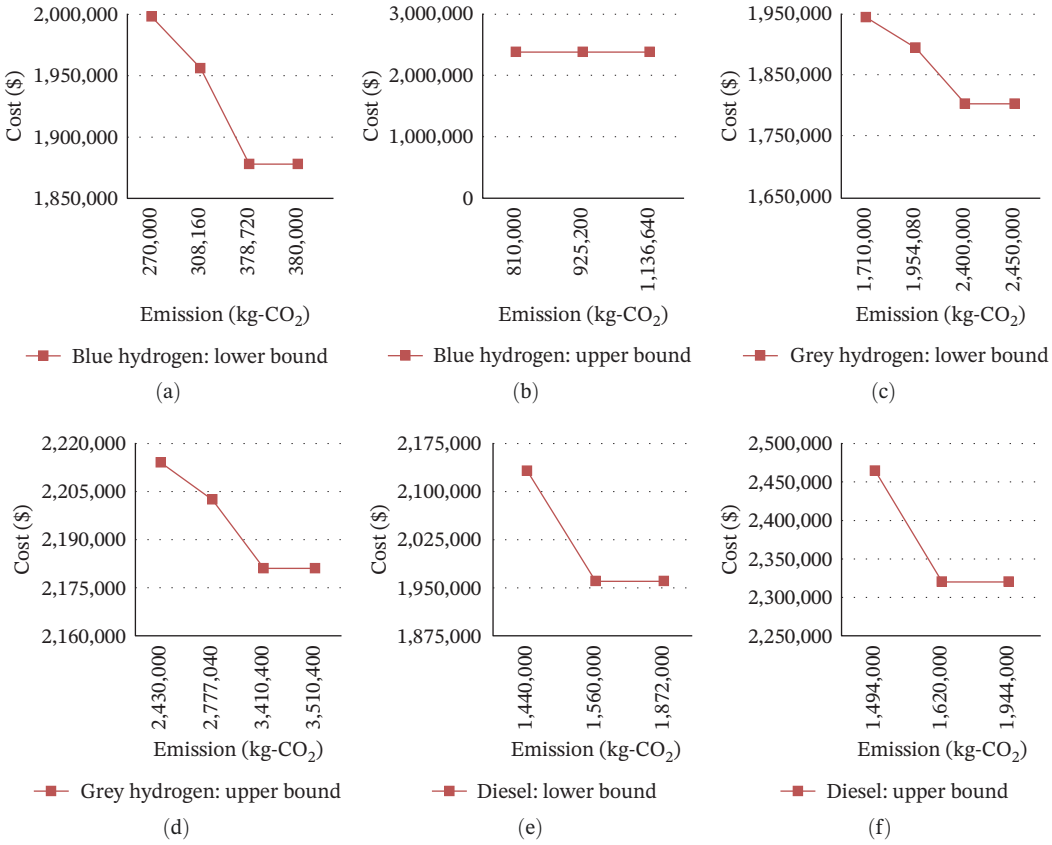

FIGURE 4 | Emission and cost trade-offs for (a) blue H-trucks, lower bound; (b) blue H-trucks, upper bound; (c) grey H-trucks, lower bound; (d) grey H-trucks, upper bound; (e) D-trucks, lower bound; and (f) D-trucks, upper bound.

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TABLE 6 | Cost and emission boundaries, and fleet sizes for both H-trucks and D-trucks over a transportation distance of 1200 km.

Truck type	Bounds	Cost boundary, $		Emission boundary, kg-CO_2		Fleet sizes		
						LDT	MDT	HDT
Blue H-trucks	Lower bound	C_b^l	1,877,920	E_b^l	378,720	$b_l:0$	$b_m:0$	$b_h:2000$
	Upper bound	C_b^u	2,376,000	E_b^u	810,000	$b_l:0$	$b_m:3000$	$b_h:0$
Grey H-trucks	Lower bound	C_g^l	1,944,000	E_g^l	1,710,000	$g_l:0$	$g_m:3000$	$g_h:0$
	Upper bound	C_g^u	2,214,000	E_g^u	2,430,000	$g_l:0$	$g_m:3000$	$g_h:0$
D-trucks	Lower bound	C_d^l	1,960,000	E_d^l	1,560,000	$d_l:0$	$d_m:0$	$d_h:2000$
	Upper bound	C_d^u	2,320,000	E_d^u	1,620,000	$d_l:0$	$d_m:0$	$d_h:2000$

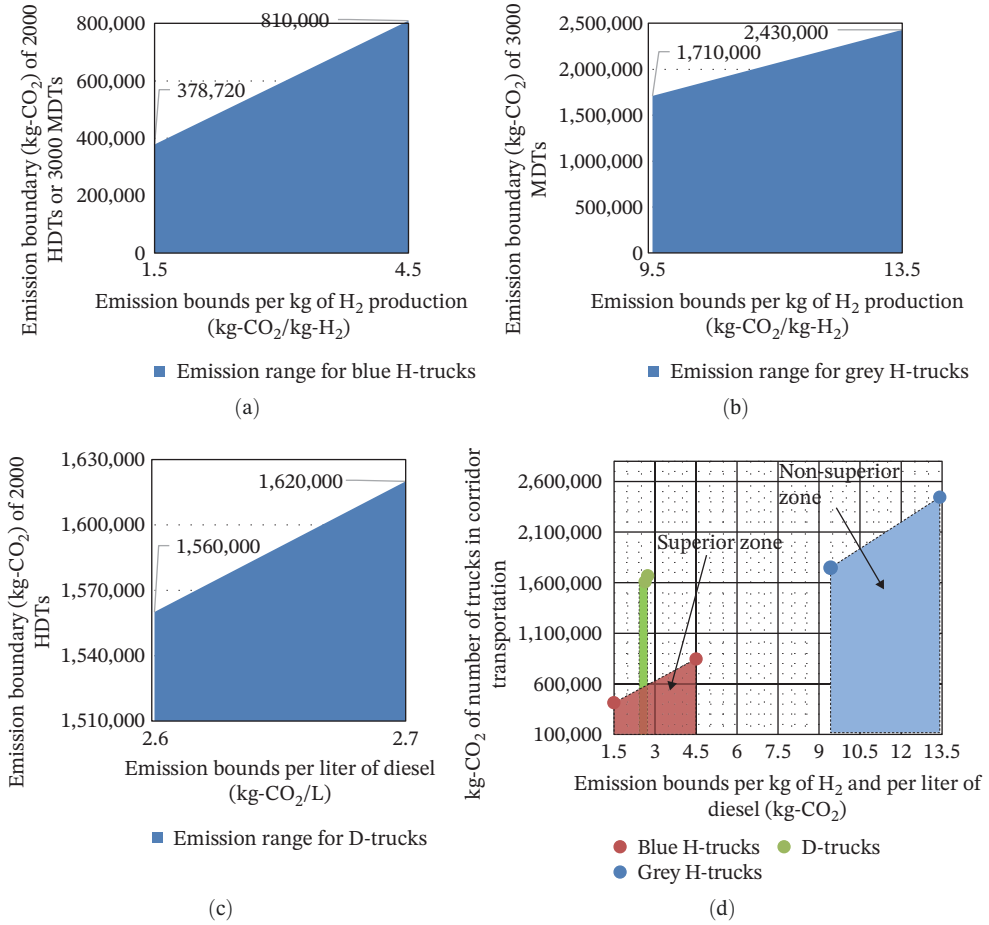

FIGURE 5 | Emission boundary for corridor transportation: (a) blue H-trucks, (b) grey H-trucks and (c) D-trucks, with (d) a comparison between H-trucks and D-trucks.

blue H-trucks can be more efficient in terms of emission minimisation compared to D-trucks. The 'non-superior zone' for grey H-trucks is noted as well, indicating ranges where D-trucks still outperform grey H-trucks. There is no trade-off between grey H-trucks and D-trucks.

5.3 | Cost Comparison and Trade-Off: H-Trucks vs. D-Trucks

Figure 6 provides a detailed breakdown of cost ranges associated with both H-trucks and D-trucks across the corridor. In Figure 6a, the cost range for blue H-trucks is shown, with costs per kilogram of hydrogen production varying from \$1.1 to \$3.2 (*X*-axis). This range leads to an overall cost boundary of \$1,877,920 to \$2,376,000 (*Y*-axis) for blue H-trucks for the transportation of 3000 MDTs or 2000 HDTs. The shaded area represents the fluctuation of hydrogen prices, indicating that costs for blue H-trucks can vary significantly based on the hydrogen production pathways. In Figure 6b, the cost per kilogram of grey hydrogen varies between \$0.8 and \$2.3, resulting in a cost boundary of \$1,944,000 to \$2,214,000 for 3000 MDTs. In Figure 6c, the cost range for D-trucks is illustrated, with diesel prices ranging from \$0.6 to \$1.2 per litre. This results in

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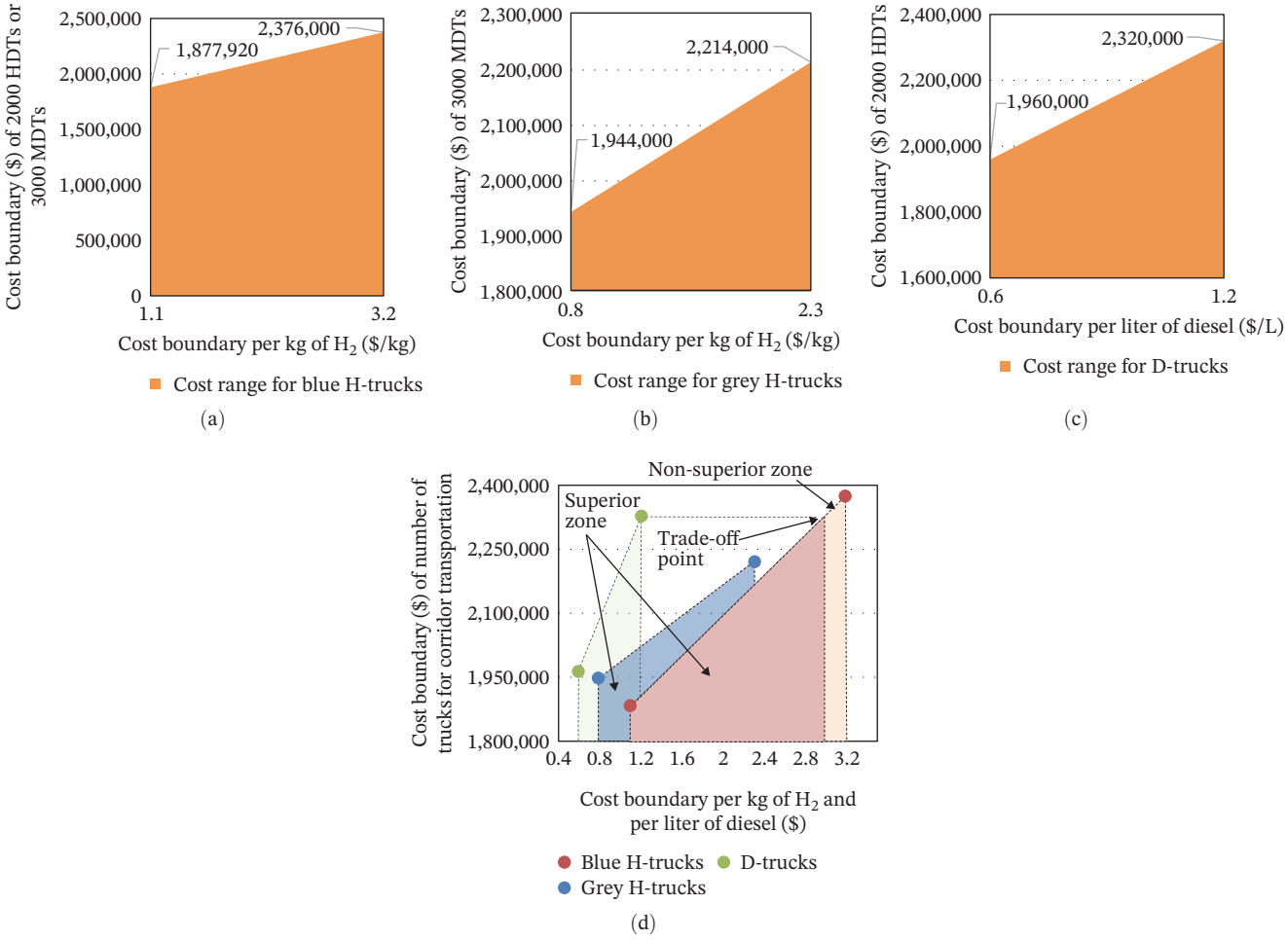

FIGURE 6 | Cost boundaries for (a) blue H-trucks, (b) grey H-trucks and (c) D-trucks, with (d) a comparison and trade-off between H-trucks and D-trucks.

a cost boundary of approximately \$1,960,000 to \$2,320,000 for 2000 HDTs, a relatively narrower range compared to H-trucks.

Finally, Figure 6d combines H-trucks and D-trucks to present a comprehensive cost comparison, highlighting a trade-off between hydrogen- and diesel-powered trucks. Figure 6d is divided into distinct zones: the 'superior zone,' where blue and grey H-trucks are shown to be the most cost-effective option; the 'trade-off point,' which marks the cost level to which blue H-trucks can outperform D-trucks, indicating that switching from diesel to blue H-trucks could be advantageous up to this threshold; and the 'non-superior zone,' where blue H-trucks are less cost-effective; on the other hand, D-trucks exhibit lower costs.

As illustrated in Figure 6d, when the upper level of diesel prices experiences slight fluctuations (±1%–10%), the cost boundary for grey hydrogen (0.8–2.3 \$/kg) remains unchanged. In contrast, the upper bound of blue hydrogen exhibits a modest variation of 0.03–0.3 \$/kg from its current upper limit of 3.0 \$/kg, suggesting that the maximum cost of blue hydrogen could reach ~3.2 \$/kg.

5.4 | Emission and Cost Reductions With the Superior Boundaries of the Hydrogen Fuels

Table 7 shows superior boundaries in terms of emissions and costs, which highlight thresholds where hydrogen options offer competitive or advantageous characteristics over diesel. For blue hydrogen, the emission lower bound is 378,720 kg-CO_2, with an upper bound threshold at 810,000 kg-CO_2. The cost boundary for corridor transportation using blue hydrogen ranges from \$1,877,920 to \$2,320,000, with a trade-off point at \$2,320,000. Emissions for blue hydrogen are bound between 1.5 and 4.5 kg-CO_2/kg-H_2, and the fuel cost per kilogram of production lies between \$1.1 and \$3.0. On the other hand, grey hydrogen lacks a defined lower emission bound and upper bound, making it not favourable in terms of emissions. However, its cost boundary for corridor transportation lies between \$1,944,000 and \$2,214,000, with production costs per kilogram ranging from \$0.8 to \$2.3. This indicates that grey H-trucks offer no emission advantage over diesel.

Table 8 shows the reduction of emissions and cost with the superior boundaries of hydrogen fuels over diesel. For blue hydrogen, emissions reduction ranges from 311.91% to 327.76% at the lower bound and from 92.59% to 100% at the upper bound. Cost reduction for blue hydrogen varies, showing a reduction of 4.37% to 23.54% at the lower bound but ranging from a decrease of 15.51% to an increase of 0% at the trade-off point. Grey hydrogen, on the other hand, shows limited reduction potential: at the lower bound, cost reductions are minimal (0.82% to 19.34%), with no emission reduction. At the upper bound, grey hydrogen exhibits no emission reduction and only a small cost advantage over diesel, ranging from a reduction of 11.47% to a modest gain of

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TABLE 7 | Superior emission and cost boundaries for hydrogen production pathways.

	Superior boundaries for the 1200 km corridor transportation				Superior boundaries for hydrogen production pathways	
	Emission boundary		Cost boundary			
Hydrogen type	Lower bound	Upper bound	Lower bound	Trade-off point/ upper bound	Emission boundary ($kg\text{-}CO_2/kg\text{-}H_2$)	Cost boundary ($/kg)
Blue hydrogen	378,720	810,000	1,877,920	2,320,000 (trade-off point)	1.5–4.5	1.1–3.0
Grey hydrogen	No lower bound	No upper bound	1,944,000	2,214,000 (upper bound)	No-boundary	0.8–2.3

TABLE 8 | Emission and cost reductions with the superior boundaries of hydrogen fuels.

	Reduction at lower bound				Reduction at trade-off point or upper bound			
	Emission reduction (%)		Cost reduction (%)		Emission reduction (%)		Cost reduction (%)	
Hydrogen type	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Blue hydrogen	311.91	327.76	4.37	23.54	92.59	100	−15.51	0
					Upper bound		Trade-off point	
Grey hydrogen	No reduction		0.82	19.34	No reduction		−11.47	4.78
							Upper bound	

Note: The minus (−) sign indicates that the cost of blue and grey hydrogen is higher than that of diesel, rather than lower.

4.78%. This data suggests that while blue hydrogen offers substantial emissions reductions and some cost savings over diesel, grey hydrogen's benefits are more limited.

5.5 | Determining the Optimal Fleet Sizes for the Corridor

Table 9 presents the per-kilometre transportation cost of blue H-trucks based on the identified cost boundaries. In contrast, Table 10 illustrates the optimal fleet sizes for varying daily demand levels across the corridor. The analysis considers daily demand ranging from 30,000 to 90,000 tons across three scenarios, in which OPL CPLEX consistently favours HDTs for the lower bound and MDTs for the upper bound. As daily demand increases in the following scenarios, the fuel limit (F_{lh}) rises accordingly, leading to higher total costs (C_b^i), emissions (E_b^i) and fleet sizes. Each scenario has a specified fuel limit range (e.g., 180,000–252,631.58 for the first scenario), yet the fleet size (LDTs = 0, MDTs = 0 and HDTs = 2000) remains consistent for the lower bound across all values within that range. For the upper bound under the same constraints, the fleet size shifts to LDTs = 0, MDTs = 3000 and HDTs = 0 in the first scenario. The fleet sizes required to meet each demand level consist solely of HDTs or MDTs, with fleet sizes ranging from 2000 HDTs or 3000 MDTs for the lowest demand scenario ($Q = 30{,}000$) to 6000 HDTs or 9000 MDTs for the highest demand scenario ($Q = 90{,}000$). There are no requirements for LDTs in these scenarios, suggesting that MDTs and HDTs are the most cost-effective and efficient choices for meeting the transportation needs of the corridor.

6 | Conclusion

This study evaluates the cost and emission performance of both H-trucks and D-trucks, examining the potential advantages of adopting H-trucks for transportation in the Gulf–Europe corridor. The analysis emphasises the environmental and economic impacts, highlighting the benefits of H-trucks in reducing emissions and optimising costs. We quantify the reduction in CO_2 emissions when using H-trucks versus traditional D-trucks and assess the cost savings associated with this shift. The main outcomes of this study are as follows:

First, to assess how much emissions and costs H-trucks reduce along the corridor, we develop bi-objective ILP models to establish emission and cost thresholds for both blue and grey hydrogen, identifying where H-trucks outperform D-trucks in terms of environmental impact and cost-efficiency. Using OPL CPLEX to solve these models, we find that emissions in the blue hydrogen production pathway range from 1.5 to 4.5 $kg\text{-}CO_2$ per $kg\text{-}H_2$, which is lower than the emissions from D-truck transportation. Additionally, the cost of blue hydrogen production per kilogram falls between \$1.1 and \$3.2; however, only costs in the \$1.1 to \$3.0 range make blue H-trucks as cost-effective as or cheaper than D-trucks. Therefore, the optimal emission and cost thresholds for blue hydrogen are 1.5–4.5 $kg\text{-}CO_2/kg\text{-}H_2$ and \$1.1–\$3.0/$kg\text{-}H_2$, respectively. In contrast, emissions from grey hydrogen production are higher, ranging between 9.5 and 13.5 $kg\text{-}CO_2/kg\text{-}H_2$, surpassing D-truck emissions. The cost of grey hydrogen production is between \$0.8 and \$2.3 per kilogram, making grey H-trucks consistently more cost-effective than D-trucks within this cost range. Consequently, a cost threshold of \$0.8–\$2.3/$kg\text{-}H_2$ is established for grey hydrogen,

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TABLE 9 | Per-km transportation cost in blue H-trucks.

Cost boundary	Production costs ($/kg-$H_2$)	Fuel (hydrogen) costs ($/km)		
		LDT	MDT	HDT
Lower bound	1.1	0.0314	0.055	0.1158
Upper bound	3.0	0.0857	0.15	0.3158

TABLE 10 | Optimal fleet sizes under varying daily demands and fuel limits.

Scenarios	Daily demand, tons	Fuel limits (F_{lh}), kg-H_2	Total cost (C_b^i), $	Total emission (E_b^i), kg-CO_2	Fleet sizes		
					LDT (b_l)	MDT (b_m)	HDT (b_h)
1	$D = 30{,}000$	180,000–252,631.58	$C_b^l = 1{,}877{,}920$	$E_b^l = 378{,}720$	0	0	2000
			$C_b^u = 2{,}340{,}000$	$E_b^u = 810{,}000$	0	3000	0
2	$D = 60{,}000$	360,000–505,263.16	$C_b^l = 3{,}755{,}840$	$E_b^l = 757{,}440$	0	0	4000
			$C_b^u = 4{,}680{,}000$	$E_b^u = 1{,}620{,}000$	0	6000	0
3	$D = 90{,}000$	540,000–757,894.74	$C_b^l = 5{,}633{,}760$	$E_b^l = 1{,}136{,}160$	0	0	6000
			$C_b^u = 7{,}020{,}000$	$E_b^u = 2{,}430{,}000$	0	9000	0

though there is no advantageous emission threshold compared to D-trucks. These findings, including the identified thresholds for blue and grey hydrogen, are discussed in detail in Section 5.4 and summarised in Tables 7 and 9, addressing RQ1.

Second, we assess the cost and emission reductions achieved by the optimal thresholds of both blue and grey hydrogen compared to diesel fuel. For blue hydrogen, at an emission level of 1.5 kg-CO_2/kg-H_2, the emission reductions range from 3.12 times (311.91%) to 3.28 times (327.76%), while cost savings at $1.1/kg-$H_2$ vary between 4.37% and 23.54%. At the higher emission level of 4.5 kg-CO_2/kg-H_2, blue hydrogen still achieves an emission reduction of 92.59% to 100%, with cost savings ranging from a decrease of 15.51% to no cost savings at all (0% for $3.0/kg-$H_2$). In contrast, grey hydrogen offers no emissions reduction over diesel due to the absence of an emission threshold advantage but does provide modest cost savings. For instance, at a cost of $2.3/kg-$H_2$, grey hydrogen's cost advantage ranges from a reduction of 11.47% to a minor increase of 4.78% over diesel. These findings demonstrate that blue hydrogen has the potential for significant emissions reductions and some cost benefits over diesel, while grey hydrogen's advantages are more limited. Detailed findings on cost and emission reductions are discussed in Section 5.4 and summarised in Table 8, addressing RQ2.

Third, we identify the optimal fleet composition for H-trucks, specifically the mix of LDTs, MDTs and HDTs that minimises costs and emissions. For a daily demand of 30,000 tons, the ideal fleet composition at the lower cost threshold includes 0 LDTs, 0 MDTs and 2000 HDTs, while at the upper threshold, it consists of 0 LDTs, 3000 MDTs and 0 HDTs. Across other demand levels, the results consistently suggest HDTs at the lower bound and MDTs at the upper bound. For the same bound, such as the lower bound, we recommend using HDTs when aiming to reduce costs, as they reduce costs by 6.39% compared to MDTs. Conversely, MDTs are preferable when the goal is to reduce emissions, as they result in a 40.27% reduction in emissions compared to HDTs. Although the choice between HDTs and MDTs depends on factors such as vehicle fixed costs, vehicle size and emissions from hydrogen production pathways, our study suggests using HDTs for cost savings and MDTs for emission reduction. The detailed findings on optimal fleet composition are presented in Section 5.5, addressing RQ3.

The integration of H-trucks into the corridor will enhance cross-border collaboration on hydrogen infrastructure and supply chains, promoting energy security and reducing reliance on fossil fuels. Additionally, our findings suggest several associated benefits, which are described below.

6.1 | Promotes Environmental Sustainability

The adoption of H-trucks in the Gulf–Europe corridor will offer a significant boost to environmental sustainability. Those produce zero direct emissions, emitting only water vapour and heat, thus drastically reducing the emission of GHG, particularly CO_2. The transition from diesel vehicles to hydrogen alternatives will significantly lower the corridor's carbon footprint, which is essential for mitigating climate change and improving air quality along this route. Moreover, the adoption of H-trucks will eliminate the release of harmful pollutants such as PM, CO, HC and SO_2, which are common in diesel exhaust. Those pollutants contribute to air pollution. However, by reducing emissions, the corridor will benefit from cleaner air, leading to improved public health and environmental quality. The transition to hydrogen vehicles is important for achieving the global temperature goal of limiting warming to 1.5°C by 2100 [77, 78]. As the transportation sector is one of the largest contributors to global GHG emissions, by adopting hydrogen vehicles, there can be a significant reduction in GHG emissions. This reduction will contribute directly to global efforts to stabilise global temperatures and mitigate the most severe impacts of climate change.

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6.2 | Achieves Global Sustainability Goals

Adoption of hydrogen vehicles supports several United Nations SDGs. First, it aligns with SDG 7: Affordable and Clean Energy, as hydrogen can be produced from renewable energy sources, ensuring a sustainable and clean energy supply. Second, it contributes to SDG 11: Sustainable Cities and Communities by reducing urban air pollution and enhancing the quality of life in cities and communities along the corridor. Additionally, it directly supports SDG 13: Climate Action by reducing GHG emissions and promoting climate resilience.

6.3 | Enhances Regional Benefits and Technological Advancements

For the Gulf region, the adoption of hydrogen vehicles will offer a pathway to diversify economies that have traditionally relied on oil and gas. Investing in hydrogen technology can create new economic sectors, drive technological advancements and enhance economic resilience. For Europe, this transition helps meet stringent emissions reduction targets and supports energy independence by reducing reliance on imported fossil fuels. This collaborative effort between Gulf countries and Europe can strengthen geopolitical ties, foster mutual economic benefits, and drive shared advancements in hydrogen technology.

6.4 | Limitations

This study faces several limitations. First, the analysis relies on accurate emission and cost data for both blue and grey hydrogen, which may vary across regions and over time. Additionally, uncertainties in geopolitical and economic factors, such as hydrogen pricing fluctuations, trade barriers and regional policy changes, could fluctuate hydrogen production costs and affect the study's findings. Variations in regional methane leakage rates influenced by differences in infrastructure, regulatory oversight and maintenance practices are not addressed. Moreover, the study focuses on optimising fleet composition and emissions boundaries for blue and grey hydrogen but does not address the effects of transitioning diesel-dependent transportation systems to hydrogen. Last, the emission and cost boundaries are based on current technological and market conditions, which may change with advancements in hydrogen production and fuel cell technologies.

6.5 | Future Research Directions

This study outlines several potential directions for future research that could enhance the current findings and reveal new insights related to the corridor. Those research areas are detailed below:

First, future research should investigate the impact of GVW on fuel consumption and carbon emission rates to achieve a more accurate calculation of CO_2 emissions. Additionally, exploring alternative hydrogen sources, such as grey hydrogen from coal gasification, turquoise hydrogen from methane pyrolysis and yellow hydrogen from solar-powered electrolysis, would be beneficial. Each type of hydrogen has distinct production costs and emission profiles, and comparing these fuels with diesel could provide valuable insights. Moreover, comparative assessments between green hydrogen and other hydrogen types under varying policies, technology and market scenarios could also reveal pathways to make green hydrogen more cost competitive. Second, future research should examine the long-term economic impacts of hydrogen vehicles, particularly their role in economic diversification and energy security in both the Gulf and European regions. Additionally, comparative studies between hydrogen and diesel vehicles in terms of efficiency, infrastructure requirements and overall economic sustainability will help identify the most effective strategies for widespread adoption. Third, optimising hydrogen distribution networks in this corridor is a critical area for future research. Studies should focus on overcoming logistical challenges in establishing a reliable hydrogen supply chain, including storage management, transportation and the development of adequate refuelling infrastructure. Addressing these factors is essential to ensuring the efficient and cost-effective delivery of hydrogen fuel throughout the corridor.

In conclusion, these research areas are essential for advancing sustainable transportation and facilitating a successful transition towards a more resilient and sustainable future.

Author Contributions

Md. Habibur Rahman: writing – original draft, conceptualisation, formal analysis, methodology, investigation. **Roberto Baldacci:** writing – review and editing, conceptualisation, supervision. **Brenno Castrillon Menezes:** writing – review and editing, conceptualisation, Supervision.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Appendix A

Appendix A1. Section A1 Pareto optimality and cost-emission trade-off for the lower bound of blue H-trucks: Using the data in Tables 2 and 3, we determine total costs and emissions in the corridor for both blue and grey H-trucks. For the lower bound of blue H-trucks, values of $C^l_{fbl} = 0.0314$, $C^l_{fbm} = 0.055$, and $C^l_{fbh} = 0.1158$ are used in Equation (A.5), while values of $E^l_{bl} = 0.0428$, $E^l_{bm} = 0.075$, and $E^l_{bh} = 0.1578$ are used in Equation (A.1). Additional costs—such as driver wages, tolls, and road fees—are also factored in, with values of \$400, \$600, and \$800 assigned to both hydrogen-powered and diesel-powered LDT, MDT, and HDT, respectively, represented as $C_{xl} = 400$, $C_{xm} = 600$, and $C_{xh} = 800$ in Equation (A.5). Our model considers $d = 1200$ km and $Q = 30{,}000$ tons, with load capacities of $V_l = 5$, $V_m = 10$, and $V_h = 15$ tons for LDT, MDT, and HDT, respectively, in Equation (A.2).

For LDTs alone, 205,714.28 kg-H_2 ($\frac{1200\text{ km}}{35\text{ kg-H}_2} \times \frac{30000\text{ tons}}{5\text{ tons}}$) is required, given their fuel economy of 35. Similarly, MDTs require 180,000 kg-H_2, and HDTs require 252,631.58 kg-H_2, with MDT and HDT fuel economies at 20 and 9.5, respectively. We use the maximum fuel quantity of 252,631.58 kg-H_2 to find the optimal fleet sizes using Equation (A.3). Equation (A.4) then calculates the necessary number of trucks (fleet sizes) that minimises emissions.

In the first step, we use Equation (A.1) (objective 1) alongside Equations (A.2)–(A.4) (constraints) to find the minimum emissions, resulting in 270,000 kg-CO_2. In the next steps, Equation (A.1) is replaced by Equation (A.5) (objective 2), while Equation (A.1) is considered as an additional constraint (Equation (A.8)). Initially, setting $E^l_b = 270{,}000$ yields $C^l_b = 1{,}998{,}000$. In the next steps, E^l_b is increased, and the corresponding transportation costs C^l_b are calculated. At the maximum E^l_b value of 378,720, C^l_b reaches 1,877,920, after which C^l_b remains unchanged, as shown in Figure 4a. The model was solved using OPL CPLEX, resulting in an optimal outcome of $E^l_b = 378,720$ and $C^l_b = 1,877,920$, with $b_l = 0$, $b_m = 0$, and $b_h = 2000$, as presented in Table 6.

First step:

Objective function

Minimise,

$$\begin{aligned} E^l_b &= \left(E^l_{bl}b_l + E^l_{bm}b_m + E^l_{bh}b_h\right)d \\ &= (0.0428b_l + 0.075b_m + 0.1578b_h)1200. \end{aligned} \tag{A.1}$$

Subject to

$$5b_l + 10b_m + 15b_h \geq 30000, \tag{A.2}$$

$$\left(\frac{1200}{35}\right)b_l + \left(\frac{1200}{20}\right)b_m + \left(\frac{1200}{9.5}\right)b_h \leq 252631.58, \tag{A.3}$$

$$b_l, b_m, b_h \in Z_+. \tag{A.4}$$

Next steps:

$$\begin{aligned} &\text{Minimize, } C^l_b = \left(C^l_{fbl}b_l + C^l_{fbm}b_m + C^l_{fbh}b_h\right)d \\ &+(C_{xl}b_l + C_{xm}b_m + C_{xh}b_h) \\ &=(0.0314b_l + 0.055b_m + 0.1158b_h)1200 \\ &+(400b_l + 600b_m + 800b_h), \end{aligned} \tag{A.5}$$

$$5b_l + 10b_m + 15b_h \geq 30000, \tag{A.6}$$

$$\left(\frac{1200}{35}\right)b_l + \left(\frac{1200}{20}\right)b_m + \left(\frac{1200}{9.5}\right)b_h \leq 252631.58, \tag{A.7}$$

$$(0.0428b_l + 0.075b_m + 0.1578b_h)1200 \leq E^l_b, \tag{A.8}$$

$$b_l, b_m, b_h \in Z_+. \tag{A.9}$$

Appendix A2. Section A2 Pareto optimality and cost-emission trade-off for the lower bound of D-trucks: Using the data in Table 4, we determine total costs and emissions in the corridor for the D-trucks. For the lower bound, we use $C^l_{fdl} = 0.06$, $C^l_{fdm} = 0.0923$, and $C^l_{fdh} = 0.15$ in Equation (A.14) and $E^l_{dl} = 0.26$, $E^l_{dm} = 0.40$, and $E^l_{dh} = 0.65$ in Equation (A.10). Additional costs are set equal to those of H-trucks with $C_{xl} = 400$, $C_{xm} = 600$, and $C_{xh} = 800$, as in Equation (A.14). Truck capacities are also aligned with H-trucks, with $V_l = 5$, $V_m = 10$, and $V_h = 15$ tons, in Equation (A.11).

For LDTs only, 720,000 L ($\frac{1200\text{ km}}{10\text{ km/L}} \times \frac{30000\text{ tons}}{5\text{ tons}}$) of diesel are required; MDTs require 553,846.15 L, and HDTs require 600,000 L. The model uses the maximum diesel demand of $F_{ld} = 720,000$ L to determine the optimal fleet size using Equation (A.12). Finally, Equation (A.13) calculates the required number of trucks that minimises emissions.

In the first step, we use Equation (A.10) (objective 1) alongside Equations (A.11)–(A.13) (constraints) to determine the minimum emissions, resulting in 1,440,000 kg-CO_2. In the next steps, Equation (A.10) is replaced by Equation (A.14) (objective 2), while Equation (A.10) is considered as an additional constraint (Equation (A.17)). Initially, setting $E^l_d = 1{,}440{,}000$ yields $C^l_d = 2{,}132{,}280$. In next steps, E^l_d is increased, and the corresponding transportation costs C^l_d are calculated. At the maximum E^l_d value of 1,560,000, C^l_d reaches 1,960,000, after which C^l_d remains unchanged, as shown in Figure 4e. The optimal solution obtained in OPL CPLEX is as follows: $E^l_d = 1,560,000$ and $C^l_d = 1,960,000$, with $d_l = 0$, $d_m = 0$, and $d_h = 2000$, as presented in Table 6.

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First step:

$$\begin{aligned}\text{Minimize, } E_d^l &= \left(E_{dl}^l d_l + E_{dm}^l d_m + E_{dh}^l d_h\right)d \\ &= (0.26d_l + 0.40d_m + 0.65d_h)1200,\end{aligned} \tag{A.10}$$

$$5d_l + 10d_m + 15d_h \geq 30000, \tag{A.11}$$

$$\left(\frac{1200}{10}\right)d_l + \left(\frac{1200}{6.5}\right)d_m + \left(\frac{1200}{4}\right)d_h \leq 720000, \tag{A.12}$$

$$d_l, d_m, d_h \in Z_+. \tag{A.13}$$

Next steps:

$$\begin{aligned}&\text{Minimize, } C_d^l = \left(C_{fdl}^l d_l + C_{fdm}^l d_m + C_{fdh}^l d_h\right)d \\ &+(C_{xl}d_l + C_{xm}d_m + C_{xh}d_h) = (0.06d_l + 0.0923d_m \\ &+0.15d_h)1200 + (400d_l + 600d_m + 800d_h)\end{aligned} \tag{A.14}$$

$$5d_l + 10d_m + 15d_h \geq 30000, \tag{A.15}$$

$$\left(\frac{1200}{10}\right)d_l + \left(\frac{1200}{6.5}\right)d_m + \left(\frac{1200}{4}\right)d_h \leq 720000, \tag{A.16}$$

$$(0.26d_l + 0.40d_m + 0.65d_h)1200 \leq E_d^l, \tag{A.17}$$

$$d_l, d_m, d_h \in Z_+. \tag{A.18}$$

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