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ADBI Working Paper Series

HYDROGEN FUEL CELL TRUCKS: TOTAL COST OF OWNERSHIP ANALYSIS FOR THE PEOPLE'S REPUBLIC OF CHINA

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Abstract

High cost is a significant barrier to the adoption of hydrogen technology in the transportation sector. Using a comprehensive total cost of ownership (TCO) analysis this study evaluates the economic viability of hydrogen fuel cell trucks (FCT) in 2023 and estimates for 2030, in the People's Republic of China's transportation sector, in comparison to electric and diesel trucks. The model quantifies the economic impact of the inconvenience associated with hydrogen refueling, a critical factor that has been insufficiently addressed in existing literature, on TCO of FCTs. The following key results with policy implications are obtained. First, the price of hydrogen has the largest impact on FCT's TCO, compared to other costs. Second, FCTs have the highest fuel consumption cost, and this gap widens over longer distances due to both poor fuel efficiency and high hydrogen price. Third, travel disutility cost (as a share of TCO) is greater for FCT comparing to electric and diesel tracks. Fourth, TCO of FCTs is greater than electric and diesel trucks, despite generous purchase subsidy in the PRC, however, it is expected that TCO of FCTs will become lower by 2030 given the expected reduction of hydrogen price. Thus, hydrogen price reduction (due to production cost decline or subsidy), and investment in hydrogen refueling infrastructure are expected to reduce FCT TCO. In 2030 TCO of FCT will become competitive with electric and diesel trucks, even without carbon tax.

Keywords: hydrogen, People's Republic of China, electric vehicles (EVs), trucks, transportation, clean transport, total cost of ownership analysis

JEL Classification: O14, O18, R42, R48

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1. INTRODUCTION

The transportation sector is a significant contributor to global greenhouse gas emissions, and it plays a crucial role in the challenge of climate change (Hensher 2018). With the pressing need for carbon emission reduction, hydrogen energy emerges as a promising clean alternative, especially for achieving decarbonization objectives in transportation (Chakraborty et al. 2022). Unlike battery electric vehicles, hydrogen-fueled transportation systems offer the advantage of independence from the electrical grid, potentially alleviating peak load pressures and enhancing overall energy security (Veziroglu 2017). In the context of the People's Republic of China (PRC), the "China Automotive Industry Development Report (2020)" reveals a stark discrepancy in emissions: Trucks constitute merely 11% of the road vehicle population but are responsible for 46% of emissions. In contrast, passenger vehicles, which make up 87% of the fleet, contribute to a comparatively lower 44% of emissions. This imbalance underscores the urgent need for more efficient and cleaner transportation solutions. Hydrogen fuel cell trucks (FCTs) harness hydrogen's high energy density to deliver efficient, virtually zero-emission power for heavy-duty transport (Dash et al. 2022). Hydrogen's substantial calorific value renders FCTs especially suited to high energydemand scenarios, such as long-distance trucking, and offers sustained power and fewer refueling stops (van der Spek et al. 2022). Thus, FCTs stand out as a viable and environmentally friendly alternative that is poised to drive forward the sustainable transformation of the heavy transport sector.

However, as a segment of new energy vehicles (NEVs) — which are vehicles powered by alternative energy sources instead of traditional fossil fuels, FCTs encounter numerous challenges during large-scale deployment. Vehicle cost and the uncertainty surrounding the return on investment of new energy vehicles deter potential buyers (Greene, Ogden and Lin 2020). Additionally, the scarcity of necessary infrastructure impedes the broader adoption of NEVs (Tarei, Chand and Gupta. 2020; Hardman et al. 2017). Specifically, the glaring inadequacy of hydrogen refueling stations for FCTs fails to keep pace with the growing demand driven by their promotion (Hao et al. 2022). Although governments have rolled out various promotion strategies aimed at addressing these barriers, including financial subsidies, the present market penetration of FCTs suggests that such interventions fall short of resolving issues related to market receptiveness and the lack of essential infrastructure, particularly hydrogen refueling stations (S. Li et al. 2022). We apply a total cost of ownership (TCO) analysis to evaluate key factors of FCTs to quantify these market barriers.

Studies have often overlooked the quantification of hydrogen refueling inconvenience. We focus on the practical application of FCTs, establishing an advanced TCO assessment model. This model supports the quantification of this inconvenience from a realistic perspective by simulating point-to-point driving routes to fill this gap. In addition, through a case study in the steel and freight industries based on the national pilot project implementation plans, we calculate and compare the TCO of FCT with alternative trucks. These results provide important implications on the feasibility of large-scale adoption of FCTs in the PRC's transportation sector. This provides a more comprehensive understanding of the TCO of FCTs, aiding stakeholders in making informed deployment decisions.

The remaining paper is structured as follows. Section 2 provides a literature review outlining the research relevant to this study. Part 3 describes the methodology, including the construction and analysis methods of the TCO model. Section 4 provides the sources and describes the research data. Section 5 presents the results and a discussion analyzing the implications of the results. Section 6 concludes with a summary of the key findings and provides policy recommendations.

2. LITERATURE REVIEW

TCO analysis has emerged as a critical evaluation tool in the transport sector, enabling stakeholders to gain a comprehensive understanding of the financial implications associated with different transportation technologies. This mode of analysis is particularly significant in the context of shifting toward more sustainable transport solutions. For instance, Kim et al. (2021) focused on a comparative TCO analysis of battery electric and hydrogen fuel cell buses for public transport systems in small to midsize cities. They discussed the techno-economic analysis of the public transport sector and the structural analysis of public transport. Suttakul et al. (2022) compared the TCO of internal combustion engines and electric vehicles in Thailand, reflecting the growing interest in studying TCO among countries promoting EVs in their transport sectors. The breadth of these studies underscores the versatility and applicability of TCO analysis, making it an indispensable tool for policymakers, businesses, and environmental strategists aiming to make informed decisions to facilitate the transition toward low-carbon transportation systems in the rapidly evolving transport sector.

Research on TCO for FCTs can be broadly categorized into two primary methodologies: micro-level and macro-level studies. Micro-level studies focus on vehicle-specific experimental data, assessing the direct costs related to performance, maintenance, and operation of individual FCTs under controlled conditions. For instance, Fiquet et al. (2020) discussed the TCO impact of various propulsion system solutions for heavy-duty long-haul trucks. The paper explored future solutions for heavy truck propulsion systems, highlighting the importance of considering TCO when evaluating different options. While such studies are invaluable for detailed insights into vehicle-specific economics, they often do not capture the broader systemic and environmental factors that can significantly influence TCO. These limitations include the inability to fully account for external costs, such as infrastructure availability, societal adoption rates, and regional policy impacts.

To address these broader aspects, macro-level studies are essential. Such studies utilize data from larger urban or regional scales, incorporating variables such as the availability of hydrogen refueling stations, the impact of regional transportation policies, and the integration of FCTs within existing vehicular fleets and public transport systems. Macro-level research can provide a more comprehensive understanding of how FCTs fit into the larger economic and environmental landscape, offering insights into potential network effects, economies of scale, and the long-term sustainability of hydrogen as a transport fuel. For these reasons, we are using macro-level research in this study. Table 1 details the scope and findings of the recent macro-level TCO studies on commercial hydrogen fuel cell trucks.

Literature	Country/Region	Transport Type	TCO Components of FCT
Hao et al. (2022)	PRC	Diesel Truck; Electric Truck; Fuel Cell Truck; Buses	Acquisition Cost: Including the initial cost of purchasing commercial vehicles. Operating Cost: Covering the operational and maintenance costs of vehicles, such as fuel, repair, and maintenance expenses. Depreciation Cost: Considering the decrease in the value of vehicles over time. Financial Cost: Including interest expenses and capital costs. Taxes: Involving taxes and related fees for vehicles. Insurance Cost: The cost of vehicle insurance. Other Costs: range anxiety cost, alternative vehicle cost.
Rout et al. (2022)	UK	Diesel Truck; Electric Truck; Fuel Cell Truck	Fuel Costs: Comparison of costs for different types of fuels (hydrogen, electricity, diesel), including purchase and usage costs. Maintenance Costs: Expenses for vehicle maintenance, repairs, and upkeep. Initial Investment Costs: Consideration of the initial costs of purchasing different types of vehicles. Operating Costs: Various expenses during the operation of vehicles, such as insurance, registration, and licensing fees. Environmental Costs: Potential consideration of the environmental impact of different fuel types, including costs related to emissions and sustainability.
Jones, Genovese and Tob- Ogu (2020)	London, UK	Diesel Truck; Electric Truck; Fuel Cell Truck	Vehicle purchase cost: Including the initial cost of purchasing hydrogen fuel vehicles. Fuel cost: Covering the fuel costs during the use of hydrogen fuel vehicles. Maintenance and repair costs: Considering the expenses required for maintaining and repairing hydrogen fuel vehicles. Energy infrastructure development cost: Including the cost of constructing and maintaining the energy infrastructure to support the operation of hydrogen fuel vehicles. Environmental impact cost: Assessing the costs associated with the environmental impact of using hydrogen fuel vehicles. Capital cost: Involving capital investment and funding costs to evaluate the economic benefits of investing in hydrogen fuel vehicles. Operating cost: Considering the day-to-day operating costs of hydrogen fuel vehicles, such as insurance, permits, and other operational expenses.
Presta, C. (2023)	EU	Diesel Truck; Electric Truck; Fuel Cell Truck	Purchase Cost: The purchase price of a product or service is one of the most direct costs. This includes the fees paid when you first buy it. Operating Cost: The costs incurred during the use of a product or service, such as maintenance, upkeep, energy consumption, etc. Maintenance Cost: The costs required to maintain a product or service, including regular maintenance, repairs, and replacement of parts. Upgrade Cost: The costs incurred when upgrading or updating a product or service to maintain its performance and functionality. Retirement Cost: The costs of disposing of a product or service when it reaches the end of its life, including scrapping, recycling, or replacement

Table 1: Summary of Macro-level Studies on FCT Cost Published from 2020 to 2024

continued on next page

Literature	Country/Region	Transport Type	TCO Components of FCT
Noll et al. (2022)	10 European countries	Diesel Truck; Electric Truck; Fuel Cell Truck	Acquisition Costs: The initial costs associated with purchasing the low-carbon drive technologies. Operating Costs: The costs incurred during the operation of the technologies, such as maintenance, repairs, and energy consumption. Fuel Costs: Specifically for vehicles or systems that require fuel, the expenses related to fuel consumption are taken into account. Residual Value: The estimated value of the technology at the end of its useful life, which impacts the overall cost. External Costs: Additional costs that may not be directly borne by the owner but have an impact on society or the environment, such as emissions and pollution.
Burnham et al. (2021)	US	Fuel Cell Truck and Cars	The costs considered in the studies include external costs in physical units and dollars, emissions of pollutants or greenhouse gases, vehicle manufacturing costs, retail prices, lifecycle costs, periodic ownership and operating costs, insurance payments, maintenance and repair costs, fuel costs, labor costs, materials costs, charger costs, and energy use.
Basma, Zhou and Rodríguez (2022)	Six countries in Europe	Diesel Truck; Fuel Cell Truck	Direct manufacturing costs: the manufacturing costs of components such as fuel cell units, hydrogen storage tanks, electric drives and batteries. Indirect costs: R&D, management costs, marketing, warranty expenses and profits, and government subsidies.
Speth et al. (2022)	EU	Diesel Truck; Electric Truck; Fuel Cell Truck	The initial investment costs for acquiring alternative fuel trucks, operational costs (such as fuel and maintenance expenses), and the total cost of ownership over the vehicle's lifespan.
Liu et al. (2020)	US	Diesel Truck; Electric Truck; Fuel Cell Truck	Vehicle-related and infrastructure fuel-related ownership costs
Mu et al. (2024)	US	Diesel Truck; Electric Truck; Fuel Cell Truck	The cost of purchasing a vehicle: the cost of the body, the cost of the power system, and the cost of energy storage. Energy cost: energy and maintenance costs. Maintenance cost: repair and maintenance costs. Residual value: residual value of the vehicle after the use phase ends.

Source: Authors' own.

The review of existing research indicates a significant oversight in the current studies: the nonintuitive costs associated with hydrogen refueling. These nonintuitive costs, such as recharging inconvenience and detour costs, heavily influence consumer purchasing decisions and the broader adoption of FCTs. Accurate quantification of these costs is crucial for the widespread acceptance and implementation of hydrogen technology in transportation (Bhardwaj and Mostofi 2022; Yan and Zhao 2022). While some studies, like those by Hao et al. (2022) and Burnham et al. (2021), have begun to address these nonintuitive costs, the scope of the studies remains limited and does not fully capture the broader implications of these costs. Additionally, the data sources commonly employed in these studies, such as interviews and household records, often fail to adequately represent broader market dynamics or the full spectrum of demographic characteristics ((Link et al. 2024). This limitation not only undermines the reliability of TCO calculations but also restricts the applicability of the findings to other regions or demographics.

Our research takes a comprehensive approach with the aim of filling these gaps by focusing specifically on the quantification of nonintuitive costs, especially the inconvenience associated with hydrogen refueling—a factor frequently overlooked in the evaluation of FCTs. We have implemented scenario-based analyses that are grounded in current governmental development plans, with a particular focus on pilot programs within sectors like the steel industry and long-distance freight. This methodology enables us to explore the practical feasibility and the real-world implications of adopting FCTs on a large scale within the PRC's transportation sector. Through this approach, we aim to provide a more complete and applicable understanding of the TCO for FCTs, which can guide stakeholders in making informed decisions about the deployment of these technologies.

3. METHODOLOGY

3.1 Total Cost of Ownership (TCO) for Trucks

The TCO for trucks provides a holistic view of the financial aspects involved in their operation and ownership. This comprehensive measure includes the purchase cost of the truck throughout the entire ownership. Maintenance cost is another key component, covering expenses related to regular upkeep and repairs necessary to keep the truck operational. Energy consumption cost takes into account the ongoing expense of fueling the truck, crucial in the context of varying fuel prices and truck fuel efficiency. Additionally, the TCO factors in travel disutility cost, which captures nontangible costs such as the inconvenience of refueling, time loss and additional labor cost. These cost categories collectively help stakeholders understand the economic implications of deploying different truck technologies in various logistical and transport scenarios.

3.2 Total Cost of Ownership (TCO) Assessment Model

In establishing our TCO estimation model, we considered the costs per unit of travel distance each year. Therefore, as shown in formula (1), the sum of all sub-costs throughout the entire ownership period is divided by the average annual travel distance over the total years of ownership to obtain the result.

$$TCO = \left(\frac{C_P + yC_M + yC_F + C_T}{yAVKT}\right)$$
(1)

where *TCO* represents the total cost of ownership. These components include C_P (purchase cost), C_M (maintenance cost), C_F fuel or electricity consumption cost), and C_T (travel disutility cost). By accumulating these costs over the ownership span, denoted as y, and then dividing by the *AVKT* (annual vehicle-kilometers traveled), we derive the average annual cost of operating the vehicle.

3.2.1 Purchase Cost Assessment Model

The model for calculating purchase cost takes into account the real process of acquiring a vehicle. Typically, the initial purchase of the vehicle body is a one-time expense, but this outlay is amortized over the entire ownership period. Additionally, the model considers the resale of the vehicle, from which the seller benefits from the proceeds obtained through depreciation. For new energy trucks, it is also important to factor in any subsidies available to buyers as well as statutory taxes. Therefore, we have developed formula (2) to clearly account for the total purchase cost.

$$C_P = V - V_{rs} - S_p + VAT \tag{2}$$

where C_P represents the purchase cost, which is counted for the entire years of ownership. Purchase cost includes the vehicle price *V*, vehicle resale price V_{rs} , purchase subsides S_p , and value added tax *VAT*.

3.2.2 Maintenance Cost Assessment Model

The model for maintenance costs is typically established based on annual expenditures. Therefore, we set the maintenance costs for each year to primarily consist of routine repair expenses and the costs incurred during the taxation process. Any corresponding maintenance subsidies (if available) were also considered. The model is represented as formula (3):

$$C_M = R + T_m - S_m \tag{3}$$

where C_M represents the maintenance cost. The main parameters for maintenance cost are repair cost *R*, taxes and fees of maintenance T_m , and subsides of maintenance S_m .

3.2.2 Energy Consumption Cost

For energy consumption costs, we focused on the average annual energy usage. Therefore, these costs are determined by the AVKT, the energy consumption rate, and the price of energy. The model is represented as formula (4):

$$C_F = AVKT \times E \times P_{energy} \tag{4}$$

where C_F represents the energy consumption cost. The main parameters for maintenance cost are *AVKT*, energy consumption rate *E*, and energy unit price P_{energy} .

3.2.3 Travel Disutility Cost

We define as "travel disutility costs" the inconvenience for new energy trucks that stems from the additional energy consumption and time wasted due to detours for refueling. The former requires consideration of the detour distance and energy consumption rate, while the latter involves accounting for the monetary value of time. Therefore, we have established an estimation model as shown in formula:

$$C_T = f(F_{det} + L_{det}, N) \tag{5}$$

$$F_{det} = f(E, d) \times P_{energy} \tag{6}$$

$$L_{det} = f(d, v) \times VOT \tag{7}$$

$$N = \frac{AVKT}{eT} = \left(\frac{2aD_{work}H_{work}}{\left(H_s + \frac{2a}{\overline{\nu}}\right)(eT - \overline{d})}\right)$$
(8)

Equations (5)–(7) express the calculation method for travel disutility cost. It is mainly calculated from the single energy consumption cost of additional detours F_{det} , the single time cost L_{det} , and the number of annual detours N. F_{det} is affected by E and detour distance as well as energy prices P_{energy} . The single time cost also needs to consider the speed v and value of time *VOT* of different driving paths. Formula (8) provides the method for calculating the average annual number of detours N in this

study. *e* represents the empty tank coefficient, *T* represents the full tank driving distance, *a* represents the single transportation distance (no detours), D_{work} represents the average annual working days and H_{work} represents daily working time, H_s is the truck loading and unloading time we consider, and \overline{v} and *d* are the average driving speed and average detour distance, respectively.

Given that real-world routes are influenced by multiple factors and cannot be estimated using a uniform scenario, this study opted to calculate detour distances by using navigation maps to simulate routes, thereby obtaining the respective detour distances. However, as simulation requires prior knowledge of intermediary points, we preestablished models for different detour scenarios, as shown in Figure 1.



Figure 1: Instructions for Setting-up Detour Scenarios

Source: Authors' own.

We assumed three detour scenarios, with the original, no-detour scenario as the baseline (O-D)L: scenario A in which the driver refuels at the station closest to the origin (O), denoted as (O-So-D); scenario B in which the driver refuels at the station closest to the destination (D), represented as (O-SD-D); and scenario C in which the driver refuels at a station between the origin (O) and the destination (D), indicated as (O-Si-D). If the total travel distance in the original scenario B, it would be 4+5; and for scenario C, it would be 6+7.

4. DATA

4.1 Data Description

This study's data sources are broad and diverse, covering market insights, policy details, and road network and facility specifics, ensuring a comprehensive and detailed analysis. Market data covers heavy-duty truck specifications, used truck sales, and energy prices, which are foundational for TCO analysis. Policy data includes new energy truck subsidies, tax benefits, and energy strategies, which are essential for evaluating policy impacts on truck economics. Road and driving data provide the basis for realistic truck route simulations, while facility information on hydrogen stations and logistics centers is crucial for operational cost and refueling convenience assessments. Additionally, statistical data on VOT, demographics, and work hours enrich the analysis of driver behavior and cost. Employing web scraping, this study

collected over 5,000 used truck prices and nearly 100,000 real truck routes, alongside comprehensive policy, facility, and statistical data. This vast dataset supports a detailed examination of FCT economic feasibility in the PRC, laying the groundwork for targeted policy recommendations and operational improvements.

4.2 Study Areas

In the current study, we focus on the application of FCTs in the logistics transportation sector, guided by the "Joint Action Initiative on Accelerating the Development of Hydrogen Energy in China." This initiative aims to expedite the nation's decarbonization process and achieve the goal of green transportation. The study primarily concentrates on major pilot provinces and cities, including Beijing City, Hebei Province, Shanghai City, Guangzhou Province, and Jiangsu Province, with specific application scenarios explored in the first three regions. These areas have policy and practical leadership in advancing hydrogen energy and FCT applications. Each pilot city has designed distinct application scenarios based on its specific policy framework. For example, Beijing's "Development Plan for Hydrogen Refueling Stations for Fuel Cell Vehicles (2021-2025)" provides a clear roadmap for hydrogen infrastructure development within the capital region. Shanghai city's "Shanghai Promotion Plan for Hydrogen Energy in the Transportation Sector" elaborates on how hydrogen can enhance urban transport systems. In Handan City, Hebei Province, the transportation of steel products and raw materials has already begun utilizing hydrogen-powered trucks in accordance with the "14th Five-Year Plan for Hydrogen Energy Industry Development in Hebei Province." The transportation scenarios considered are of two main types: long-distance freight relying on highways, involving interprovincial or even cross-regional bulk material transport, and short-distance logistics within urban areas, typically associated with daily commercial activities and the distribution of goods. These scenarios not only demonstrate the applicability of FCTs across different transportation needs but also impose specific demands on infrastructure, such as hydrogen refueling stations, aimed at maximizing the economic and environmental benefits of hydrogen-powered trucks. Through such practical exploration and policy support, the prospects for FCT applications will gradually become clearer in the coming years, providing valuable experiences and data to support green transportation solutions in the PRC and globally.

4.3 Assumptions for Trucks' Parameters in 2023

In accordance with the policies, the logistics scenarios primarily utilize hydrogenpowered heavy trucks, specifically within the 49-ton tractor segment. Table 2 details the hypothetical parameters set for trucks powered by three types of energy sources: hydrogen, electricity, and diesel. Furthermore, electric trucks (ETs) are categorized into two sub-types for the simulation: battery-swapping electric truck (SBET) and battery electric truck (BET). These distinctions are crucial for assessing the performance and feasibility of each truck type under various operational conditions outlined in the study.

In order to evaluate the long-term implications and cost-effectiveness of each truck type over a realistic operational lifespan, this study assumes a 10-year ownership period for heavy-duty trucks, which aligns with government regulations on maximum service life before decommissioning. Key parameters in the cost model include national and local subsidies (specifically, for FCT, the national subsidies are about 60,000 RMB, the local subsidies are maximum to 15,000 RMB), a 10% purchase tax in the PRC, |and a 33% depreciation rate derived from second-hand truck prices. For all financial calculations presented in this paper, the exchange rate used was 1 RMB = 7.24 USD,

based on the prevailing exchange rate at the time of the analysis (Feb. 2024). Calculations assumed 249 official working days in 2023, with an 8-hour daily operation. The energy prices at the point of sale are 33.24RMB/kg of hydrogen; 1.2RMB/kwh of electricity; 7.5RMB/Liter of diesel.

Truck	Segment	Drive Form	Load, Ton	Vehicle Weight, Ton	Average Energy Consumption (Fully Loaded), per 100 km	Tank/Battery Capacity
FCT	Tractor/Trailer	6×4	49	11	11 kg	52 kg
SBET				20	200 kwh	300 kwh
BET						
DT				9	40 liter	900 liter

Table 2: Simulated Trucks' Parameters

Note: FCT = hydrogen fuel cell truck; SBET = battery swapping electric truck; BET = battery electric truck; DT = diesel truck.

Source: Authors' own.

4.4 Assumptions for 2030

To delve into the effects of carbon tax policies on the TCO of FCTs, this study adopts the International Energy Agency's (2021) methodology for calculating diesel carbon emissions¹, which is equal to 2.68 CO₂ emissions kg/liter; this is combined with the International Monetary Fund's (2021) recommended carbon pricing for high-income emerging market economies such as the PRC (\$50 per ton of CO₂) to forecast the future fuel consumption costs of diesel trucks (a 1.035 RMB/liter increase in diesel price). Considering the PRC's hydrogen price target for 2030, the 2030 hydrogen price is set at 18 RMB (approximately \$2.5) per kilogram (Y. Li et al. 2022). Lithium-ion battery prices assumed to decrease by 25% from 2023 to 2030 (Neubauer et al. 2011). The Appendix shows changes in 2030 parameters relative to 2023.

5. RESULTS AND DISCUSSION

5.1 The Purchase Cost of FCTs is Only 1.81% Greater than DTs in 2023, Mainly Due to Subsidies in the PRC

As shown in Figure 2, purchase price (before subsidies) exceeds 1 million RMB, substantial subsidies reduce the 10-year annualized purchase cost (the purchase price is divided by 10) of FCTs to 30,766 RMB/year, which is only 1.81%² greater than of diesel trucks (30,219 RMB per year). In contrast, BETs have the highest annualized purchase cost at 61,645 RMB/year, while SBETs are lower at 54,342 RMB/year.

¹ CO₂ Emissions(kg/liter) = Diesel Density × CO₂ Production Coefficient, where Diesel Density is 0.85, CO2 Production Coefficient is 3.16.

² 1.81%=(30,766 RMB-30,219 RMB)/30,219 RMB.



Figure 2: Annualized Purchase Cost for Different Types of Trucks

Note: FCT = hydrogen fuel cell truck; SBET = battery swapping electric truck; BET = battery electric truck; DT = diesel truck. The 10-year annualized purchase cost is calculated by dividing the purchase price by 10.



Figure 3: Annual Maintenance Cost for Different Types of Trucks

Note: FCT = hydrogen fuel cell truck; SBET = battery swapping electric truck; BET = battery electric truck; DT = diesel truck.

Figure 3 shows the comparison of maintenance costs. The proton exchange membrane (PEM) used in FCTs is a critical and wear-prone component that requires replacement as efficiency declines, resulting in an annual maintenance cost of 35,000 RMB for FCTs. BETs have the highest maintenance cost at 70,000 RMB per year. Although the maintenance cost of FCTs is slightly higher than that of SBETs and DTs, it remains significantly lower than that of BETs. Although our model takes into account government subsidies for maintenance costs, no reliable basis was found in the case analysis, so the subsidy was set to 0 in this calculation.

5.2 FCTs Have the Highest Fuel Consumption Cost per km, Due to Hydrogen Price and Fuel Consumption Rate

To accurately assess annual energy consumption costs for heavy-duty trucks, simulations of four specific scenarios were conducted relying on the precise and verified routes provided by "Gaode Maps" (https://lbs.amap.com). These scenarios encompass various distances and operational contexts within and between regions.



Figure 4: Original Transportation Distance in Different Situations

Note: 1. Transport between steel product warehouses and finished goods terminals within Shanghai City (Shanghai_short_1); 2. Movement between steel product warehouses within Shanghai City (Shanghai_short_2); 3. Logistics transport from the steel plant of Baosteel in Shanghai City to steel plants in Jiangsu Province, Anhui Province, and Hubei Province (Shanghai long distance – over 400 km); 4. Material transport between coking plants and steel mills within Handan City (Handan short distance – about 47 km); 5. Goods transport from the Beijing Outer Cargo Center to major ports in Tianjin City and Hebei Province (Beijing medium distance – about 200 km).

The calculated annual energy consumption costs for different types of trucks are provided in Figure 5. The findings reveal that FCTs consistently incur the highest energy costs across all routes. Electric Trucks (SBETs and BETs) and DTs have similar costs, with the greatest cost disparity for FCTs observed in medium to long-distance scenarios. This is due to the combination of higher hydrogen price and fuel consumption rate compared to electricity and diesel. Hydrogen costs 33.24 RMB/kg with a consumption rate of 11 kg/100 km, electricity costs 1.2 RMB/kWh with a consumption rate of 200 kWh/100 km, and diesel costs 7.5 RMB/L with a consumption rate of 40 L/100 km. These differences result in per-kilometer costs of 3.66 RMB/km for FCTs, 2.4 RMB/km for Electric Trucks, and 3 RMB/km for DTs. Consequently, the fuel

consumption cost for FCTs exhibits a nonlinear growth as driving distance increases. This is due to the multiplicative effect of both the higher unit fuel price and the elevated fuel consumption rate, which leads to an accelerating divergence in total energy costs over longer distances, particularly when compared to the more linear cost scaling of electric and diesel trucks.



Figure 5: Annual Energy Consumption Cost for Different Types of Trucks

Note: 1. Transport between steel product warehouses and finished goods terminals within Shanghai City (Shanghai_short_1); 2. Movement between steel product warehouses within Shanghai City (Shanghai_short_2); 3. Logistics transport from the steel plant of Baosteel in Shanghai City to steel plants in Jiangsu Province, Anhui Province, and Hubei Province (Shanghai long distance – over 400 km); 4. Material transport between coking plants and steel mills within Handan City (Handan short distance – about 47 km); 5. Goods transport from the Beijing Outer Cargo Center to major ports in Tianjin City and Hebei Province (Beijing medium distance – about 200 km).

Moreover, single factor analyses on vehicle price, energy price, detour distance, and major component price were conducted and are shown in Table 3. It was found that energy price has the most significant impact on TCO. A 10% increase in energy price results in a TCO increase of 7.95% for FCTs, 7.21% for both ETs, and 6.16% for DTs. A 10% increase in vehicle price leads to a TCO increase of 2.34% for FCTs, 1.91% for charging ETs, 1.85% for SBETs, and 0.98% for DTs. A 10% increase in detour distance causes a 0.6% increase in TCO for FCTs. A 10% increase in the price of major components results in a 0.11% increase in TCO for FCTs and a 1.05% increase for BETs.

The above results imply that changes in energy (hydrogen, diesel and electricity) prices will have the largest impact on TCO (compared to changes in truck price, detour distance and main parts price), and thus relative competitiveness of trucks. Since FCTs consistently incur the highest energy costs (Figure 5), a decline in hydrogen price (e.g. due to hydrogen production cost reduction or subsidy) will have a large impact on FCT's TCO.

	Truck Price 10% ↑	Energy Price 10% ↑	Detour Distance 10% ↑	Main Parts Price 10% ↑
FCTs	2.34%	7.95%	0.60%	0.11%
SBETs	1.91%	7.21%	0.00%	0.00%
BETs	1.85%	7.21%	0.00%	1.05%
DTs	0.98%	6.16%	0.00%	0.00%

Table 3: Single Factor S	Sensitivity Anal	ysis Results
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5.3 Travel Disutility Cost (Share in TCO) of FCTs is Greater than SBET, BET and DT and is the Highest for Short-distance Routes

The annual travel disutility cost was thoroughly analyzed, especially for FCTs. Figure 6 displays a comparison of the average single detour distance and the average original transport distance. Within a year, detour distances and frequencies for FCTs exhibited considerable variation across different transportation scenarios. For short-distance transport (below 50 kilometers), the detour per trip can be 5–8 times longer than the trip distance, and for around 5 kilometers, the detour is 1.4 times the trip distance. In long-distance transport scenarios (over 400 kilometers), the detour per trip accounts for merely 4.3% of the trip without refueling; for Beijing medium distances scenario (approximately 200 kilometers), the detour is 16% of the original distance.



Figure 6: Distance of Detour and Original Transportation Across Routes

Note: 1. Transport between steel product warehouses and finished goods terminals within Note: 1. Transport between steel product warehouses and finished goods terminals within Shanghai City (Shanghai_short_1); 2. Movement between steel product warehouses within Shanghai City (Shanghai_short_2); 3. Logistics transport from the steel plant of Baosteel in Shanghai City to steel plants in Jiangsu Province, Anhui Province, and Hubei Province (Shanghai long distance – over 400 km); 4. Material transport between coking plants and steel mills within Handan City (Handan short distance – about 47 km); 5. Goods transport from the Beijing Outer Cargo Center to major ports in Tianjin City and Hebei Province (Beijing medium distance – about 200 km).

The frequency of refueling detours for each route was estimated. As shown in Figure 7, the derived travel disutility cost for FCTs varies by route, with long-distance (over 400 kilometers) scenarios incurring an annual average cost of 20,410 RMB, while short-distance (below 50 kilometers) routes face costs of 16,326 RMB (Shanghai short1), 26,518 RMB (Shanghai short2) and 48,640 RMB (Handan); the medium-distance case (approximately 200 kilometers) faces the highest cost at 60,935 RMB. The average travel disutility cost across all scenarios constitutes 5.9% of the TCO. With reference to previous research (Hao et al. 2022), we estimated the travel disutility cost for SBETs to be 7,000 RMB, accounting for 2.1% of TCO, mainly due to detours to battery-swapping stations; for charging-type ETs, given both the detour to charging stations and the waiting time for charging, the cost is estimated at 15,000 RMB, representing 3.9% of TCO.

This result highlights the magnitude of the cost of refueling detours (up to 5.9 % of TCO), which can be reduced by investments in infrastructure for the expansion of hydrogen refueling and electric charging infrastructure. From annual detour costs results, long distance route are more economical than short-distance route. This can also serve as an important reference for the hydrogen refueling infrastructure planning the specific routes for the widespread adoption of FCTs.



Figure 7: Annual Travel Disutility Cost for FCT Hydrogen Refueling Across Routes

Note: 1. Transport between steel product warehouses and finished goods terminals within Shanghai City (Shanghai_short_1); 2. Movement between steel product warehouses within Shanghai City (Shanghai_short_2); 3. Logistics transport from the steel plant of Baosteel in Shanghai City to steel plants in Jiangsu Province, Anhui Province, and Hubei Province (Shanghai long distance – over 400 km); 4. Material transport between coking plants and steel mills within Handan City (Handan short distance – about 47 km); 5. Goods transport from the Beijing Outer Cargo Center to major ports in Tianjin City and Hebei Province (Beijing medium distance – about 200 km).

5.4 FCTs' TCO is Still Greater in Comparison to Other Trucks, But it is Likely to Become Lower from 2030 Due to Hydrogen Price Decline

Although, the subsidy in the PRC has significantly impacted the TCO of FCTs, the high hydrogen prices result in a greater TCO compared to other powertrain trucks in 2023. Overall, as illustrated in Figure 8a, the TCO for FCTs in 2023 is the highest at

451,777 RMB, followed by the BETs at 382,336 RMB, DT at 354,870 RMB and SBETs at 327,063 RMB.

If a carbon tax is implemented in 2030, it will significantly increase the fuel consumption costs for DTs, rising TCO of DT from 354,870 RMB (Fig 8a) to 393,174 RMB (Fig 8b). TCO of BET declines from 382,336 RMB (Fig 8a) to 364,866 RMB (Fig 8b) mainly due to the expected decline of lithium-ion battery price, which for simplicity we assume does not affect TCO of SBET. The TCO of FCT will decline from 451,777 RMB in 2023 to 286,582 RMB in 2030 and become lower compared to other trucks, mainly due expected decline of hydrogen price. This will lead to FCT having the lowest TCO in 2030 compared to SBET, BET and DT. As shown in Figure 8b, the estimated TCO in 2030 is the lowest for FCTs at 286,582 RMB, compared to SBETs at 327,063 RMB, BETs at 364,866 RMB, and DTs with carbon tax at 393,174 RMB (Fig 8b) and event DT without carbon tax at 354,870 RMB (Fig 8a).



Figure 8: Total Cost of Ownership for Different Trucks

Note: FCT = hydrogen fuel cell truck; SBET = battery swapping electric truck; BET = battery electric truck; DT = diesel truck.

6. CONCLUSION AND POLICY RECOMMENDATIONS

Cost is a significant barrier to the adoption of hydrogen technology in the transportation sector. This paper uses a comprehensive TCO analysis to identify financial obstacles and opportunities for promoting FCT. This study evaluated the economic viability of FCT in the PRC. Our study lays an analysis of the TCO for FCTs, ETs, and DTs, with a focus on crucial aspects such as vehicle and energy costs, detour distances, and major component prices. Our research significantly contributes to the field by quantifying the often-overlooked inconvenience of hydrogen refueling for FCTs—the quantification of travel disutility cost. By examining pilot programs in the steel industry and freight sectors, we have demonstrated the practical feasibility and real-world implications of large-scale FCT adoption in the PRC's transportation sector. This approach offers a comprehensive understanding of the TCO for FCTs, enabling stakeholders to make well-informed decisions regarding their deployment. We calculated the following annual costs: purchase, maintenance, energy (fuel)s, disutility, and TCO for each truck: FCT, SBET, BET and DT. In addition, we calculated the estimated TCO in 2030.

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Despite the substantial subsidy in the PRC, the TCO of FCTs remains the highest comparing to other trucks, mainly due to hydrogen price. The expected hydrogen price decline (to \$2.5/kg) in 2030 will greatly reduce TCO of FCT, making it lower by 20% than DT (even without carbon tax). Carbon tax (50\$/ton) could help with making TCO of DT even more higher, making TCO of FCT lower by 27% than DT. Each part of TCO is provided below.

Purchase Cost

The purchase cost of FCTs in 2023 is lower than DTs due to the subsidy in the PRC. Despite the high initial cost, substantial subsidies reduce the annualized purchase cost of FCTs to 30,766 RMB³, close to DTs at 30,219 RMB. In comparison, BETs have the highest annual purchase cost at 61,645 RMB, while SBETs are lower at 54,342 RMB. Nevertheless, TCO of FCT is greater than other trucks due to other costs.

Maintenance Cost

FCTs have an annual maintenance cost of 35,000 RMB, slightly higher than DTs at 30,000 RMB and SBETs at 30,000 RMB but significantly lower than BETs at 70,000 RMB.

Energy (Fuel) Consumption Cost

FCTs consistently incur the highest energy consumption costs compared to SBET, BET and DT, the difference is large particularly in medium- to long-distance routes, with hydrogen costing 3.66 RMB/km compared to electricity at 2.4 RMB/km and diesel at 3 RMB/km. In order to mitigate the growing cost disparity of FCTs over longer distances, policies should focus on improving hydrogen fuel efficiency and subsidizing hydrogen prices

Disutility Cost

The travel disutility cost is greater for FCT (5.9% of TCO) compared to SBET (2.1% of TCO) and BET (3.9% of TCO). The travel disutility cost of FCTs, is the highest for short-distance logistics, emphasizes the importance of hydrogen refueling infrastructure.

Based on the above results, we provide the following policy recommendations. Currently, TCO of FCT is the highest compared to other tracks (even with substantial perchance price subsidy). Reduction of TCO of FCT requires not only reduction (e.g. subsidizing) purchase cost, but also reduction of hydrogen price and development of infrastructure for refueling. Hydrogen price is expected to fall by 2030 making TCO of FCT lower than other tracks.

We acknowledge limitations in the projection of future scenarios. Elements like the future value of time (influenced by inflation rates and average income) and future electricity prices (shaped by the overall energy landscape) hold significant potential for further exploration. Setting parameters through in-depth research in these areas could refine our understanding and predictions for the transportation sector's evolution. We did not consider other benefits of using FCT. Beyond their contribution to reducing carbon emissions, FCTs offer advantages such as faster refueling times compared to electric trucks and the potential for a sustainable brand image that appeals to environmentally conscious customers. These factors make FCTs an attractive option, even with a higher cost.

³ All cost calculations used an exchange rate of 1 RMB = 7.24 USD.

Building on our current findings, our future research direction aims to delve into the comprehensive environmental and carbon emission costs over the lifecycle of these transportation options. This expanded focus will not only enhance our grasp of the economic implications but also the environmental impact, paving the way for more informed policy recommendations and industry practices that align with sustainable development goals. This approach signifies a step toward a holistic evaluation that considers both the economic and ecological footprints of transitioning to greener transportation technologies.

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APPENDIX: ASSUMPTIONS FOR 2023 AND 2030

Parameter	2023 Assumption	2030 Assumption
Truck Types	Hydrogen, SBET, BET, Diesel	Hydrogen, SBET, BET, Diesel
Ownership Period	10 years	10 years
National Subsidy (FCT)	60,000 RMB	TBD
Local Subsidy (FCT)	15,000 RMB	TBD
Purchase Tax	10%	10%
Depreciation Rate	33%	33%
Hydrogen Price	33.24 RMB/kg	18 RMB/kg
Electricity Price	1.2 RMB/kWh	1.2 RMB/kWh
Diesel Price	7.5 RMB/L	8.535 RMB/L (with carbon tax)
Carbon Emission (Diesel)	N/A	2.68 kg CO2/liter
Lithium-ion Battery Cost Reduction	N/A	25% reduction from 2024 levels
Exchange Rate	1 RMB = 7.24 USD	TBD
Working Days/Year	249	Assumed same as 2023
Daily Operation	8 hours/day	Assumed same as 2023