

Article

Characterizing the Economic and Environmental Benefits of LNG Heavy-Duty Trucks: A Case Study in Shenzhen, China

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Abstract: Heavy-duty trucks (HDTs) in road freight are a primary contributor of PM_{2.5} and NO_x emissions in many cities. Shenzhen, a megacity of China, has already made great efforts to promote the green transport transition, including via the Liquefied Natural Gas (LNG) HDTs program, which may be the largest alternative fuel vehicle promotion program in the world. In order to fully understand the actual efficiency of such program, the economic and environmental impacts of LNG HDTs were analyzed in this study. The results revealed that, while the capital cost of LNG HDTs is higher than that of diesel HDTs, the aggregated cost during the entire operation period of LNG HDTs is 10% to 17% lower than that of diesel HDTs. By replacing existing diesel HDTs mode (including China-I to China-V) with LNG HDTs (100%), environmental impact analysis showed that PM_{2.5} and NO_x emissions could be reduced by 96.7% and 73.2% in the city level, respectively. Moreover, the environmental benefits of using purely LNG HDTs versus just China-V diesel HDTs were also compared, which indicated that LNG substitution is superior to China-V, with a reduction of 20.9% for PM_{2.5} and 35.4% for NO_x, respectively. Overall, the effectiveness of the promotion of LNG HDTs is notable in Shenzhen, and these findings could provide references for other cities to promote LNG HDTs and beyond.

Keywords: liquefied natural gas (LNG); heavy-duty truck (HDT); economic benefit; environmental impact; Shenzhen City



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1. Introduction

Playing a critical role in the national economy, the transportation sector is presented with significant challenges, such as associated environmental issues [1]. Due to rapid economic development and urbanization, there has been a boom in road transportation in China. At the end of 2020 [2], the total number of vehicles in China amounted to 372 million. In India [3], rapid economic growth and massive urbanization has significantly promoted transport emissions. The transport sector consumes 29% of total energy demand, with the dominant 93% share being oil. Along with the large amount of energy consumption, traffic emissions are also high. Among them, 74% of transport emissions are from road transportation. Recent studies show that traffic-related air pollution is causing wide and urgent concern worldwide, especially in large developing countries and regions [4–7]. All around the world, road freight is one of the largest contributors to energy consumption and exhaust emissions. According to WHO's report, the most serious atmospheric pollutants are particulate matter (PM₁₀ and PM_{2.5}), nitrogen oxides (NO_x) and ground-level ozone (O₃), which are harmful to human health. From the China Mobile Source Environmental Management Annual Report 2021 [2], PM (Particulate Matter) and NO_x (Nitrogen Oxide)

emitted by trucks are of a significantly higher level than that of passenger vehicles in China. Heavy-duty trucks (HDTs), with a total mass of 14 tons or more, are mainly used in logistics enterprises in China. The maintenance of exhaust after-treatment devices of trucks is largely overlooked. As a result, it is very difficult to monitor and control emissions derived from HDTs. As shown in Figure 1, there are around 7.62 million HDTs in China, which account for 3.00% of the total number of vehicles. However, these HDTs contribute to 33 thousand tons of PM and 4630 thousand tons of NO_x, which accounts for 52.1% and 75.4% of the total emissions from all vehicles, respectively. It is worth noting that PM_{2.5} is one of key pollutants in atmospheric pollution in China, and NO_x is a major precursor of regional O₃ and secondary PM_{2.5} [8–10]. With new national air quality standards taking effect, PM_{2.5} and NO_x have become the focus of the future pollution control [11].

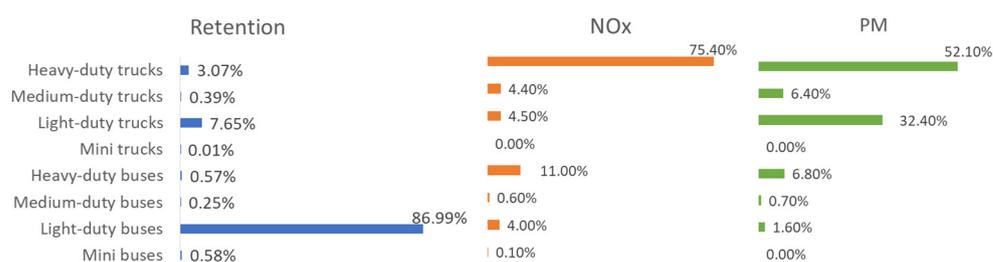


Figure 1. Relationships among vehicle retention, PM, and NO_x distribution in China in 2020.

Vehicle classification, retention and emissions are based on the China Mobile Source Environmental Management Annual Report 2021 released by the Ministry of Ecology and Environment of the People’s Republic of China [2]. Given that the unit of emissions is 10,000 tons, the amounts of NO_x and PM emitted by mini trucks and mini buses are less than 0.001, displayed here approximately as zero.

There are a number of advantages associated with the use of natural gas as a transportation fuel. These include wide availability, cost savings and environmental friendliness [12]. There are two forms of natural gas as a vehicle fuel: compressed natural gas (CNG) and liquefied natural gas (LNG) [13].

The primary fuels of HDTs include gasoline and diesel. There are some choices of substitutions for conventional fuels. While electric vehicles have advantages in environmental protection, due to their significant reduction of emissions per kilometer traveled as compared with conventional vehicles, they are only suitable for light-duty vehicles [14,15]. In addition, CNG’s energy density is too low to maintain the power of HDTs. The advantages of LNG are safety and environmentally friendliness, while its supply safety is just behind diesel and gasoline. Therefore, LNG has become the priority of alternative vehicle fuels in many countries. In addition, the ratio of natural gas in energy supply has increased rapidly.

Shenzhen, a megacity in south China, has transformed from a small fishing village with 60,000 residents in the 1980s to an international city with over 17.49 million permanent population in 2020 [16]. Neighboring the Hong Kong Special Administrative Region, it has become China’s first and the most successful Special Economic Zone. Shenzhen’s gross domestic product (GDP) reached 2767.0 billion RMB by the end of 2020 [17]. As a demonstration city for the national low-carbon strategy, Shenzhen is facing significant environmental challenges similar to other megacities in China, while much attention has been paid to the reduction of PM_{2.5} at the city scale. Local official statistics revealed that the mileage of urban roads and turnover volume of freight and passenger transport in Shenzhen have increased rapidly due to the rapid economic and social development in the area [17]. Transport has been recognized by the Shenzhen government as a key factor to achieve the goal of urban energy-saving and air quality improvement. The complexity associated with environmental issues has led to much controversy in both environmental policies and the role of the transport sector. Specifically, the Shenzhen government has made a lot of efforts to promote LNG HDTs to replace existing diesel HDTs in the road

freight since 2015. The promotion scale aims for up to 15,000 HDTs before 2020, which will be one of the largest LNG truck promotion programs in urban areas around the world [18]. In 2018, Shenzhen issued relevant policies to subsidize LNG HDTs, which once again promoted their development [19].

Natural gas vehicles (NGVs) have played a critical role to improve the air quality of urban areas around the world, e.g., America, Canada, Europe and China [20,21]. NGVs mainly includes school buses, waste haulers and buses especially, since travel distances are relatively short and a central refueling network already exists [21]. In China, CNG buses and LNG buses were introduced to the bus fleet in Beijing in 1999 and 2012, respectively [22,23]. There are a number of advantages associated with LNG buses compared to their CNG counterparts, such as higher energy density, lower investment in supporting infrastructure and longer service life [24]. In the United States, the number of urban buses powered by natural gas (including CNG and LNG) has tripled between 2000 and 2015 [25,26]. An analysis of technology and policy tradeoffs indicated that NGVs could have significant market penetration in Class 7–8 trucks in the United States depending on technological and economic uncertainties [20], which provides a good reference for China, to some extent.

From an environmental perspective, the engine type of HDTs is almost the same as ignition natural gas (NG) buses, and emission patterns are also similar to these vehicles due to their similar characteristics [27]. Natural gas engines have been used in urban transit buses as an alternative to diesel engines due to their lower PM and NO_x emissions [28,29]. The regular emissions from spark NG engines are much lower than the emissions from the latest technology diesel engines with after-treatment devices, measured by chassis dynamometer testing facilities [30,31]. By using dual fuel mode (e.g., natural gas and diesel), NO_x and PM emissions can be reduced significantly compared with normal diesel combustion [12]. Guo et al. (2014) found that NG buses perform better than diesel buses in terms of lower NO_x and PM emissions, fewer particles and smaller particle mass [22]. The PM_{2.5} emitted from an LNG vehicle is smaller than that from a diesel vehicle [32]. Similarly, CNG and LNG technologies also help to reduce the NO_x emissions by as high as 73% compared to Euro-V diesel buses [9].

Some studies attempted to evaluate greenhouse gas (GHG) mitigation potentials. Tong et al. (2015) compared the life cycle GHG emissions from medium and heavy-duty trucks using natural gas as fuel. Their study indicated that two of the key approaches to reducing GHG emissions from natural gas-fueled media and heavy-duty trucks are improving the fuel efficiency and reducing the methane leakage rate [31,33]. Zhang et al. (2014) investigated the fuel consumption and CO₂ emissions of urban public buses in Beijing that used various fuel systems (e.g., conventional diesel, natural gas and diesel hybrid). Natural gas buses have slightly lower CO₂ emission factors but higher fuel consumption relative to diesel buses [23,34]. In Europe, the transport sector plays a critical role in the GHG emissions mitigation strategy. Arteconi et al. (2010) compared the life cycle of GHG emissions of heavy-duty vehicles in the European market that used diesel and LNG as fuels. Their study suggested that a 10% reduction of GHG emissions can be achieved by using LNG compared to the diesel option [13]. This is in line with Graham et al. (2008)'s study that GHG emissions of heavy-duty vehicles can be reduced by as high as 20% when switching diesel to natural gas [35]. Osorio-Tejada J et al. (2017) found that LNG trucks would be an attractive option compared to diesel oil and hydro-treated vegetable oil (HVO) on the premise of environmental priority and government policy support [36].

In summary, previous studies mainly focused on the emissions reduction of a single HDT for LNG substitution while the policy promotion at the city level was largely overlooked. Thus, this study attempts to fill this gap by focusing on the evaluation of economic and environmental advantages by promoting LNG HDTs at the city level. Normally, alternative fuel vehicles provide fleet operators novel opportunities to reduce fuel costs and emissions. However, fleet operators may be unfamiliar with the performance and costs associated with these vehicles. In this paper, by taking Shenzhen city as an example, a

Monte Carlo simulation method is combined with Shenzhen Atmospheric Environmental Quality Improvement Plan (SAEQIP). Then, the economic and environmental effects of the development of LNG HDTs in road freight are predicted dynamically. Using the results obtained, we can finally put forward policy suggestions for developing a cleaner road freight industry.

2. Application of LNG HDTs in Shenzhen

There were over 3.589 million motor vehicles in Shenzhen by the end of 2020. The vehicle density in Shenzhen is approximately 510 vehicles per kilometer of road length, which ranks first in China. In 2020, the total container throughput of the Shenzhen Port reached 26,548 thousand Twenty-foot Equivalent Units (TEUs), ranking the 4th globally in the past year [17]. According to The Fourteenth Five-year Comprehensive Urban Traffic Planning of Shenzhen, Shenzhen is planning to become a global logistics hub [37]. Therefore, it is expected that the freight demand at Shenzhen will remain at a high growth rate in future. The number and vehicle kilometers traveled (VKT) of HDTs will also maintain rapid growth. In Shenzhen, the primary source of local PM_{2.5} emissions is automobiles, with 52% of PM_{2.5} coming from existing diesel HDTs [11]. Therefore, controlling the emissions of HDTs has to become a key factor for air quality improvement [34]. The reduction of PM_{2.5} and NO_x emissions would largely rely on the management of HDTs' emissions.

2.1. The HDTs in Shenzhen

Shenzhen government issued the Shenzhen Atmospheric Environmental Quality Improvement Plan (SAEQIP) (2017–2020) with a target of a rapid replacement of HDTs with newer, cleaner vehicles, the percentage of which was to be more than 20% (about 15,000) before 2020. To promote the application of LNG HDTs, the Shenzhen Development and Reform Commission provides a subsidy of 20,000 RMB to each LNG vehicle purchased from July 2018 [19]. With national and district-level government subsidies [38], the total subsidy amount is up to 6200 USD per vehicle, which almost covers half of the purchase difference between a LNG vehicle and a diesel vehicle in the same configuration. Considering the lower operational cost of LNG vehicles (e.g., the fuel and regular maintenance), a number of enterprises have shown interest in the replacement of old diesel HDTs with LNG HDTs.

These HDTs can be classified as follows: (1) container tractors—around one-thirtieth of these are only used in the ports, while others are long-haul container tractors mainly serving the Pearl River Delta freight; (2) engineering dump trucks; (3) engineering mixer trucks; and (4) other heavy-duty trucks for the logistics sector (see Table 1) [39].

According to the official statistics of the Shenzhen Port and Freight Management Bureau, there were approximately 80,366 HDTs in Shenzhen by the end of 2016, and 1.8% of them (1494 vehicles) were LNG HDTs [17]. The distribution of LNG HDTs in Shenzhen and the performance of these vehicles obtained by our investigation are shown in Table 1. The reason for why the performance of long-haul container trucks, engineering dump trucks and engineering mixer trucks is modest is that there are few LNG filling stations along their transit lines, resulting in unloaded runs which would reduce their benefits.

Table 1. Major properties of HDTs in Shenzhen city.

Type	Container Truck		Engineering Dump Truck	Engineering Mixer Truck	Others
	Internal	Long-Haul			
					
Main applications	Transportation of goods in port	Transportation of goods for a long distance	Transportation of sand, soil, etc., with a large open container that can pour goods onto the ground	Transportation of concrete, with a mixer tank	Logistics
Penetration of all HDTs (%)	1%	37%	5%	6%	51%
LNG HDT performance	Good	Modest	Modest	Modest	-

Based on the investigation, survey and data of the Shenzhen Port and Freight Management Bureau.

2.2. LNG Supply Security

China's natural gas supply is supported by both domestic production and import [39]. For Shenzhen, the main sources of LNG include inter-provincial import and foreign import. One of the major projects supplying LNG from other provinces to Shenzhen is the Second West–East Gas Pipeline Project, supplying 40 billion m³/year gaseous state natural gas. In addition, a small amount of LNG is transported to Shenzhen by road freight from Inner Mongolia, Xinjiang and other regions.

Foreign imports include shipping from Australia, Qatar, Indonesia, Yemen, Malaysia, etc. LNG-receiving terminals are mainly distributed in eastern coastal regions, and Shenzhen has the largest number and scale of LNG terminals in China. The capacity of LNG-receiving terminals in Shenzhen is about 16.1% of the whole country [39]. It would significantly contribute to the security of supply and meeting diversification targets. Along with LNG terminals in adjacent cities (e.g., Dongguan, Zhuhai, Jieyang, Putian and Haikou), LNG supply security is fully guaranteed.

2.3. LNG Fueling Stations

By the end of 2017, there were 24 LNG fueling stations in Shenzhen (Figure 2) [40]. The density of LNG fueling stations is significantly lower than that of gas and diesel fueling stations in Shenzhen. For example, one of the largest automotive LNG suppliers, China National Offshore Oil Corporation (CNOOC, Beijing, China), had built 13 LNG fueling stations scattered in six districts by the end of 2016, providing a LNG refilling service for a variety of vehicles (e.g., buses, coaches, container tractors, engineering dump trucks and engineering mixer trucks) [41]. Refilling a gas tank of a LNG vehicle is quicker than refilling a diesel vehicle due to the high pressure of the gas dispenser. As a result, the level of service of LNG fueling stations is almost the same as gas and diesel fueling stations.



Note: Data are from Housing and Construction Bureau of Shenzhen Municipality, and edited by authors

Figure 2. The distribution of LNG fueling stations in Shenzhen city.

3. Methodology

The promotion of LNG HDTs in Shenzhen's road freight industry is one of the largest-scale promotion programs around the world. A lot of efforts are required to ensure the efficiency of this program, e.g., government subsidies and voluntary participation by freight fleet operators. Therefore, it is imperative to conduct an economic and environmental analysis of this program. The main focus of the economic analysis is the vehicle cost, with the main indicators being the annual cost and breakeven year of various types of HDTs. Similarly, the environmental analysis mainly focuses on pollutants, such as $PM_{2.5}$ and NO_x , adopting the MOVES model.

3.1. Economic Analysis Methods

Container tractors, engineering dump trucks, and engineering mixer trucks are typical types of LNG vehicles to be promoted in the road freight. To analyze the economic benefits of LNG HDTs compared with diesel HDTs, the first step is to investigate their purchase, maintenance and fuel consumption through a variety of methods, such as an official database, and field survey. Official data sources mainly include the Shenzhen Statistical Yearbook and Shenzhen Port and Freight Management Bureau statistical reports. Field surveys were conducted among ports, freight enterprises and market dealers, including vehicle properties and operating features.

One of the critical factors during the decision-making process for the replacement of diesel HDTs with LNG HDTs is cost-effectiveness [42]. The annual cost per vehicle is a critical indicator of economic benefits. The cost of HDTs mainly consists of purchase cost and operational cost. In terms of purchase cost, LNG HDT cost is higher than diesel HDT cost in the same configuration. This difference is mainly due to the type of engine and fuel tank. As for operational cost, this consists of maintenance cost (includes the cost of regular maintenance and unscheduled repair) and fuel cost (dependent on fuel price and use intensity).

Operating features vary according to types of HDTs. Therefore, different indicators should be used to calculate the use intensity. VKT is the most appropriate indicator for container tractors and engineering dump trucks. For engineering mixer trucks, operational time per year is the most appropriate indicator. The engine is running and emitting pollutants all the time during the transportation process, because it not only makes the vehicle run but also keeps the mixer tank rotating to maintain the concrete's liquid state [43].

In this study, vehicle purchase cost is distributed among service life to obtain the annual purchase cost. Furthermore, the average annual purchase cost and operational expense are summed to facilitate the comparative analysis of LNG and diesel vehicles.

(1) Container tractors & engineering dump trucks

$$Cost_i^E = \frac{Cost_i}{Years} + Cost_{i,M} + FC_i \times VKT \quad (1)$$

where i represents the fuel type of each vehicle (LNG or diesel); $Cost_i^E$ represents the annual cost of each vehicle powered by fuel i (USD/year); $Cost_i$ represents the purchase cost of each vehicle powered by fuel i (USD); $Years$ represents the service life of the vehicle (years); $Cost_{i,M}$ represents the annual average maintenance cost of each vehicle powered by fuel i (USD/year); FC_i represents the price of fuel i per kilometer (USD/km); VKT is the annual average vehicle mileage (km/year) [44].

(2) Engineering mixer trucks

$$Cost_i^E = \frac{Cost_i}{Years} + Cost_{i,M} + DC_i \times Days \quad (2)$$

where i represents the fuel type of vehicle (LNG or diesel); $Cost_i^E$ represents the annual cost of each vehicle powered by fuel i (USD/year); $Cost_i$ represents the purchase cost of each vehicle powered by fuel i (USD); $Years$ represents the service life of this vehicle (years); $Cost_{i,M}$ represents the annual average maintenance cost of each vehicle powered by fuel i (USD/year); DC_i represents the average daily fuel cost of each vehicle powered by fuel i ; $Days$ is the average vehicle operating days per year (day/year).

The break-even year is another important indicator for road freight enterprises. As the purchase cost of LNG HDTs is higher than that of diesel HDTs, the return on investment is a common consideration to be taken. The breakeven year is influenced by a number of factors, most of which are non-determined factors. Therefore, the breakeven year is simulated through the Monte Carlo method with the assistance of Crystal Ball software in this study. A number of factors were considered during the simulation process such as subsidy, vehicle type, fuel price, use intensity and fuel consumption rate.

3.2. Environmental Analysis Methods

A variety of air pollutants are emitted by vehicles such as PM_{2.5}, NO_x, hydrocarbons (HC) and carbon monoxide (CO). The PM_{2.5} and NO_x emissions derived from HDTs account for over 50% of the total emissions in Shenzhen. A series of measures were taken to improve air quality, with the main focus being on the reduction of PM_{2.5} and NO_x. Therefore, this study focuses on the reduction of these two pollutant emissions by means of promoting LNG or China-V diesel HDTs instead of original diesel HDTs. The emissions from vehicles are calculated as follows:

$$EMIS_i = \sum_k \sum_j VP_{jk} \times EF_{ijk} \times CF \times VKT_j \times 10^{-6} \quad (3)$$

where i represents pollutant type (PM_{2.5} and NO_x in this study); j represents fuel type (LNG or diesel); k represents the emission standard (corresponding to China-I, China-II, China-III, China-IV and China-V standard); $EMIS_i$ is the vehicle emissions of pollutant i (ton/year); VP_{jk} is the number of emission standard k vehicles using fuel j ; EF_{ijk} is the emission factor of pollutant i of emission standard k vehicles using fuel j (g/km); CF is the correction factors of emission factor; VKT_j is the annual average vehicle mileage traveled of fuel j vehicle (km/year) [45].

Vehicle emission factor is affected by a large number of factors, such as engine technology, fuels, local meteorological conditions and driving patterns. Local meteorological adjustment factors can significantly affect vehicle emissions, including temperature, humidity and altitude. Since Shenzhen neighbors the South China Sea, there is no need to take altitude into consideration. The temperature and humidity factors were taken into account by referring to the technical guide released by the Ministry of Environmental Protection.

3.3. Introduction of MOVES Model and Parameters Settings

MOVES (Motor Vehicle Emission Simulator) is a traffic emission calculation model developed by United States Environmental Protection Agency (EPA, Washington, DC, USA). This model provides an accurate estimate of vehicle emissions at several scales, which has been developed over 20 years and widely adopted since [46,47]. In this paper, the latest revision, MOVES 2014, was selected to calculate traffic emissions under different conditions. In the MOVES model, four key components were used in the following calculations: Total Activity Generator (TAG), Operating Mode Distribution Generator (running OMDG), Source Bin Distribution Generator (SBDG), and Emission Calculator. In SBDG, the source bin takes vehicle type, age, load, engine type and fuel type into consideration.

3.3.1. Vehicles' Parameters Settings

In this paper, typical LNG HDTs and diesel HDTs, with the same horsepower and configuration meeting the China-V emission standard, of three types of HDTs were chosen and compared. According to the most common vehicle brand in Shenzhen, a questionnaire survey was conducted among local market dealers in different districts of Shenzhen, including model number, purchase cost, horsepower and drive type. By calculation, the average purchase costs of different vehicle types were obtained. The information of these vehicles is shown in Table A1.

The operating parameters of HDTs mainly include four parts: vehicle maintenance cost, use intensity, service life and fuel consumption rate. Fuel consumption rate, service life and maintenance cost were collected from the Shenzhen Port and Freight Transportation Management Bureau. Vehicles in different enterprises may have different use intensity since their diverse performance. Therefore, the intensity is assigned with three kinds of value, namely the minimum value, the likeliest value and the maximum value, which are obtained by means of expert consultation (see Table A2).

3.3.2. The Prices of Fuels

The past 2 years witnessed a significant fluctuation of fuel prices in China. The fuel prices of diesel and LNG in the past 2 years were collected from the China National Offshore Oil Corporation Shenzhen Gas Energy Co., Ltd., one of the largest automotive LNG suppliers in Shenzhen (See Figure A1).

LNG price is closely linked to the diesel price following the form of Equation (4).

$$P_{LNG} = a \times P_{Diesel} \quad (4)$$

where P_{LNG} represents the price of LNG (USD/kg); P_{Diesel} represents the price of diesel in the market (USD/L); a is a coefficient set by the pricing mechanism established by government for new energy industrial development, its value is stabilized at 0.955 with minor change.

3.3.3. Characteristics of Meteorological Conditions

The statistical characteristics of meteorological features in 2016 are shown in Table A3. The humidity was above 50% across the whole year. A temperature of 25 °C was taken as the critical value. The high-temperature season was classified as those days with an average temperature of higher than 25 °C (from May to October). The rest of the year was classified as the low-temperature season (from November to April of next year). The emissions during these two types of seasons were calculated separately, which were summed to the annual pollutant emissions.

4. Results and Discussions

4.1. Economic Benefits

In this study, the prices of fuels under different levels were used to analyze the economic benefits comprehensively. These data were combined with the service life and

annual use intensity of vehicles in order to calculate the annual cost of a single HDT and its breakeven year.

The results show that LNG HDTs outperform diesel HDTs with respect to the cost savings. However, such economic benefits are subject to the fluctuation of fuel prices. When the price of diesel is relatively low, the economic advantage of LNG HDTs will be weakened to some extent.

4.1.1. Annual Cost Per Vehicle

The annual costs of three types of HDTs is shown in Figure 3. These results shows that, while annual cost will be affected by fuel price to a greater extent, LNG HDTs always perform better economically. The annual cost per LNG HDT is 10% to 17% lower than that of a diesel HDT on average. For container tractors, savings of 4122 USD can be achieved per vehicle every year on average by switching diesel to LNG. With a huge use intensity, the average service life of engineering dump trucks is only 3 years. For dump trucks, replacing diesel with LNG can achieve 8356 USD of savings on average per vehicle every year. LNG engineering mixers can save 6781 USD on average per vehicle every year compared with diesel fuel.

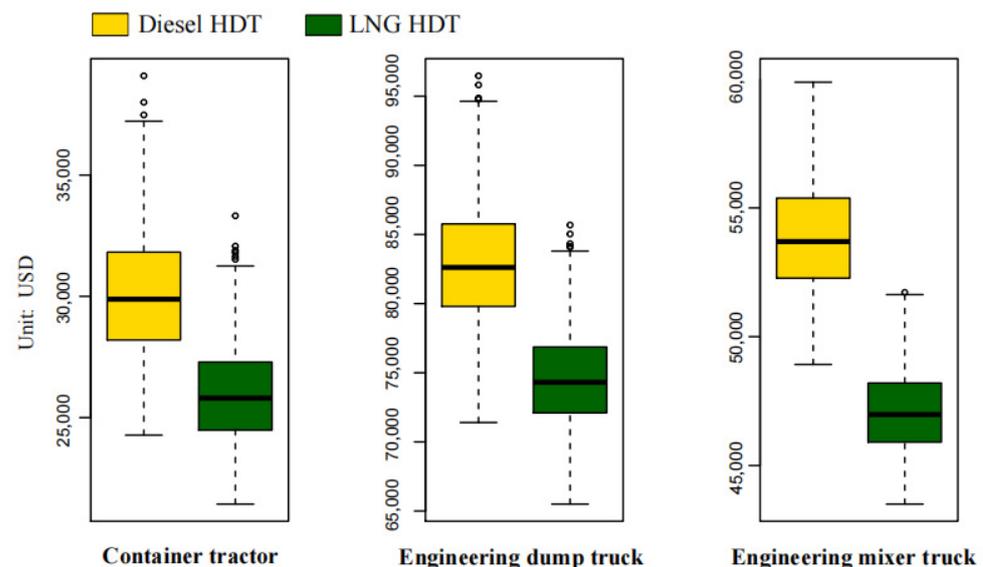


Figure 3. Box-plot of annual cost of three types of HDT. Note: the error bars for scenarios denote the variances under the normal distribution with 95% confidence interval.

4.1.2. Cost Tradeoff Evaluation

Monte Carlo simulation method is used to explain and leverage the cost, considering two scenarios. The first scenario is without subsidies from the government (Scenario 1). The second scenario is with the maximum subsidies (Scenario 2), namely 6200 USD per vehicle. According to our previous study, the breakeven year of the three types of HDTs under two scenarios are quite different [43].

With the help of subsidies, the breakeven year due to various risks can be reduced to a large extent compared with Scenario 1. Moreover, the uncertainties of the economic impact are the same. Under Scenario 2, the purchase difference of container tractors can be covered by 1.63 years approximately, 1.09 years lower than that without subsidies. As for LNG engineering dump trucks, it would take 0.50 years to recover the cost difference with subsidies and 0.98 years without subsidies. In comparison with diesel mixer trucks, LNG trucks can recover the cost difference within 0.36 years on average with the help of subsidies, which was a third of that without subsidies.

4.2. Environmental Benefits

For the measurement of PM and NO_x emissions, the status quo was compared with three promotion scenarios. Based on the aims of SAEQIP (2013–2016) [48], the amount of newly electric or LNG middle-duty trucks (MDTs) and HDTs was supposed to be 25,000 by the end of 2014. Then, before the end of 2015, the increasing number of electric or LNG middle-duty trucks and HDTs should have been roughly 10,000, and the share of electric or LNG trucks should have been no less than 50% of the total trucks. In this research, the emission estimation of LNG HDTs and traditional diesel HDTs are the main focus. Considering a rough ratio of MDTs and HDTs, the number of replaced HDTs was set as 15,000 in Scenario 2, to meet the aim of 2014. Subsequently, the replacing number was set as 35,000 in Scenario 3 to achieve the share of 50%. After that, the situation of upgrading all existing HDTs was put forward as Scenario 4. In each scenario, there are two plans for promotion, namely Plan A (promoting China-V diesel HDTs) and Plan B (promoting LNG HDTs). The baseline and three scenarios are discussed below.

Scenario 1 (S1): Maintaining the status quo, i.e., HDTs will not be upgraded to LNG HDTs or China-V diesel HDTs.

Scenario 2 (S2): Replacing 15,000 heavy-polluting HDTs, which are gasoline vehicles failing to meet the China-I emissions standard or diesel vehicles failing to meet the China-III emissions standard, corresponding to the promotion scale of SAEQIP.

Scenario 3 (S3): Replacing 35,000 existing HDTs, corresponding to the medium-term promotion scale of SAEQIP.

Scenario 4 (S4): Upgrading all existing HDTs to LNG HDTs or China-V (Euro-V) diesel HDTs.

4.2.1. PM_{2.5} Emissions

The PM_{2.5} emissions of each scenario are summarized in Table 2 and Figure 4. Compared with Scenario 1, the replacement of 15,000 heavy-polluting HDTs with LNG HDTs could bring about a reduction of 761 tons of PM_{2.5} (the ratio of reduction is 36.0%). The replacement of 15,000 heavy-polluting HDTs with China-V diesel HDTs could remove 672 tons of PM_{2.5} (the ratio of reduction is 31.9%), is 89 tons more emissions than that of LNG HDTs. If all existing HDTs are replaced by cleaner vehicles, the PM_{2.5} emissions would be the lowest among all scenarios. The reduction rate of PM_{2.5} could be as high as 96.7% if all existing HDTs are replaced by LNG HDTs. If all HDTs are replaced by China-V diesel HDTs, the reduction rate of PM_{2.5} will be lower, emitting 440 more tons of PM_{2.5} relative to the LNG HDTs. Therefore, it can be concluded that the promotion of LNG HDTs is better than China-V diesel HDTs in terms of PM_{2.5} emissions reduction.

4.2.2. NO_x Emissions

The NO_x emissions of each scenario are summarized in Table 3 and Figure 5. It can be observed that the promotion of LNG HDTs is also better than that of China-V diesel HDTs in terms of NO_x emissions reduction. The reduction rate of NO_x increases along with the growing number of vehicles. In comparison with Scenario 1, the replacement of 15,000 heavy-polluting HDTs with LNG HDTs could remove 10,266 tons of NO_x (the ratio of reduction is 16.3%). By contrast, the replacement of 15,000 heavy-polluting HDTs with China-V diesel HDTs could remove 5880 tons NO_x (the ratio of reduction is 9.3%), which is 4386 tons more emissions than that of LNG HDTs. If all existing HDTs are replaced by cleaner vehicles, the NO_x emissions will be the smallest among scenarios. The reduction rate of NO_x could be as high as 73.2% if all existing HDTs are replaced by LNG HDTs, almost twice the reduction rate of China-V diesel HDTs.

Table 2. The PM_{2.5} emission and reduction of each scenario.

Scenarios	Plan	Introduction	Emissions in High-Temperature Season	Emissions in Low-Temperature Season	Annual Emissions	Annual Reduction	Avg. Reduction Rate
S1	-	Maintaining the status quo	895 t	1210 t	2106 t	-	-
S2	A	Promoting 15,000 China-V diesel HDTs	609 t	824 t	1434 t	672 t	31.9%
	B	Promoting 15,000 LNG HDTs	573 t	774 t	1345 t	761 t	36.0%
S3	A	Promoting 35,000 China-V diesel HDTs	455 t	615 t	1070 t	1036 t	49.2%
	B	Promoting 35,000 LNG HDTs	368 t	498 t	866 t	1240 t	58.8%
S4	A	Promoting 76,000 China-V diesel HDTs	217 t	293 t	510 t	1596 t	75.8%
	B	Promoting 76,000 LNG HDTs	30 t	40 t	70 t	2036 t	96.7%

Note: Reduction is the difference between each promoting scenarios and Scenario 1.

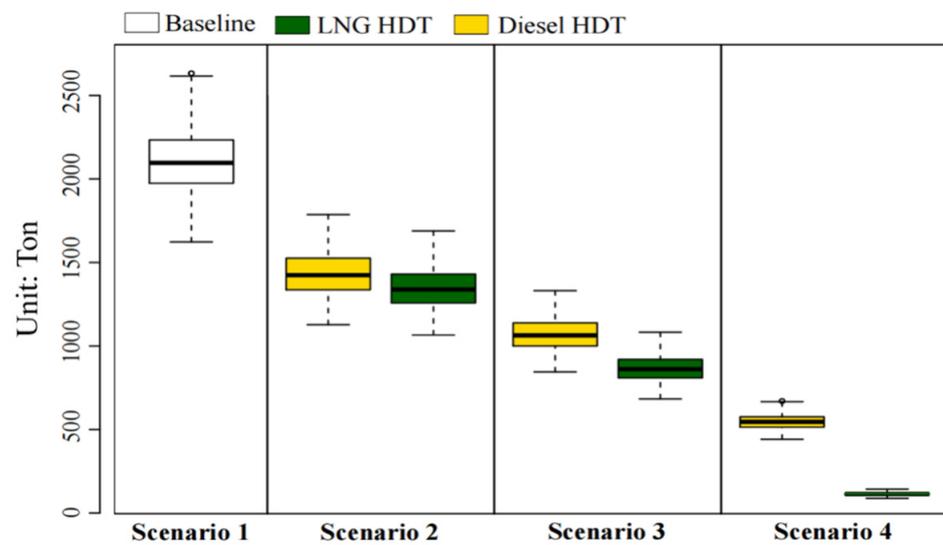


Figure 4. Annual average PM_{2.5} emissions of four scenarios (The error bars for scenarios denote the variances under the normal distribution with 95% confidence interval).

Table 3. The NO_x emission and reduction of each scenario.

Scenarios	Plan	Introduction	Emissions in High-Temperature Season	Emissions in Low-Temperature Season	Annual Emissions	Annual Reduction	Avg. Reduction Rate
S1	-	Maintaining the status quo	32,669 t	30,344 t	63,013 t	-	-
S2	A	Promoting 15,000 China-V diesel HDTs	29,627 t	27,518 t	57,133 t	5880 t	9.3%
	B	Promoting 15,000 LNG HDTs	27,352 t	25,406 t	52,747 t	10,266 t	16.3%
S3	A	Promoting 35,000 China-V diesel HDTs	25,996 t	24,146 t	50,078 t	12,935 t	20.4%
	B	Promoting 35,000 LNG HDTs	20,689 t	19,218 t	39,894 t	23,119 t	36.7%
S4	A	Promoting 76,000 China-V diesel HDTs	20,309 t	18,864 t	39,103 t	23,910 t	37.8%
	B	Promoting 76,000 LNG HDTs	8763 t	8140 t	16,903 t	46,110 t	73.2%

Note: Reduction is the difference between each promoting scenarios and Scenario 1.

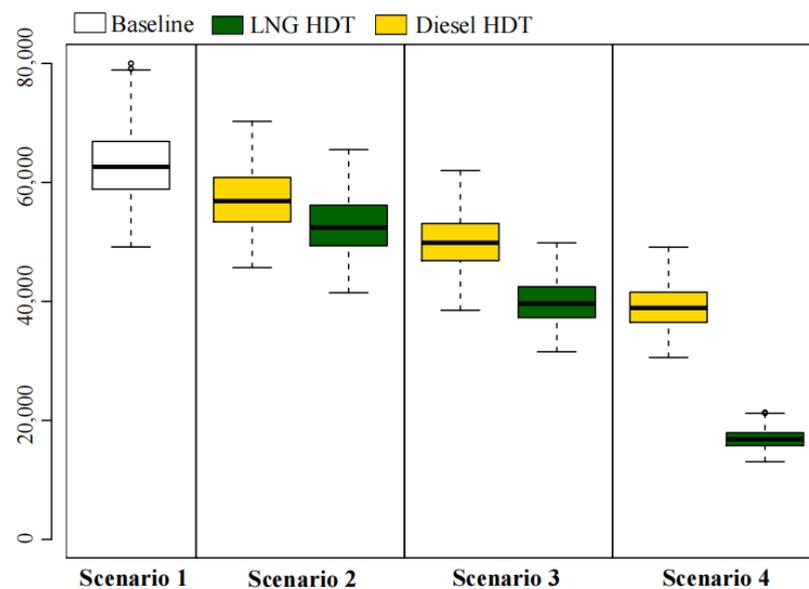


Figure 5. Annual average NO_x emissions of four scenarios (The error bars for scenarios denote the variances under the normal distribution with 95% confidence interval).

4.3. Discussion

From an economic perspective, LNG trucks have the advantage of saving a considerable amount in fuel costs. The above analysis shows that the LNG truck is more affordable than the diesel truck regardless of changes in current and future prices. Accordingly, the gap of purchase costs of all three types of HDTs can be recovered in 1/3 of the vehicles' service life without subsidies. When subsidies are available, the economic benefits would be even more significant and the gap of purchase costs can be recovered in 1/6 of the vehicles' service life. Therefore, LNG HDTs are more efficient than conventional diesel HDTs from an economic perspective. It can be concluded that the economic benefits have a substitute impact on the ownership of LNG HDT. Currently, the LNG/diesel price ratio is about 0.955 in Shenzhen. Under such a price ratio, it is not likely that the ownership of LNG HDTs will see significant growth, except for internal container trucks. However, if the price of diesel is higher or the ratio can be gradually adjusted to 0.8:1 or even lower, the fast growth of LNG HDT ownership can be expected.

In the view of environmental benefits, there are several points for further discussion:

1. According to the curves shown in Figure 6a, both diesel HDTs and LNG HDTs can rapidly decrease PM_{2.5} emissions, which implies that the existing high-pollutant HDT is one of the main contributors of total PM_{2.5} emissions. Compared to diesel HDT, LNG HDT performs better in PM_{2.5} emission reduction under different replacement ratios, and achieves a quite high reduction percentage (96.7%) when totally substituting existing HDTs. The reduction rules can benefit policy-makers to meet several kinds of requirements for arranging vehicle control and replacement in different zones.

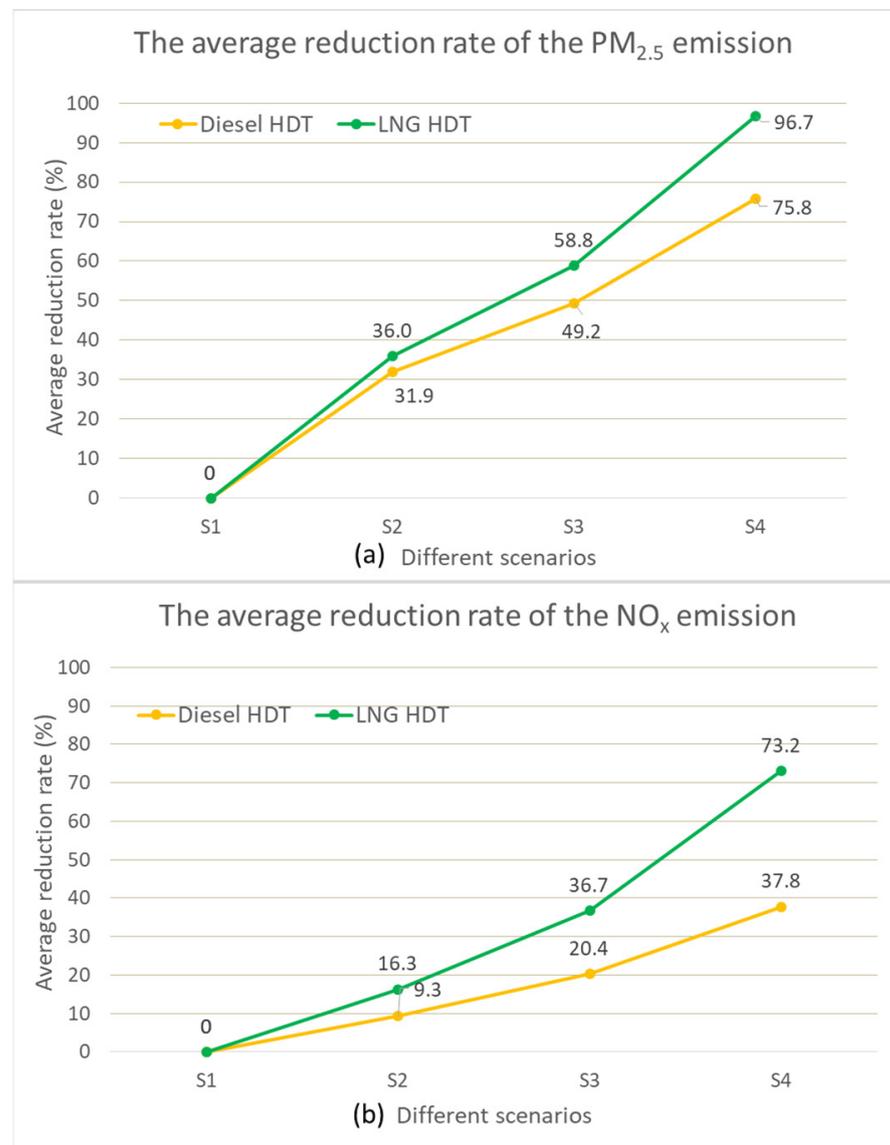


Figure 6. The average reduction rate of emissions under different scenarios: (a) the PM_{2.5} emission; (b) the NO_x emission.

- From Figure 6b, LNG HDT replacement can significantly reduce NO_x emissions, while diesel HDT replacement has a relatively slight effect on the reduction. In Scenario 4, LNG HDTs showed a sharp reduction rate of 73.2%, but diesel HDTs reached a rate of just 37.8%, indicating that diesel HDTs are comparatively limited in NO_x emission reduction. In this kind of situation, LNG HDTs are a better alternative.

5. Conclusions and Recommendation

In this paper, the economic and environmental benefits of the promotion of LNG HDTs program at the city scale were characterized by using Shenzhen as a case study. LNG HDTs have the advantage of saving considerable fuel costs compared to diesel HDTs, ranging from 10% to 17%. Meanwhile, the promotion of LNG HDTs could significantly reduce PM_{2.5} and NO_x emissions of HDTs, by 36.0% and 16.3% respectively. To summarize, the effectiveness of the promotion of LNG HDTs is significant in Shenzhen city, and these findings could provide references for other cities, particularly port cities, to firmly promote LNG HDTs and beyond.

In order to promote LNG vehicles in the freight industry, two policy measures could be considered. (1) Policy and financial support need to be intensified so as to optimize

the quantity and layout of LNG fueling stations. The major obstacles to developing LNG fueling stations include available land for the construction, huge investment and a complicated approval process. Therefore, the government should issue a series of policies and financial support, such as the introduction of private investment, the prioritization of land use and a new approval process for LNG fueling stations. If the security of supply is weak and diversification targets do not meet the requirement of the city, new LNG terminals should be installed on the city outskirts. (2) The market behavior of freight fleet operators could be directed towards LNG HDTs rather than diesel HDTs. Moreover, the advantages of LNG HDTs (e.g., the performance, costs and environmental friendliness) should be publicized properly and effectively. On the other hand, the LNG/diesel price ratio has gradually adjusted to a lower rate and policies need to be strengthened on LNG HDT purchase subsidies. In particular, the subsidy for replacing aging HDTs with LNG vehicles should be higher than normal, to accelerate the elimination of aging automobiles to guarantee the goal of reduction of total vehicle emissions while maintaining vehicle fleet growth.

Overall, the potential economic and environmental benefits of LNG HDTs for megacities were analyzed in this study. The findings and recommendations provide useful inputs for the policy-making process. This paper also provides a guiding development framework for promoting LNG HDTs. This is of high relevance to other cities in China and even other countries with an interest in promoting LNG HDTs. However, when borrowing experience from the Shenzhen case, the uniqueness of Shenzhen's conditions should be fully considered. First, natural gas has been promised as a cleaner energy for the whole country in the near future, and promoting natural gas vehicles is an important aspect of this. However, the reasonableness of developing LNG HDTs should be seriously considered in areas where natural gas supply cannot be guaranteed. Second, the government plays an important role in LNG pricing policy and in keeping LNG prices lower than diesel. In countries where natural gas pricing is market-oriented, the situation would be quite different. Third, policy and regulations are critical for every aspect of promoting LNG HDTs in China, where the government dominates resource allocation. LNG HDT subsidy policy and infrastructure issues are all substantially affected by policies. In other countries, this could be a totally different story.

There are some limitations associated with the macro level approaches proposed in this study: (1) Our approach was concise, and mainly analyzed economic and environmental benefits on the macroscopic level. Some non-critical aspects, such as average load of HDT, were not taken into consideration. (2) The investigation has constraints. Sample sizes, which obtained vehicle property information and operating features, were not big. Even some of the data were obtained through expert consultation. As a result, the triangular distribution was used in a Monte Carlo simulation, instead of normal distribution. (3) The data used to determine the unit emission factors for each type of HDT were taken from governmental databases and may not necessarily be sufficient to represent the current and rapid change in the transportation sector of Shenzhen. Furthermore, many earlier studies of real-world emissions can differ quite a lot from ones based on emission standard requirements. Indeed, extensive data on vehicles is necessary for a detailed study of the transport sector. In the future, this evaluation model could be further improved by expanding its scale, type and variety of impacts. Other critical factors such as rate of inflation, technology, fuels and driving patterns could also be incorporated in future studies.

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Appendix A

Table A1. The information of chosen three types HDT.

Vehicle Type	Fuel Type	Brand	Model Number	Purchase Cost	Horsepower	Drive Type
Container tractor	LNG	C&C TRUCKS	SQR4181N5Z	\$47,270	260 hp	4 × 2
	Diesel	Dongfeng	EQ4160GLN	\$32,021	260 hp	4 × 2
Engineering dump truck	LNG	C&C TRUCKS	SQR3252N6T4	\$65,568	290 hp	6 × 4
	Diesel	Dongfeng	DFL3250AW	\$53,369	290 hp	6 × 4
Engineering mixer	LNG	CIMC	ZJV5254GJBSZ01	\$75,937	340 hp	6 × 4
	Diesel	CIMC	ZJV5254GJBSZ01	\$66,788	340 hp	6 × 4

Data source: fields survey.

Table A2. The operating parameters of HDTs.

Vehicle Type	Use Intensity (Min, Likeliest, Max)	Fuel Consumption Rate	Lifetime	Maintain Cost
Container tractor	(7000, 8000, 9000) km/month	LNG: 0.247 kg/km; Diesel: 0.30 L/km	10 years	LNG: 3202 USD/year; Diesel: 3586 USD/year
Engineering dump truck	(9000, 10,000, 11,000) km/month	LNG: 0.5 kg/km; Diesel: 0.6 L/km	5 years	LNG: 3050 USD/year; Diesel: 2745 USD/year
Engineering mixer	(330, 355, 365) day/year	LNG: 90 kg/day; Diesel: 118 L/day	3 years	LNG: 5855 USD/year; Diesel: 4757 USD/year

Data source: Shenzhen Port and Freight Management Bureau and fields survey.

Table A3. The meteorological feature of Shenzhen in 2016.

Meteorological Conditions	January	February	March	April	May	June	July	August	September	October	November	December
Avg. temperature (°C)	16.3	17.7	20.2	23.3	27.2	29.5	29.1	29.1	28.2	25.7	23.6	17.4
Avg. humidity (%)	63	70	78	72	80	77	74	73	71	68	68	69

Data source: Shenzhen Climate Bulletin 2016 published by Meteorological Bureau of Shenzhen Municipality.



Figure A1. The history data of diesel price. Data source: Adjustment Calendar of Domestic Refined Oil Price in 2015 and 2016 from China Economic Informatica Service.

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