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Natural gas as vehicle fuel in China: A review

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ABSTRACT

Natural gas vehicles offer the benefits of reducing oil use, CO_2 emissions and air pollutants. Promoting the use of natural gas vehicles is considered as one of the most important strategies towards sustainable transportation. China made remarkable progress in promoting natural gas vehicles over recent years, and its 4.6 million natural gas vehicles in 2014 represented the world's largest natural gas vehicle fleet. In this paper, the development of natural gas vehicles in China is reviewed based on a triple-perspective (Fuel-Vehicle-Infrastructure) technical–economical framework. The review indicates that (a) pricing of vehicle-use Compressed Natural Gas (CNG) and Liquefied Natural Gas (LNG) is essential in determining natural gas vehicle development. A pricing principle similar to the fixed CNG/gasoline price ratio (0.75:1) should be applied to LNG/diesel price ratio; (b) for CNG passenger vehicles, the modified CNG vehicles, with ¥3000–5000 additional cost, is more attractive to consumers than originally manufactured CNG vehicles, with about ¥10,000 additional cost. Vehicle retrofit should be permitted by the government with the pre-condition that retrofit standards are strictly enforced; (c) for CNG/LNG transit buses, the deployment is strongly affected by local government's preference. In regions with sufficient natural gas supply, the government should prioritize the deployment of CNG/LNG transit buses rather than other technologies; (d) for LNG commercial vehicles, with ¥60,000–80,000 higher cost than their counterpart diesel vehicles, financial incentive is critical for their development. China's current vehicle subsidy scheme should be extended to cover LNG commercial vehicles; (e) regarding refueling infrastructures, interference with urban land-use planning and long-time administrative approval are the major barriers. Local governments should launch dedicated plans and strategies to support the further deployment of CNG/LNG refueling infrastructures.

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1. Introduction

Vehicles have been used to provide high-quality transport services for human society over the past century. The vehicle transport system gradually evolved into the current status, which is dominated by internal combustion engine (ICE), petroleum-derived liquid fuels and widespread refueling infrastructures. However, with increasing global concerns over energy and environmental issues, the conventional vehicle transport system is facing severe challenges [1].

Global vehicle stock experienced rapid growth over the past decade. Total vehicle stock increased from 0.49 billion in 1985 to 1.18 billion in 2013 [2]. This rapid growth created huge demand for oil. International Energy Agency (IEA) estimated that over 53% of global primary oil consumption was used to meet 94% of global transport energy demand in 2010 [3]. Vehicles are also causing great environmental impacts. As estimated by IEA, road transport was responsible for 16.9% of global energy-related CO_2 emissions in 2012 [4]. The tailpipe emissions from vehicles are the major drivers behind urban hazy weather. Substantial technological and behavior changes are needed to achieve a more sustainable vehicle transport system.

To use natural gas as vehicle fuel is one of the most feasible pathways towards sustainable vehicle transport system. Compared with conventional gasoline and diesel vehicles, natural gas vehicles offer the benefits of reducing oil use, CO_2 emissions and air pollutants. As estimated by Hekkert et al., the life cycle CO_2 emissions of Compressed Natural Gas (CNG) and Liquefied Natural Gas (LNG) vehicles are 25% and 18% lower than their counterpart gasoline vehicle model [5]. Ou et al. conducted a similar study in China's context, revealing the fact that 10–20% and 5–10% Greenhouse Gas (GHG) emissions reductions can be achieved by switching from gasoline vehicle to CNG and LNG vehicles [6]. Global natural gas vehicle stock experienced rapid growth over the past decade, from 1.3 million in 2000 to 22.4 million in 2014, as shown in Fig. 1 [7–9]. At the same time, natural gas refueling infrastructures have also experienced rapid expansion. The global distribution of natural gas vehicles in 2014 is illustrated in Fig. 2. As estimated by IEA, global natural gas vehicle market share will keep increasing in the coming years and maintain at a level of around 10% through 2050 [10]. More importantly, with the progress of natural gas extracting technology, both the recoverable reserves and actual production of natural gas have increased significantly [11–13]. Under such a circumstance, natural gas is expected to play a much more important role in the transition of vehicle transport system [14–20].

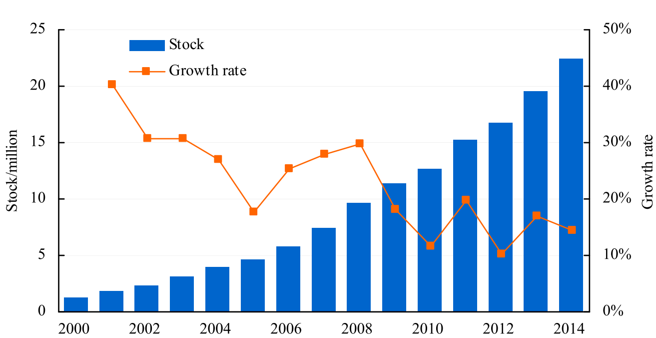

Fig. 1. Global natural gas vehicle stock 2000–2014.

China is very representative when analyzing the role of natural gas vehicle in the transition of vehicle transport system [21,22]. China now has the world's largest vehicle market. Domestic vehicle sales increased from 2.1 million in 2000 to 23.5 million in 2014 [23]. Accordingly, vehicle stock reached 154 million in 2014 [24]. Considering China's huge population basis and low vehicle ownership level, there is solid further growth potential in China's vehicle market [25,26]. With such a big and increasing vehicle market, China is facing very severe energy and environmental challenges [27–31]. As a solution to these challenges, China has been promoting natural gas vehicles over the past decade [32–35]. China's four million natural gas vehicles represent the world's largest natural gas vehicle fleet, accounting for 17.8% of global total. Meanwhile, China's natural gas refueling stations reached over 6500 in 2014, representing 24.4% of global total [7–9].

In this study, we perform a comprehensive review on the development of natural gas vehicles in China. This review contributes to (1) establishing a triple-perspective (Fuel-Vehicle-Infrastructure) technical–economical framework for assessing the vehicle transport systems; (2) providing a comprehensive policy review and experience summary for other countries seeking to promote natural gas vehicles. The whole review is organized as follows: the next section discusses the necessity of using natural gas as vehicle fuel in China from the energy supply and demand perspectives. Following this, the technical assessment of possible pathways of using natural gas as vehicle fuel is conducted. The subsequent section focuses on assessing policies associated with natural gas fuel, vehicle and infrastructure. Based on the assessments, policy implications are raised in the next section. The final section concludes the whole review.

2. Natural gas as vehicle fuel in China

The use of natural gas as vehicle fuel in China is mainly driven by three factors. First, China has strong incentive to find alternatives to conventional petroleum-derived vehicle fuels. With booming vehicle stock, China's oil import increased from 70 mt (megaton) in 2000 to 310 mt in 2014 [24]. Accordingly, the dependence rate on oil import increased from 30.2% to 59.6%. In the foreseeable future, China's domestic oil production is projected to sustain at the current level, around 200 mt per year. The incremental oil demand will have to be met by oil import. It is commonly believed that the dependence rate on oil import will be higher than 70% by 2030. This heavy dependence on oil import caused great concerns over national energy security. It should be noted that the international oil price maintained at low level over recent years, which partially released China's pressure on oil import. However, due to the non-renewable nature of oil resource and the uncertainty in oil price, there is high possibility that oil price will go back to a high level in the long term. Finding alternatives to conventional petroleum-derived vehicle fuels is an essential measure to reduce oil import. Vehicles are also important

Fig. 2. Global natural gas vehicle distribution in 2014,
Note: the bubble size denotes the number of natural gas vehicles in a certain country.

sources of urban air pollutants. According to Ministry of Environmental Protection (MEP), total NO_x, PM, HC and CO emissions from vehicles were 6.3 mt, 0.6 mt, 4.3 mt and 34.3 mt in 2014, respectively [36]. China's many big cities have experienced long-time hazy weather over recent years, which can be partially attributed to increasing vehicle use. It was estimated that vehicles were responsible for 31.1% of PM2.5 emission from local sources in Beijing, topping any other single sources [37]. There is urgent need in reducing the vehicle tailpipe emissions by switching to cleaner vehicle fuels. Besides, China is under huge pressure from the international community on GHG emissions control. According to the US–China Joint Announcement on Climate Change, China promises that its total CO_2 emissions should peak before 2030 [38]. Finding low-carbon alternatives to petroleum-derived fuels is another priority in China's vehicle transport system.

Second, China's natural gas supply capacity has great growth potential, as shown in Fig. 3. China's natural gas consumption was 180 billion m^3 in 2014, accounting for around 6% of total primary energy consumption [24]. This share is much lower than global average, which was 27% in 2014 [11]. China's natural gas supply is supported by both domestic production and import. Regarding domestic production, conventional natural gas production was 128 billion m^3 in 2014. Unconventional natural gas production was 4.9 billion m^3 in 2014, including 3.6 billion m^3 of coal-bed gas and 1.3 billion m^3 of shale gas. According to China's national plan, domestic productions of conventional natural gas, coal-bed gas and shale gas are expected to reach 185, 30 and 30 billion m^3 in 2020, respectively [39,40]. Regarding natural gas import, China promoted the constructions of cross-border natural gas pipelines and LNG terminals aggressively over recent years, as shown in Table 1. As a result, natural gas import experienced rapid growth. Pipeline natural gas import and LNG shipping import were 31.3 and 27.0 billion m^3 in 2014, accounting for over 30% of total natural gas supply. In the years to come, natural gas import is expected to keep a higher growth rate than domestic production, reaching around 115 billion m^3 in 2020. Overall, China's total natural gas consumption is expected to account for 10% of primary energy consumption in 2020 [39].

Third, natural gas for vehicle use is a priority among all natural gas applications. Natural gas, as the cleanest primary energy, has a wide range of applications. Major applications include industrial use, power generation, fertilizer production, residential use, commercial use and vehicle use. All of these sectors have great demand

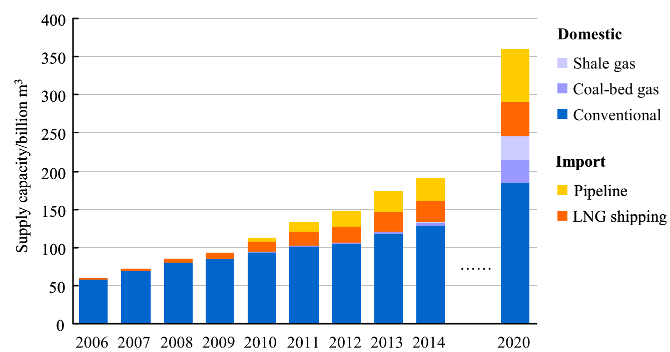

Fig. 3. China's natural gas supply capacity outlook to 2020.

for natural gas. So although China's natural gas supply capacity will be increasing rapidly in the coming years, natural gas supply will likely still fall behind market demand. Under such a circumstance, China issued several guidance documents, in which natural gas applications were classified into different priorities, as shown in Table 2 [41,42]. Natural gas for vehicle use offers the benefits of not only replacing oil use, but also reducing vehicle tailpipe emissions, which has direct impact on urban environment and human health. With these considerations, vehicle-use natural gas was classified as a high-priority application. The share of vehicle-use natural gas consumption out of total consumption was estimated to increase from 8% in 2010 to 20% in 2014 [43]. This share is expected to experience further growth in the coming years.

3. Technology assessment

Natural gas can be utilized as vehicle fuel through several pathways, as Fig. 4 shows. These six pathways differ in terms of technology maturity, vehicle performance and the energy-environmental-economical impacts. Table 3 compares the six pathways from multiple dimensions [44–50].

3.1. CNG pathway

CNG propulsion technology is mostly applied on taxis and private passenger vehicles through retrofit of conventional gasoline vehicles [51]. Natural gas is compressed and stored onboard in

Table 1
China's natural gas import facilities.

	Pipeline/LNG terminal	Major Operator	Design capacity/billion m^3	Operating since	Gas sources
Pipeline	West–east pipeline, 2nd line	CNPC	30.0	2011	Central Asia
	West–east pipeline, 3rd line	CNPC	30.0	2014	Central Asia
	China–Russia, east line	CNPC	38.0	Under construction	Russia
	China–Russia, west line	CNPC	30.0	Under negotiation	Russia
	China–Burma	CNPC	12.0	2013	Burma
LNG shipping	Shenzhen, Guangdong	CNOOC	15.0	2006	Qatar, Australia, Indonesia, Malaysia, Yemen, etc.
	Putian, Fujian	CNOOC	10.6	2008	
	Yangshan, Shanghai	CNOOC	12.6	2009	
	Ningbo, Zhejiang	CNOOC	8.4	2012	
	Zhuhai, Guangdong	CNOOC	4.2	2013	
	Jieyang, Guangdong	CNOOC	2.8	2014	
	Hainan	CNOOC	4.2	2014	
	Shenzhen, Guangdong	CNOOC	5.6	2015	
	Tianjin	CNOOC	3.1	Under construction	
	Rudong, Jiangsu	CNPC	14.0	2011	
	Dalian, Liaoning	CNPC	12.6	2011	
	Tangshan, Hebei	CNPC	14.0	2013	
	Qingdao, Shandong	Sinopec	12.6	2014	
	Beihai, Guangxi	Sinopec	7.0	2015	
	Dongguan, Guangdong	JOVO	1.4	2012	

Notes: CNPC: China National Petroleum Corporation; Sinopec: China Petroleum and Chemical Corporation; CNOOC: China National Offshore Oil Corporation; JOVO is the English trademark of Jiufeng Group LLC.

high-pressure gas tanks. Like gasoline engine, natural gas engine is also based on spark ignition technology. Natural gas engine can be converted from conventional gasoline engine with retrofit to fuel injection and ignition systems. Compared with conventional gasoline vehicle, the major advantage of CNG vehicle is its low fuel cost. Normally, the fuel cost of CNG vehicle is 20–40% lower than gasoline vehicle, depending on CNG and gasoline prices. Besides, CNG vehicle offers the benefits of reducing oil use and GHG emissions. The tailpipe emissions of CNG vehicle are also significantly lower than gasoline vehicle [52,53]. However, the major barrier of CNG vehicle penetration is its reliance on CNG refueling infrastructure, which is not compatible with the existing oil refueling infrastructures. The CNG refueling infrastructure needs considerable investment to deploy, which costs ¥4–6 million per station. Social acceptance and administrative approval are also barriers for infrastructure deployment. In addition to infrastructure issues, from the economic perspective, the initial vehicle retrofit cost is around ¥3000–5000 per vehicle. For drivers with low driving intensity, the payback period can be several years, which reduces the willing to own. Besides, CNG vehicle faces the problems of engine power degradation, driving range limitation, luggage space loss, and higher maintenance cost.

3.2. LNG pathway

The major difference between LNG vehicle and CNG vehicle is the way that natural gas is stored. On LNG vehicles, LNG is stored in a dedicated heat-insulating tank with low temperature. By using LNG, the energy storage capacity and driving range are well enhanced, and can be comparable to conventional vehicles. On the other hand, the use of LNG storage tank significantly increases the vehicle cost. As a result of these characteristics, LNG propulsion technology is mainly applied on commercial heavy-duty buses and trucks. Compared with conventional diesel vehicles, the major advantage of LNG vehicle is overall cost reduction. The fuel cost of LNG vehicle is normally 20–40% lower than diesel vehicle, depending on LNG and diesel prices. For commercial logistics trucks with annul driving distance of over 100,000 km, the initial purchase cost increase can be recovered within one year. Besides, vehicle tailpipe emissions of LNG vehicles can be more easily controlled compared with diesel vehicles. However, penetration of LNG vehicles faces the same barrier as CNG vehicles, the lack of LNG refueling infrastructure. Current technology also allows LNG to be used as an addition to diesel engines [54].

3.3. Methanol pathway

Natural gas can be used to produce methanol through several technology pathways. Low proportion methanol–gasoline blend, normally with methanol proportion of 5–15%, can be used directly on conventional gasoline vehicles. High proportion blend, normally with methanol proportion of higher than 85%, and pure methanol can only be used with engine retrofit. The major advantage of methanol vehicle is the relatively lower ownership cost. Vehicle retrofit costs only ¥500–1000 per vehicle. Fuel cost is normally 30–50% lower than gasoline vehicle. Infrastructure is not an issue with methanol vehicle, as methanol can be distributed and supplied through existing oil refueling infrastructures. However, from the energy and environmental perspectives, due to the efficiency loss in the methanol production process, the life cycle energy consumption and GHG emissions of methanol pathway is higher than CNG and LNG pathways.

3.4. GTL pathway

Gas-To-Liquid (GTL) is derived from natural gas using a Fischer–Tropsch chemical process [55]. The characteristics of GTL fuel is very close to conventional diesel, and can be used directly on diesel vehicles. The major benefit of using GTL is that GTL can share the existing vehicle fleet and refueling infrastructures without any modifications. However, the current cost of GTL production is higher than conventional diesel, which prevents its mass commercialization. Besides, the transformation process from natural gas to GTL causes energy efficiency loss. As a result, the life cycle energy consumption and GHG emissions of GTL pathway is higher than CNG and LNG pathways.

3.5. H_2 pathway

H_2 is the major fuel for fuel cell vehicles, which can be derived from natural gas reforming [56]. Fuel cell vehicles offer the benefits of zero tailpipe emissions and lower life cycle energy

Table 2
Natural gas utilization priority classification in China.

Category	Applications
Prioritized	• Urban use
	– Residential use, including cooking and water heating
	– Public facility use, including school, hotel, office building, commercial building, etc.
	– Vehicle use, including transit bus, taxi, logistics vehicle, passenger vehicle, sanitation vehicle, freight vehicle, etc.
	– Centralized heating consumers
	– Natural gas air conditioners
	• Industrial use
	– Interruptible consumers in the construction materials, electro-mechanical, textile, petrochemical, and metallurgy sectors
	– Interruptible hydrogen production from natural gas
	• Others
	– Distributed energy projects (with energy efficiency of higher than 70%)
	– Natural gas vessels in inland waterways, lakes and coastal regions
	– Urban natural gas storage facilities for emergency and peak-shaving
	– Coal-bed gas power generation project
	– Combined heat and power generation (CHP)
Permitted	• Urban use
	– Distributed heating consumers
	• Industrial use
	– Industrial use as alternative to oil and Liquefied Petrol Gas (LPG)
	– Industrial use for newly established projects
	– Industrial use as alternative to coal with good environmental and economical benefits
	– Industrial boiler use in central urban area
	• Power generation
	– All power generation projects except CHP and base-load generation in coal-rich regions
	• Chemical use
	– Uninterruptible hydrogen production from natural gas
	• Others
	– Small liquefaction facilities for peak-shaving and storage
Restricted	• Chemical use
	– Expansion of existing ammonia synthesis capacity with natural gas as feedstock; Natural gas as alternative to coal as feedstock for ammonia synthesis
	– Minor C1 chemical projects
	– Newly established nitrogenous fertilizer project with natural gas as feedstock
Prohibited	• Power generation
	– Base-load generation in coal-rich regions
	• Chemical use
	– Expansion of existing methanol production capacity with natural gas as feedstock
	– Natural gas as alternative to coal to produce methanol

consumption and GHG emissions. However, the current cost of fuel cell vehicle is far higher than conventional vehicle. Besides, H_2 refueling needs dedicated infrastructure. Currently, fuel cell vehicles and H_2 fuel are still under small-scale demonstration, with more than 1000 fuel cell vehicles deployed in several Chinese cities [57].

3.6. Electricity pathway

Natural gas can be used to generate electricity, and then used on electric vehicles (EV). EVs are very aggressive competitors of natural gas vehicles. The development of EVs was remarkable in China over recent years [58]. The major advantage of EVs is zero tailpipe emissions and lower life cycle energy consumption and GHG emissions. As estimated by Ou et al., the life cycle GHG emissions of EVs powered by natural gas-based electricity are 36–47% lower than conventional gasoline vehicles [47]. The GHG reduction can be as high as 71–73% when Carbon Capture and Storage (CCS) technology is applied in the power plants. As a comparison, the life cycle GHG emissions reduction by switching

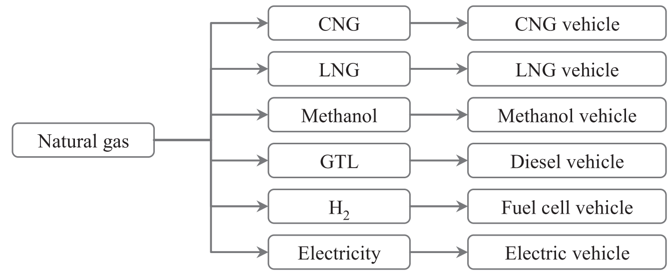

Fig. 4. Pathways of using natural gas as vehicle fuel.

from gasoline vehicle to CNG vehicle is only 10–20%. However, compared with natural gas vehicles, the major disadvantage of EVs is the high cost. Currently, EV price is about 100–200% higher than conventional vehicles. This cost disadvantage is temporarily offset by the generous subsidy from the government. However, the cost issue will eventually emerge with the phase-out of the subsidies. Besides, limited by battery technology, EV's low range capacity and long charging time are both preventing its application in some potential niche markets, such as taxis, where CNG vehicles have much better competitiveness.

By the comparison of the six major pathways through which natural gas can be used as vehicle fuel, it can be concluded that CNG and LNG pathways make good sense in economical and environmental terms, but face the challenge of refueling infrastructure deployment. The H_2 and electricity pathways are promising in environmental benefits, but are currently not economically feasible. Besides, they also face the infrastructure challenges. The methanol and GTL pathways offer the possibility of replacing gasoline and diesel in the most compatible way, especially in terms of infrastructure. But they are not as energy-efficient as CNG and LNG pathways. There is trade-off among performance, infrastructure, economical, energy and environmental aspects for each pathway. No pathway has absolute advantage over other pathways. Relatively, the CNG and LNG pathways are currently gaining higher market share and social acceptance. In this review, we focus on the CNG and LNG pathways.

4. Policy assessment

Driven by the expectation that natural gas as vehicle fuel has a bright future in China, both the number of natural gas vehicles and refueling stations experienced rapid growth over recent years. The historical natural gas vehicle stock is illustrated in Fig. 5. It can be found that not only the absolute natural gas vehicle stock was increasing, the share of natural gas vehicle stock out of total vehicle stock was also increasing, from 0.2% in 2000 to 3.1% in 2014. CNG vehicles represent the majority of natural gas vehicle fleet, with their stock accounting for 95% of the total stock in 2014. LNG vehicles only started to penetrate the market over the recent five years. Figs. 6 and 7 illustrate the spatial distributions of natural gas vehicles and refueling stations in 2013. It can be found that CNG vehicles mainly concentrated in China's western and northern regions. The three provinces with the highest CNG vehicle stocks, Shandong, Xinjiang and Sichuan, accounted for 54% of national total stock in 2013. Different from natural gas vehicles, natural gas refueling stations showed a much more homogeneous distribution. This can be explained by the fact that even the operation of a small natural gas vehicle fleet needs the support from a full refueling system. For the same reason, the ratio of CNG/LNG refueling stations, which was around 2:1 in 2013, was much lower than the ratio of CNG/LNG vehicles, which was around 25:1 in the same year.

Table 3
Comparison of the pathways of utilizing natural gas as vehicle fuel.

Pathway	Vehicle performance	Environmental impact	Ownership Cost	Infrastructure
CNG pathway	• Engine power normally falls by 10–20% after retrofit • Lower driving range, which is typically 150–200km • Gas tank installation typically occupies 10–20% of luggage space	• Lower CO2 emissions and air pollutants compared with gasoline vehicle	• Vehicle cost: Vehicle retrofit from gasoline vehicle to gasoline/CNG bi-fuel vehicle costs ¥3000– 5000 per vehicle • Fuel cost: normally 20–40% lower than gasoline vehicle, depending on CNG and gasoline prices • O&M cost: higher O&M cost due to engine corrosion problems	• Dedicated CNG refueling infrastructure needed, which costs ¥4–6 million per gas station
LNG pathway	• Engine power comparable to diesel engine with the same displacement • Driving range comparable to conventional vehicles	• Lower CO2 emissions and air pollutants compared with diesel vehicle	• Vehicle cost: dedicated LNG HDT costs ¥60,000–80,000 more than diesel truck • Fuel cost: normally 20–40% lower than diesel vehicle, depending on LNG and diesel prices • O&M cost: comparable to conventional vehicles	• Dedicated LNG refueling infrastructure needed, which costs around ¥8–12 million per gas station
Methanol pathway	• Comparable to conventional vehicles	• Higher life cycle energy consumption and GHG emissions compared with conventional pathway	• Vehicle cost: vehicle retrofit from gasoline vehicle to methanol vehicle costs ¥500– 1000 per vehicle • Fuel cost: normally 30–50% lower than gasoline vehicle, depending on methanol and gasoline prices • O&M cost: comparable to conventional vehicles	• Compatible with existing refueling infrastructure
GTL pathway	• Comparable to conventional vehicles	• Higher life cycle energy consumption and GHG emissions compared with conventional pathway	• Vehicle cost: Same with diesel vehicle • Fuel cost: much higher than diesel • O&M cost: comparable to conventional vehicles	• Compatible with existing refueling infrastructure
H_2 pathway	• Comparable to conventional vehicles	• Zero emission during vehicle use • Life cycle energy consumption and GHG emissions lower than conventional pathway	• Vehicle cost: currently around 200% higher than gasoline vehicle, but can be much lower with mass commercialization • Fuel cost: normally over 50% lower than conventional vehicle, depending on H2 and gasoline prices • O&M cost: higher than conventional vehicle	• Dedicated H2 refueling infrastructure needed, which costs ¥10–20 million per station
Electricity pathway	• Lower driving range (typically 100–300 km, depending on battery capacity) than conventional vehicle due to battery capacity limitation	• Zero emission during vehicle use • Life cycle energy consumption and GHG emissions lower than conventional pathway when generating electricity with natural gas	• Vehicle cost: currently 100–200% higher than gasoline vehicle, depending mainly on battery capacity • Fuel cost: normally 70–90% lower than gasoline vehicle, depending on electricity and gasoline prices • O&M cost: higher due to possible battery replacement	• Dedicated charging infrastructure needed

4.1. Fuel aspect

4.1.1. CNG pricing

Historically and currently, China's domestic natural gas pricing is orientated by the government. The central government mandates the upstream prices (wellhead price before 2013, urban gate station price after 2013), and set disciplines for end-use prices. By referring to the disciplines, local governments mandate the end-use prices, including residential use, vehicle use, commercial use, industrial use, etc. Generally, vehicle-use CNG prices are significantly higher than CNG prices for other uses. Since 2005, China' central government implemented a series of reforms on natural gas pricing policy, as shown in Table 4 [59–64]. The essential idea behind the reforms is to gradually shift from government pricing to market pricing. Another major driver behind the reforms is to increase natural gas price to stimulate natural gas supply. It should be noted that in the 2007 and 2010 announcements by the National Development and Reform Commission (NDRC), the discipline for vehicle-use CNG pricing was raised. The ratio of vehicle-use CNG price (measured in ¥/m^3) to #90 gasoline price (measured in ¥/L) was recommended to be 0.75:1. The major purpose behind NDRC's recommendation on CNG/gasoline price ratio is to moderate CNG consumption by vehicles, which potentially affected natural gas supply for other sectors, given the circumstance that total natural gas demand was growing beyond the supply capacity.

The natural gas pricing reforms had substantial impacts on vehicle-use CNG prices. Fig. 8 shows the historical vehicle-use CNG price changes in selected provinces and cities. Generally, vehicle-use CNG prices exhibited a significant increasing trend over the past decade. Prices are mostly lower than ¥2.5/m^3 in 2006, but higher than ¥3.5/m^3 after 2015. There were two major price hikes during this process. The first price hike emerged between 2007 and 2008, during which Qingdao, Zhengzhou and Sichuan increased their local vehicle-use CNG prices by ¥0.3–0.5/m^3. This phenomenon is basically a response to the 2007 NDRC announcement, which recommended local governments to adjust the CNG/gasoline price ratio to the level of 0.75:1. The second price hike lasted from 2010 to 2013, during which major cities all excessively increased their prices by ¥1–2/m^3. This major price hike corresponded to the 2010 NDRC announcement, which significantly increased the natural gas wellhead prices. Besides, the 2010 NDRC announcement re-clarified the 0.75:1 CNG/gasoline price ratio discipline that local governments should follow.

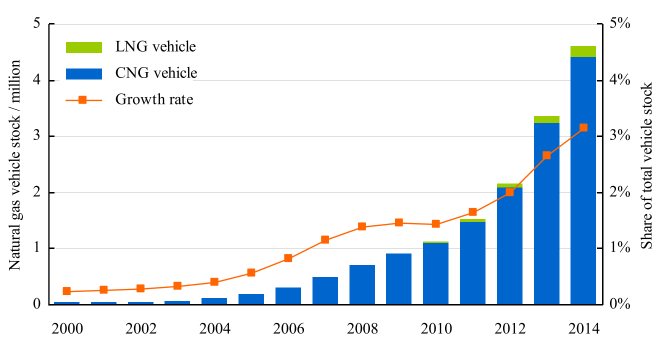

Fig. 5. China's historical natural gas vehicle stock 2000–2014.

Fig. 9 shows the historical local CNG/gasoline price ratio changes. Generally, the CNG/gasoline price ratio showed an increasing trend. The price ratio was mostly between 0.4:1 and 0.6:1 in 2009, but higher than 0.6:1 after 2015. At the same time, the disparity among different provinces and cities gradually shrank. Local CNG/gasoline price ratios converged to the interval of 0.6:1–0.75:1, which is in line with the central government guidance. With China's natural gas pricing reform deepening, it is likely that the correlation between vehicle-use CNG price and gasoline price will be further tightened.

The impact of CNG price changes on CNG vehicle market growth is substantial. Fig. 10 simulates the payback time of switching from conventional gasoline to CNG passenger vehicle under different CNG/gasoline price ratios. Four driving intensity profiles are assumed. The 5000, 10,000 and 15,000 km/year profiles generally represent private passenger vehicles with low, medium and high driving intensities. When CNG/gasoline price ratio changes between 0.5:1 and 0.8:1, the payback times for the three driving intensities are 3.8–7.3, 1.9–3.7 and 1.3–2.4 years. Specifically, when CNG/gasoline price ratio is 0.75:1, the payback times for the three driving intensities are 6.3, 3.2 and 2.1 years. Under such a circumstance, the incentive for drivers with low driving intensities to switch from conventional vehicle to CNG vehicle is quite limited. Only drivers with very high driving intensities are likely to consider switching to CNG vehicles. For the 80,000 km/year profile, which generally represents the driving intensity of taxis, the payback time is lower than one year. Even when the CNG/gasoline price ratio is as high as 0.8:1, it takes only half a year to get the payback. Therefore, taxis are very likely to switch to CNG vehicles when circumstance permits. Regional experiences also support the analysis. It is demonstrated that with a CNG/gasoline price ratio of lower than 0.6:1, CNG vehicle market shows high speed growth. With CNG/gasoline price ratio of 0.6:1–0.75:1, CNG vehicle market grows in a mild pattern.

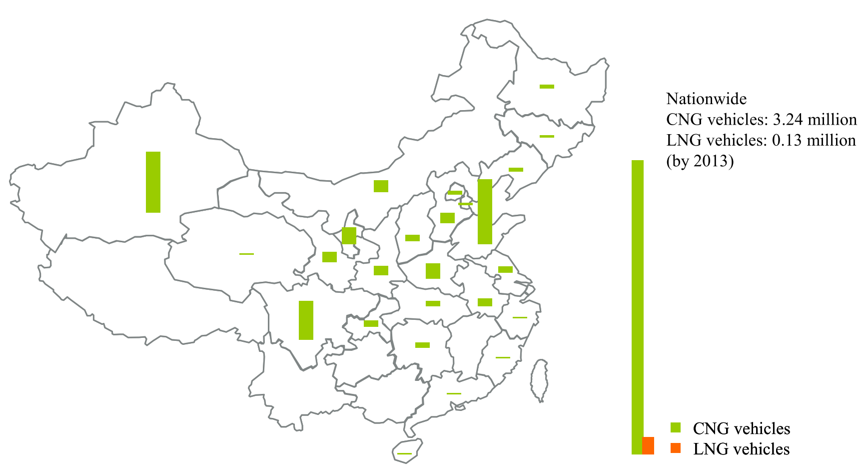

Fig. 6. Spatial distribution of natural gas vehicles in China. Note: Only CNG vehicle spatial distribution is illustrated. LNG vehicle spatial distribution is not available in existing statistics.

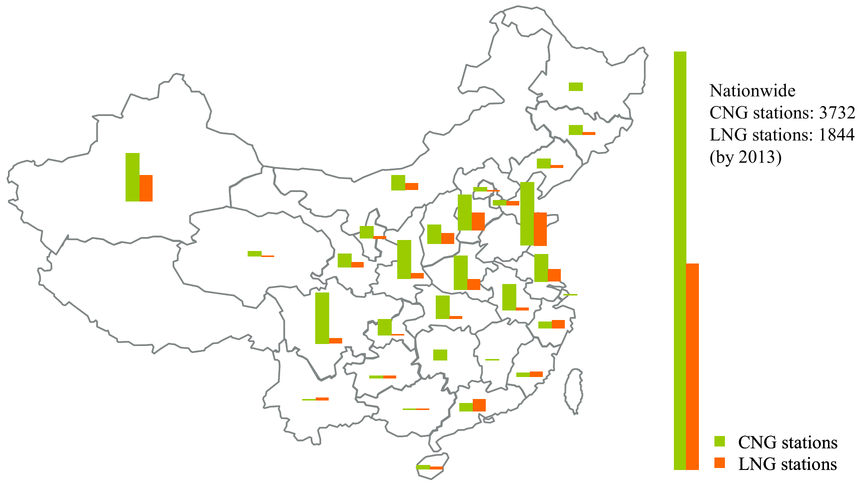

Fig. 7. Spatial distribution of natural gas refueling stations in China.

Table 4
Major historical reforms of China's natural gas pricing policy.

Year	Major reforms
2005	• Natural gas wellhead base price was correlated to the weighted average price of crude oil, LPG and coal. This base price was adjusted on an annual basis. • Natural gas consumptions were divided into three categories, which were industry use, fertilizer use and urban use. By referring to the wellhead base price, a government guiding wellhead price was specified for each consumption category and each natural gas producer. • Natural gas producers and downstream purchasers can negotiate wellhead prices within +10% of the government guiding wellhead prices. • A temporary two-tier pricing mechanism was established to ensure a smooth transition. • As a result of the new pricing policy, natural gas wellhead prices were increased, which significantly stimulated China's domestic natural gas production.
2007	• The government guiding wellhead prices for industrial uses were increased by ¥0.4/m3. • The ratio of vehicle-use CNG price to #90 gasoline price (CNG/gasoline price ratio) was recommended to be adjusted to 0.75:1.
2010	• The government guiding wellhead prices were increased by ¥0.23/m3 for all producers, which further stimulated domestic natural gas production. • The two-tier pricing mechanism initiated in the 2005 reform was terminated. • CNG/gasoline price ratio was recommended to be adjusted to 0.75:1.
2013	• The government shifted from wellhead price management to urban gate station price management. • The government specified the price caps of urban gate station natural gas for all provinces. The price caps were correlated to the prices of fuel oil and LPG. • Natural gas consumption was no longer categorized, implying that natural gas trades with all purposes follow the same urban gate station price cap (except for residential consumption). • A temporary pricing mechanism with different price caps for stock and increment consumptions was established to ensure a smooth transition. • As a result of this reform, national average natural gas urban gate station price increased from ¥1.69/m3 to ¥1.95/m3.
2014	• The pricing of imported LNG and unconventional natural gas (shale gas, coal-bed gas, and coal-to-gas) started to be fully market-based. • The price cap for stock natural gas consumption was increased by ¥0.4/m3.
2015	• The pricing of natural gas direct supply from producer to end-user started to be fully market-based. • The price caps for stock and increment natural gas consumptions were unified through increasing the price cap of stock consumption by ¥0.04/m3 and decreasing the price cap of increment consumption by ¥0.44/m3.

With CNG/gasoline price ratio of higher than 0.75:1, CNG vehicle market will show slow growth or even shrink.

It should be noted that for transit buses and taxis, the impact from CNG price changes can be offset in many ways. For example, many cities shifted the burden of CNG price increases to taxi rides through fuel surcharges. Some local governments offered subsidies to CNG transit bus operators. Besides, transit buses and taxis normally travel for over 80,000 km per year, which maximizes the benefit of lower fuel cost. Therefore, taxis and transit buses are more resilient to CNG price changes. Given the 0.75:1 price ratio discipline that the government is likely to insist in the foreseeable future, China's CNG vehicle growth is expected to be mainly in taxi and transit bus sectors.

4.1.2. LNG pricing

China's LNG supply comes from both domestic LNG production and shipping import. By 2014, there are over one hundred domestic LNG producing factories. Nearly half of these factories are distributed in Northwestern China. Productions from these factories represented about three quarters of total LNG supply in 2014. As these facilities rely on domestic natural gas as feedstock, the factory-gate LNG price is very sensitive to domestic natural gas pricing policy. LNG shipping import accounted for about one quarter of total LNG supply in 2014. The LNG receiving terminals distribute mainly in eastern coastal regions. The terminal-gate LNG price is mainly affected by the trade price of the Asian LNG market, which is typically linked to oil prices.

Although the natural gas feedstock prices for domestic LNG factories are affected greatly by non-market factors, the end-use LNG prices are fully market-based. Besides vehicle use, LNG is also used as distributed residential fuel in regions where natural gas pipeline network can not reach, and as peak-shaving fuel for natural gas networks. Under such a circumstance, LNG price is directly affected by changes in market supply and demand. LNG price can show very significant seasonal fluctuations. This is quite different from the end-use CNG prices, which is under the control from both central and local governments.

Most LNG vehicles are heavy-duty commercial vehicles. The major competitors to LNG vehicles are diesel heavy-duty commercial vehicles. Therefore, the comparison between LNG and diesel prices has substantial impact on LNG vehicle market. As Fig. 11 shows, total LNG heavy-duty truck (HDT) sales increased

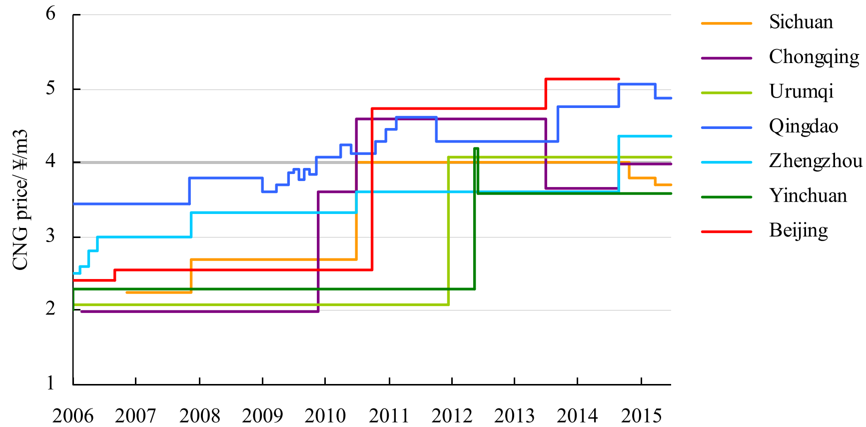

Fig. 8. Vehicle-use CNG price changes in selected provinces and cities.

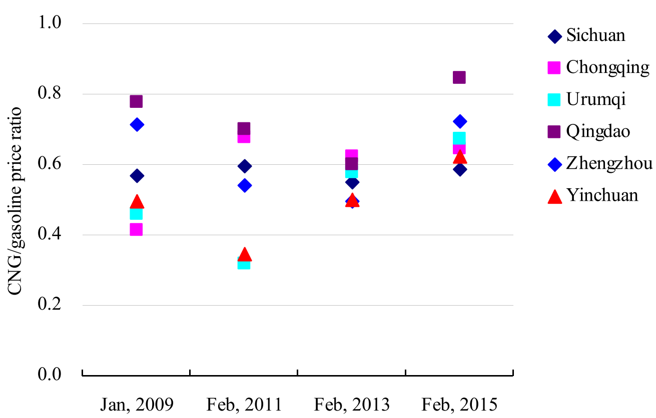

Fig. 9. CNG/gasoline price ratio changes in selected provinces and cities.

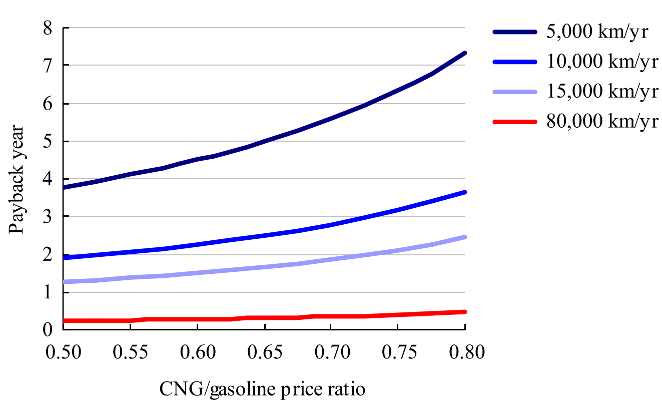

Fig. 10. Payback times of switching from gasoline to CNG passenger vehicle Note: major assumptions are (a) retrofit cost is ¥5000 per vehicle; (b) the fuel consumption rates of CNG passenger vehicle and the counterpart gasoline passenger vehicle are 7.2 m^3/100 km and 8.0 L/100 km, respectively; (c) Gasoline price is ¥6.0/L; (d) discount rate is ignored.

from around 500 in 2009 to 43,000 in 2014. From 2009 to 2012, LNG HDT sales maintained high growth rate, reaching over 400% in 2012. This rapid market expansion was mostly the response to high diesel price, relatively low LNG price, and a strong expectation that the cost advantage of LNG HDTs will be maintained. However, LNG HDT sales growth became to slow down since 2013 and decreased to 40% in 2014. This twist in growth rate can be attributed to two factors. On one hand, due to the new natural gas pricing policy implemented in July 2013, the price of natural gas feedstock for domestic LNG factories increased significantly.

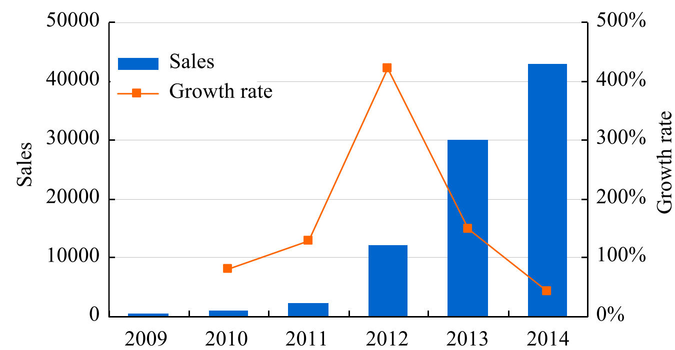

Fig. 11. China's LNG HDT sales 2009–2014.

Accordingly, China's domestic LNG price experienced a major hike in the latter half of 2013, from about ¥4200/t in June 2013 to ¥5400/t by the end of 2013. On the other hand, due to the steep fall of international oil price during 2014, China's domestic diesel price dropped significantly, from ¥7985/t in the beginning of 2014 to ¥5900/t at the end of 2014. Under the combined impacts from these two factors, the operating cost advantage of LNG HDTs is significantly reduced. Correspondingly, the market confidence in the future development of LNG HDTs is weakened, which is reflected in the decline of the LNG HDT sales growth rate. From the experiences of the past five years, it can be concluded that the future of LNG commercial vehicles is mostly determined by how LNG price will compare with diesel price.

4.2. Vehicle aspect

In this section, polices are reviewed by three categories, CNG passenger vehicles, CNG/LNG transit buses, and LNG commercial vehicles.

4.2.1. CNG passenger vehicles

It was estimated that currently 80% of CNG passenger vehicles (taxis and private passenger vehicles) are modified from conventional gasoline vehicles. The other 20% of CNG passenger vehicles are Original Equipment Manufacturer (OEM) vehicles. The reason behind the 80–20% share pattern is the consumer's cost considerations. The cost of vehicle retrofit from conventional gasoline vehicle to CNG–gasoline dual fuel vehicle is only ¥3000–5000 per vehicle. Major modifications include CNG tank installation and engine retrofit. However, for a typical OEM CNG vehicle, the Manufacturer Suggested Retail Price (MSRP) is about ¥10,000 higher than its counterpart gasoline vehicle, as Table 5 shows [65–70]. As a result, most consumers, especially private consumers,

Table 5
Comparison on MSRPs of duel-fuel and gasoline passenger vehicle models.

OEM	Modal	MSRP/¥	
		Duel-fuel	Gasoline
DFM-Citroen	Elysee	94,800	83,800
	C-Quatre	117,800	107,800
DFM-Peugeot	301	95,700	84,700
	308	114,900	105,900
Beijing Hyundai	Elantra	95,300	86,800
	Moinca	120,300	111,800
Chery	Qiyun2	55,300	47,800
JAC	Heyue	74,800	61,800
DFM	Fengshen S30	70,800	59,800
FAW Tianjin	Weizhi V5	70,900	51,900
Lifan	620	60,800	50,900

chose to own CNG vehicles through vehicle retrofit rather than purchasing OEM vehicles.

The attitudes of local governments towards CNG vehicle retrofit are quite different. Some local governments have encouraged CNG vehicle retrofit, with the aim of stimulating local CNG vehicle use, such as Sichuan, Shandong and Xinjiang. However, some local governments have strictly prohibited CNG vehicle retrofit. Their major concerns behind the prohibition include retrofit quality assurance and safety issues. CNG vehicle retrofit is normally conducted by local vehicle retrofit companies. The equipment and skill levels of the companies are quite mixed. Some companies do not have the capacity to ensure retrofit quality. As a result, frequent accidents associated with non-complying CNG tank installation have been reported. The emissions and dynamic performances of the modified vehicles are also unregulated. On the national level, the central government issued an exposure draft on regulating CNG vehicle market at the end of 2014 [71]. The essential idea behind the exposure draft is to prohibit CNG vehicle retrofit and promote OEM CNG vehicles. This reflects the central government's attitude towards CNG vehicle regulation.

The governments' attitudes towards CNG vehicle retrofit had significant impacts on CNG vehicle penetration. Normally, the regions where CNG vehicle retrofit is encouraged had relatively larger CNG vehicle fleets. In contrast, CNG vehicle growths were almost halted in regions where CNG vehicle retrofit is prohibited. If China's central government insists to prohibit CNG vehicle retrofit, it can be expected that local CNG vehicle retrofit will be gradually eliminated. CNG vehicle market will be dominated by OEM vehicles. This implies a higher cost barrier for the consumers willing to switch to CNG vehicles, which will have very negative impact on further penetration of CNG vehicles.

4.2.2. *CNG/LNG transit buses*

In China, many transit bus companies are state-owned or partially state-owned. The decision-makings of the transit bus companies are highly affected by local governments. Under the increasing pressure from urban air pollution, many local governments considered CNG/LNG transit buses as a part of clean urban transportation system, and announced CNG/LNG transit bus development targets. Table 6 summarizes the local development targets and financial incentives for CNG/LNG transit buses [72–79]. CNG and LNG transit buses are different in terms of range capacity, vehicle cost, fuel cost, infrastructure requirement, etc. Specifically, as the prices of CNG and LNG fuels are determined through different mechanisms, the comparison of fuel cost can change significantly over time. Generally, LNG transit buses show higher market potential in the long term. As a result of both financial and administrative factors, China's CNG/LNG transit buses have been growing rapidly over recent years, and are expected to maintain the current growth trend in the coming years.

Before CNG/LNG transit buses, LPG transit buses have been regionally promoted as a possible alternative to diesel transit buses [80]. However, due to the limited production capacity of LPG fuel, LPG transit buses faced the challenge of high fuel cost. The tailpipe emissions from LPG buses are also very controversial. As a result, many of such deployment projects have been canceled.

4.2.3. *LNG commercial vehicles*

It was estimated that 70% of LNG commercial vehicles were HDTs, while the other 30% were mostly interurban buses. Most LNG commercial vehicles are OEM vehicles. The purchasing prices of LNG commercial vehicles are much higher than conventional vehicles, mostly due to the cost caused by LNG tanks. Taking LNG HDT for example, the price of a LNG HDT is ¥60,000–80,000 or around 20% higher than its counterpart diesel HDT. Most HDTs and interurban buses are operated by logistics and passenger transport companies. These entities are highly sensitive to the one-time purchase cost. Therefore, to promote the deployment of LNG commercial vehicles, it is very important to reduce the price gap between LNG commercial vehicles and conventional vehicles through financial aids.

On the national level, China initiated a multi-phase subsidy scheme for what is called 'New Energy Vehicles'. Battery electric vehicle, plug-in hybrid electric vehicle, and fuel cell vehicle are all qualified for generous purchase subsidies [58,81,82]. However, controversially, CNG/LNG vehicles are not covered in this subsidy scheme. On the local level, several provinces and cities have announced their local vehicle subsidy schemes with LNG commercial vehicles covered, as Table 6 summarizes.

The Ministry of Transport (MOT) is the competent authority of commercial vehicles. MOT showed significant positive attitude towards the use of LNG commercial vehicles. Since 2011, MOT initiated the Special Fund for Energy Conservation and Emissions Reduction in the Transport Sector [83]. A part of the fund is dedicated to promoting the use of LNG commercial vehicles in logistics and passenger transport companies. The fund is allocated to companies operating LNG vehicle fleets in the form of bonuses. The amount of bonus for a certain company is determined by the estimated amount of energy conserved through the use of LNG vehicles. The fund dedicated to natural gas vehicles increased from ¥75 million in 2011 to ¥236 million in 2014, posing very positive impacts on LNG vehicle market growth. However, MOT set a high threshold for bonus application. For example, to be qualified for the bonus, the annual energy conservation from a single entity should be higher than 375 t of oil equivalent (toe). Besides, the amount of energy conserved has to be audited by third-party. Under such a circumstance, only some large operating companies can be eligible for the bonus. Many private and small operators are basically excluded from the fund.

As the major competitor to LNG commercial vehicles, conventional diesel commercial vehicles are facing the challenges of more stringent emissions regulation. It is expected that with the phasing in of China's updated vehicle emissions standards, the purchase cost of diesel commercial vehicles will increase significantly due to the application of advanced emissions control technologies. Besides, the fuel cost will also increase due to the use of higher quality diesel with higher prices. Generally, the cost advantage of LNG commercial vehicles to diesel commercial vehicles will be more significant. On condition that both the central and local governments can maintain a stable financial aid to LNG commercial vehicles, LNG commercial vehicles are expected to show higher growth rate in the coming years.

Table 6
Local targets and incentives for promoting natural gas vehicles.

Province/City	Penetration target	Incentive
Shanghai	• 2017 target – Energy-saving and new energy transit bus: 30%	• Purchase subsidy – LNG transit bus: ¥300,000/vehicle
Jiangsu	• 2015 target – LNG interurban bus: 5000 (20% of total) – LNG commercial truck: 1000 – CNG taxi: 10% growth – CNG/LNG transit bus: 5% growth	• Purchase subsidy – LNG commercial vehicle: ¥20,000/vehicle
Shandong	• 2016 target – CNG taxi: 65,000 (90% of total) – CNG/LNG transit bus: 20,000 (50% of total) – LNG interurban bus: 7000 (15% of total) – LNG commercial truck: 21,500 (1.5% of total)	• Purchase subsidy – CNG/LNG transit bus: ¥30,000/vehicle • Demonstration transport lines for LNG buses and trucks • Priority on approval for natural gas commercial vehicles • Program evaluation to lay foundation for further development
Shanxi	• 2014–2016 target for new energy vehicles – Tier I cities: higher than 40% – Tier II cities: higher than 30% – Tier III cities: phasing in from 10% to 30%	• Purchase subsidy – LNG HDT: ¥10,000/vehicle – CNG truck: ¥2000/vehicle • Highway toll for LNG HDT is reduced by half in Shanxi province
Shenzhen		• Purchase subsidy – LNG commercial vehicle: ¥20,000/vehicle
Dongguan	• 2015 target – CNG taxi: higher than 90% – CNG transit bus: higher than 90% – CNG sanitation vehicle: 100%	• Purchase subsidy – CNG taxi: ¥2000/vehicle – CNG/LNG transit bus: ¥20,000/vehicle • Retrofit subsidy – CNG taxi: ¥3000/vehicle – CNG/LNG transit bus: ¥4500/vehicle

4.3. Infrastructure aspect

The relationship between natural gas vehicle development and natural gas refueling station deployment is a typical chicken and egg problem. On one hand, the development of natural gas vehicles needs the infrastructure to be ready beforehand. On the other hand, the deployment of natural gas refueling stations has to be based on the scale operation of natural gas vehicles.

The major builders and operators of natural gas refueling stations are the big-three state-owned oil companies, CNPC, Sinopec, and CNOOC. Besides, some local energy companies are also actively involved in natural gas refueling infrastructure construction. For the big-three oil companies, the considerations on the deployment of natural gas refueling stations are mainly based on national energy strategy, rather than the short-term benefits. Driven by the expectation that natural gas will play an important part in vehicle fuel, major energy companies showed very positive attitude towards natural gas refueling station deployment. Even under the 2013–2014 LNG–diesel price twist, during which many LNG refueling stations suffered losses, major energy companies still set very ambitious targets of natural gas refueling stations deployment in the coming years.

Natural gas refueling station establishment is also closely related to local governments. During natural gas refueling station establishment, the procedures of rationality verification, site location selection, quality supervision and inspection, all need the approval from the government. As natural gas refueling station construction concerns urban land-use planning, energy planning and public safety issues, local governments are typically very cautious about it. As a result, the administrative procedures typically take quite a long time, which severely dragged the overall project progress.

Realizing the critical role the government plays in promoting natural gas refueling stations deployment, more and more local governments launched dedicated plans to accelerate the construction of natural gas refueling stations. These plans typically offer financial incentives, land-use preferential policies, and administrative support for natural gas refueling station operators. It turns out that in regions where such incentives exist, natural gas refueling stations showed significantly higher growth rates.

5. Policy implications

Policies play a critical part in promoting the development of natural gas vehicles and related refueling infrastructures. Based on China's experiences, we propose the following policy instruments that can be utilized to improve the development environment of natural gas vehicles.

(a) Sustaining vehicle-use CNG/gasoline and LNG/diesel price ratios at reasonable levels. Based on regional comparison, it can be concluded that CNG/gasoline price ratio has substantial impact on CNG vehicle ownership. Regions with lower CNG/gasoline price ratios tend to have better response of CNG vehicle ownership, and vice versa. This is supported by Zhang's works, in which energy price is demonstrated to have significant impacts on technology choice and energy efficiency [84]. Currently, China's central government recommended the vehicle-use CNG/gasoline price ratio to be 0.75:1. This ratio implied very limited incentives for CNG vehicle ownership, especially for private passenger vehicles with low driving intensities. Under such a price ratio, it is not likely that CNG vehicle ownership will see significant growth, except in the taxi and transit bus sectors. However, if the price ratio can be gradually adjusted to 0.6:1 or even lower, the fast growth of CNG vehicle ownership can be expected.
LNG/diesel price ratio also has substantial impact on LNG commercial vehicle development. Currently, China's vehicle-use LNG price is fully market-based. LNG price can experience significant fluctuations caused by temporary market supply and demand changes. The LNG price hike in the latter half of 2013 is an example. Given that LNG commercial vehicles are in the early stage of market penetration, such price fluctuation can have very negative impacts on the market confidence in LNG commercial vehicles. It can also mislead the strategy of LNG vehicle manufacturers. To set up a stable environment for LNG vehicle development, the vehicle-use LNG price can be temporarily linked to diesel price. With vehicle-use LNG/diesel price ratio maintained at a reasonable level, the market confidence in LNG commercial vehicles can be well strengthened.
(b) Permitting CNG vehicle retrofit with matched vehicle retrofit standards, quality supervision and inspection mechanisms.

CNG vehicle retrofit has high market acceptance. Compared with OEM CNG vehicles, modified CNG vehicles offer higher flexibility and lower cost. Regional experiences suggest that if CNG vehicle retrofit is completely prohibited, CNG vehicle ownership growth will be severely harmed. As mentioned above, due to safety and quality concerns, China's central government tended to prohibit CNG vehicle retrofit, and promote OEM CNG vehicles instead. Although safety and quality issues associated with CNG vehicle retrofit can be simply avoided in this way, the price would be a significant negative impact on CNG vehicle ownership. From our perspective, the disadvantages of this policy outweigh its advantages. Instead, we recommend that China should improve CNG vehicle retrofit standards and tighten quality supervision and inspection. Based on this, CNG vehicle retrofit can be encouraged.

(c) Providing financial incentives for LNG commercial vehicle purchases. Currently, the purchasing cost of LNG commercial vehicles is much higher than the counterpart diesel commercial vehicles. As the major operators of LNG commercial vehicles, the logistics and passenger transport companies are highly sensitive to purchasing cost. Therefore, to reduce the one-time purchase cost of LNG commercial vehicles through financial incentives is very important, especially in the early stage of their market penetration. However, LNG commercial vehicles are not covered in China's national new energy vehicle subsidy scheme. We recommend that both the central and local governments should consider providing subsidies for LNG commercial vehicle purchases.

(d) Prioritizing CNG/LNG transit bus development in natural gas-rich regions. As discussed above, the development of CNG/LNG transit buses is highly affected by the preference of local governments. Compared with other low-emission or zero-emission bus technologies, including hybrid electric buses, full electric buses and fuel cell buses, CNG/LNG buses offer the benefits of higher technology maturity and lower cost. In natural gas-rich regions, CNG/LNG transit buses should be promoted with priority. For cities with large areas and good financial capacities, LNG transit buses are the most suitable choices. For smaller cities with lower financial capacities, CNG transit buses can be deployed in the near term as a transition to LNG transit buses.

(e) Establishing regional strategies for natural gas refueling infrastructure deployment. Natural gas station deployment is related to local land-use planning, energy planning and safety issues. The attitude of local governments towards natural gas station is very critical. Regional experiences demonstrated that with special favor of the local government, natural gas refueling stations can be established with much higher efficiency. We recommend that in natural gas-rich regions, local government should establish dedicated plans and strategies for the deployment of natural gas refueling infrastructures. Specifically, the land-use demand from natural gas refueling station construction should be incorporated into the overall urban land-use planning.

6. Conclusive remarks

In this review, we discuss the rationale of promoting the use of natural gas as vehicle fuel in China from the perspectives of China's energy situation and resource endowment. By comparing different pathways of using natural gas as vehicle fuel, we conclude that CNG pathway and LNG pathway are the most appropriate pathways. Then based on a triple-perspective (Fuel-Vehicle-Infrastructure) technical–economical framework, we review China's policies and regulations related to natural gas fuel, vehicle and infrastructure. Based on China's experiences, we raise several recommendations on further promoting natural gas vehicle development in China. The major contribution of this review is to establish the triple-perspective analyzing framework on vehicle transport systems. This framework can be used not only to analyze the use of natural gas as vehicle fuel in China, but also to analyze the use of other alternative transportations fuels in other regions.

This review aims to provide a guiding policy framework for promoting natural gas vehicles. This is of high relevance to other countries with interests in promoting natural gas vehicles. However, when borrowing experiences from the China case, the uniqueness of China's national conditions should be fully noticed. First, China has promising natural gas supply capacity growth in the near future, which is expected to account for 10% of primary energy consumption in 2020. Under such a circumstance, the necessity of developing natural gas vehicles is obvious. However, in countries where natural gas supply can not be well guaranteed, the reasonableness of developing natural gas vehicles should be seriously considered. Second, natural gas pricing policy in China is quite unique, in which government plays a more important role than market. The development of natural gas vehicles depends greatly on the government's pricing policy. This can be quite different in countries where natural gas pricing is market-oriented. Third, policy and regulation are critical for every aspect of promoting natural gas vehicles in China. CNG vehicle retrofit regulation, subsidy policy, transit bus deployment, and infrastructure issues are all substantially affected by policies. This results from China's social institution in which the government dominates resource allocation. In other countries, this can be a totally different story.

As this review focuses on revealing natural gas vehicle issues in one single country, the international comparison would be a valuable further step [85]. For example, natural gas pricing policy and its impact on natural gas vehicle development can be quite unique in different countries. International comparison will provide multi-context perspectives into the policy issues that single-country study can not reveal. Besides, Good practice from international comparison can be promoted globally with higher confidence.

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