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Development of an Aggregate Forecasting and Impact Evaluation Modeling Framework for China’s Passenger and Freight Fleets

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Abstract

China's road transportation contributed about 8% of the country's GHG emissions in 2020. Chinese government has made the commitment of reaching "carbon peak in 2030 and carbon neutrality in 2060". Among all the sectors, transportation is one of the most challenging and essential ones to mitigate GHG emissions. The experienced economic development and improvement in people's living standards have increased vehicle ownership for both passenger vehicles and freight trucks. For the road transportation sector, electrification of the fleet represents one of the most important measures to reduce criteria pollutants and GHG emissions.

By modeling passenger and freight vehicle fleets, this study projects the vehicle growth based on economic projections and the changes in demographic characteristics of the population during 2010 to 2050. The study developed a stock and sales model considering vehicle survival rates by vehicle types to reflect the different vehicle retirement and replacement schedules. Moreover, the study designed three sets of fleet electrification scenarios considering different technology penetration and deployment levels for different vehicle type. The scenario analysis extensively explored the energy consumption and GHG emission trajectories for the different vehicle growth scenarios, electrification pathways and renewable energy penetration rates in the grid. The scenarios also considered, as mentioned, changes in the demographics. For instance, in aging society scenario (considering an aging and decreasing fertility demographic), fleet growth rates slow down in the following three decades. This scenario results in a reduction of energy consumption and GHG emission from the road transportation sector.

The scenario analysis extensively explored the energy consumption and GHG emission trajectories of the different vehicle growth scenarios, electrification pathways, and renewable energy

penetration rates in the grid. From the scenarios analysis, in the aging society vehicle growth scenario, the decelerate vehicle ownership growth rates would bring down the energy consumption and GHG emission from road transportation sector.

With the electrification pace stated in the NEV Development Technology Roadmap, the scenarios with truck electrification could bring down the GHG emission 26.6 to 30.4% than the electrification targets solely met through light-duty vehicles electrification, which highlight the need electrify both light-, and medium- and heavy-duty vehicles to achieve the larger reductions. Concentrating on light-duty will be enough to achieve reductions as needed by the country's reduction targets. However, at present, most of the electrified vehicles are small private light duty passenger vehicles, and the current trends of increased vehicle sizes, would make it impossible to reach the carbon neutrality target. Consequently, a faster electrification and more deployment in the trucking sector would help to significantly bring down the energy consumption and GHG emissions. Furthermore, vehicle electrification must be accompanied by a rapid renewable energy penetration in the power grid to achieve GHG emissions reduction. The models show that if the electricity grid significantly phases out coal fired electricity down to 30% by 2030, GHG emissions from the cleaner fleet could reach carbon neutrality by 2050.

To provide some context on the potential feasibility of the scenarios, the study conducted a case study in Shenzhen, which has been able to achieve a very large penetration of the electric vehicles in its transit fleet. The case study included a total cost of ownership analysis of the electric bus fleet, and compare it to the traditional diesel bus. Battery electric bus reached cost parity with the diesel bus with the support of governmental subsidies, and when environmental cost are considered, these buses are preferable to diesel ones.

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1 Introduction

With a booming economic development from the 1990's to the present, China's GDP has grown by an average of 9.1% annually in the past two decades of from 2001 to 2019 (SSBC, 2002-2020). The economy has developed much faster in China in the past 30 years compared with the rest of the world.

The automotive market in China has also grown simultaneously alongside their economic development. After surpassing the United States (US) in 2009, China has had the largest automobile sales market till now. China also became the largest crude oil importer in the world in 2017, with the dependency on imported oil reaching 67.4% (Liu & Jiang, 2017). While it took 50 years for vehicle ownership in the US to grow from 10 to 150 per thousand people, it only took 20 years in China. While the economy is projected to continue growing, albeit at slower pace, the auto industry is still expected to grow and keep contributing to the economic growth, employment, and improved quality of life. Throughout this period, factors such as increased energy dependence, changes in Chinese demographics with new characteristics, e.g., the younger generation behaves differently than their precursors, and the need to reduce GHG emissions and criteria air pollutants from road transportation, have highlighted the need for potential changes in the country. With respect to the vehicle fleet and its impacts, it is important to understand *how can these changes affect the vehicle growth in China? and what would be the consequences for energy requirements and emissions?*

The commercial truck fleet was only 11.2% in the total automobile population in China, but was responsible for emitting 77.9% of the PM2.5 of the total vehicle fleet emissions in 2017 (MEE, 2018). Commercial trucks are closely related to freight activities, which usually grow with the economic development. Therefore, another important question is *how will truck structure change* *over time and how will they affect the energy consumption and environmental effects from vehicle?* Considering the emissions share of trucks, truck fleet electrification should significantly contribute to air emission reductions.

Consequently, the Chinese national government has prioritized the development of New Energy Vehicles (NEVs, including Plug-in Electric Vehicles, Battery Electric Vehicles and Fuel Cell Vehicles) starting back in 2009. Within just nine years of development, by 2017, China was the largest NEV market in the world, with 45% of the world's NEV passenger vehicle market and more than 95% of the world battery electric bus market. Moving forward, *what will be the constraints of the NEV market development, and will China's automobile market continue to be the NEV dominant one?*

Moreover, China's GHG emissions are not only a national issue but also a global concern, China is now the largest GHG emitter in the world. Urban air pollution is also one of the most significant problems in China cities. With a PM2.5 annual average concentration of 65 parts per million (ppm) in Beijing, it significantly exceeds the WHO recommended health level. According to an air emissions inventory released by Beijing, vehicles contributed 30-45% of the PM2.5 emissions. To contend with the issue, China has committed to peak its GHG emissions by 2030 and reach carbon neutrality by 2060. To reach the emission goals and reduce energy consumption, there is a focus on the road transportation sector, given the vehicles are used for long periods after purchase. The sales structure, vehicles lifetime, and operation behavior characteristics would result in different energy and emission profiles and would ultimately affect whether the national government's carbon neutrality commitments is met.

To shed light into some of these issues, in this dissertation, I will project the total vehicle growth in China in the mid- to long-term (2030 and 2050 respectively) by examining the country's economic growth and demographic changes in Chapter Two. The analyses use aggregate time series models and market elasticities from a sample of developed countries (with similar economic and demographic characteristics, and vehicle technology states). Top-down vehicle fleet structure decomposition to predict the future vehicle compositions. Chapter Three concentrates on a particular segment, and through a case study in Shenzhen investigates the Total Cost of Ownership (TCO) of battery electric buses and diesel buses; Chapter Four discusses the methods and truck fleet projections at the provincial level in China considering economic growth, adjusting and calibrating by mode shifts. truck growth in Chapter Four at the provincial level with estimation of economic growth, adjust and calibrate by mode shift; Chapter Five analyzes and projects New Energy Vehicles (NEV) growth through the design and evaluation of different scenarios for passenger vehicles, light trucks, heavy-duty trucks, and transit buses, using a transportation transition model. Additionally, the chapter shows the energy consumption and GHG emissions results from the scenarios. Finally, Chapter Six discusses final remarks and policy recommendations.

2 Vehicle Projections in China

2.1 Growth in Vehicle Ownership

Over the past three decades, China's energy demand has experienced rapid growth. China Petroleum and Chemical Industry Association and BP announced that the country consumed 608.4 million tons (4.46 billion barrels) and imported 420 million tons of oil (3.08 billion barrels) in 2017, 69% of which were imports (BP, 2018; Liu & Jiang, 2017). The road transportation sector was the primary consumer of oil. In 2016, 86.6% of gasoline and 70.0% of diesel were consumed by road transportation (SSBC, 2017).

Vehicle[1] ownership was the key factor affecting China's road transportation energy demand. Over the last 20 years (1997-2016), China's vehicle market has experienced rapid growth. As presented in Figure 2-1, automotive sales have risen from 2.37 million in 2001 to 28.88 million in 2017, with an average annual growth rate of 16.7%. As shown in Figure 2-2, the Chinese vehicle stock increased from 12.2 million in 1997 to 185.7 million in 2016, with an average annual growth rate of 15.5%; the number of vehicles per 1000 people increased from 9.8 in 1997 to 134.3 in 2016, with an average annual growth rate of 14.8%. Due to the fast growth of passenger vehicles and a relatively slower growth of buses and trucks, the proportion of passenger vehicles rose from 49.8% in 2002 to 86.4% in 2016.

[1] The motor vehicle fleet can be classified as automobiles or highway vehicles, motorcycles, and low-speed rural vehicles in China. In this text, except specially noted, "vehicles" or "automobiles" only refer to automobiles, including passenger vehicles and commercial vehicles.

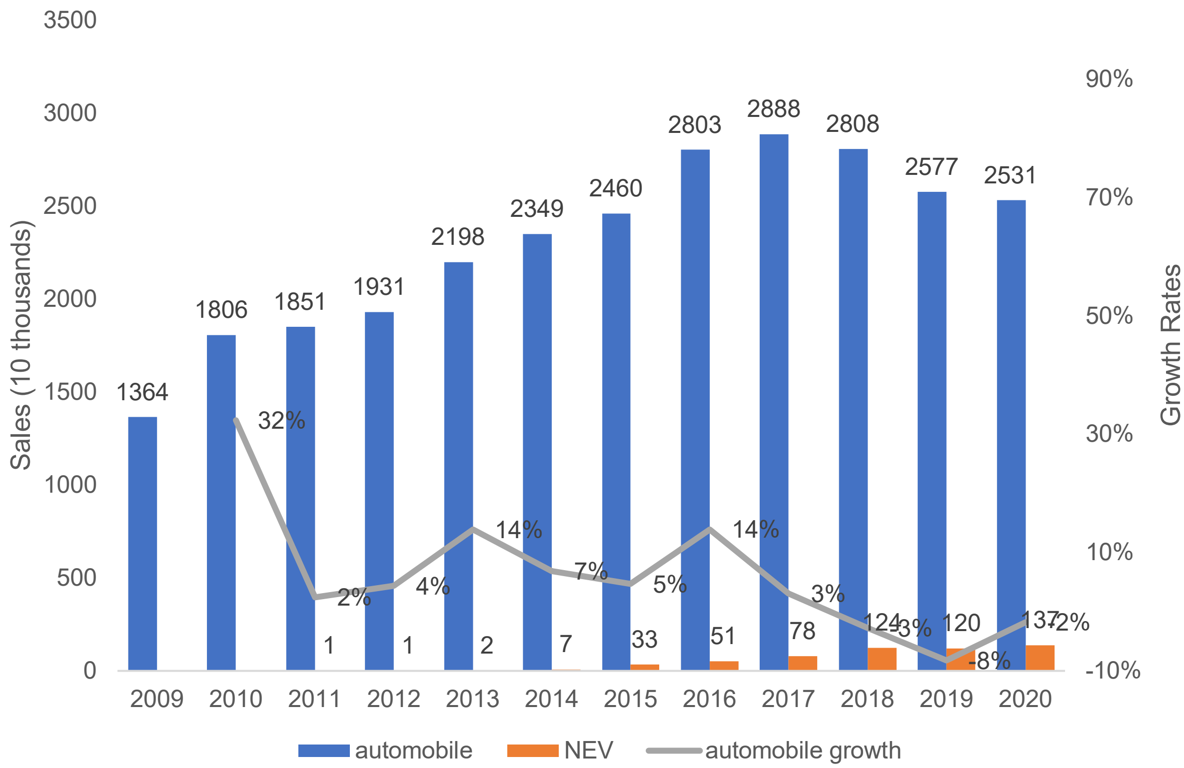


Figure 2-1 China vehicle sales and growth rate 2009-2020

Data source: China Association of Automobile Manufacturers

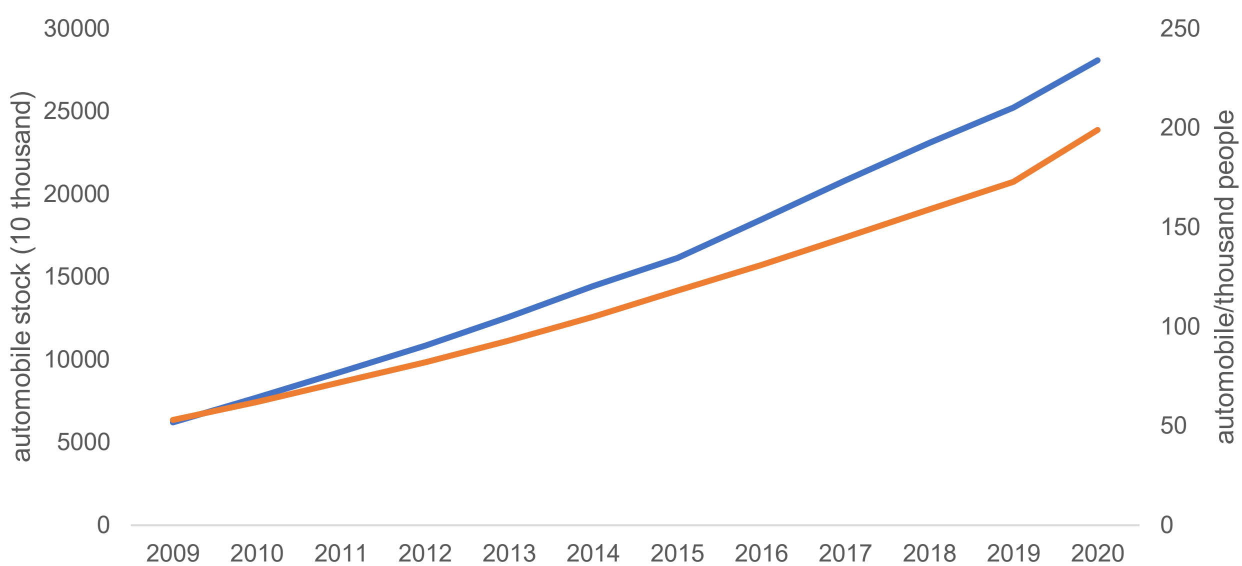


Figure 2-2 Total vehicle and vehicle per 1000 people in China 2009-2020

Data source: China Statistic Yearbook 2010-2020

Between 1997 and 2016, the Chinese economy experienced an average growth rate of 12%, with the per capita GDP growing from $1,168 to $5,577 (2000 constant US dollars). However, the economic growth is slowing down to 6.7% in 2018 and 6.0% in 2019. The growth rate decreased to 2.3% in 2020 caused by the COVID pandemic broke out in early 2020.

2.2 Vehicle classification system

The vehicle classification system in China is unique in the world. According to the classification in the statistic yearbook, vehicles are classified into three categories: passenger vehicles, trucks and other. Passenger vehicles (PVs) are further classified as large PVs (buses), medium PVs, small PVs and micro-PVs based on the length and the number of the seats on the vehicle. Trucks are further classified as heavy trucks, medium trucks, light trucks and micro trucks based on the weight and loading capacity. Other vehicles represent specific usage vehicles including sanitation vehicles, fire trucks, etc.

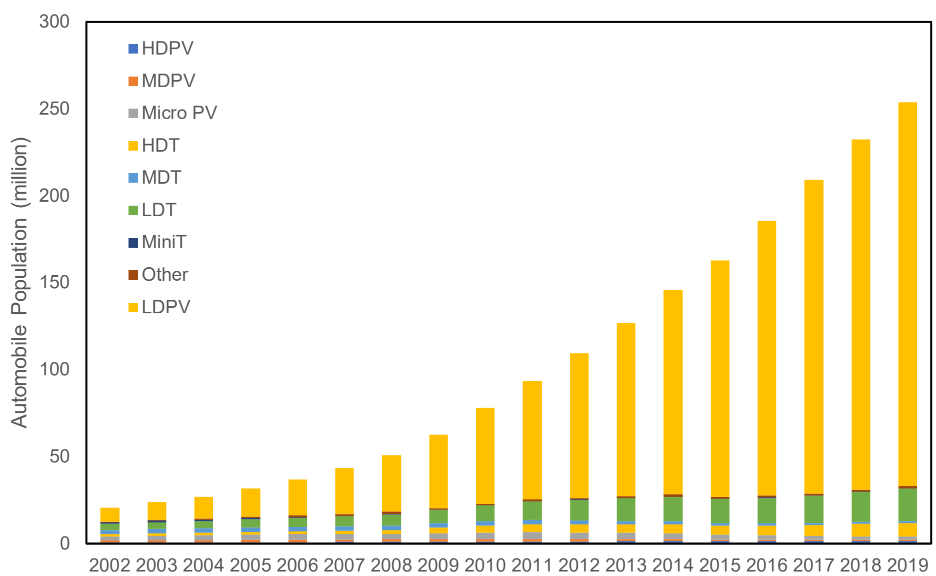


Figure 2-3 China Vehicle stock 2002-2019

In this work, the large PV will be further divided as transit bus and other bus; small PV will be further divided into private vehicles, taxi, and other PVs to reflect the different activity level and survival years. The vehicle classification in this research is represented in Figure 2-4.

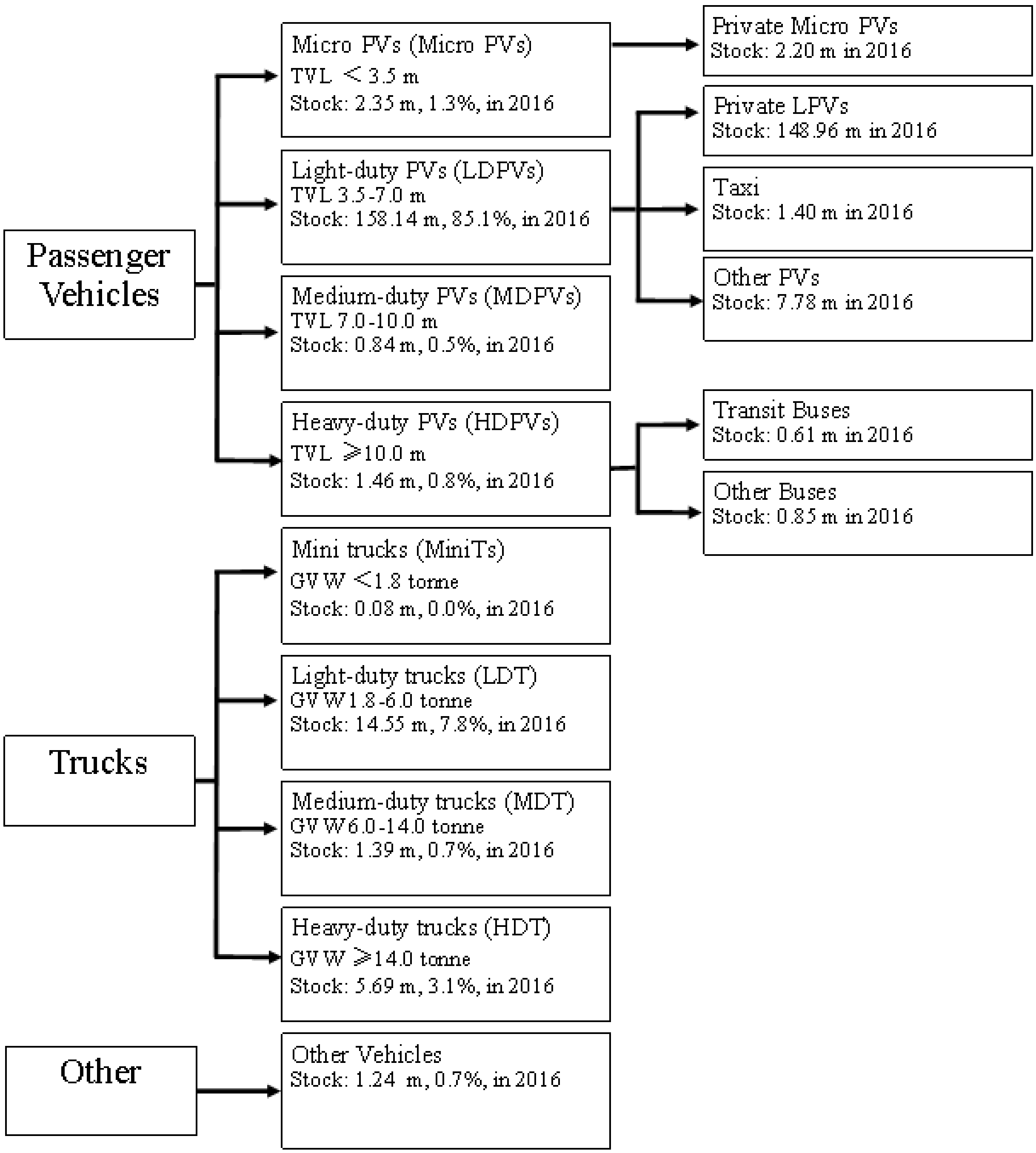


Figure 2-4 Vehicle classification in this research

2.3 Demographics

As the economies improve and develop, fertility rates typically begin to decrease. Together with the increase in life expectancy, populations in some European countries and Japan are aging with people older than 65 exceeding 20% of the population.

Due to the harsh population control policy of the "one-child policy" implemented in 1980s, China has experienced more rapid fertility decreases and aging comparing to other countries. While China has loosened the population control policy and couples can now legally have two children start in 2015, and further three in 2020, it now seems extremely hard to correct the demographic imbalance, as the cost of raising a child is very high in the country, and the fertility rate hasn't been increased much after the birth control policy loosen.

The United Nations recently projected that, from 2000 to 2050, the population in China will grow steadily, reaching its peak in 2030 at 1.45 billion. After 2030, due to low fertility rates, the population will drop to 1.38 billion in 2050. The distribution of people aged 0-14, 15-64 and older than 65 was 25.6%, 67.5% and 6.9% in 2000; 15.9%, 67.9% and 16.2% in 2030; 14.7%, 61.3 and 23.9% in 2050 as shown in Table 2-1.

Table 2-1 Age group structure in China 2000-2050

	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
aged 0-14	25.6	20.5	18.1	18.2	18.2	17.3	15.9	14.9	14.6	14.7	14.7
aged 15-64	67.5	71.8	73.5	72.4	70.1	69.2	67.9	65.7	63.4	62.6	61.3
aged 65+	6.9	7.7	8.4	9.5	11.7	13.5	16.2	19.5	22.1	22.8	23.9

DATA SOURCE: UNITED NATIONS, 2018

With a decreasing population, the experienced increase in vehicle ownership will weaken after 2030. For Japan, the population peaked in 2009, and people older than 65 reached 16.2% in 1998. The vehicle per 1000 people stagnant start in 1992, with a growth rate less than 3%; in 1998, the growth rate was 1.4%, and -0.2% in 2009. This study assumes China would follow a similar trend to Japan's trend of thirty years ago, with a decreasing growth rate of the vehicle ownership.

The assumption here is that the young generation group (aged 20-50) fuels most of the vehicle purchase and ownership growth; but with a decreasing population in this young generation group, the vehicle ownership will shrink. More discussion on the life cycle stage assumption and cohort generation effect will be discussed in section 2.4.3.

2.4 Forecasting vehicle fleet and activity levels

Many different methods have been applied for vehicle projections. (De Jong, Fox, Daly, Pieters, & Smit, 2004) reviewed and classified the car ownership models into nine groups based on various criteria. Aggregate project models based on income growth or population composition, disaggregate models analyzing the individual or household life cycle, household composition, presence of child, income level, vehicle cost, etc., among others.

The advantage of aggregate models includes low data requirement, flexibility, and capabilities to make short, medium and long forecasts. On the other hand, the disaggregate models consider the individual or household preferences and choices, the market supply and vehicle characteristics, but have heavy data requirements, and thus are mostly used for short term forecasts.

2.4.1 Aggregate time series models

Following the development of the diffusion theory, vehicle/car share adopted the sigmoid shape curve over time (Norton & Bass, 1987). Adoption grows slowly at the beginning, getting faster in the middle stage, and gradually slowing down and reaching a saturation level. Following this idea, sigmoid models were adopted to describe the vehicle adoption stages. (Button, Ngoe, & Hine, 1993) estimated a logistic model and presented the vehicle growth rate of developing countries.

With different saturation rates of 300 to 450 per thousand people scenarios, they estimated the vehicle ownership for selected low-income countries.

Arguing an asymmetric effect of income on vehicle ownership in (J. M. Dargay, 2001), (J. Dargay & Gately, 1999) adopted the Gompertz function and analyzed vehicle and car adoption income elasticities with data from 26 countries including high-income and low-income countries between 1960 and 1992 and made projections for the vehicle growth to 2015. With a partial adjusted lag effect, the modified Gompertz function adopted could be written as

$$V_{it} = \gamma\theta e^{\alpha e^{\beta_i GDP_{it}}} + (1-\theta)V_{it-1}$$

in which

V_{it} is the vehicle ownership in country *i* in year *t*

θ is the lag effect partial adjustment parameter

γ is the same saturation rate for all the countries

GDP_{it} is the per capita income in country *i* in year *t*

β_i is the curve rate of country *i*

α is a common curve rate for all countries

J. Dargay, Gately, & Sommer (2007) using more data from 45 countries between 1960 and 2002, updated the model and projected for worldwide vehicle projection for 2030. The researchers modeled different saturation rates for different countries based on urbanization levels and population density. Considering the case of South Africa, where vehicle ownership increased during a period of negative income between 1960 and 2002, the authors made a modification of the income lag effect to reflect this asymmetric impact. With the modified saturation function, partial adjusted lag effect and random error term, the modified Gompertz function adopted could be written as

$$V_{it} = (\gamma_{MAX} + \lambda\overline{D}_{it} + \varphi\overline{U}_{it})(\theta_R R_{it} + \theta_F F_{it})e^{\alpha e^{\beta_i GDP_{it}}} + (1 - \theta_R R_{it} - \theta_F F_{it})V_{it-1} + \varepsilon_{it}$$

in which

V_{it} is the vehicle ownership in country *i* in year *t*

θ_R *and* θ_F are the lag effect partial adjustment parameter for rising and falling income

γ_{MAX} is the reference max saturation rate of US

λ *and* φ are the adjustment parameters of population density and urbanization

$\overline{D}_{it}$ *and* $\overline{U}_{it}$ are the population density and urbanization level comparing of country *i* in year *t* to US

GDP_{it} is the per capita income in country *i* in year t

β_i is the curve rate of country *i*

α *i*s a common curve rate for all countries

ε_{it} is the random error term of country *i* in year t

R_{it} *and* F_{it} are the rising and falling income of country *i* in year t

The above studies provide an understanding on the income elasticity of vehicle ownership and provided a reference vehicle and car growth curve considering the economic growth, population density, and urbanization level of a country.

Recent projection studies on China vehicle growth are mostly following this methodology and will be reviewed and discussed in section 2.4.4.

2.4.2 Factors affecting car ownership and usage

There have been many discussions on vehicle ownership and car trips leveling off trends in developed countries including the UK, US, Germany, and others. This trend is referred to as "peak car" or "car leveling off" (Goodwin & Van Dender, 2013; McDonald, 2015; Metz, 2013; Millard-Ball & Schipper, 2011; Stokes, 2013) and different factors have been discussed as contributors to this 'peak car' phenomenon.

Headicar (2013) analyzed the growing trend of the spatial distribution of urbanization which reverse the historical suburban sprawl. McDonald (2015) and Metz (2013) emphasized that the growth of electronic communication, online shopping, and home working substitute car transport. The increase in the supply of alternative modes, their advantages of reliability, coupled with the declining marginal utility of increased car trip distances in the increasing congestions in the cities. The young generation taking higher education and delaying their life milestones of marriage or partnership and parenting, thereby delaying their access to cars (DfT, 2015; McDonald, 2015). Research also showed that high-frequency ride-hailing service users tend to give-up their car ownership (Clewlow & Mishra, 2017).

While the factors contributing to reducing car ownership and car travel demand analyzed in the literature in industrialized countries happen after the countries have experienced motorization, they are also evidenced in the developing countries and affecting travel demand. While motorization is still in the fast-development stage in China, the transit supply, online commence and ride hailing services are also providing negative effects on car ownership and usage. This work considers the effect of the two direction forces -- positive force from economic development and motivation of motorization, and negative forces from information and communication technologies (ICT), young people tending to delay their life milestones and living in urban area, wide adoption of ride hailing services -- will determine the vehicle saturation level in China.

2.4.3 Cohort effects and population aging

Age cohort analysis bases on the assumption that the behavior of different age cohorts is different and due to behavior inertia, people at specific cohort would maintain the same behavior. (Stokes, 2013) used the Great Britain National Travel Survey data, analyzed the different degrees of access to a car for male and female at different age groups, and projected future vehicle populations for each gender / age group.

McDonald (2015) compared the trips made by millennials (people born in 1980-2000) and generation X (people born in the late 1960s and 1970s) in 1995, 2001 and 2009 from the National Travel Survey and confirmed that car trips decreased. While the demographic change contributed 10-25% to the trip decrease, the difference between millennials and generation X contributed 35-50%, and economic dampening contributed about 40%.

China's senior generation (50+ years old) of today grew up prior to the 1960s, when a car-owning lifestyle had not been much established, and they continue to have a low car ownership status. The lifestyles of people after retirement in China are active on health care, exercise in community parks and join group travel. Most of them are less likely to own a car in the next decades. On the other hand, the new generations have grown up with a higher car ownership and more travel mode choices. They are the segment owning most of the cars and can be expected to keep owning cars through their lifetime.

2.4.4 Summary of China's vehicle projections

With a saturation rate of 807 per thousand people in China, (J. Dargay et al., 2007) projected that there would be 390 million cars in China by 2030. (Huo, Wang, Johnson, & He, 2007) adopted the Gompertz model and projected for highway vehicles in China in 2030 using $V_i = V^* \times e^{\alpha e^{\beta EF_i}}$. With saturation rate ($V^*$) set at 400, 500, and 600 vehicles per 1000 people, they projected the vehicle stock to reach 486 to 662 million in 2050. However, considering that the vehicle stock in 2005-2010 alreadt exceeded their projection, Huo & Wang (2012) updated the model by adopting a vehicle sales price adjusted model. They set the saturation rate at 400 and 500 vehicles per 1000 people and projected the total vehicle stock with Gompertz function and projected reducing vehicle price. The new results project 530-623 million total vehicles by 2050. Hao, Wang, & Yi (2011) used a hybrid projection model for private passenger vehicle, urban public transport vehicles and economic utility vehicles and found that the vehicle population was sensitive to household income and vehicle price. They projected that China's vehicle population would reach 363.8 and 606.7 million in 2030 and 2050.

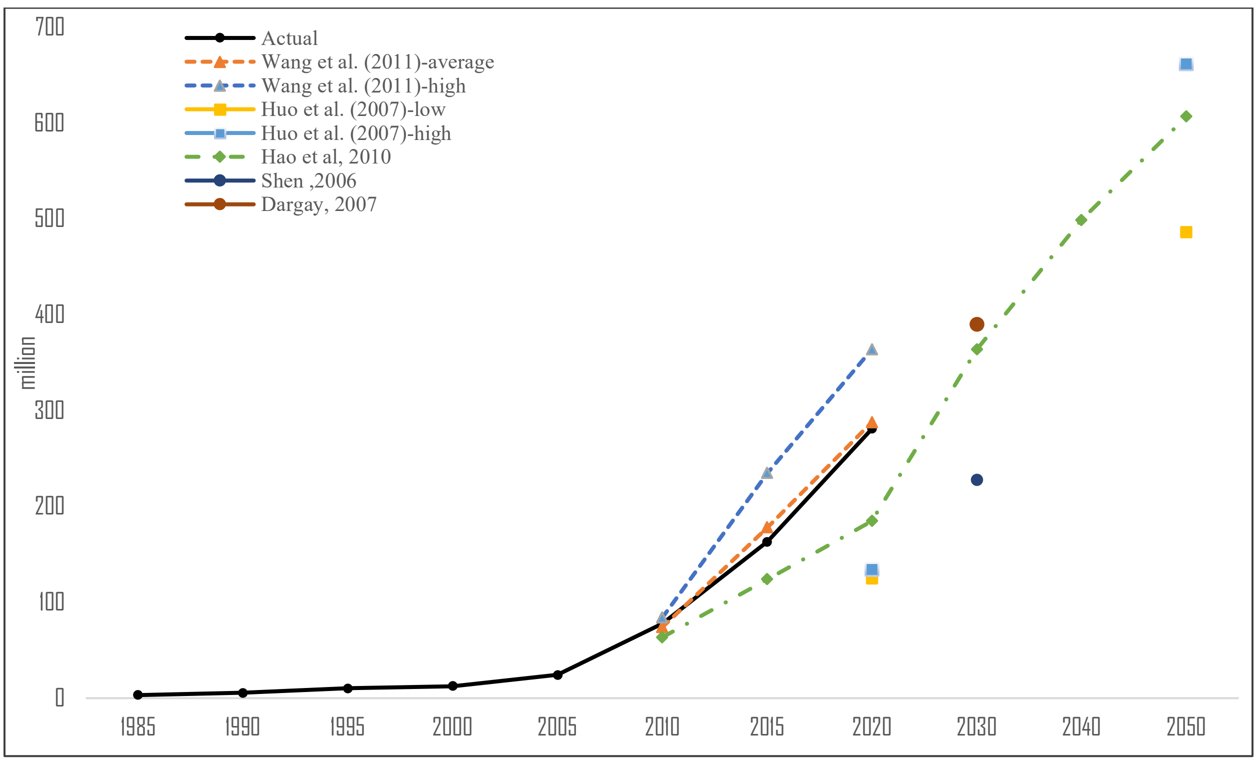


Figure 2-5 China vehicle projection results from literature and actual sales

From another perspective, Wang, Teter, & Sperling (2011) reviewed the vehicle ownership growth in developed countries during the early days before they reached 300 vehicles per 1000 people and adopted the growth rate for China, which resulted in a much higher growth projection comparing to other research results in Figure 2-5. Comparing the actual ownership numbers in 2008-2020, the projection results in Wang et al. (2011) matched the actual sales very well of the seven countries average scenario.

Adopting this method of using the seven countries average growth rates, the growth rate of vehicle ownership in China would be 3.1% in 2020-2030, 2.9% in 2030-40 and 0.9% in 2040-50. Based on the performance of these projection, this work uses this scenario of vehicle ownership as the Business As Usual (BAU) scenario, and it projects the total vehicle ownership in China would be 494.6 million in 2050.

2.4.5 China vehicle saturation level

The saturation level of vehicle ownership per 1,000 people is a critical factor in total vehicle population estimation for aggregate time series models. The literature has examples of research with different assumptions about the saturation level for China (Table 2-2), for example, Button et al. (1993) used data only from low-income countries, assumed different saturation levels of car ownership for five grouped countries and assumed China would have a saturation level of 300-450 cars per 1,000 people. J. Dargay & Gately (1999) assumed a case in which all countries have a same saturation level of 850 vehicles, among which 620 are cars, for the researched 26 countries including China. Considering the urban population and population density constrain, J. Dargay et al. (2007) assumed different saturation levels for different countries, and assumed China had a saturation of 807 vehicles per 1,000 people. Huo & Wang (2012) considered the urbanization and population density in China, assumed saturation levels of 400 and 500 per 1,000 people respectively for a low and high scenario. Wu, Zhang, & Ou (2014) took Dargay's 807 vehicles as the saturation level for their projection. Peng, Ou, Yuan, Yan, & Zhang (2018) assumed 376 for most provinces and 250 per 1,000 people for four municipalities (Beijing, Shanghai, Tianjin, Chongqing) and built a bottom-up model for the total vehicle stock projection. As discussed, there is a wide range of assumptions and uncertainty regarding the saturation level.

Table 2-2 Saturation level adopted in literatures

Source	Button, 1993	Kobos, 2003	Dargay, 2007	Wang 2012			Wu 2014	Peng et al. 2018			CATARC, 2018
				High	Mid	Low		High	Mid	Low	
Saturation	300-450	292	807	600	500	400	807	497	376	250	350-400

DATA SOURCE: LITERATURES

Overall, population density and urbanization have been the only considered factors affecting the saturation level in previous research. This study also considers the impact that demographic structure will have on the saturation level of vehicle ownership in China.

2.5 Aggregate Time Series Model

In the aggregate time series model, we consider income growth, whether there is an automobile industry in the country, population density, urbanization level as the key factors determining the growth rate of vehicle ownership.

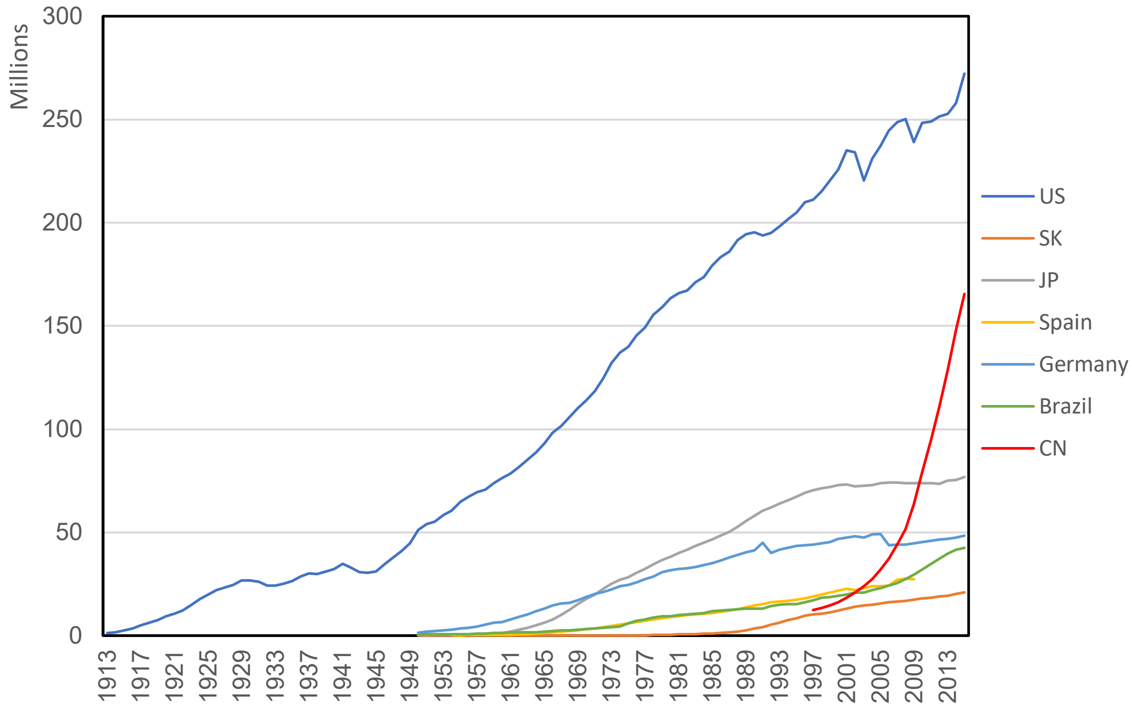


Figure 2-6 Vehicle stock growth in selected countries 1913-2015

Figure 2-6 shows the the historical development of vehicle ownership between 1913 and 2015 for a sample of countries. US led motorization rates and reached vehicle ownership of 272 million in 2015. China started its motorization process in the 1990s and with a large population, the vehicle stock reached 165 million in 2015 and 281 million by 2020.

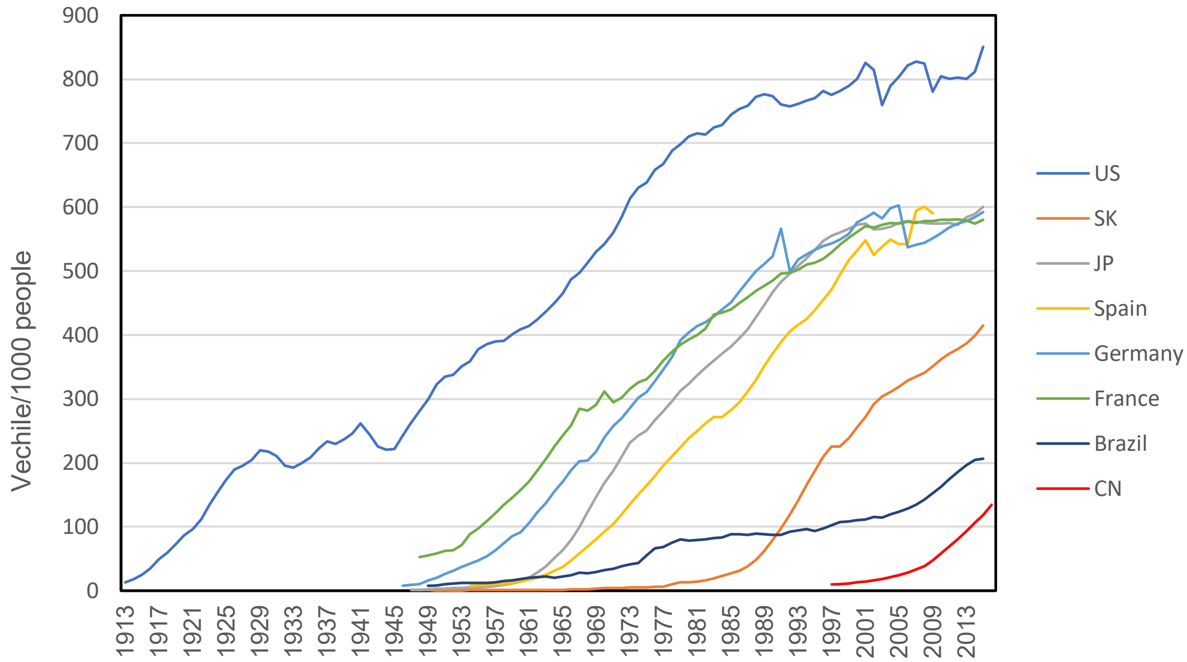


Figure 2-7 Vehicle per 1000 people in selected countries 1913-2015

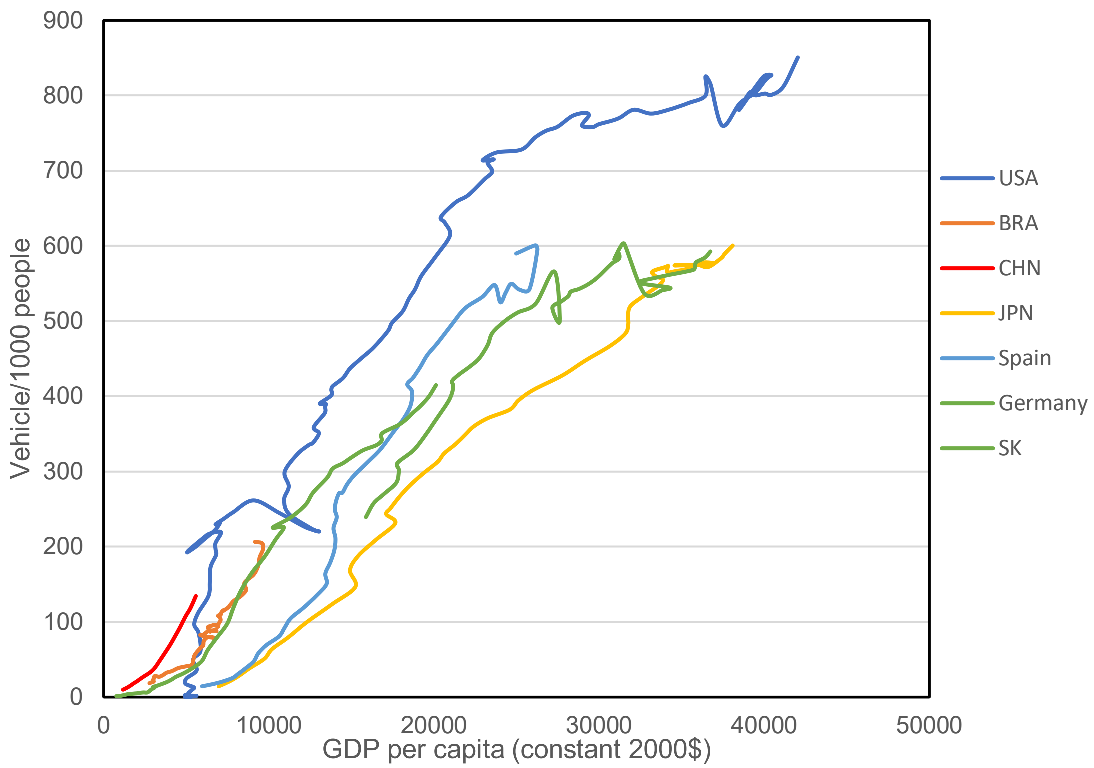


Figure 2-8 Vehicle per 1000 people at different economic level in selected countries

Figure 2-7 shows trends in the motorization rates (per 1000 people) and Figure 2-8 shows the development as a function of per capital GDP. Comparing to vehicle ownership of 850 per 1000 people in the US, 600 in Europe countries and Japan, China had 134 vehicles per 1000 people in 2015 and 199 in 2020. Taking the S shape development theory, China is now at a fast-developing stage. From the GDP development perspective, China exceeds other countries and have higher vehicle ownership at a lower economic level (Figure 2-8).

2.6 Bass diffusion model

Diffusion theory describes a new product or technology spreading through consumers. Diffusion theory divides consumers into five groups based on the characteristics and time of innovation adoption: innovators, early adopters, early majority, late majority and laggards (Rogers, 2010). Developed from this diffusion theory and sigmoid adoption curve theory, the Bass model, Gompertz model, and logistic model are extensively used in modeling various innovative technologies. The Bass model is one of the best well-known and widely adopted innovation diffusion models. Bass divided the consumers into two groups of innovators, those attracted by mass advertisement and the imitators due to a word-of mouth effect (Bass, 1969, 2004).

The stability and uncertainty of the modeling results from the Bass model have been discussed in the literature. Generalized Bass Model and other models were proposed to incorporate other parameters like cost, income, information, new generation of the product (Horsky, 1990; Norton & Bass, 1987). The Bass model has been widely adopted in the modelling studies of alternative fuel vehicles (Al-Alawi & Bradley, 2013; Cao & Mokhtarian, 2004; Jeon, 2010). The development of the model is to make inference of the parameters of m, p, and q. The parameter m represents the market potential of the innovation, and mostly comes from exogeneous sources, e.g. analogy to historical sales of other products.

In this study, instead of modeling the exact sales value of ZEVs, we modeled the ZEV market share with the cumulative sigmoid shape increase from the Bass model. By assuming of fully electrification as the saturation level of ZEV development, adopting the sigmoid curve of the cumulative market entrants as the yearly market share for ZEVs, the work regress the derived ZEV market share data between 2010 and 2018 and predicts the ZEV market share in the following decades. The simulation result (in Figure 2-9) shows a take-off of the market share at around 2025, and the sales of ZEVs in China will take 93% of the automotive market by 2030. Combining the ZEV sales with our total automobile market prediction result together (in Figure 2-10), the ZEV sales in China will reach 32.5 and 41.9 million respectively in the lower and higher scenarios.

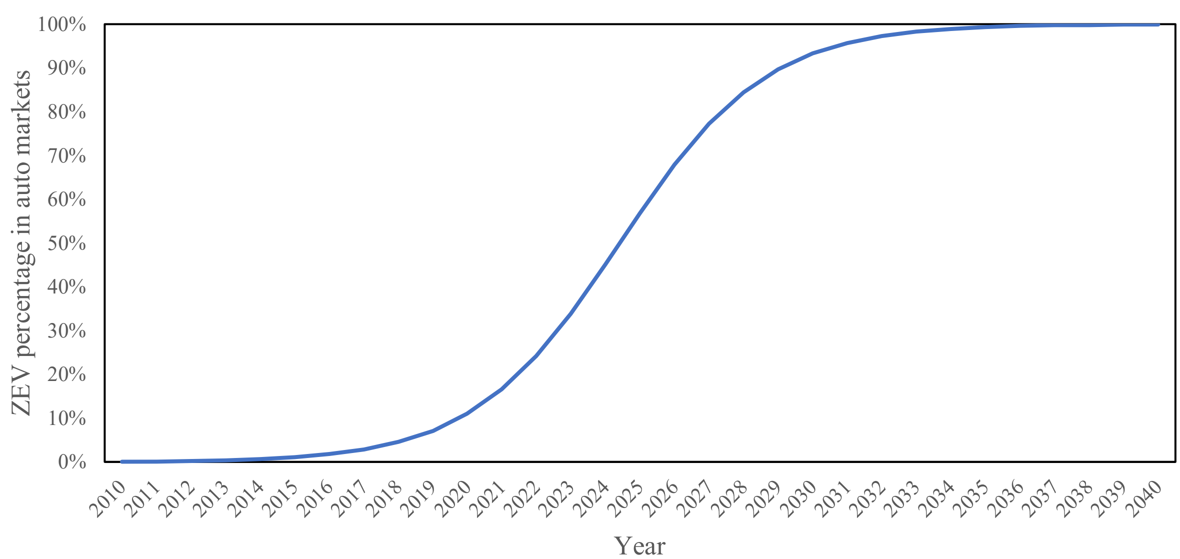


Figure 2-9 ZEV market share modeling from modified Bass model

reveals accelerated growth around 2025 and reaching 93% market share in 2030

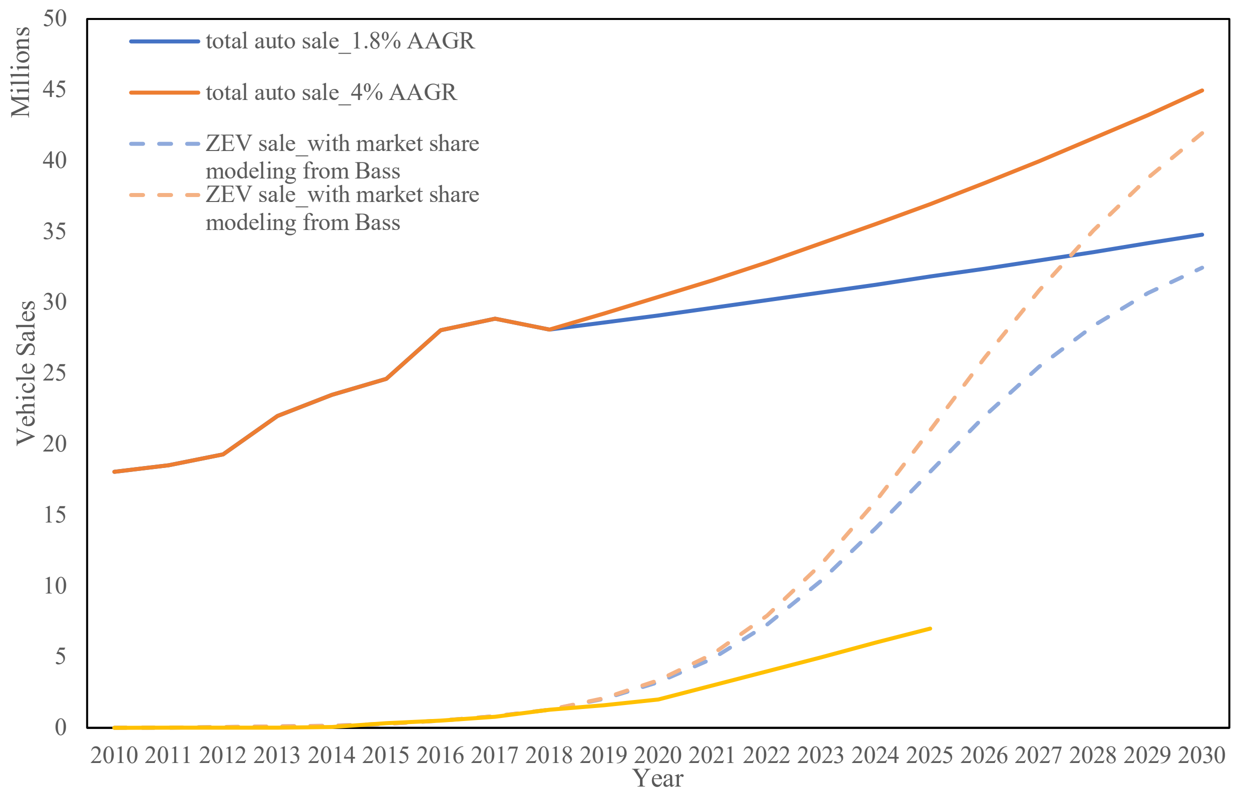


Figure 2-10 Two scenarios of automobile market and ZEV market forecasting with ZEV market share simulated from modified Bass model

2.7 Age-cohort effects scenario analysis

Cohort effect reflects the automobile ownership in two ways: life cycle milestone effects and cohort behavior preferences. Life cycle milestone effects refer to the important milestones affecting the vehicle adoption, like marriage, parenting, employment, retirement. Cohort behavior preferences refer to the different age groups growing-up experience or attitudes affecting vehicle adoption and giving-up.

For the car ownership and annual driving distance of the household head at different age group, as shown in Figure 2-11, Prskawetz, Leiwen, & O'Neill, (2004) found that car ownership peak at household head at age of 40-44, and the car ownership of households for people older than 65 will drop to 42% and further for older ages. This implies a decreasing car ownership demand for people after retirement who do not need to commute and give up their car ownership.

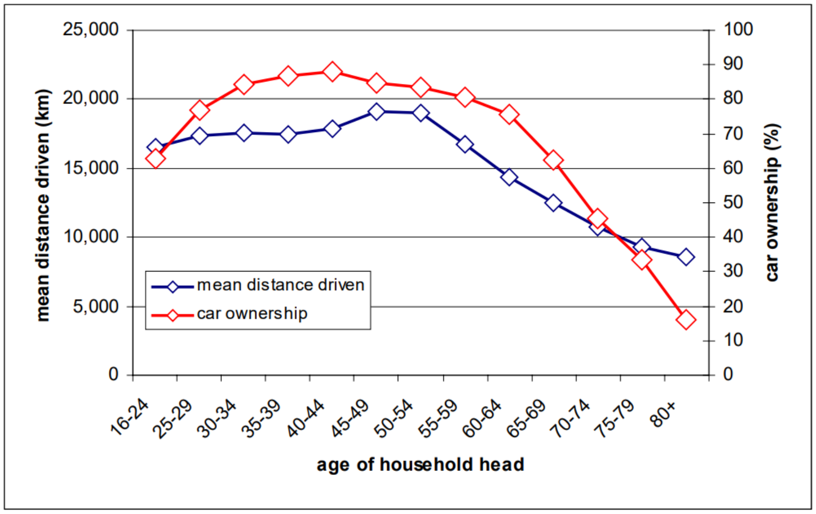


Figure 2-11 Mean distance driven and car ownership by age of household head

(Prskawetz et al., 2004)

Vehicle registration data between 2011 and 2015 (Figure 2-12) shows that people younger than 50 represents around 90% of total registration.

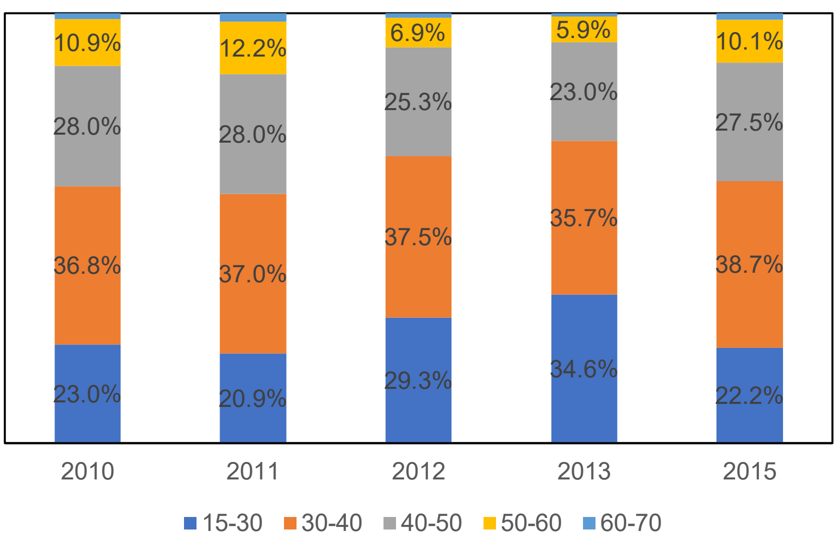


Figure 2-12 Age group distribution of automobile registration 2010-2015

Recalling that this study assumes that people younger than 20 and older than 70 do not own a vehicle. The rest of the population are divided into five age groups: 20-29, 30-39, 40-49, 50-59 and 60-69. Based on the vehicle registration distribution in between 2010 and 2015 and the life cycle vehicle ownership rates (Prskawetz et al., 2004; Stokes, 2013), the total vehicle ownership in 2015 were distributed to the five age groups (Table 2-3). Since China is still on the motorization process, the total vehicle ownership rate in the five age groups is all increased for the same cohort in the following years for people younger than 60 years old.

Table 2-3 Vehicle ownership in age groups in 2015

Age group	age distribution from census	Population in 2015 (*10k)	Vehicle Registration in 2010-2015	LDPV in 2015 (*10k)	LDPV Ownership in each age group in 2015
Total		137462		13670.1	
0-19	22.0%	30233	0%	0	0%
20-29	16.6%	22878	26.1%	3567.0	15.6%
30-39	14.5%	19870	37.3%	5094.5	25.6%
40-49	17.6%	24162	26.3%	3596.9	14.9%
50-59	13.2%	18119	9.0%	1236.2	6.8%
60-69	9.7%	13299	1.3%	175.6	1.3%
70+	6.5%	8901	0%	0	0%

With an aging society, people turn to save more for future years instead of consuming more at their young and medium ages, which could result in a stagnated economic. By investigating the economic development in Japan and Korea for different aging stages and the vehicle ownership elasticity index, we calibrated our cohort estimation with the resulting in total vehicle ownership below (Table 2-4).

Table 2-4 vehicle stock in an aging society projection result

	2010	2015	2020	2025	2030	2035	2040	2045	2050
STOCK (million)	77.2	161.6	273.4	285.9	299.0	306.6	314.3	323.9	333.7

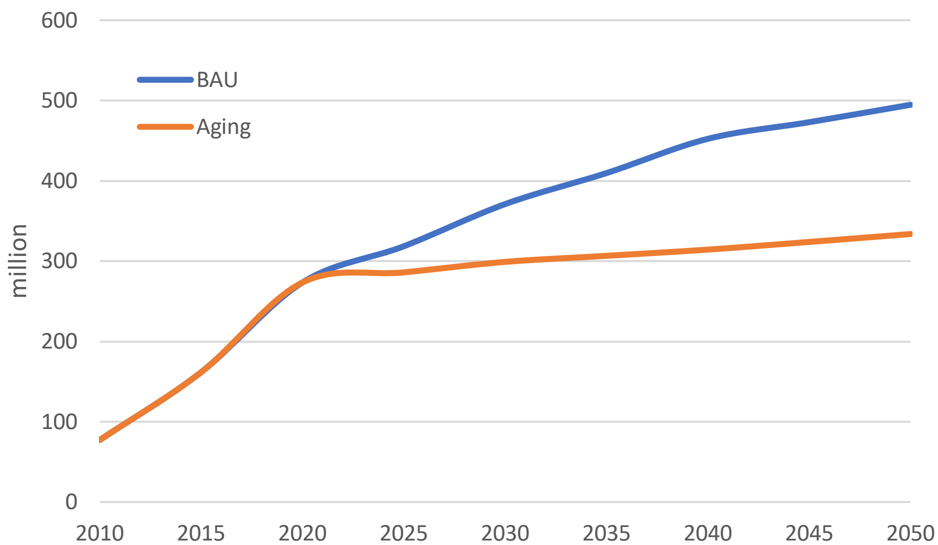


Figure 2-13 vehicle stock in 2010-2050 of BAU and aging society scenarios projection

2.8 Results and Discussion

Considering the economic growth and society demographic change, the vehicle total stock will reach 495 million and 334 million in 2050 in the BAU and aging society scenarios (Figure 2-13).

After reviewing the vehicle stock projection methods and results in the literature, we analyzed estimates of the demographic characteristics of a rapid aging trend. By reviewing vehicle purchase behavior in the population age groups and the vehicle usage behaviors from the literature, we can understand how the older group would be less likely to own a car, thus decreasing the total vehicle ownership momentum. With the rapid aging population and consequently slowed down economic growth, the stock would plateau at the present value and reach 334 million in 2050.

The growth in the vehicle ownership would affect whether China could reach its energy conservation and emission mitigation targets. It will be further explored it in chapter 5.

3 Bus electrification in Shenzhen, Case study

In this chapter, the author investigate how Shenzhen fully electrified its transit bus fleet by comprehensively analyzing the cost composition of the Battery Electric Bus and comparing it with the diesel bus counterpart. The success in the transit bus fleet shed light on the feasibility of extending the electrification to the whole vehicle fleet and the deployment scenarios developed in the following chapters.

In China, the transport sector was the fastest growing sector for carbon dioxide emissions between 1990 and 2015, with an increase of 682 percent reaching 836.6 metric tons of carbon dioxide in 2015 (IEA, 2017). Since 2009, China has placed great emphasis on the promotion of electric mobility, recognizing that the electrification of the transit bus fleet reduces local and global emissions, while at the same time, strengthens the local automotive industry and reduces oil dependency. With strong promotion from all levels of governments, China's urban transit bus fleet, had more than 324,000 are electric buses by the end of 2019, increased from 0.33% in 2013 to 46.8% in 2019 (MOT, 2020)[2]. China is the only economy worldwide with a large-scale implementation of electric buses and is one of the early adopters to have the operational experience of a whole lifecycle. These lifecycle experiences and lessons learned from an electric mobility programs are extremely valuable to the rest of the world to understand the technology, policies, infrastructure, and operational design requirements.

One of the earliest adopters of electric mobility was the city of Shenzhen, in China’s south-eastern province of Guangdong. Shenzhen’s electrification experience offers a rare opportunity in understanding the challenges of enacting wide scale, system-level change from a small electric bus

[2] Source: MOT, Statistical Bulletin on the Development of the Transportation Industry in 2019

pilot to a mass market. Shenzhen began adopting electric buses in 2009, under a national electric vehicle demonstration program that challenged ten cities across China to deploy at least 1,000 electric vehicles each year for three years.[3] In 2017 Shenzhen became the first city in the world that fully electrified its urban transit fleet—16,359 electric buses. Shenzhen is also approaching the goal of fully electrifying its taxi fleet of 21,609 taxis—99 percent electrified with 21,485 electric taxies at the end of 2019.[2]

3.1 Shenzhen Bus Group

Shenzhen is served by three major bus operating companies: SZBG, Eastern Bus Company (EBC), and Western Bus Company (WBC). All three are joint ventures with public and private shares. The three companies run routes in the central urban area and outer districts. Meanwhile, there are several other small bus-operating companies that run a small number of bus routes in suburban areas.

SZBG is the oldest company among the three major bus companies, having started its bus service in 1975, under the name of Bao'an County Shenzhen Town Bus Company. At this humble stage, they only operated one route with two buses, and had twelve employees. The company was restructured as a state-owned bus operating company in 1983. It was restructured again as a joint venture company with investments from Hong Kong SAR, China in 2004. Currently SZBG has three major stakeholders: public share (55%), Jiulong Bus Company of Hong Kong SAR, China (35%), and others (10%).

3 http://www.mof.gov.cn/zhengwuxinxi/caizhengwengao/2009niancaizhengbuwengao/caizhengwengao2009dierqi/200904/t20090413_132178.html

Among the three main bus operating companies, SZBG serves 332 routes, has 6,007 buses in operation (in 2019), and carried about 606 million passenger trips (in 2018, see Table 3-1). Overall, SZBG accounted for a little more than one-third of the number of routes, total kilometers and total passenger trips of the three major companies. The average annual running distance for each bus was similar for the three bus operating companies with about 62,000 kilometers per bus each year (Table 3-2).

Table 3-1 Operational data of the three transit bus companies in Shenzhen (2018)

	Number of Routes	Length of Routes (km)	Number of Buses	Annual Bus-Travel Distance (million km)	Annual Passenger Trips (million)	Ticket Fare Revenue (million yuan)
SZBG	332	6,923.24	5,988	374.11	605.66	1,348.8
EBC	275	7,267.84	5,795	360.90	474.66	1,217.8
WBC	361	6,542.21	4,976	306.84	462.73	1,018.6
Total	968	20,733.29	16,759	1,041.85	1,543.05	3,585.2

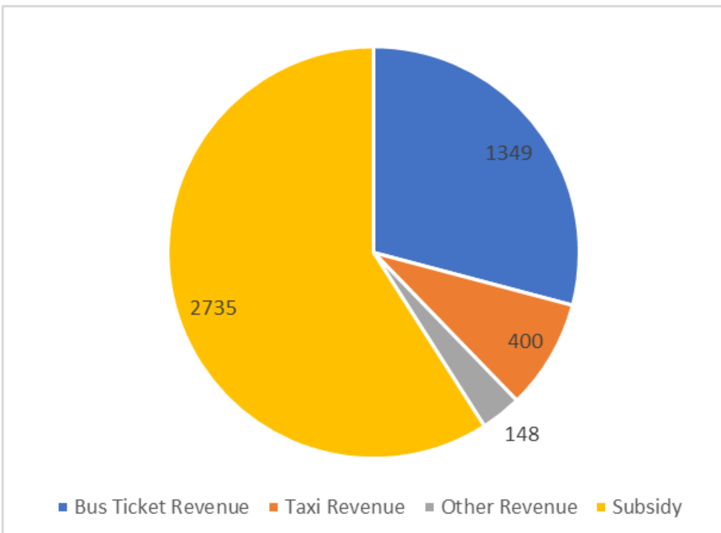
Table 3-2 Per route bus statistics of the three transit bus operating companies)

	Average route length (km)	Average number of buses per route	Annual bus-running distance per route (million km)	Annual Passenger trips per route (million)	Annual travel distance per bus (thousand km)	Annual passenger trips carried per bus (thousand)
SZBG	20.85	18	1.13	1.82	62.477	101.146
EBC	26.43	21	1.31	1.73	62.278	81.909
WBC	18.12	14	0.85	1.28	61.664	92.992
Average	21.42	17	1.07	1.59	62.166	92.073

SBG's buses are operated by five bus subsidiary companies divided into 67 bus fleets. The business areas of SBG include city bus, medium- and short-distance bus services, taxis, vehicle rental service, vehicle parts, vehicle repair and maintenance, housing, property management, hotel, advertising and retail operations. With the introduction of electric vehicles, SBG has also entered the market of electric vehicle charging infrastructure including design, construction, operations and maintenance.

The main revenues of SBG are ticket fares of buses and taxi services (Figure 3-1). The bus service is considered a public service in Shenzhen, so the fare is kept low. SBG receives substantial amounts of subsidies from Shenzhen municipality based on the total mileage of bus services provided. With the subsidy, SBG turned in profits of 101 million yuan in 2018.

Figure 3-1 Total Income of SZBG in 2018 (million yuan)



3.1.1 Routes and fare

SBG operates about 340 service routes with 6,007 buses as of December 2019. These routes are divided into 204 routine and main lines, 53 branch lines, 37 express lines, 21 night lines, 14 rush hour lines and 12 holiday lines.

SZBG bus routes vary in length from 2–74 kilometers, though most vary between 12 and 28 kilometers. Eighteen buses on average serve each route, though routes with as many as 75 buses exist. Passengers pay between one and ten yuan, and most routes are priced at two yuan (Table 3-3).

Table 3-3 Introduction of different type of lines

Type of line	Introduction	Operating hour	Ticket fare
Routine and main bus lines	More than half of the total number of lines	6:30 - 23:00	2 yuan ($0.28) or 10 yuan ($1.4) for long-distance
Branch lines	Connect communities to metro stations or shared bus terminal stations	6:00 - 20:00	1 yuan ($0.14)
Express lines	Connect business centers and large communities with few stops in-between	6:30 - 23:00	1-2 yuan ($0.14-0.28)
Night lines	Night operation	23:00 - 6:30	1-2 yuan ($0.14-0.28)
Rush hour lines	Service during peak commuting hours with fewer stops (Some of the rush-hour express line buses operate only one direction according to the passenger demands)	morning peak (07:00 - 09:00) and evening peak (17:00 - 19:30)	3-7 yuan ($0.43-1.00)

Source: SBG

3.1.2 Ridership

Shenzhen's bus and metro systems support the bulk of public transit transportation modes apart from about ten percent passenger trips by taxi. With metro system expanding rapidly, the annual bus passenger ridership dropped from 2.2 billion in 2013 to 1.6 billion in 2018 (SZMTC, 2019). The patronage of SZBG buses dropped from 833 million riders in 2013 to 607 million in 2018, on average decreasing eight percent annually. Shenzhen's metro network development plan of 2016–30 would increase its service to 32 lines, with 1142 kilometers in operation by 2030. The role of bus services in Shenzhen is to provide more feeder services to the metro network, and consequently, the bus network has been restructured to provide a more flexible service to the passengers.

However, with full electrification of the bus fleet in 2017 (Figure 3-4), SZBG witnessed a ridership increase of 2.4 percent. How much of this increase was on account of the electrification is unclear, as Shenzhen also introduced on-demand services as well as more flexible routes to connect suburban communities and metro stations around the same time (Figure 3-2).

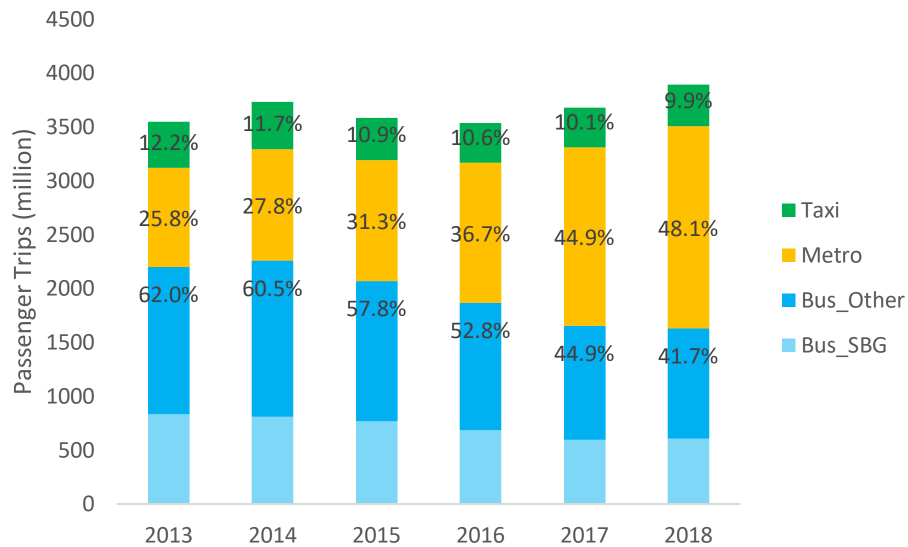


Figure 3-2 Public transport trips in Shenzhen

Source: SZBG annual report 2014-2019

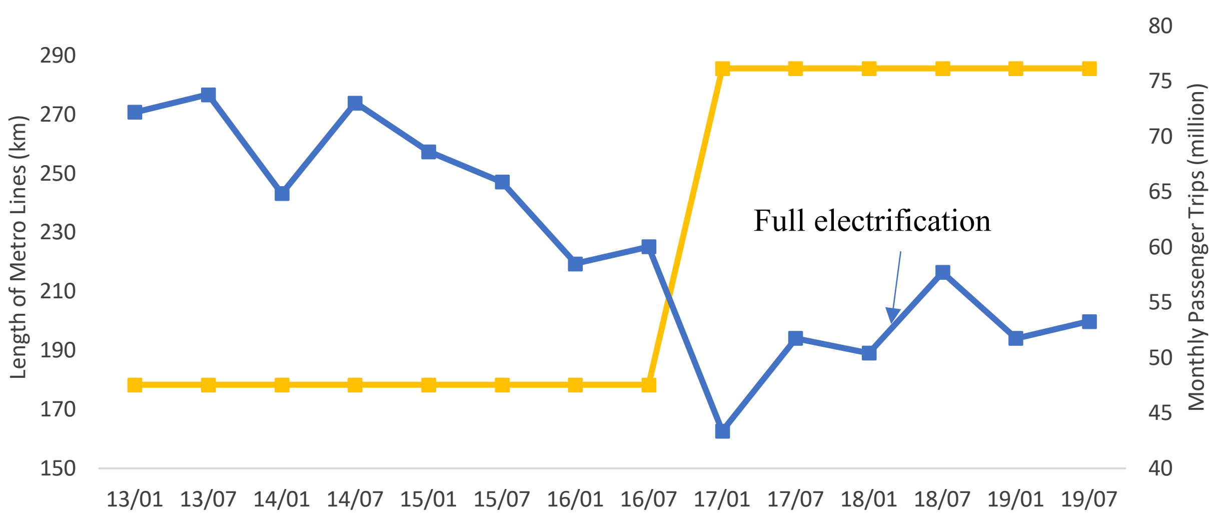


Figure 3-3 length of Shenzhen metro service lines and SBG monthly bus passenger trips

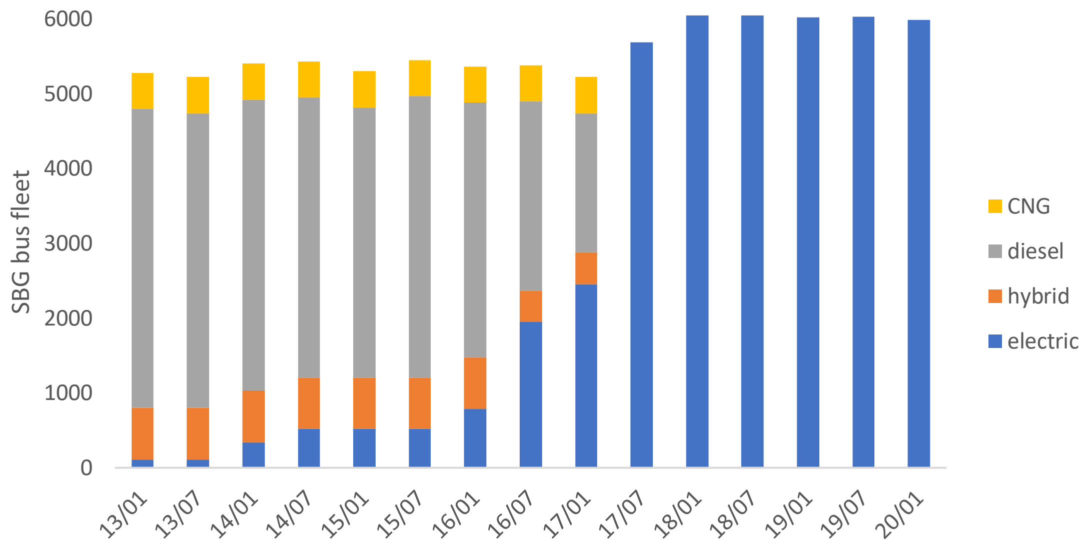


Figure 3-4 Bus composition in SZBG fleet

The urban metro network line length extended from 178 km to 286 km in Oct 2016 (Figure 3-3). As a result, the bus passengers dropped significantly from July 2016 to January 2017, as shown in Figure 3-3. SBG's full replacement of the bus fleet to electric in July 2017 gradually raised the ridership in the following two years. The adoption and expansion of the on-demand transit bus service also contributed to the passenger trips growth.

3.1.3 Bus fleet

The SBG fleet is primarily composed of buses from BYD, Nanjing Golden Dragon Bus (NJGD), and Wuzhoulong (WZL) (Table 3-4). Manufacturers provided lifetime warranty for the key parts for electric buses. Manufacturers also provide free battery change when the battery degrades. Shenzhen's electric buses are predominantly BYD K8 model (Figure 3-5), which is 10.5 meters long and has a 250 kilometer-battery range, characterized by a 2-hour DC fast charging (or 4–5-hour AC slow charging) battery.

Table 3-4 SBG bus models Original Equipment Manufacturer (OEM) composition

OEM	**Number of buses**	**Percentage**
BYD	4787	79.1%
NJGD	1032	17.0%
WZL	234	3.9%

Figure 3-5 Dominant bus model in SBG, BYD K8

3.1.4 Charging infrastructure

SZBG worked closely with charging operators/charging service providers on the charging station construction and operation. By the end of 2019, SZBG has 104 charging stations for their buses. An additional 10 stations are under construction and about 20 more stations are planned for construction. Of the 104 available charging stations, there are a total of 1,707 charging terminals with 2,989 charging plugs.

3.1.5 On-demand bus services

On-demand electric bus services, including the Youdian bus and U+ minibus service, were introduced for travelers via the Youdian Chuxing application on mobile devices. The application was jointly developed and operated by SBG and DiDi Chuxing Company—the top ride hailing company in China.

The Youdian bus service was launched in 2016 to meet commuting demand with direct service that was not covered by regular bus routes. With the Youdian Chuxing smartphone application, passengers can request a direct bus service between an origin-destination (o-d) pair either joining an existing route request or adding a new route. If the proposed new route receives enough passengers, then the customized bus service would start operation. The bus routes are constantly updated based on the demands from passengers. Typically, this service is more expensive than the regular bus fare, and passengers can purchase tickets to reserve a seat using their mobile phone. Some 1,008 Youdian bus routes operated in 2018.

U+ minibus service was launched in 2019 to serve first- and last-mile mobility. It is a dynamic on-demand service without fixed routes or stops—so called 'micro-transit.' The service can respond to the passengers' real-time travel requests. The application matches passengers demand with the minibuses' routes, so that the minibuses routes in this system are dynamic and subject to minor detours to allow sharing while accommodating individual requirements.

3.2 SBZG's bus electrification journey

SBG electrified their bus fleet over eight years from 2009 to 2017 (Table 3-5). The procurement was phased, dividing the bus procurement in batches for a smoother deployment. By the end of 2017, the entire fleet of 6,053 buses was electrified, among them, 4,964 were heavy-duty buses with a bus body length of more than ten meters and 1,089 were medium-duty buses of less than ten meters.

Table 3-5 Timeline of Shenzhen Bus Electrification

Time	Event
May 2008	First hybrid bus in trial operation
June 2009	10 hybrid buses in service*

Time	Event
July 2011	101 electric buses and 26 electric minibuses in service
September 2012	First bus line with all electric fleet launched
November 2015	545 electric buses, 100% electrification target set by the STC
June 2017	Electrification completed with 6053 electric buses

Note: *The plug-in hybrid buses have worse reliability and higher outrage rate than diesel bus and electric bus during operation. The management team decided to shift to full-electric strategy soon after the purchase. Then the hybrid buses get phased out after eight years operation and no more hybrid buses got purchased after this batch products.

The electrification has three phases: a *demonstration stage* in 2009–2011, followed by a *targeted electrification* from 2012–2015, and a *large-scale electrification* from 2016–2017.

3.2.1 Demonstration stage

China's nationwide new energy vehicles (NEV) promotion started with the 'Ten Cities with One Thousand Electric Vehicles' demonstration program in 2009 (Wang et al., 2017). Among the ten major cities selected, Shenzhen was one of these earliest demonstration cities. SBG was one of the first operating companies to purchase the Wuzhoulong plug-in hybrid electric buses at that time. In 2011, Shenzhen hosted the International 26th Universiade[4] and launched 101 Build Your Dream Company (BYD) K9 model buses, all of which were battery electric buses.

3.2.2 Targeted electrification

All newly purchased buses from 2011 onwards by SBG were all electric. One hundred and ninety BYD K9 buses and 210 A10 buses from Wuzhoulong (see detailed fleet composition in Table 3-6) were added to the SBG electric bus fleet in 2013. With the operation of the vehicles in these two stages, SBG has built confidence in the use of new technology for transit buses.

Table 3-6 Electric Bus Models of SBG fleet

Model #	**% of fleet**	**OEM**	**Model**	**Length (m)**	**Number**	**Procurement Year**	**Lifetime (years)**

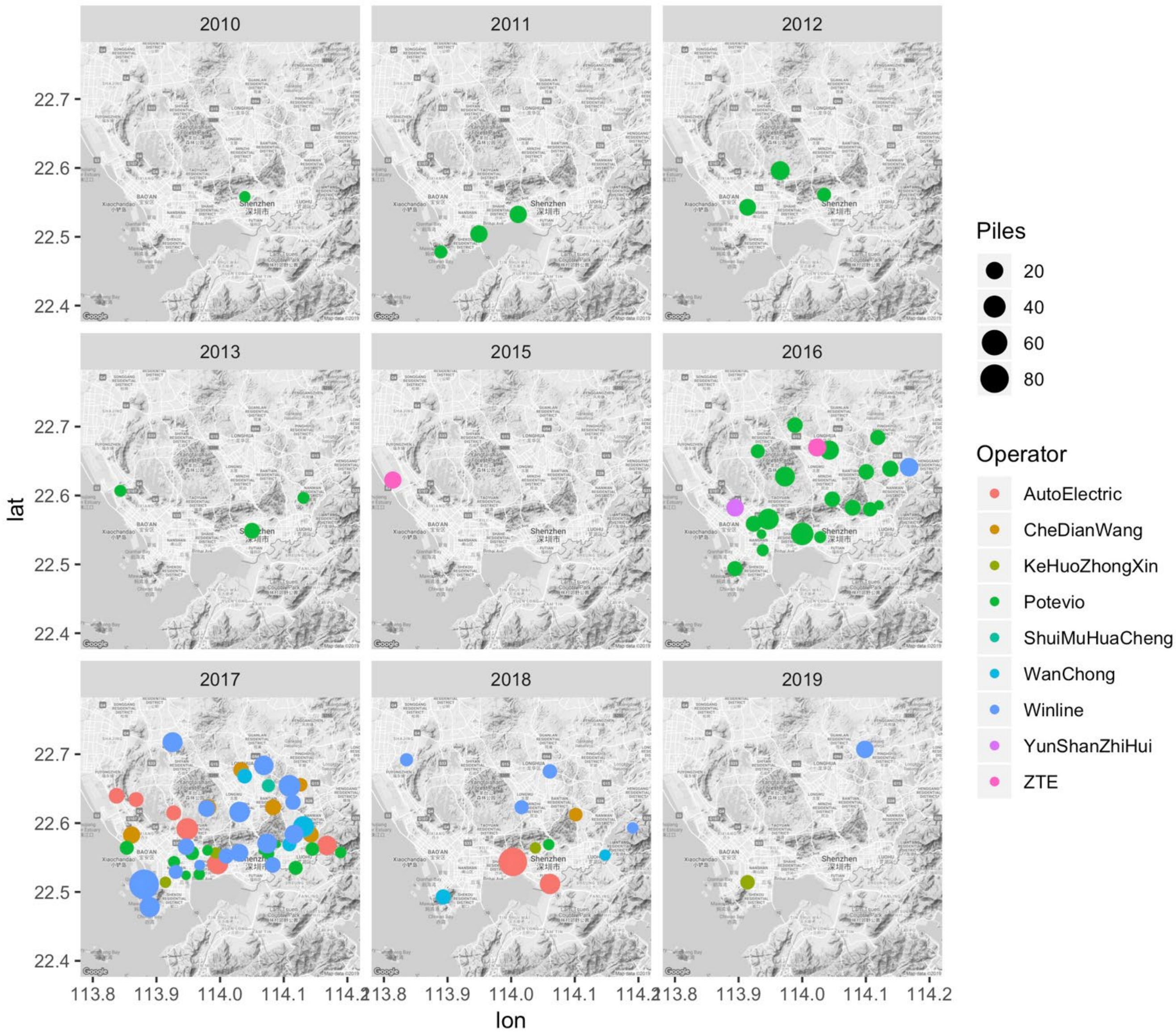
CK6100LGEV2	65.9%	BYD	K8	10.49	3990	2016–17	8
NJL6859BEV9	17.0%	NJL	NJL	8.49	1032	2016–17	5
BYD6100LLEV	6.7%	BYD	C8	10.20	403	2017	8
CK6120LGEV	4.8%	BYD	K9	12.00	291	2011–13	8
FDG6113EVG	3.5%	WZL	A10	11.49	210	2013	8
BYD6100LSEV	1.2%	BYD	Double Deck	10.49	70	2017	8
BYD6711HZEV	0.5%	BYD	BYD_7	7.10	33	2016–17	5
FDG6751EVG2	0.4%	WZL	WZL_7	7.50	24	2011	5

3.2.3 Large-scale electrification stage

Three batches of 1,600, 3,573 and 355 electric buses were procured between 2015 and 2017 completing the fleet electrification. SZBG became the first transit bus company worldwide with a 100 percent electric bus fleet with 6,053 buses on June 8, 2017. All the 16,539 buses across all the three bus-operating companies in Shenzhen were electric by the end of 2017.

SZBG first planned charging stations at bigger terminal stations serving multiple routes to provide service for buses running on several different routes. Longer routes and more frequent operation were provided with another charging station at the other terminal of the route. After several years of development of charging infrastructure, most of the routes now have access to at least one charging station at the terminal of each route.

Figure 3-6 SBG charging stations, available years and operators



Charging operators provide the construction, operation and management of the charging infrastructure. Potevio Group Corporation (PGC) and Winline Technology (Yonglian) are the two largest charging operators who provide most of the charging facilities for SBG. Potevio Group Corporation built and provided most of the charging stations for SBG. After 2017, more companies entered the market and built a significant number of new bus charging stations (Figure 3-6). Before construction of a charging station, SZBG communicates frequently with the charging facilities provider on the location, size, charging speed and charging capacity of the stations. SZBG pays the charging operators the electricity fees and a charging service fee.

3.3 Key Lessons: coordination and collaboration

One of the main challenges in urban mobility in cities in China is the lack of cross-agency communication and coordination. Departments within the same municipal government are often reluctant to share information, and sometimes compete for resources with overlapping responsibilities. Unlike traditional bus companies, bus manufacturers and gas stations who dealt with mature products and clear supply chains, the electric bus was new with unclear roles and responsibilities among players. With more sectors and players involved, the transition to electric public transport requires even wider scale of coordination and policy synergy. Uncertainties of the technology and supply chain as well as demand response also require a viable model for all stakeholders to collaborate.

Shenzhen's solution

Coordination: Shenzhen municipal government established the Shenzhen Energy Conservation and New Energy Vehicle Demonstration and Promotion Leading Group (SNEVLG) that engages all levels of its diverse stakeholders to actively participate through frequent deliberations to achieve consensus and cooperation among different parties towards the same goal—promoting NEV development.

Collaboration: Government, vehicle manufacturers, charging service providers, and bus operators collaborated closely through a viable business model with risks and costs allocated to the appropriate party. SBG's close dialogue with the transportation bureau, the development and reform commission, the state-owned assets supervision and administration commission put SBG's agenda to the forefront of policy development. Manufacturers provided extended warranties for the key parts of the electric buses especially the batteries. While increasing the purchase price of buses, it shifted the technology risk to manufacturers who have the highest technical capacity to manage such risks, so are incentivized to keep innovating and improving bus performance. SBG's close partnership with the bus manufacturer (for example, onsite supervision at manufacturing stage) and the charging service provider (service standard and depot renovation) proved to be critical in overcoming the technology maturity, financial, and operation challenges. SBG also collaborated productively with private enterprises and non-profit organizations including Tencent, Huawei, BYD, Didi Chuxing, the Urban Transportation Association, and Haylion Technology to explore innovations on intelligent dispatch systems, on-demand bus service, route optimizations, and autonomous driving technologies.

Public Consulting and Participation: SBG cares about the voice of the passengers. SBG conducts three types of activities to address their concerns. It initiated its first campaign called "Friends of the Bus" in 2010; an online and offline service where passengers can leave comments and take part in events such as focus-group forums and polls. SBG was able to make sure the comments from passengers were addressed efficiently using an online platform. SBG also regularly hosts offline events to get to know its passengers rather than as an impersonal stakeholder to whom they provide services. SBG also collects large datasets to understand their customers. SBG collected detailed traveling origin and destination data of its passengers and the bus operation with its intelligent dispatch system. SBG has the ability to analyze the demand and on-board occupancy to further optimize the routes and improve quality of service.

3.4 Economic analysis for Bus Electrification

Electric vehicles have gained much attention and are promoted by many countries, not only for their emission reduction potential, but also because of operational cost savings. Breetz and Salon

(2018) analyzed the TCO of battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), and internal combustion vehicles (ICEVs) in 14 metropolitan cities and found that the TCO of BEVs are still more expensive than the alternatives and concluded the government subsidy was essential for BEV deployment. Much of the literature finds that the initial capital cost of the EVs is higher, but the operational cost of energy and maintenance is lower than that of conventional fuel alternatives (Breetz and Salon, 2018; G. Wu et al., 2015). Our study investigates whether these findings extend to bus operation, by collecting actual financial and operational data from Shenzhen Bus Group, as SBG is one of the few bus companies with large-scale deployment since 2015, their results are particularly valuable to present more insights.

We estimate the TCO of bus operation, covering the capital cost, maintenance cost, energy cost, tax and fees, which happened over the lifetime of the Battery Electric Bus (BEB) and Diesel Bus (DB). Tornado analyses reveal how much each of the variables would affect the TCO results. Additionally, a Monte Carlo simulation helped analyze the effect of combined changes over multiple variables.

3.4.1 Bus TCO

The TCO model to compare the cost of ownership between a BEB and an equivalent diesel bus.

3.4.1.1 Selection of sample buses

Shenzhen is a megacity with more than ten million population. Urban bus transit services 4.2 million of passenger rides every day. The municipal government set eight years as the lifetime of heavy-duty transit buses to operate in Shenzhen to ensure reliability and safety of the bus's operation. In other countries, the lifetime of 12 years is more common for transit buses; and the effect of the bus's lifetime on TCO will be analyzed using sensitivity analysis. Eight years of lifetime and 66,000 km of annual driving distance were adopted in our analysis for both BEB and DB.

In this study, the BYD K8 (CK6100LGEV2) is an ideal choice to represent the BEB model, for it represents 66 percent in the SBG fleet after their shift to full electrification. Our study selected a comparable diesel bus model, the Yutong 10.5-meter diesel bus (ZK6105HG1A), as it also was SZBG's dominant model before electrification (Table 3-7).

Table 3-7 BEB and diesel bus model configurations

Bus picture		
Vehicle Model	CK6100LGEV2	ZK6105HG1A
Propulsion fuel	Battery electricity	Diesel National VI standard
Length (m)	10.490	10.500
Width (m)	2.500	2.500
Height (m)	3.150	3.050
Curb weight (kg)	11700	10300
Gross vehicle weight (kg)	18000	16500
Total maximum passengers or seats (including driver and passengers)[a]	87/32	95/32

Source: www.chinabus.com
Note: a. Seat numbers of 87/32 mean 32 seats, with a total passenger capacity (including standing passengers) of 87.

3.4.1.2 Replacement Rate

If a single BEB can accomplish the driving task of a diesel bus, the replacement rate should be one. The earliest BEB models (BYD K9 and WZL A10) were only adopted on specific routes with a shorter distance and not able to fully replace diesel bus trips. For regular routes, their estimated replacement rate was about 0.8. Today, SZBG's BEB fleet, mostly BYD K8, is able to cover all the routes through SBG's refined management and operation, resulting in a replacement of 1.

3.4.1.3 Bus TCO model

The TCO model reveals all the costs related to ownership and operation over the lifetime of a bus. The analyses use the following TCO equation:

Equation 3-1

$$\text{TCO} = Cost_{capital} + \sum_{t=1}^{T} \frac{Cost_{operation\_t}}{(1+r)^{t-1}} - \frac{ResidualValue}{(1+r)^{T}}$$

$$Cost_{operation\_t} = Cost_{tax\ and\ fees\_t} + Cost_{energy\_t} + Cost_{maintenance\_t}$$

Where:

- TCO is the present value of the total cost of ownership for the ownership period
- $Cost_{capital}$ is purchase cost, which can be paid one time at procurement or financed over the lifetime of the bus, and includes procurement tax and registration fees
- Residual Value is the resell price or scrappage value at the end of the ownership period
- $Cost_{operation\_t}$ includes the insurance and fees, electricity or fuel cost, and maintenance cost every year
- r is the yearly discount rate

- T is the period of total ownership

The TCO model presented in this study only includes the direct costs associated with bus use and ownership. The indirect costs are excluded, for example, deliberate scheduling efforts for BEB operation and charging, health benefits resulting from environment improvement and noise reduction. The labor costs of drivers, mechanists or technicians and refueling or recharging staff are also excluded.

3.4.1.4 Capital cost

As a corporate client, SBG receives bulk purchase capability and enterprise discounts. The price (Table 3-8) may not represent the market price for individuals or smaller bus buyers. Additionally, the national and local government provided generous subsidies to promote the adoption of electric buses during the procurement stage. The results are presented with and without subsidies to reveal its importance in comparing the TCO of the two technologies. Since the fiscal support is phasing out in China and does not exist in many other jurisdictions, the no-subsidy scenario is an essential reference for other cities.

Table 3-8 bus price and subsidies

	Bulk procurement contract price in 2016 (thousand yuan)	National Subsidy in 2016 (thousand yuan)	Shenzhen municipal Subsidy in 2016 (thousand yuan)	SZBG payment (thousand yuan)
BYD-K8	1580	500	500	580
Yutong diesel bus	508	0	0	508

SBG substituted all the diesel buses (5528 diesel buses) with BEBs in only two and a half years during 2015–17, however, procuring this volume of BEBs put a tremendous financial burden on the company. SBG worked with the leasing company and developed a financing plan to procure the buses. SBG procured the electric buses based on their demand and specification, and the financing leasing company paid for the BEBs to the manufacturers.[1] With the leasing plan, SBG pays the lease seasonally to the financing company with an annual interest of 4.16 percent over the eight-year lifetime of the buses. To represent the purchase cost and the subsidies, the study used annual payment at the end of each year to the financing company and converted the annual payment to consider the discount rate. The capital cost for diesel bus is assumed with the same financial plan and same interest and discount rate as the electric buses.

3.4.1.5 Operation cost

3.4.1.5.1 Energy cost

The annual energy cost in each year is the cost of fuel or electricity consumption.

Equation 3-2

$$Cost_{energy\_t} = Price_{energy\_t} \times EE_{energy\_t} \times Distance_{energy\_t}$$

EE_{energy_t} is the energy efficiency of fuel or electricity consumption per kilometer. The diesel price has fluctuated in the past years and the analyses used the average bulk purchase price of diesel at 5.09 yuan per liter.

The energy cost of BEB consists of the price of electricity and service fee. It could vary upon the ratio of charging time of the day (Table 3-9). SBG average charging ratio at peak, normal and valley was 12.5 percent, 24.1 percent, 63.4 percent, resulting in a weighted average price of 0.8576 yuan per kilowatt hour. With the variation of the electricity price of time of day and service fees, the analyses considered a range of energy cost of 0.6511 to 1.4476 yuan per kilowatt hour for the sensitivity analysis.

Table 3-9 Electricity Price at the time of the day

	Time of Day	Hours	Industry Electricity Price yuan/kWh	Service Fee yuan/kWh	Total yuan/kWh
Peak	9:00–11:30, 14:00–16:30, 19:00–21:00	7	1.0516	0.396	1.4476
Normal	7:00–9:00, 11:30–14:00, 16:30–19:00, 21:00-23:00	9	0.6991	0.396	1.0951
Valley	23:00–07:00	8	0.2551	0. 396	0.6511

Energy efficiency varies with buses running on routes that differ in speed, acceleration, the slope of the road, drivers' driving habits, and other factors. SBG provides training and peer competition for the bus drivers, encouraging them to improve the energy consumption for both BEBs and diesel buses (Table 3-10). The BEB energy consumption data in year one to four are based on the actual statistics from SBG, and the later four years are estimated constantly at the fourth year's level.

Table 3-10 Diesel and Electricity consumption efficiency

Energy consumption efficiency	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
Diesel bus (L/100 km)	37	38	38	38	38	38	39	39
BEB (kWh/100 km)	94	92	98	104	104	104	104	104

3.4.1.5.2 Maintenance Cost

Over the eight years of a bus's lifetime, diesel buses undergo scheduled regular maintenance every 20,000 kilometers to check the status of the bus, repair or replace small parts, fill up fluids, check and replace tires if needed, fix wear outs and prevent further malfunction. In the fourth year of operation, diesel buses receive overhaul maintenance to check the engine, chassis and body, and more thorough check and repair. Based on SBG's statistics, the average maintenance cost of a diesel bus is at 0.779 yuan per kilometer.

The electric engine and transmission components are far simpler in a BEB. Additionally, the BEB technology has improved since SBG adopted it in 2015, and as a result, the rate of malfunction dropped substantially. With greater confidence in their products, the BEB manufacturers provide eight years warranty for BEBs' 3-e system (electric control, electric motor, and batteries). This has led to significant lower maintenance costs, labor burdens, and on-campus repairs compared to diesel buses. The maintenance cost typically consists of tire replacement cost, and regular and advanced maintenance costs.

1) Tire replacement

Tire replacement cost for a diesel bus is about 90 yuan per 1000 kilometers. Tire replacements for BEBs are slightly higher at 125 yuan per 1000 kilometers for two reasons. First, the total weight of the vehicle is greater than diesel bus. Second, BEB has in-wheel electric motors playing a role in the propulsion and braking process, which wear down tires. As a result, the tire cost for the BEB is about 38.8 percent higher (SZBG).

2) Regular maintenance

During regular maintenance for diesel buses, a maintenance crew performs a series of tasks including an oil change, tire rotation, transmission fluids refill, brake fluids refill, as well as checking or replacing a variety of mechanical parts.

Maintenance for BEBs is substantially lower because of the simplicity of the technology. The most essential parts are the electronics—the battery, the electric motor, and the electronic controllers—and are included in the manufacturer's complimentary warranty contract, and provide coverage over the entire operating period of the bus. Technicians from SBG estimate that the regular maintenance cost has dropped from about 600 yuan per 1000 kilometers for diesel buses to 200 yuan per 1000 kilometers for BEBs.

3) Overhaul maintenance

Overhaul maintenance for the diesel buses is scheduled at the end of the fourth year of each bus's operation (average mileage at 260,000 km). The process includes testing and repairing the engine, air conditioner compressors, and bus body. The tests also cover the braking system, usually replacement of the oil seal; the transmission system, replacing the clutch and driveshaft; the electronic system, replacing the generator, and lighting lines; the power system; and the malfunctioning parts of steering system, knuckle, and booster. The overhaul maintenance costs for a diesel bus are around 160,000 yuan on average (about 30% of the capital cost).

The manufacturer provides a lifetime warranty for the motor, battery, and electric control systems for BEBs. The bus body also consists of aluminum alloy instead of steel, which does not need to be replaced over its lifetime. Therefore, BEBs do not require overhaul maintenance schedule. Based on data from SBG, for the first four years of operation, the maintenance cost of BEBs can be as low as 17 percent of the diesel bus's maintenance cost. However, the maintenance cost increases gradually the next four years. Similar to the energy efficiency data, the analyses here used the actual data of diesel buses and first four years for BEBs (Table 3-11), and made a conservative estimation for BEBs in years 4–8 with an increase rate of 20 percent. Additionally, the Monte Carlos simulation in the sensitivity analyses consider a 20 percent and 100 percent of diesel bus's maintenance cost as BEB's maintenance cost as the boundaries.

Table 3-11 Maintenance cost for diesel buses and BEBs

Maintenance Cost (yuan/1000 km)	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
Diesel bus	318	476	502	2706	546	567	581	541
BEB	75	152	211	242	290	348	418	501

3.4.1.6 Operation subsidies

Transit bus operation relies heavily on the municipal government subsidy for its operation. The Shenzhen Municipal Transportation Commission (SMTC) provided SBG 244,000 yuan per diesel bus per year for operational subsidy. The subsidy was mainly used for the overheads of SZBG, and thus are not included in the bus TCO calculation. SMTC provides 422,700 yuan per BEB each year of operation with annual mileage of no less than 64,000 kilometers.

3.4.1.7 Other costs and variables

3.4.1.7.1 Taxes and Fees

With the governmental incentive policies, the purchase tax and other taxes are waived for transit buses and for new energy vehicles (NEVs); however, SBG still pays mandatory liability insurance of vehicle traffic accident of 3,140 yuan and commercial vehicle insurance of 2,100 yuan every year and operation fees of 804yuan per bus. These taxes and fees are the same rate for BEBs and DBs.

3.4.1.7.2 Discount rate

The typical adopted discount rate in literature lies between 1 and 15 percent. To represent the opportunity cost, the analyses used the discount rate of seven percent for the baseline analysis, with a range between 3 and 11 percent considered in the sensitivity analysis (Table 3-12).

Table 3-12 Variables and range adopted in TCO literature

		Vehicle Type	Data and Methodology	Region	Discount Rate	Life year analyzed	Annual Distance
Passenger Vehicle	(Breetz and Salon, 2018)	PHEV, BEV, ICEV		14 states in the USA	7% for baseline, 5%, 10%, 15% for sensitivity analysis	5	Varied on average VMT (Vehicle Miles Traveled) of the states
	(Palmer et al., 2018)	PHEV, BEV, ICEV		Japan, the UK, and California, and Texas in the USA	3.5–4% for baseline, 2-11% for sensitivity analysis	3	Varied on region, range of 6,213-15,641 miles
Bus	(Nurhadi et al., 2014)	BEB with different battery size and charging speed	Scenario analysis	Norway	1%	8	93,000 km
	(Lajunen and Lipman, 2016)	BEB, Plug-in Hybrid Bus, CNG bus, Fuel-cell Bus	Simulation	California, USA and Finland	4%	12	None
Bus	This study	BEB, Diesel bus	Real practice data	Shenzhen, China	7% for baseline, 3–11% for sensitivity analysis	8	66,000 km

3.4.1.7.3 Residual Value

After their lifetime, buses are phased out from the fleet. Typically, the residual value of a diesel bus and BEB is assumed as 5 percent of the original purchase price.

3.4.2 TCO results

Without purchase subsidy, the present value of lifetime total cost of BEB would be 2.02-million-yuan, 21 percent higher than diesel buses' total cost of 1.67 million yuan. With government subsidy, the total cost of BEB would be 1.07-million-yuan, 36 percent less than that of diesel buses (Table 3-13, Figure 3-7).

Table 3-13 Present Value of Diesel bus and Battery Electric bus

	DB	BEB	BEB_subsidy

Capital (k Yuan)	549.15	1707.99	626.98
Energy (k Yuan)	919.46	435.30	435.30
Maintenance (k Yuan)	371.60	129.24	129.24
Tax and fee (k Yuan)	43.70	43.70	43.70
Residual (k Yuan)	-20.65	-64.23	-23.58
TCO Present value (k Yuan)	1863.26	2251.99	1211.64
TCO per kilometer (Yuan/km)	3.53	4.27	2.29
TCO/km to Diesel bus	100%	121%	65%

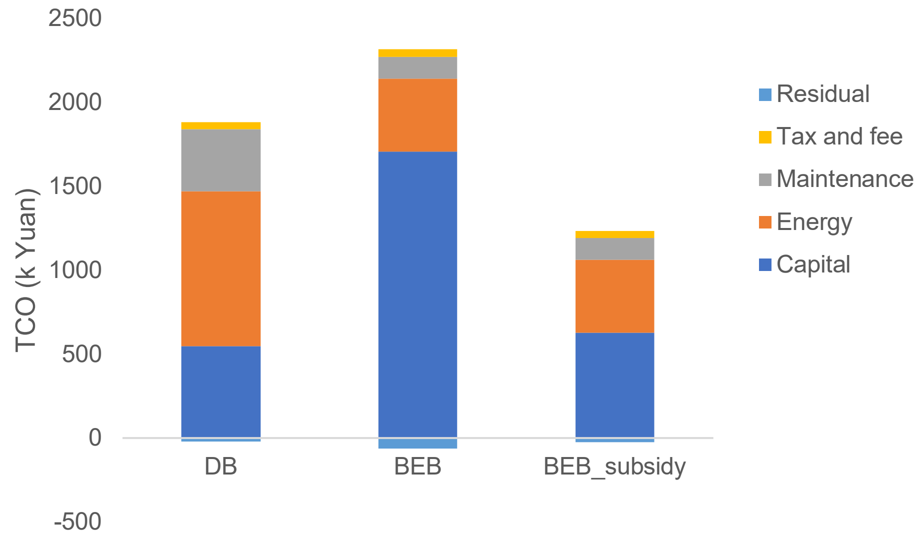


Figure 3-7 Value of the composition of the bus costs in 2019

Table 3-14 TCO results compared with results from literature

Studies		Bus setting	Original Results		Transformed Results	
This study, 2020		Diesel bus			3.53	(¥/km)
		Electric bus with purchase subsidy, without charger			2.29	(¥/km)
		Electric bus without purchase subsidy, without charger			4.27	(¥/km)
(Lajunen & Lipman, 2016)	Finland cycle	Diesel bus	0.75	(€/mile)	9.34	(¥/km)
		Electric bus without charger	0.95	(€/mile)	11.83	(¥/km)
		Electric bus with charger	1.05	(€/mile)	13.07	(¥/km)

USA_ CA cycle	Diesel bus	1.70	($/mile)	19.04	(¥/km)
	Electric bus without charger	2.10	($/mile)	23.52	(¥/km)
	Electric bus with charger	2.30	($/mile)	25.76	(¥/km)
Nurhadi et al., 2014	Electric bus 1 extra battery and 1 normal charger	8.44	(SKr/km)	11.56	(¥/km)
	Hybrid bus	11.23	(SKr/km)	15.39	(¥/km)

Results of Shenzhen case are compared with other TCO results of BEB road cycles operations in Sweden, and simulated TCO with the road cycles in Finland and California (Figure 3-7 Value of the composition of the bus costs in 2019

Table 3-14). Our results are lower than of other research results, mainly because of lower BEB prices and generous government subsidy, lower maintenance cost and non-extra battery cost because the lifetime warranties by the BEB companies and other savings.

3.4.3 TCO sensitivity and uncertainty analysis

1) ***Sensitivity analysis*** helps diagnose the most important variables that affect the results of the TCO analysis.

The tornado plots in Figure 3-8 and Figure 3-9 show the results of the variables affecting the TCO of diesel bus and BEB with purchase subsidies.

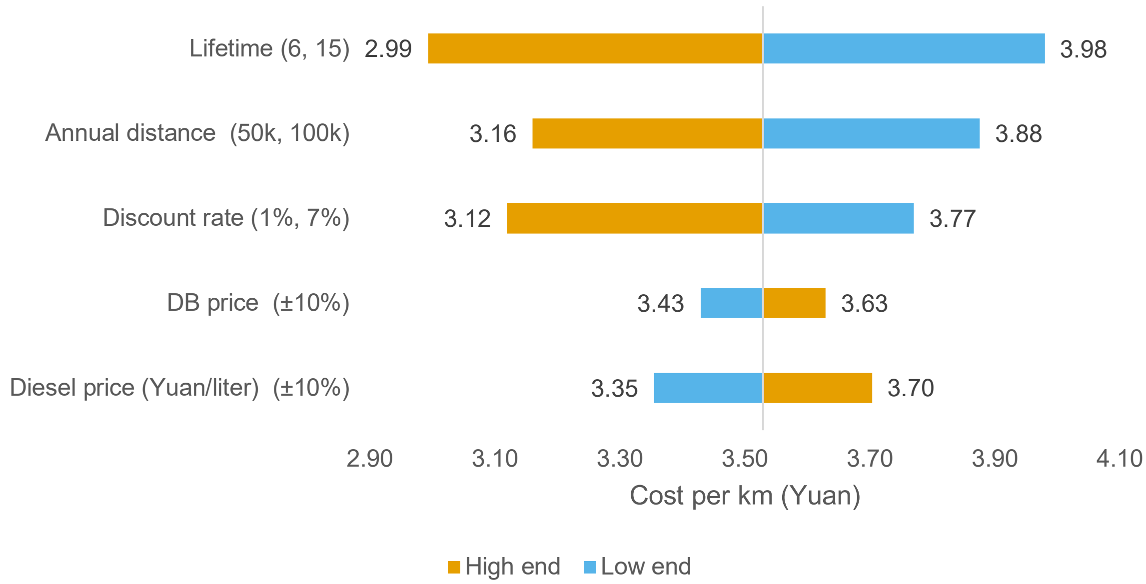


Figure 3-8 Variables that affect the Diesel Bus TCO per kilometer

The increase of lifetime, annual driving distance and discount rate will bring down the per kilometer cost of the diesel bus operation of more than 10%, and a ten percent increase in the bus price or diesel price will increase the unit cost with less than 5%. TCO per kilometer changes most with our variation setting of a bus operation's lifetime. If the length of operation decreases from eight to six years, TCO per kilometer will increase 12.8 percent to 3.98 yuan; if the lifetime extends to fifteen years, TCO per kilometer will decrease 15.2 percent to 2.99 yuan. The increase of annual driving distance will bring down the share of capital costs per kilometer. As a result, increase the yearly operating distance to 100k km will decrease the TCO per kilometer to 3.16 yuan, and a shorter yearly distance of 50k km will increase the TCO per kilometer to 3.88 yuan. The discount rate of one percent results in a unit TCO result of 3.77 yuan, and a seven percent discount rate will bring down the TCO to 3.12 yuan per kilometer. A ten percent increase in diesel price will result in a TCO per kilometer to 3.70 yuan, while a ten percent decrease in the diesel bus price will bring the TCO per kilometer to 3.35 yuan. That happens because the energy cost consumes 49.3 percent in TCO, higher than that of capital cost at 29.5 percent (Figure 3-9).

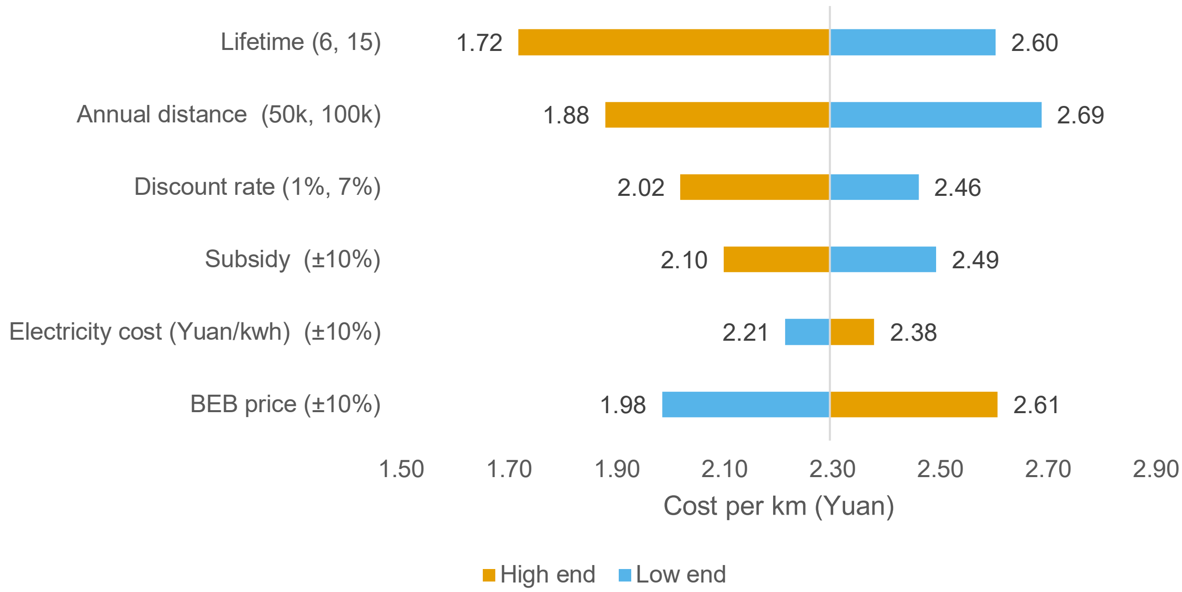


Figure 3-9 Variables that affect BEBs TCO per kilometer with subsidy

The BEB TCO per kilometer results mirror those of the diesel bus costs with fluctuations in the variables. Increase in the bus prices and electricity would raise the TCO per kilometer, and an increase in the operating lifetime, annual driving distance, discount rate, and subsidy amount would decrease the TCO per kilometer. Should the working lifetime decrease from eight years to six years, would make the TCO grow from 2.29 to 2.60 yuan. Extending the lifetime to fifteen years and with the BEB companies to continue the lifetime warranties, would result in the cost per kilometer a 25% decrease to 1.72 yuan. Extending the annual driving distance to 100k km would bring down the cost per kilometer 18% to 1.88 yuan. 10% increase of the bus price would result in a 13.6% increase in the unit cost. With a discount rate of 1% would bring a 12% decrease of the per kilometer cost. Another 10% subsidy would bring down the unit cost 8.6% down to 2.10 yuan. A 10% variation of the electricity cost would result in a 3.6% of the per kilometer cost (Table 3-9).

2) Uncertainty Analysis

As mentioned, the analyses employed a Monte Carlo (MC) simulation to illustrate changes in the TCO when parameter changes are considered simultaneously for carious cost items (Table 3-15). The triangular distribution is a simplified representation of normal distribution, which sets the base the highest probability, and together with the minimum and maximum numbers, determine the shape of the variable distribution. The uniform distribution represents that the variable has an equal likelihood in the assumed range. The analyses consider these two types of distributions. Figure 3-10 and Figure 3-11show the results of the simulations and show the resulting TCO distributions.

Table 3-15 Monte Carlo Distribution settings for Diesel Bus and BEB

	Minimum	**Base**	**Maximum**	**Distribution**
Diesel price (yuan/L)	4.0	5.09	6.0	Triangular
Electricity price (yuan/kWh)	0.65	0.86	1.45	Triangular
Annual mileage (1000 km)	50	66	100	Triangular
Discount Rate	1%	3%	7%	Uniform
Lifetime (year)	6	8	12	Triangular
Fuel Efficiency (L/100 km)	34	37.9	42	Triangular
Energy Efficiency (kWh/100 km)	80	107	120	Triangular
Maintenance BEB or Diesel bus	20%	36%	100%	Triangular

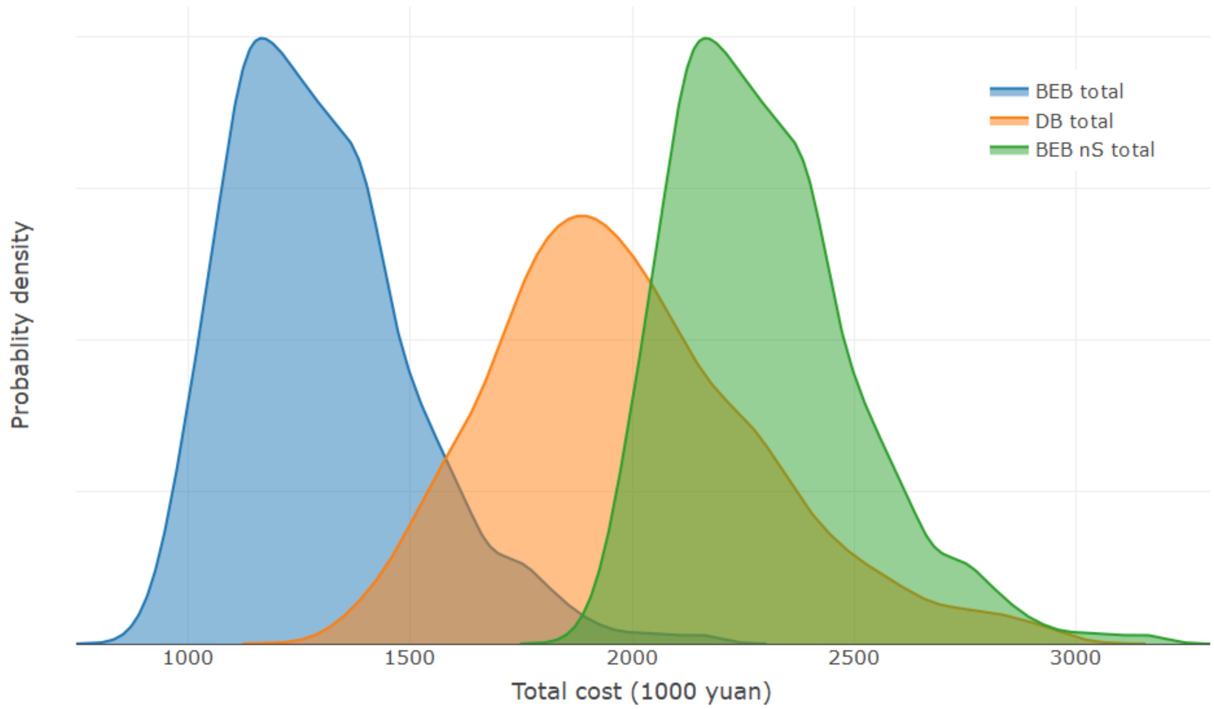


Figure 3-10 Total Cost Distribution

Note:

Diesel bus total refers to its TCO, BEB total refers to its TCO with subsidy, BEB nS total refers to its TCO without subsidy.

The diesel bus TCO distribution sits between the BEB TCO with and without subsidy, which echoes the results in the baseline analysis. The total cost of a diesel bus is between 1.12 to 3.15 million yuan, the cost of a BEB is between 0.75 to 2.30 million yuan with the subsidy and between 1.75 to 3.30 million yuan without the subsidy.

The energy cost and maintenance cost of diesel bus are 49 percent and 20 percent of its TCO respectively, and the total distance of the bus operation over its lifetime varies accordingly with the assumptions of a lifetime, annual driving distance, and diesel price. As a result, the TCO of the diesel bus has a wider distribution in the Monte Carlo analysis. With a longer annual distance and longer operation lifetime (on the right side of the curves), there is a high probability that BEB even without subsidy would have comparable or lower TCO than DBs (Figure 3-10).

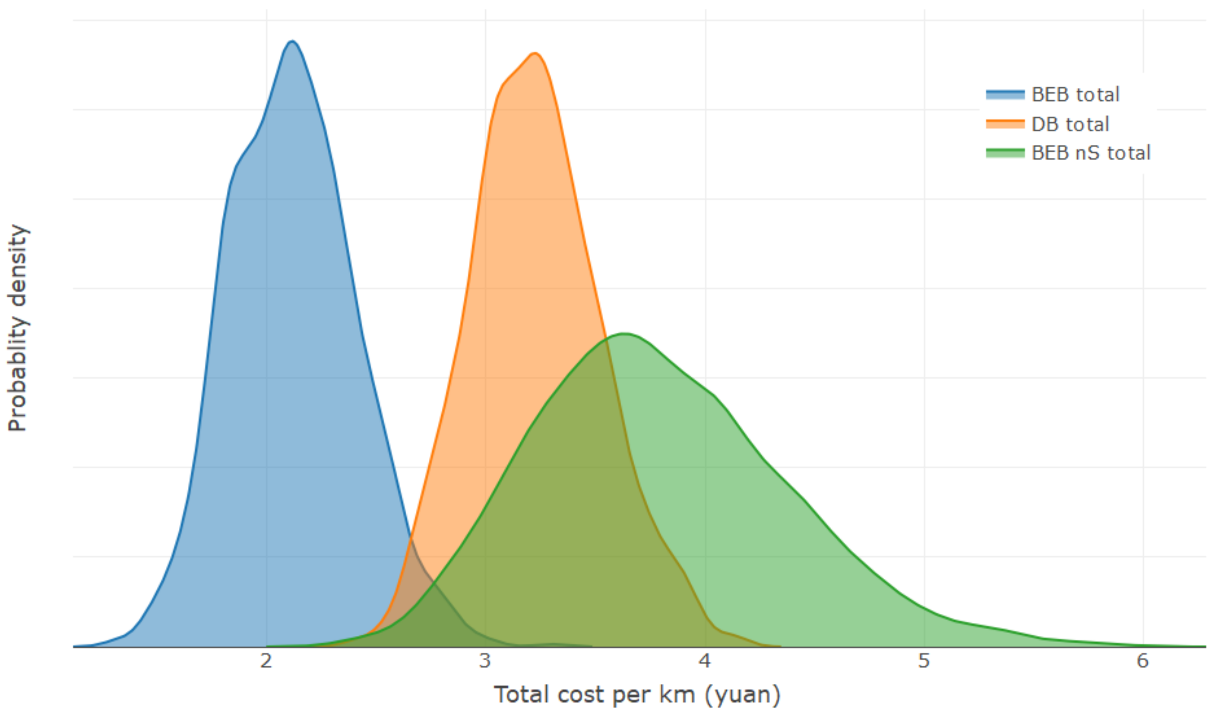


Figure 3-11 Unit cost Distribution (per kilometer)

The total driving distance contributes to the wider distribution of the diesel bus's TCO, while in the per kilometer analysis, the variation in the total driving distance cancels out in the differences of the unit cost. As a result, per kilometer costs for the diesel bus have lower variation compared to the total cost, but augment the fluctuations in diesel price, discount rates, and other variables.

However, in the BEB per kilometer costs, the TCO is significantly affected by assumptions regarding driving distances. As a result, the per-kilometer cost of BEBs without subsidy has greater variation than those observed in the total cost.

However, from the MC results, there still high probability that the unit cost of BEBs without subsidy would be comparable or lower than that of the DBs (Figure 3-11).

3.5 Charging Infrastructure TCO

Before the electrification of their bus fleet, SBG owned two gas stations with several vehicles to provide fuel for their diesel buses. SBG also hired specialized staff to fuel the fleet. For BEBs, the charging service providers bear the cost of the construction and operation of the charging station with qualified staff, and the bus company pays only the electricity cost and service fees associated with charging. One hundred and four charging stations with a total of 1,707 charging terminals were built to serve the BEB fleet by the end of 2018.

This study estimates the total cost from the perspective of the charging station owner. The total cost comprises costs of construction of the charging station, the high- and low-voltage lines and devices for transmitting electricity to the charging station, the cost of chargers, land rental, operation of the charging station, and the residual value of the charging station after its service life. The revenues of the charging station owners are the service fee paid by SBG.

Many factors affect the size of charging stations, such as land availability, charging demand at different locations, speed of charging terminals, and grid capability. This study assumed a typical charging station to contain 20 charge terminals rated at 150 kilowatts and 40 bus parking spots. An electric bus (i.e., BYD K8) can be fully charged over two hours at a rate of 150 kilowatts. The buses charge between 23:00 and 05:00 hours, off-peak hours in Shenzhen, and we assumed the serving capacity of the charging station to be 60 buses every day.

Access to land has become increasingly challenging in Shenzhen because of a combination of lack of available land and electricity capacity in the distribution grid. Any new charging station requires significant power grid infrastructure upgrades to increase its capacity. Over the period 2016–18, safety requirements of transformers became significantly more intense, which consequently increased construction costs. Previously, the charging station company could employ a simple container-type transformer, which was flexible and had no requirements for housing. However, newer rules require transformers to be properly housed, necessitating both land ownership, and concrete and permanent constructed facilities.

The main stakeholders in the charging business in Shenzhen comprise utility companies, charging station manufacturers, charging service providers, and landowners. This study used data from SWT, a charging service provider who also is a charger manufacturer, thereby facilitating relatively lower costs for stations' initial investment and maintenance.

Figure 3-12 Liuyue Charging station operated by Winline

a. (upper-left) BEB at charging dock; b. (upper right) Charging operated by professional charging staff wearing protective glove; c. (bottom) BEBs line up in charging station docks.

3.5.1 Infrastructure TCO model

Estimates of the TCO of the charging station included initial capital cost, operation cost, and residual value.

Equation 3-3

$$Cost_{total} = Cost_{initial} + \sum_{t=0}^{T} \frac{Cost_{operation\_t}}{(1+r)^t} - \frac{ResidualValue}{(1+r)^T}$$

$$Cost_{initial} = \sum_{j} (n_{Pile_j} * Cost_{Pile_j}) + Cost_{construction} + Cost_{electricitypowerincrease}$$

In year *t*,

$$Cost_{operation\_t} = Cost_{LandRent} + Cost_{labor} + Cost_{maintenance}$$

3.5.2 Initial Investment

3.5.2.1 6.3.2.1 Construction and grid connection

Existing bus parking lots could be transformed into a charging lot simply by installing the chargers. A newly constructed charging station would include the construction of the pavement, office, and chargers. Advanced structures like a roof could be built to protect the buses from rain. A solar roof was constructed in some stations to charge the buses with clean electricity.

In the case of a sample charging station with 40 bus parking spots within 10,000 square meters in area, 300 square meters were allocated to the charging facilities and related housing. Twenty 150 kilowatts DC fast charging terminals with 40 charging plugs were installed. The construction costs included high-voltage cable and equipment, low-voltage cable and hardware, charging terminals, safeguard and fire prevention devices, and other miscellaneous civil works construction expenses (Table 3-16).

Table 3-16 Cost Structure of a Charging Station Construction

	Expenses (million yuan)
High-voltage cable and equipment	2.18
Low-voltage cable and equipment	1.59
Charging terminals	1.62
Safeguard and fire prevention devices	0.19
Construction expenses	2.10
Total	7.68

Often, the high voltage and electricity demands of the charging station exceed the capacity of the existing regional grid. The local grid company must upgrade the distribution network and transformers to accommodate the charging stations. In some cities, this service is a significant cost and constitutes a significant portion of the total cost (Xiong et al., n.d.). In Shenzhen, the grid company upgrades the network, and the charging service providers pay for the costs.

3.5.2.2 Charging terminals

The cost of charging terminals has been steadily decreasing over time from about 750 yuan per kilowatt in 2016, to 450 yuan per kilowatt in 2019. Since most of the charging terminals were constructed in 2016 and 2017, we assume the average cost of charging terminals is approximately 700 yuan per kilowatt.

3.5.2.3 Municipal subsidy

The municipal government provides a subsidy for the construction of charging stations. For DC fast-charging stations, the municipal government provided a subsidy of 300 yuan per kilowatt in

2016, and increased it to 600 yuan per kilowatt based on the total power of the charging station in 2017 and thereafter.

3.5.3 Operation Cost

3.5.3.1 Land Rental

Historically, SBG experienced a shortage of bus parking lots. Before full electrification, about half of the diesel buses parked on the streets during nighttime. However, BEB required enough parking spaces to be built to accommodate charging during night time. Therefore, more bus parking lots had to be built, equipped with charging facilities to meet the demand. The charging service providers and bus companies worked hard to expand parking and charging facilities. Some of the parking lots and charging stations only have the temporary land-use permits by leasing, instead of ownership of lands, which leads to higher risks of operation if lands were to be withdrawn by owners for other purposes.

The average monthly land rent in 2016 varied between 10–100 yuan per square meter based on their locations. Our study assumes a base rate of 30 yuan per square meter. In this case, twenty 150 kilowatts charging terminals and related housing are estimated to occupy about 300 square meters land, for which the charging service provider absorbs the cost of rent.

3.5.3.2 Labor

Unlike private electric passenger vehicles, charging is not performed by the driver but rather by specialized electricians at the bus charging stations to minimize safety risks. On average at Winline Technology, the labor allocation is approximately one-seventh to one-tenth electrician per charging terminal, working three shifts per day, and amounted to four staff members with an annual labor cost of about 288,000 yuan.

3.5.3.3 Repair and maintenance

During our interviews, it was revealed that the repair and maintenance costs were about 3,000 yuan per charging terminal every year. The repair and maintenance costs for 20 charging terminals in this case would approximate to 60,000 yuan annually.

3.5.4 Lifetime and Residual value

Factors that affect the lifetime of the charging stations include the availability of land, the length of time to construct the charging station, and the lifetime of cables, devices, and chargers. In Shenzhen, the most challenging issue affecting the lifetime of the charging station is land access.

Typically, the designed life of a charger is eight to ten years. Our study assumed that the charging station has permanent land availability, and that the lifetime of charging terminals is eight years. It is to be expected that after eight years of operation, the cost and the technical configuration of the charging terminals could also change substantially on account of technology evolution, and the charging terminal devices would be replaced with zero residual value. But the cables or tunnels and transformers have a design life of about thirty years with appropriate maintenance. The residual value of the assets at year eight is estimated at 50 percent of the original capital cost.

3.5.5 TCO results

The total cost of a charging station with 20 charging terminals of 150 kilowatts is 7.30 million yuan at a seven percent discount rate. The cost of cables, initial construction, and labor costs are the largest three contributors to the total cost, followed by cost of the charging terminals, land rental, maintenance and supporting devices (Figure 3-13). The subsidy from the government canceled the charging terminal cost, which relieved the burden for the investors at the initial stages. Distributing the total costs over the 60 buses it services, the value of charging terminal cost is 121,000 yuan per bus.

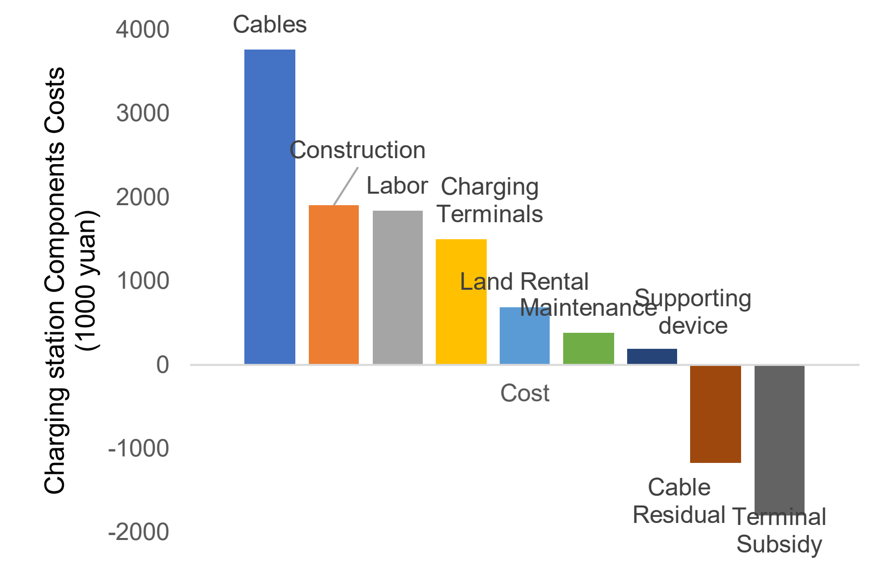


Figure 3-13 Value of Charging Station Cost Components in 2019

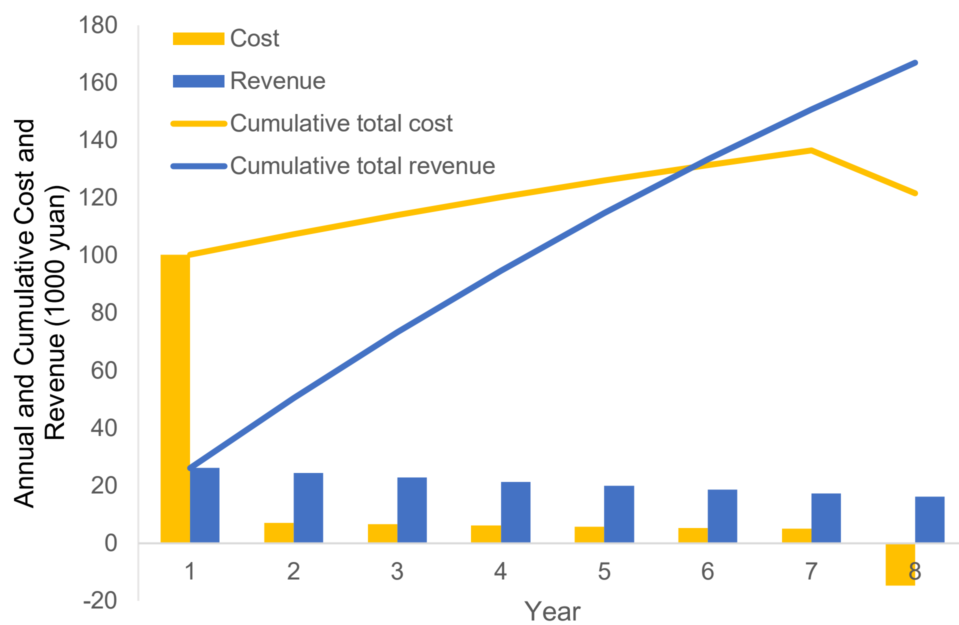


Figure 3-14 Yearly and Cumulative Costs and Revenues for each Bus Charging

The charging station operator can get about 37 percent revenue return over eight years[2] when comparing the present value of service fee per bus over eight years of 176,000 yuan. It would take six years to get back the original investment in our assumption of each charging terminal serving only three buses a day (Figure 3-14). The payback period could shorten to 4–5 years taking the cable's residual value into account.

3.5.6 Discussion

In Shenzhen's massive replacement of the BEB process, government incentives and the manufacturer's full lifetime warranty played a significant role in making BEB's TCO lower than the diesel fleet for the bus operating company. The development and evolvement of BEB technology made it possible to replace the diesel bus with 1:1 ratio. With the technology development and massive production, the TCO of BEB will drop steadily in the following years, making it more comparable with the TCO of a diesel bus.

Lower energy costs and lower maintenance costs could save the transit bus operation company a great amount of money through the operation years of BEBs. With the passenger trips shifting from bus to metro service, bus routes get modified from longer commuting routes to shorter ones, serving more as feeder lines connecting the metro stations with business centers and residential communities. As a result, the annual driving distance is envisaged to decrease further for urban buses. From our analysis, a longer driving distance could improve the cost efficiency of BEBs, and we would recommend that the bus companies extend the lifetime of the buses and extend the warranty with the BEB manufactures to capture more benefits from BEBs.

The charging service providers invest heavily on the charging infrastructure. With the government subsidy at the early stage, charging service providers would need four to five years, on average, to get return on their investment. The charging stations at bus parking lots serve only BEBs. However, with better operation arrangements, the bus charging stations have the opportunity to provide charging services to electric taxies, electric logistic vehicles and private EVs when vacancy arises, to increase profits from service fees. Land availability for charging stations still remains as one of the key issues in Shenzhen and requires the careful planning and implementation of land use for urban areas.

3.6 E-bus cost-benefit estimation

Criterial air pollution (CAP) emissions from diesel bus operation and power generation can harm human health, impair visibility and damage building. Greenhouse gas (GHG) emissions from transport accelerate global warming and its negative impacts on the planet. When evaluating the adoption of new technologies like Battery Electric Buses, cost-benefit analysis helps to present its social and environmental benefits making them comparable to traditional technologies which often have lower upfront costs but high external cost due to CAP and GHG emissions. When analyzing alternative technologies, the avoided emissions are the benefit of the implemented environmentally friendly alternative.

The damage cost approach uses a multi-step damage function to analyze the effects on air quality from pollutant emission, the relationship between air quality and health effects, causality of population exposure and population characteristics, the morbidity and mortality caused by the air pollutants, and statistical life value to monetize damage caused. As each step involves uncertainty and assumptions, cumulatively they the results show high levels of variability. Therefore, the result is usually presented with a wide range, while the high end can be very high due to high statistical life value assumptions based on local salary levels for example.

Two other widely adopted damage valuation methods are hedonic pricing and contingent valuation. In hedonic pricing, the environmental damage of an activity is estimated through a proxy, e.g. housing price. In contingent valuation, the willingness to pay (WTP) of the specific environmental benefit is surveyed and evaluated considering demographic characteristics of the surveyed population.

This study calculate the life-cycle CAPs and GHGs emission benefits of BEB based on the cost analysis and environmental estimation. We include CAPs of $PM_{2.5}$, PM_{10}, NO_x, VOC, and SO_2; and GHGs of CO_2, CH_4, NO_2 in CO_2e.

3.6.1 CAPs and GHGs

We consider two strategies for assessing the CAPs and GHGs damage costs. While GHGs emissions accumulate in the atmosphere warming the planet, CAP emissions are relevant for local air pollution. Therefore, we adopt global GHG marginal cost in the estimation, to account for its impact on climate change.

CAP valuation, on the other hand, should be based on local air quality impacts, city population characteristics, and statistical life value for residents. Shenzhen is leading in Chinese cities on air quality and air emission control. From 2014 to 2019, as shown in Figure 3-15, the annual average pollutant concentrations in Shenzhen are better than most Chinese cities and have been dropping for $PM_{2.5}$, PM_{10}, NO_2, and SO_2. Considering the air quality and residents' income in Shenzhen, we adopt the EU 28 countries' average damage cost for CAPs for Shenzhen.

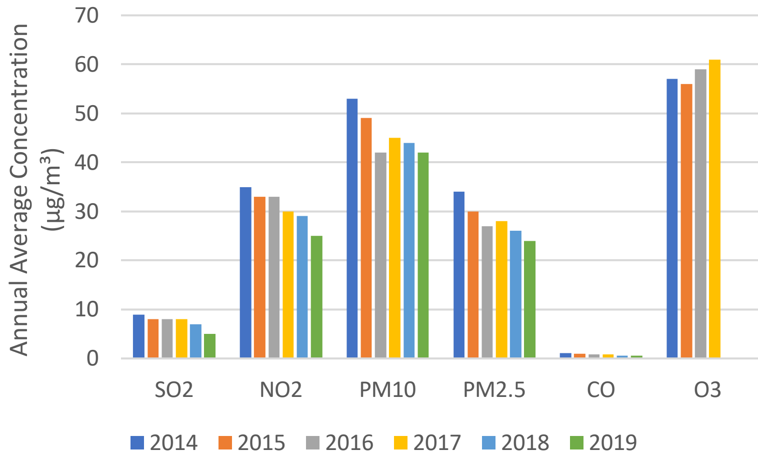


Figure 3-15 Annual average air quality in Shenzhen during 2014-2019[4]

Based on analysis from the IPCC, the UNFCCC Paris Agreement states that world temperature should not increase more than 2 degrees in 2100 compared to the pre-industrial levels and strong efforts should be made to stay within 1.5 degrees.

China is a signatory to the Paris Agreement and has made a commitment to reduce its GHG emissions. Shenzhen is one of the seven pilots for carbon trading markets in China. In 2019, the trading price of carbon on the Shenzhen market was 20-30 CNY/ton ($2.86-$4.29/ton) (H. et al., 2019), much lower than the amount from the US and the EU.

GHG emissions are global externalities. In order to capture social benefits from reduced GHG emissions or costs from increased emissions in economic analysis, shadow price of carbon is adopted in GHG accounting in the World Bank financed projects[5]. Instead of a central estimate, a range of values is used to justify the uncertainty and the need to consider country context. From

[4] The O_3 statistic record changed from annual average concentration to 90 percentile concentration in and after 2017 and not included here.
Source: Shenzhen Ecology and Environment Bureau, Shenzhen Environmental Status Bulletin 2014-2019, http://meeb.sz.gov.cn/xxgk/tjsj/ndhjzkgb/
[5] Guidance notes on shadow price of carbon in economic analysis. The World Bank, Nov 12, 2017

2017 to 2050, the lower value of shadow price of carbon ranges from US$ 37 to 78 per ton CO_{2e} and higher value from US$75 to 156 per ton CO_{2e}, as shown in Table 3-19.

3.6.2 Marginal cost for damage estimation

marginal damage costs of CAPs and GHGs from literatures.

Table 3-17 Marginal costs from literature

Price	**Unit**	**NO_X**	**VOC**	**$PM_{2.5}$**	**PM_{10}**	**SO_2**	**CO2e**
(Tong et al., 2017)	2015$/ton	5,422	25,912	270,596		84,823	41
		13,309	NA	272,885		27,439	
EU28	€/kg	21.3	1.2	381	22.3	10.9	
	$/ton[6]	23,856	1,344	426,720	24,976	12,208	
WB guidance	$/ton						37-75 in 2017; 75-156 in 2050
Shenzhen carbon price, 2019	¥/tonne						20-30

The study uses the European Commission (Schroten et al., 2019) EU 28 average data for the CAP externality estimation, as listed in Table 3-18 and Table 3-19. The analyses adopt the range of CO2e price from 2017 to 2024 from the World Bank Guidance, in the eight-year life cycle of BEB.

Table 3-18 CAP cost from EU 28

Unit	**NO_X**	**VOC**	**$PM_{2.5}$**	**PM_{10}**	**SO_2**
$/ton	23856	1344	426720	24976	12208

Table 3-19 Shadow price of carbon (US$/tCO2e)

[6] We adopted exchange rate of €1=$1.12, and $1= ¥7.00

Year	2017	2018	2019	2020	2021	2022	2023	2024
Low	37	38	39	40	41	42	43	44
High	75	77	78	80	82	84	86	87

3.6.3 Emissions and benefits

The yearly emission from BEB and DB are shown in Table 3-20. The total benefit of avoided CAP is US$ 102,453, in which 61.9% is from NOx reduction, 21.9% is from PM2.5 reduction, 14.6% from GHG reduction.

As shown in Figure 3-18, including the environmental costs, the total cost of operating with DB would be higher than that of BEB. That demonstrates the justification of the fleet electrification.

The total subsidy SBG received from the national and local governmental for one bus was one million CNY (equivalent to about US$ 0.15 million) in 2016. The benefits from CAPs and GHGs are 30% less than the subsidy. The social environmental benefit is lower than the government investment. It indicates the government could lower the subsidy for the BEB promotion.

Table 3-20 Estimated air pollutant and economic benefits for the bus fleet

Pollutant	NO_X	VOC	$PM_{2.5}$	PM_{10}	SO_2
Diesel bus (ton/year)	0.375	0.004	0.007	0.012	0.002
E-bus (ton/year)	0.007	0.000	0.000	0.000	0.008
Difference (ton/year)	0.368	0.004	0.007	0.012	-0.006
US$ per year	8772.9	5.1	3098.0	290.8	-71.5
US$ per 8 years (i.e. life cycle) (with discount rate of 3%)	63430.8	37.2	22399.3	2102.4	-517.3

Table 3-21 Estimated GHG emissions and economic benefits for the bus fleet

Year	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
Low	1267	1301	1335	1370	1404	1438	1472	1506
High	2568	2636	2671	2739	2808	2876	2944	2979
US$ per year	1917	1969	2003	2054	2106	2157	2208	2243
US$ per 8 years (i.e. life cycle) (with discount rate of 3%)	15001							

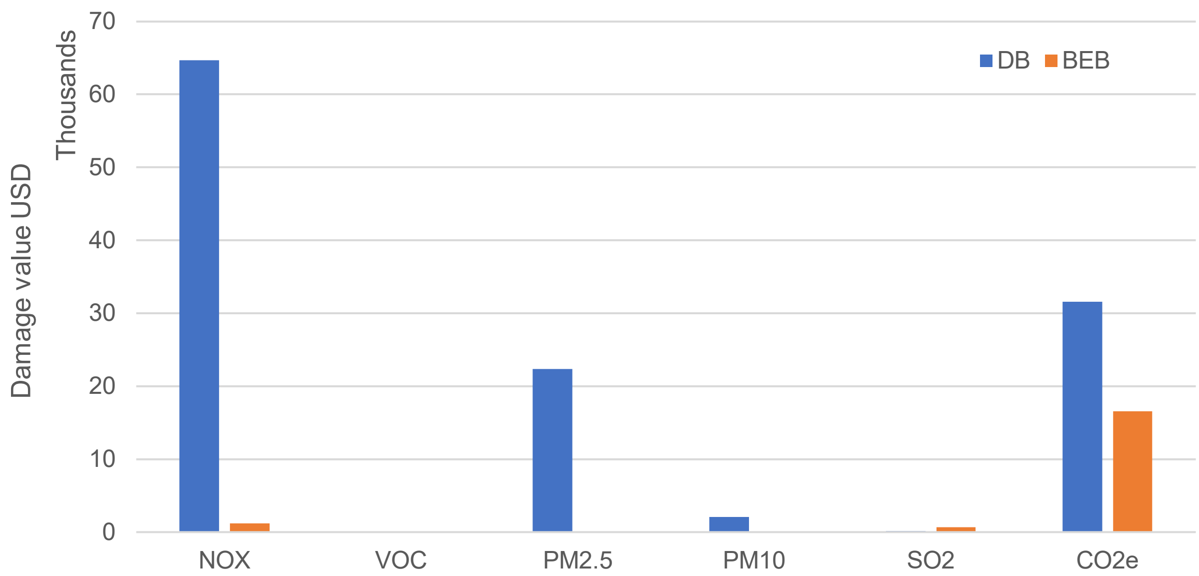


Figure 3-16 Bus operation pollution damage from DB and BEB

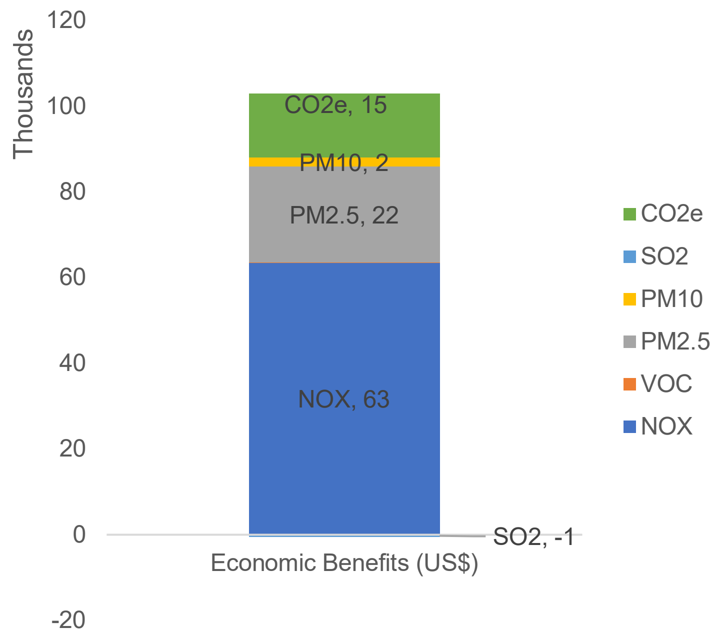


Figure 3-17 Economic Benefits from BEB avoided CAPs and GHGs in 8 years

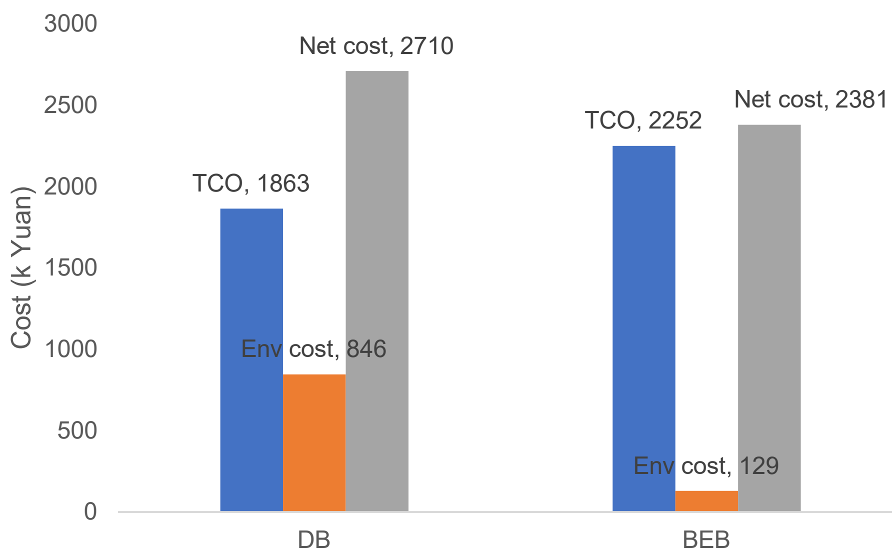


Figure 3-18 TCO and environmental cost of DB and BEB

3.6.4 Discussion

Cost-benefit analysis provides a critical reference for designing and adopting effective emission control policies. BEBs replace DBs to avoid the negative externalities from the DBs operation. We estimate the environmental benefits of the replacement comparing BEB with DB on the CAP and GHG benefits. Our result shows that air emissions reduction benefits from the adoption of BEB in SBG is about 70% of the government subsidy.

As in our cost analysis chapter, we assume the mileage of the buses run in the same length before and after electrification; the number of buses needed in the fleet kept the same to transport the same number of passengers and passenger trips. However, in practice, the numbers vary upon operation. The transit bus lines get restructured to accommodate the operation and charging schedules; the number of passengers and distance of passenger travels was also affected by the operation of the city subway system and other transportation modes. We consider the comparison of the same activity of DB and BEB on a 1:1 ratio. It could be further refined in future work when more detailed data available. When other cities consider adopting BEBs, the cost and benefit differences caused by the fleet number and operation structure change should be considered.

The total benefit from air pollutants emission matches the subsidy from the governments. It justifies the subsidies for supporting the transit fleet electrification. We didn't include other benefits, such as noise reduction, passenger and driver comfortability improvement, grid stability improvement, easier data collecting of bus operation, smoother technology evolvement to the fleet operation, etc. The benefit estimation is conservative. We are confident with the result that transit bus fleet electrification brings significant benefits to the city residents.

Shenzhen leads in all the cities in China to electrify the entire transit bus fleet in 2017 and electrified more than 99% of the taxi fleet and full-time ride hailing vehicles in 2020. They provided their experience on conquering the challenges and effective practices to other cities by trainings and meetings. It verifies the feasibility and cost effectiveness of adopting the electric vehicles in the urban transit and taxi fleet and will spread the high electric vehicle adoption rates to other cities in China.

4 Truck projection in China

Trucks contribute more air pollutants per vehicle compared to passenger vehicles. The truck fleet was only 11.2% in the total automobile population in China, but was responsible for emitting 77.9% of the $PM_{2.5}$ of the total vehicle fleet in 2017 (MEE, 2018). The truck fleet is also decreasing in percentage of the total vehicles in China due to the high growth rate of passenger cars. However, due to the higher activity level (annual VKT), lower fuel efficiency, and higher emission factors, the energy consumption and emissions contribution from trucks will far exceed those from the passenger cars if the vehicle growth continues with the same trends in the future.

The truck growth in China had a lower increase rate comparing to the growth of passenger light duty vehicles. As shown in Figure 4-1, the stock of trucks increased from 8.1 million in 2002 to 27.8 million in 2019. With the prosperity of internet-based commerce, the light trucks which are widely used for urban delivery increased rapidly. Heavy-duty trucks for long haul goods movements also increased over the last two decades. The mini trucks and Medium-duty trucks (MDT) together only accounted for 0.5 percent in the truck fleet in 2019.

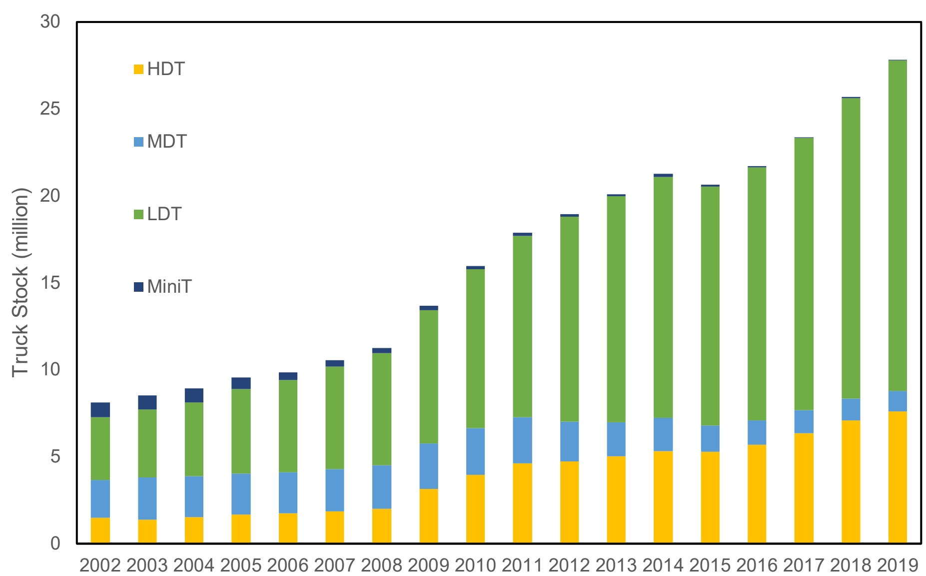


Figure 4-1 Truck growth in China 2002-2019

Trucks are mainly used for freight goods movement. As Figure 4-2 shows, from 1997 to 2016, with the high speed of economic development and average yearly 12% GDP growth in China, the total freight shipment growth rapidly. However, the mode which grown fastest has being the road truck movement, which had an average yearly growth rate of 7%, with the highest growth rate of 16.9% in 2008. The growth in the waterway, air and pipeline shipment also grew together with the economic development with an average yearly growth rate of 9.7%, 9.7% and 8.9%. from 1997 to 2016, the road freight has been the leading mode in the shipping tonnage share, at 76.4% in 1997 and 75.4% in 2016.

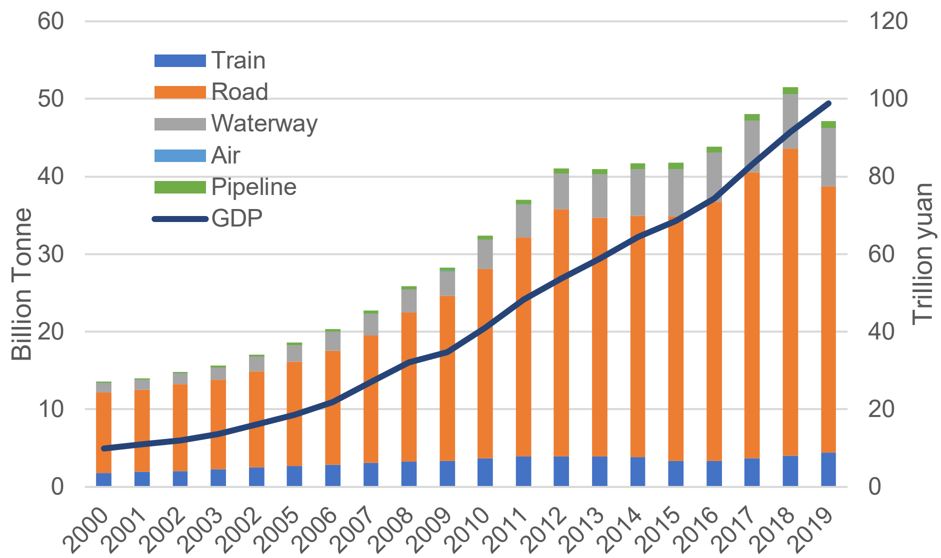


Figure 4-2 Mode Share of Freight Total Tonnage 2000-2019

Data source: China Statistic Yearbook 2020

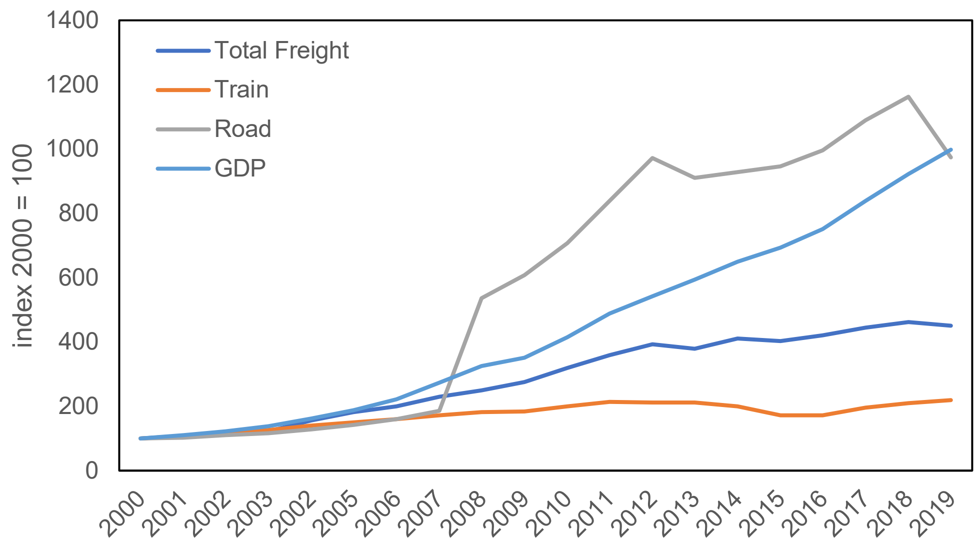


Figure 4-3 China GDP, freight, rail and road tonne-km trends index 2000-2019

Data source: China Statistic Yearbook 2020

4.1 Methodology and data

Freight is closely bound to economic development. (Bennathan, Fraser, & Thompson, 1992) analyzed cross-section data of 33 countries of freight transport demand and total GDP and country area. They demonstrated "about unity (1.02)" elasticity of road freight amount to the GDP. The experience in the developed countries demonstrated a decreasing elasticity with the GDP growth. As both passenger vehicle market and truck fleet market grow in conjunction with an increase in income, a cointegration test is conducted to identify the interaction between passenger vehicles and truck fleets.

The rail freight has lagged in development over the past few decades due to a lack of capacity and lower priority of goods movement in the rail transportation. With the rail capacity expansion and governments intention to shift the road freight to rail, the rail freight is anticipated to gradually siphon freight from the road sector.

The electrification of urban delivery trucks has been greatly promoted in cities like Shenzhen. In 2017, about 50% of the urban delivery trucks have been upgraded to electric vehicles with government subsidy and preference on the right of way policies. With a case study of Shenzhen, the electrification of truck fleet will provide important policy implications for the national truck fleet electrification.

4.2 Online merchandise development and fast delivery service

The online merchandise boomed in 2003 in China and surge rapidly in the flowing decade. The fast delivery developed closely with the online merchandise industry. For now, dozens of fast delivery companies provide one-day delivery for the regional delivery and sevearl day delivery country wide.

This has greatly changed the traditional goods movement pattern and the demand of vehicle types. In the tradition mode, the heavy-duty trucks had higher demand and light trucks only used for last mile delivery to the shopping malls or supermarkets.

In the on-line commerce dominate era, the light trucks and mini vans take more substantial roles in the goods movement logistics. With the COVID pandemic breakout in January 2020, the instant delivery service and e-commerce becoming more important in people's daily life as people are encouraged to stay at home.

Mini vans and light trucks will be the first to be electrified in the truck sector as shown in the leading cities like Shenzhen and Beijing. There are not many electric heavy-duty trucks on the market with a competitive price with the traditional heavy-duty trucks yet. Innovative business models are needed for the electrification of the heavy-duty trucks, for example, battery swap technology, and separative operation of vehicles and batteries.

4.3 Shenzhen truck electrification

Shenzhen is leading the truck electrification in China. Started in 2017, Shenzhen have 23.8% of the light-duty trucks and mini vans electrified in 2020. The vans and light trucks for urban package delivery and goods movement in Shenzhen. As documented by Shenzhen New Energy Promotion Association, in-operation electric light-trucks in Shenzhen was 7159 in 2020 (SZMTB, 2021).

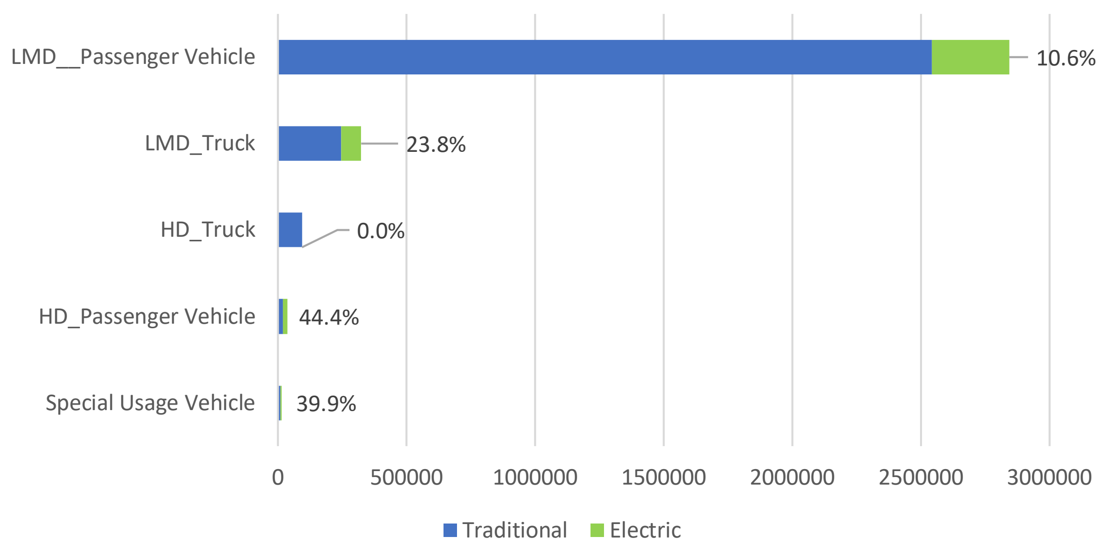


Figure 4-4 Electric vehicle portion in different vehicle types in Shenzhen in 2020

4.4 Provincial Economic Development and Truck Growth

The truck growth and deployment in the 31 provinces have different characteristics based on their economic development. Overall, for all the provinces, the truck ownership and yearly new deployment grow together alongside the economic development of the region. For provinces with higher agriculture and industrial development, the goods movement demands would be higher. At the same time, provinces with more than a third of their economy in industry, experience truck growth rates that are less tied to their economic development compared to the provinces with more goods movement. As shown in Figure 4-1, micro trucks and medium-duty trucks account for a decreasing proportion of the freight fleet, therefore the trucks are grouped into two sectors: light-duty trucks (LDT) including the micro trucks and light duty trucks; and HDT including medium duty trucks and heavy-duty trucks.

Here we reviewed the LDT and HDT truck registration in the 31 provinces in China through 2001 to 2019 (in Figure 4-5and Figure 4-6). Among the 31 provinces in the six regions, Hebei (HB) in North China, Guangdong (GD) in South Central China and Shandong (SD) in East China have the highest truck registration for both LDT and HDT.

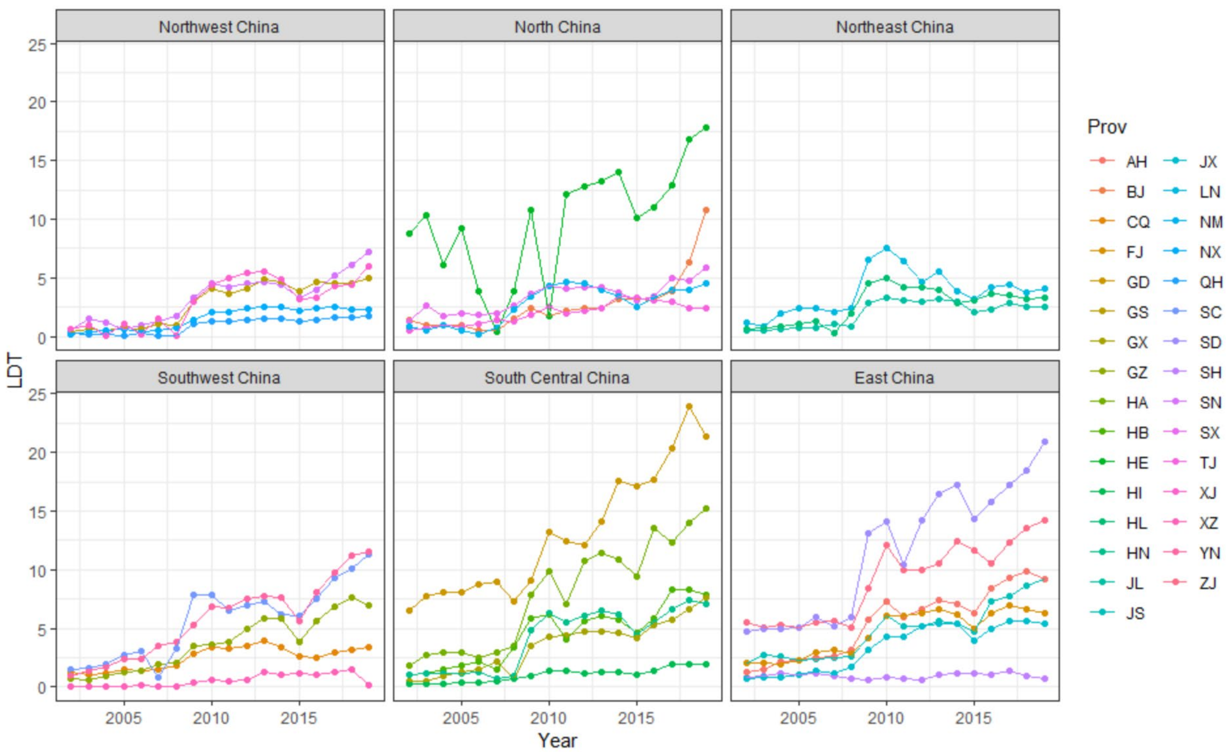


Figure 4-5 LDT new registrations through 2002-2019 in 31 provinces

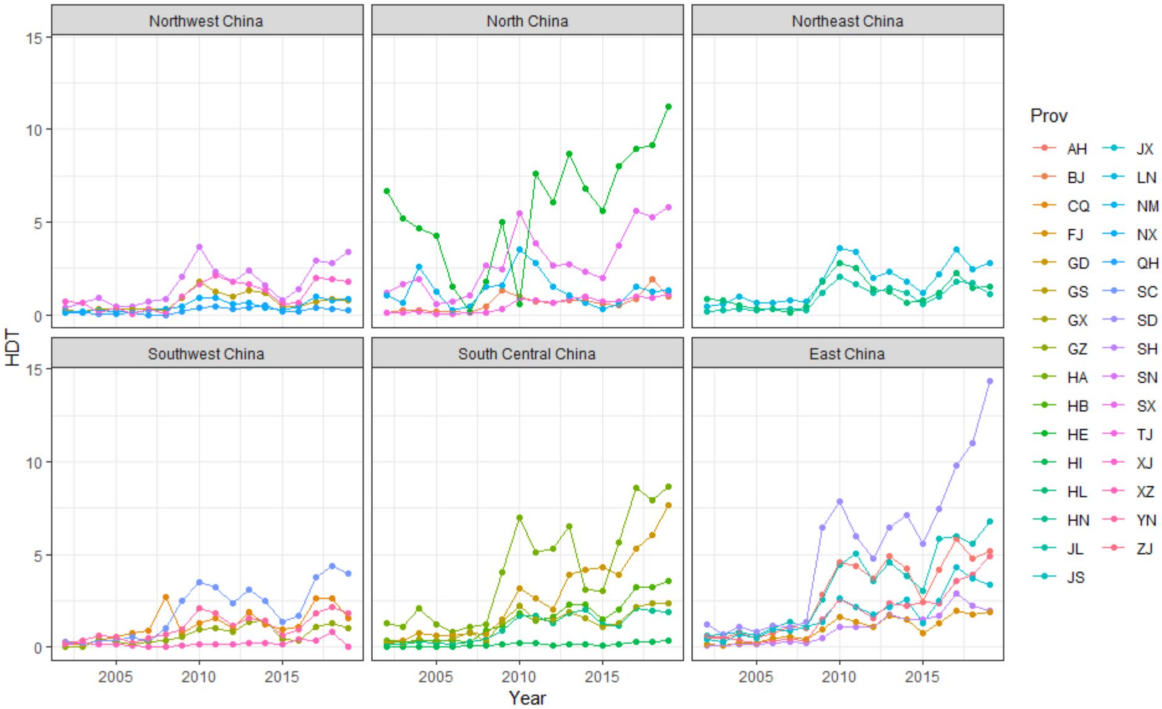


Figure 4-6 HDT new registrations through 2002-2019 in 31 provinces

Figure 4-7 provincial LDT registration grow together with the GDP

The relationship of economic growth and truck registration (Figure 4-7). For all the provinces, the LDT and HDT registration grow with the economic growth. However, in east China region, the growth rates vary the most in the six regions for different provinces, where Shanghai and Jiangsu have much lower growth of truck registration with the economic development.

With a transformed correlation, we build the below model to reflect the growth of the LDTs from the growth of provincial GDP.

$$\log Y_{LDT} = \beta_1 \log X_{GDP} + \beta_2 Factor(X_{Province}) + \varepsilon$$

$$Y_{LDT} = e^{(\beta_1 \log X_{GDP} + \beta_2 Factor(X_{Province}) + \varepsilon)}$$

The regression results are presented in Table 4-1.

Table 4-1 Regression coefficients and the significance of the factors for LDT registration

		ESTIMATE	STD. ERROR	T VALUE	PR(>|T|)	
LG_GDP		0.92085	0.02964	31.07	<2e-16	***
FACTOR(PROV)AH	Anhui	-7.20143	0.30198	-23.85	<2e-16	***
FACTOR(PROV)BJ	Beijing	-8.13499	0.30501	-26.67	<2e-16	***
FACTOR(PROV)CQ	Chongqing	-7.47113	0.28916	-25.84	<2e-16	***
FACTOR(PROV)FJ	Fujian	-7.39599	0.30542	-24.22	<2e-16	***
FACTOR(PROV)GD	Guangdong	-7.36106	0.33587	-21.92	<2e-16	***
FACTOR(PROV)GS	Gansu	-6.85744	0.2686	-25.53	<2e-16	***
FACTOR(PROV)GX	Guangxi	-7.34039	0.28941	-25.36	<2e-16	***
FACTOR(PROV)GZ	Guizhou	-6.76895	0.27537	-24.58	<2e-16	***
FACTOR(PROV)HA	Henan	-7.32406	0.31552	-23.21	<2e-16	***
FACTOR(PROV)HB	Hubei	-7.58005	0.30701	-24.69	<2e-16	***
FACTOR(PROV)HE	Hebei	-6.91282	0.3087	-22.39	<2e-16	***
FACTOR(PROV)HI	Hainan	-7.18262	0.2513	-28.58	<2e-16	***
FACTOR(PROV)HL	Heilongjiang	-7.51958	0.28843	-26.07	<2e-16	***
FACTOR(PROV)HN	Hunan	-7.72218	0.30554	-25.27	<2e-16	***
FACTOR(PROV)JL	Jilin	-7.48834	0.28012	-26.73	<2e-16	***
FACTOR(PROV)JS	Jiangsu	-8.27286	0.33229	-24.9	<2e-16	***
FACTOR(PROV)JX	Jiangxi	-7.40745	0.29186	-25.38	<2e-16	***
FACTOR(PROV)LN	Liaoning	-7.56216	0.30261	-24.99	<2e-16	***
FACTOR(PROV)NM	Inner Mongoria	-7.51686	0.28633	-26.25	<2e-16	***
FACTOR(PROV)NX	Ningxia	-6.48634	0.24206	-26.8	<2e-16	***
FACTOR(PROV)QH	Qinghai	-7.03116	0.23589	-29.81	<2e-16	***
FACTOR(PROV)SC	Sichuan	-7.43853	0.3088	-24.09	<2e-16	***
FACTOR(PROV)SD	Shandong	-7.2287	0.32674	-22.12	<2e-16	***
FACTOR(PROV)SH	Shanghai	-9.05747	0.30951	-29.26	<2e-16	***
FACTOR(PROV)SN	Shaanxi	-7.47555	0.29251	-25.56	<2e-16	***
FACTOR(PROV)SX	Shanxi	-7.12222	0.28813	-24.72	<2e-16	***
FACTOR(PROV)TJ	Tianjing	-7.50804	0.28216	-26.61	<2e-16	***
FACTOR(PROV)XJ	Xinjiang	-7.3521	0.27744	-26.5	<2e-16	***
FACTOR(PROV)XZ	Tibet	-6.98761	0.21763	-32.11	<2e-16	***
FACTOR(PROV)YN	Yunnan	-6.73579	0.2887	-23.33	<2e-16	***
FACTOR(PROV)ZJ	Zhejiang	-7.23012	0.32115	-22.51	<2e-16	***

Table 4-2 Regression coefficients and the significance of the factors for HDT registration

		ESTIMATES	TD. ERROR	T VALUE	PR(>|T|)	
LG_GDP		1.24684	0.07391	16.869	< 2e-16	***
FACTOR(PROV)AH	Anhui	-8.92087	0.75314	-11.845	< 2e-16	***
FACTOR(PROV)BJ	Beijing	-11.3083	0.76069	-14.866	< 2e-16	***
FACTOR(PROV)CQ	Chongqing	-10.0094	0.72118	-13.879	< 2e-16	***
FACTOR(PROV)FJ	Fujian	-10.9621	0.76173	-14.391	< 2e-16	***
FACTOR(PROV)GD	Guangdong	-10.6307	0.83767	-12.691	< 2e-16	***
FACTOR(PROV)GS	Gansu	-9.59709	0.66988	-14.326	< 2e-16	***
FACTOR(PROV)GX	Guangxi	-10.0256	0.72179	-13.89	< 2e-16	***
FACTOR(PROV)GZ	Guizhou	-9.9462	0.68678	-14.482	< 2e-16	***
FACTOR(PROV)HA	Henan	-8.32435	0.78691	-10.579	< 2e-16	***
FACTOR(PROV)HB	Hubei	-10.5284	0.7657	-13.75	< 2e-16	***
FACTOR(PROV)HE	Hebei	-6.46451	0.7699	-8.397	4.29E-16	***
FACTOR(PROV)HI	Hainan	-9.33733	0.62675	-14.898	< 2e-16	***
FACTOR(PROV)HL	Heilongjiang	-10.0491	0.71934	-13.97	< 2e-16	***
FACTOR(PROV)HN	Hunan	-10.894	0.76202	-14.296	< 2e-16	***
FACTOR(PROV)JL	Jilin	-9.89529	0.69862	-14.164	< 2e-16	***
FACTOR(PROV)JS	Jiangsu	-9.9862	0.82873	-12.05	< 2e-16	***
FACTOR(PROV)JX	Jiangxi	-9.54428	0.7279	-13.112	< 2e-16	***
FACTOR(PROV)LN	Liaoning	-10.0746	0.75472	-13.349	< 2e-16	***
FACTOR(PROV)NM	Inner Mongoria	-9.78135	0.71412	-13.697	< 2e-16	***
FACTOR(PROV)NX	Ningxia	-8.57978	0.6037	-14.212	< 2e-16	***
FACTOR(PROV)QH	Qinghai	-8.53131	0.58831	-14.501	< 2e-16	***
FACTOR(PROV)SC	Sichuan	-10.1563	0.77015	-13.187	< 2e-16	***
FACTOR(PROV)SD	Shandong	-7.69613	0.8149	-9.444	< 2e-16	***
FACTOR(PROV)SH	Shanghai	-11.1166	0.77192	-14.401	< 2e-16	***
FACTOR(PROV)SN	Shaanxi	-9.74692	0.72953	-13.36	< 2e-16	***
FACTOR(PROV)SX	Shanxi	-8.32393	0.7186	-11.583	< 2e-16	***
FACTOR(PROV)TJ	Tianjing	-10.384	0.70372	-14.756	< 2e-16	***
FACTOR(PROV)XJ	Xinjiang	-9.66457	0.69194	-13.967	< 2e-16	***
FACTOR(PROV)XZ	Tibet	-7.66666	0.54278	-14.125	< 2e-16	***
FACTOR(PROV)YN	Yunnan	-10.1226	0.72002	-14.059	< 2e-16	***
FACTOR(PROV)ZJ	Zhejiang	-10.885	0.80095	-13.59	< 2e-16	***

The regression shows that the GDP and each province specific factor are significant variables affecting the LDT registration. Among all the provinces, Shanghai, Jiangsu, and Beijing are the three province or cities that have the smallest coefficient of LDT registration with economic development. It may be caused by the higher contribution of third industries in the economy and more stringent environmental regulations in this area. The results for HDT registration are similar to that of LDTs.

In conjunction with GDP growth rates adopted from International Monetary Fund (IMF) and adjusted economic projection including the impacts aging society (Table 4-3), we project the provincial truck growth in the following decades from our regression results.

Table 4-3 GDP growth Scenarios

	GDP GROWTH RATE	2026-2030	2031-2035	2036-2040	2041-2045	2046-2050
S1	IMF	0.057	0.046	0.036	0.027	0.022
S2	Ageing society	0.045	0.033	0.009	0.0088	0.01

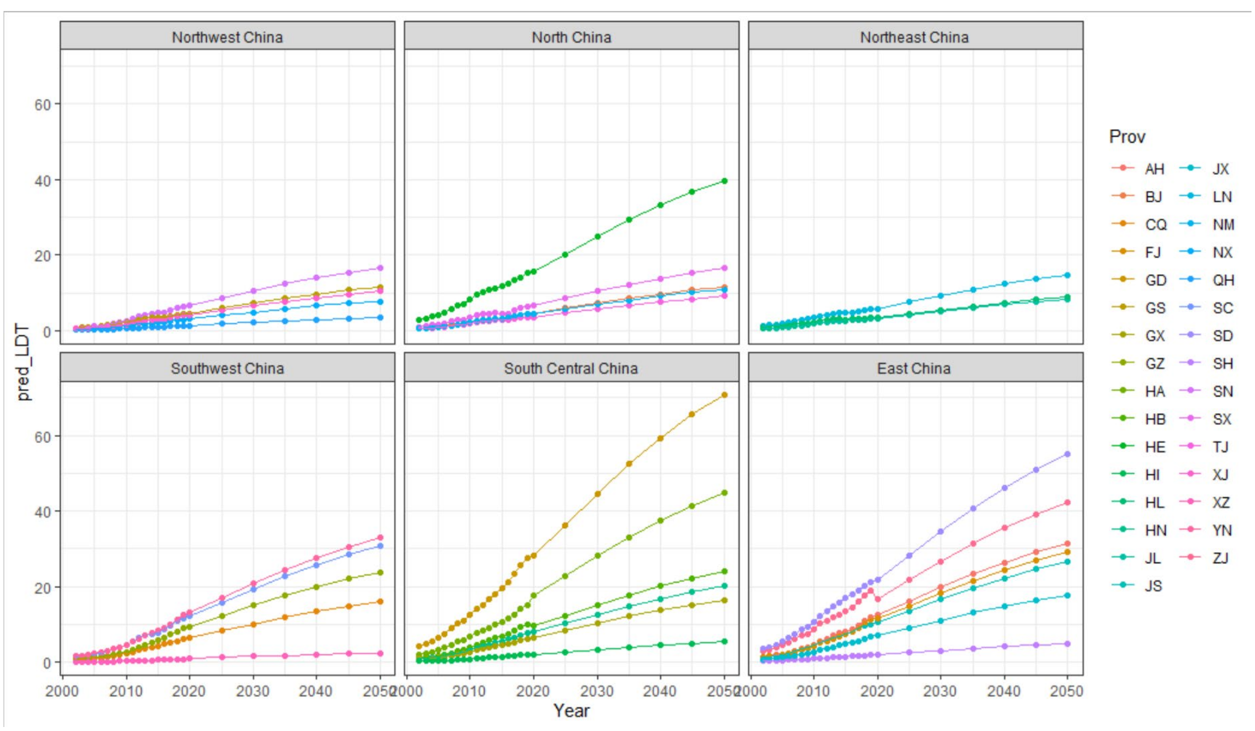


Figure 4-8 LDT growth from Scenario 1 Economic projection

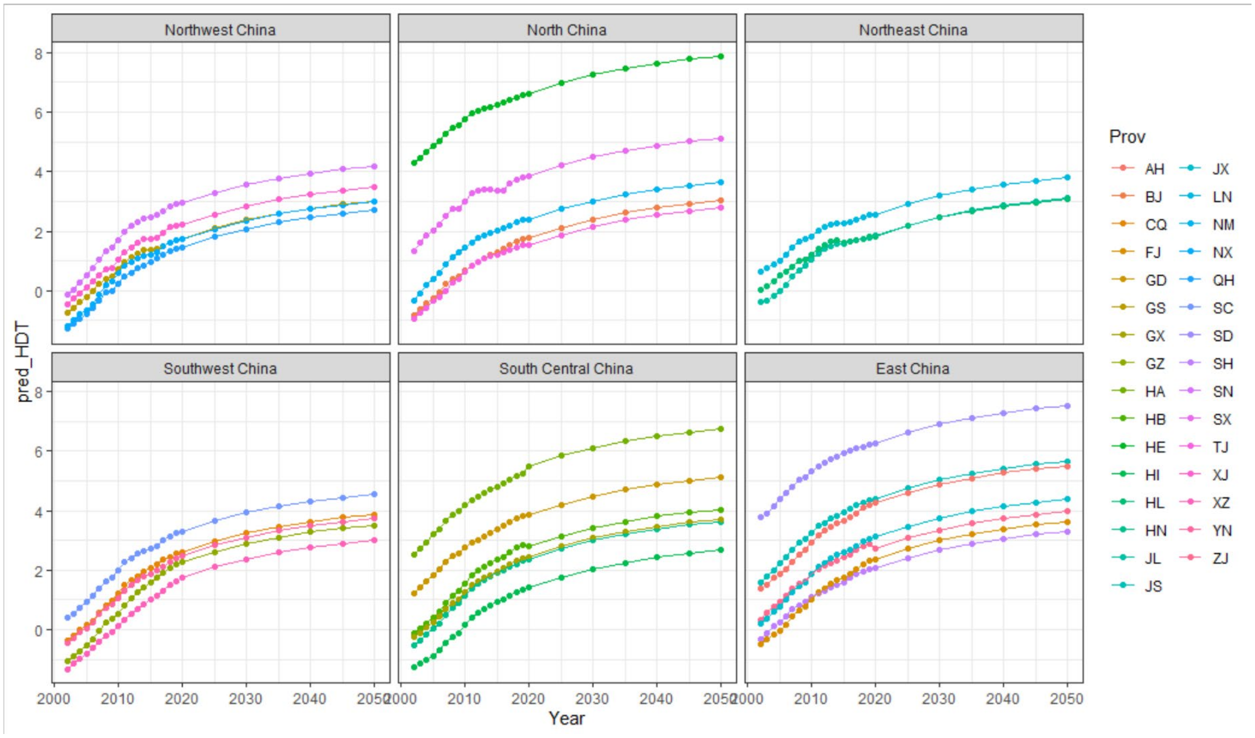


Figure 4-9 HDT growth from Scenario 1 Economic projection

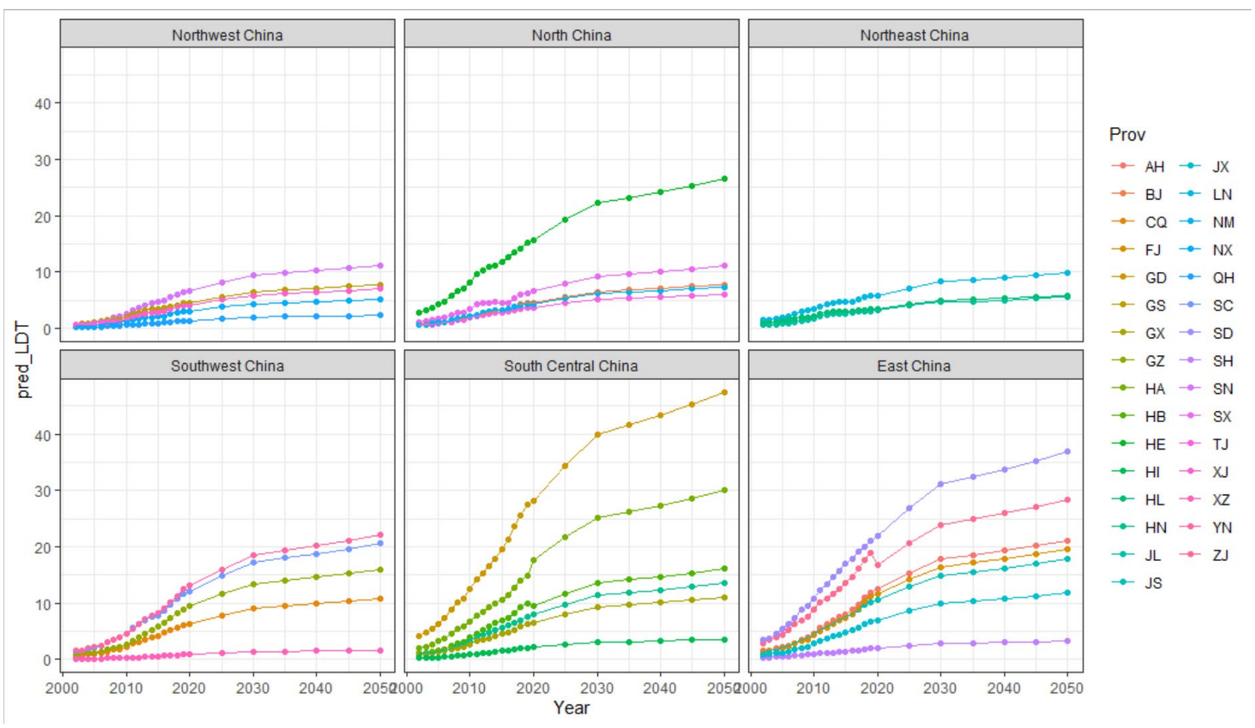


Figure 4-10 LDT growth from Scenario 2 Economic projection

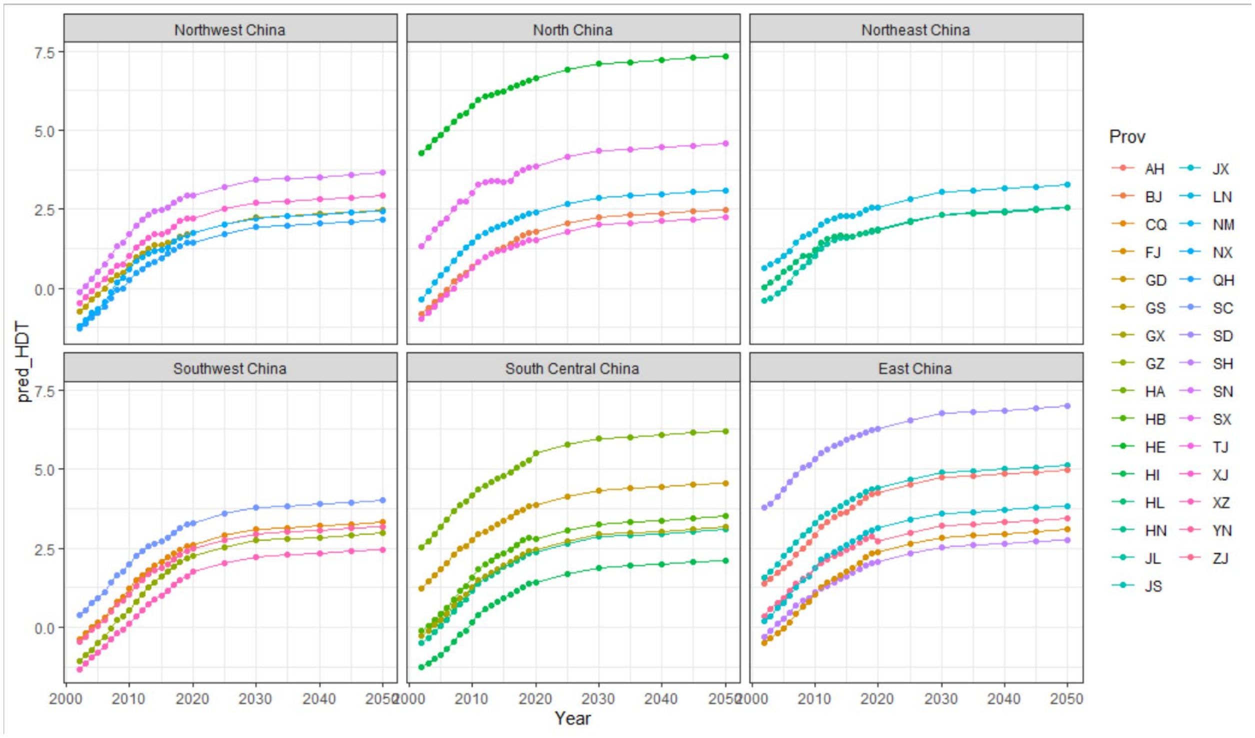


Figure 4-11 HDT growth from Scenario 2 Economic projection

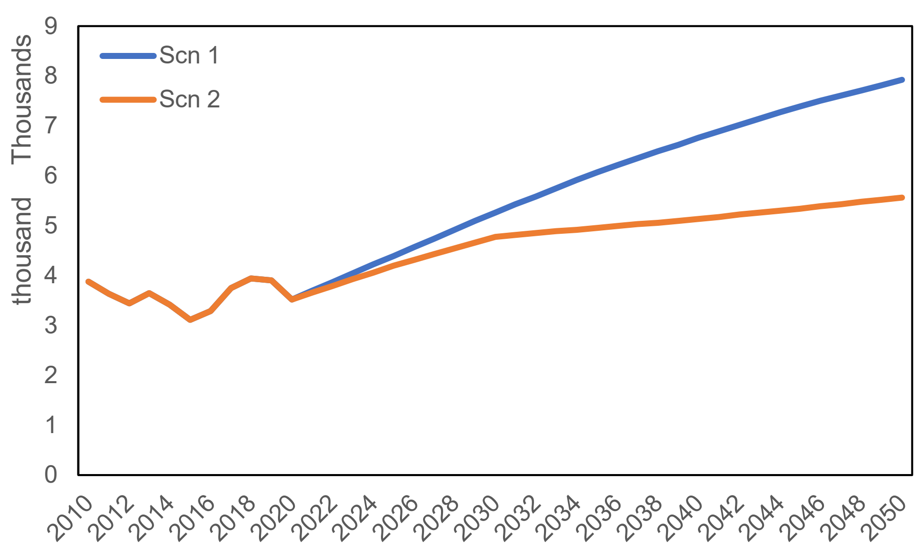


Figure 4-12 Truck sales projection results

4.5 Results and Discussion

Combining different registration patterns in different provinces, the total truck registration projection results are 5.5 million in 2050 for the low economic growth scenario and 7.9 million in 2050 for the high economic growth scenario. Among them, the light duty trucks percentage increase from 69.9% in 2010 to 83.9% in 2050 for the high scenario and to 80.0% in the low growth scenario. The heavy-duty truck sales will grow to 1.27 million in 2050 and 1.10 in 2050 million respectively in the high and low growth scenarios.

From our projection, the truck registration and truck fleet stock will continue to increase in the next three decades, and the intensity of the usage will be maintained. The energy consumption and GHG emission growth from truck sector is an inevitable sector and efforts for GHG emission mitigation in the truck sector is important. The energy consumption and GHG emission impacts from truck sector will be further explored in the next chapter.

5 Energy Consumption and GHG Emission results of Fleet Electrification Scenarios

5.1 NEV development in China

Battery Electric Vehicles, Plug-in Hybrid Electric Vehicles, and Fuel Cell Vehicles, these are referred to as New Energy Vehicles (NEV) in China. With goals of promoting the technology innovation, automobile industry development, protecting the energy security and vehicle emission reduction, the Chinese government set the goal to promote the NEVs development in 2009 with a program of "ten cities, thousands of EVs". There have been dozens of policies followed up with great amounts of incentives and requirements. The NEV credit requirement was implemented in 2017; it would be in effect start from 2019 and substitute the incentives to stimulate the industry development. Key stakeholders involved in the NEV development include government agencies, automobile industry, customers, and others. In 2020, China sold 1.367 million NEVs and increase the sales penetration rate to 5.4%. NEV sales exceeded 1 million for three consecutive years, and ranked first in the world for six consecutive years. By the end of 2020, China's NEV fleet reached 4.92 million, accounting for 1.75% of the total number of vehicles (China State Council, 2021).

With a review of the EV development and the government policy setting, analysis of industry technology development and customers attitudes, projection on the EV development into 2030 and 2050 will be made with different scenario settings.

Due to the technology feasibility, average daily travel distances, and the ability of governmental intervention, the probability of electrification of public fleet like urban transit and urban delivery light trucks will be higher than private passenger vehicles and long-haul heavy trucks. In this section, the analysis will be conducted based on a bottom-up approach: the total NEV projection will be the aggregation of the projections of different vehicle types.

5.2 Background and Overview on NEV development

5.2.1 2030 Development Technical Roadmap

The "Energy-saving and New Energy Vehicle Technology Roadmap" (hereafter referred to as "the Roadmap") was released in October 2016 and updated in October 2020 by Ministry of Industry and Information Technology (MIIT) and China's Society of Automotive Engineers. The Roadmap (Jun Li, 2016) set comprehensive goals and pathways for energy saving vehicles, Battery Electric Vehicles, Plug-in Hybrid Electric Vehicles, Hydrogen Electric Vehicles, connected vehicles, vehicle batteries and light-weighting technologies development. In the Roadmap, the goal of NEV sales would take more than 7% in 2020 (5.4% in actual sales), 20% in 2025, 40% in 2030 and 50% in 2035. The Roadmap also developed goals for the charging infrastructure. The charging piles should be more than 5 million in 2020, more than 20 million in 2025 and more than 80 million in 2030.

5.2.2 NEV Credit Requirements

Inspired by the California ZEV mandate regulation, MIIT adopted the automobile dual-credit policy, intended to replace the financial subsidies with the credit policy to incentivize the automobile companies to produce vehicles of NEVs and ICEs with higher fuel efficiency. Released on September 27, 2017, the NEV dual credit policy requires the vehicle manufactures to meet NEV credit of 8% in 2018 (soft), 10% in 2019 and 12% in 2020 (MIIT, 2017). Credit requirements for 2021 and later will be determined and released based on the progress of the first years.

ZEV credit policy provide positive stimulation and motivation for manufactures to produce and sell more electric vehicles. Suppose similar effects will happen in China and based on the credits computation for manufactures in 2016 and 2017, we can make EV production projections of the manufactures.

5.2.3 Challenges

With the development of the NEV industry and generous government subsidies and other incentives, the development on the NEV developments still facing a lot of challenges.

5.2.3.1 Parking space and home charging

The residential building structures in China is dominate with apartments of multiple households reside in the same building. As a result, the ratio of parking spot with residential unit is very low especially in old building clusters. Ou, Lin, He, & Przesmitzki (2018) analyzed the communities in Chinese Tier 1, Tier 2 and Tier 3 cities and found that about 30% of the communities with parking availability for communities built before 2005 and about 50% of the ones built between 2005-2015. Hardman et al. (2018) found the most important charging location is home, then work and public locations by reviewing the literatures on consumer preference. While the Chinese government is making aggressive planning and building plans of public charging (Council, 2015), it may not resolve the consumers concern on the inconvenience of using NEVs. The public charging utilization rate was less than 15% in 2017 as stated by officials from National Energy Administration[7].

5.2.3.2 NEV sales in cities

The private passenger vehicle sales in China are mainly concentrated in the cities with a license plate restrain and separate free plate quota for NEV like Beijing, Shanghai, Guangzhou and Tianjin. However, for sales of private NEVs in other cities with no similar policies, the adoption of NEVs is very low.

[7] http://www.nbd.com.cn/articles/2018-01-22/1185602.html, Accessed on July 24, 2018.

China is now the second largest oil consumer and biggest oil importer in the world, with oil importation dependency of 69% in 2017 (BP, 2018). China is also the biggest GHG emitter and is committed to cutting GHG emissions intensity by 60-65% by 2030 compared to 2005. Urban air pollution is also one of the most significant problems in Chinese cities. Since transportation is one of the most significant sectors on energy consumption and GHG and criteria air pollutants emission, the future transportation structure, activity level, fuel economy level and grid portfolio will together shape the future energy consumption and air emissions.

The goal of the impact evaluation work is to account the current energy consumption and air emissions from the road transport, to develop the trajectory of the future oil and electricity demand of the different vehicle stock growth and NEV penetration scenarios and to identify to what extent of vehicle fleet electrification penetration could reach significant GHG or criteria air pollutant emission reduction.

5.3 Methodology and data

With the increase of percentage of NEV in the vehicle fleet, the energy source of grid will be crucial for calculating the GHG reduction potential. If the fossil energy source (for example, coal) dominant the grid as it is now, it is possible that the life cycle GHG emission from the fleet would be higher for EVs than ICEVs. By estimating different scenarios with combinations of vehicle ownership growth rate, electric vehicle penetration, and grid generation source mix, we estimate the energy consumption and GHG emission from the vehicle fleets.

5.3.1 Model

The model adopted in this study modifies from the Transportation Transition Model (TTM) developed by Fulton et al. (2019). The Transportation Transition Model is an Excel based model, covering modules modeling multiple vehicle types, vehicle technologies, and vehicle fuels. It operates by separating the vehicle sales in each year and fleet at each age for different vehicle type and technology, and is able to model the fleet behavior based on the scenario settings for different sales scenarios with combinations of different technology pathways. The model sets LDVs and HDVs in two separate Excel files and link them with a control sheet. For each vehicle type with specific technology, an individual sheet includes the vehicle stock at different age in each year. In this way, common characteristics like survival rates, VMT and fuel carbon intensity could separately set for LDVs and HDVs. The outputs are vehicle stock, VMT, energy consumption and GHG emission for each year under each scenario settings.

5.3.2 Vehicle Types

5.3.2.1 Light duty passenger vehicle

The light duty vehicles refer to vehicles less than 3.5 tonne, including passenger cars, SUVs and taxies, as they have different fuel efficiency, annual driving distances and electrification paces.

5.3.2.1.1 Passenger car

Passenger cars is the largest sector in the vehicle sales. Over the years, the passenger sedans are growing steadily and taking more than half in the passenger light duty vehicles. With the enlarging of the vehicle sizes people taken, the cars are gradually losing their dominant role to SUVs (from 70% in 2010 to 50% in 2050 in light-duty passenger vehicles).

5.3.2.1.2 SUVs

In this vehicle sector, the light trucks category here includes SUVs, MPVs, and cross-over vehicles, which are taking an increasing portion in the passenger light duty vehicles in the sales in the past two decades. We assume the enlarge of the passenger vehicles size will continue and it will keep on taking more percentage in the light duty passenger vehicles (from 30% in 2010 to 50% in 2050 in light-duty passenger vehicles).

5.3.2.1.3 Taxi

Taxies here include both the municipal taxies and TNC ride hailing service vehicles operated by Didi Chuxing, Caocao Chuxing, T3 Chuxing etc. Traditional taxies have higher annual driving distance of 100,000-200,000 km per year depending on it operates for one shift or two shifts every day. Accordingly, the vehicles would retire between 4-6 years based on the vehicle's traveled distance and vehicle deteriorate status. Taxies are leading in the vehicle sectors on the electrification progress. Cities like Shenzhen, Taiyuan, Haikou etc. have fully electrified their taxi fleet, more cities have set their goals of fully electrify their taxi fleet before 2025. The taxi fleet has been strictly under the government's regulatory and the quota of the amount of taxi cars has been frozen for many years. The total amount of the taxies has been hovering at 1.4 million for the past decade.

Due to the abundance of natural gas in some regions, some taxi drivers modify their vehicles from gasoline fuel to dual fuel of both gasoline and natural gas by adding a gas tank in the trunk. However, there is no statistical count of the number of natural gas taxis. However, with Hubei, Shanxi, and Hainan, which are rich in natural gas supply, we estimate the taxies with natural gas fuel would be 20% in 2015-2020.

Emerging in 2014, the TNC vehicles gradually changing the ways of how people reserve and take the taxis, attracting more private passenger cars in providing and sharing their vehicles for the service. Past the early days of explosive expanding, the TNC companies were required to also get permissions and compliance from MOT by acquiring operation and drivers' certificate for operating TNC cars. As of 2020, based on the MOT bulletin, a total of 1.36 million vehicles have been certified for operating TNC vehicles, with a monthly total trip of 643 million in August 2021[8].

5.3.2.2 Heavy-duty Vehicles

5.3.2.2.1 Transit bus and other bus

In China, with the surging in the development of urban metro system and inter-city high speed rail development, the demand for the urban transit buses and inter-city passenger buses has been slightly decreasing in the past five years. As described in Section 3.1.2, the bus rides have been steadily decreasing in urban areas. At the same time, like the case in chapter three, the local governments have authority on the vehicle fleet updates of urban transit buses. This could result in a much faster high percentage electrification fleet turn-over for urban transit bus fleet. For the inter-city buses, the daily driving distance and intensity are higher than that of the urban buses, but there are few electric bus adoptions, and the pace of electrification would be slower depending on the cost potential of the battery-swap technology and fuel cell bus technology.

5.3.2.2.2 Trucks

We separate the heavy-duty vehicles into light-duty trucks (less than 5,500kg), heavy-duty trucks (heavier than 5,500kg), dump truck, semi-trailer tractor, transit bus and other bus.

Light duty trucks are mostly operated for short haul goods movements, with an average annual driving distance of around 50,000 km and lifetime of eight years. Heavy-duty trucks vary between 5,500 kg to 49,000 kg. They operate for various purpose and for both short-haul and long-haul operations. However, based on big data estimation, most of the vehicles operates with an annual driving distance of 50,000 – 150,000 km. Dump trucks typically weight in the range of 16 tons to

[8] MOT, August 2021, https://www.mot.gov.cn/jiaotongyaowen/202109/t20210918_3619174.html

31 tons. Semi-trailer tractors are mostly heavy-duty and are mostly used for long-haul heavy goods transportation.

5.3.3 Survival Rates and VKT

5.3.3.1 Survival Rates

The survival rates of the vehicles describe the survival and retirement of the vehicles over the lifetime of the vehicles. In China, the Ministry of Commercials made requirements for the retirement of the vehicles at specific age and distance traveled limit for different vehicle types. Zheng etc. (2019) analyzed the survival rates for passenger vehicles with

Adopted the model from Lu et al. (2018), and modify it by fitting the interrelationship between historical stock and sales for each vehicle type and minimizing the error between the predicted and actual values, the survival curves and parameter values for each vehicle type are shown in Table 5-1 and Figure 5-1.

$$r_{i,m} = \frac{1}{1 + \exp\left(\alpha_{i,m}\left(\frac{j}{L_{50,i,m}} - 1\right)\right)}$$

Table 5-1 Parameters for estimating the survival rates

(modified from Lu et al. 2018)

VEHICLE TYPE	α	L50
CARS	7.1	13.9
SUVS	7.7	15.5
TAXI	45	4.5
URBAN BUS	75	7.5
INTERCITY BUS	7.7	10.6
HDT	7.2	10.2
LDT	6.1	8.7

In the fitting process, this study finds that in fitting the number of vehicles to the calendar year with a static fixed survival rate, the predicted value of sales in recent years is higher than the actual value, showing a gradual extension of vehicle survival years from the past to the present. The Chinese auto market is still in a continuous development phase, and as vehicle quality improves and average vehicle prices increase, households keep their vehicles longer. In major large cities such as Shanghai, the average annual household mileage has decreased in recent years due to traffic congestion and increased supply of alternative travel modes, which also reduces vehicle wear and tear and may bring about an increase in the overall fleet vehicle age. In future studies, dynamic survival curve simulations can be used to reflect this trend.

$$Stock_{m,i,j,k} = \sum(Sales_{m-j,i,k} \times r_{j,i})$$

$$Sale_m = \frac{Stock_m - \sum_{j=1}^{n}[Sale_{m-j} * r(j)]}{r(0)}$$

Where the $r_{j,i}$ is the survival rate of vehicle type i in year j

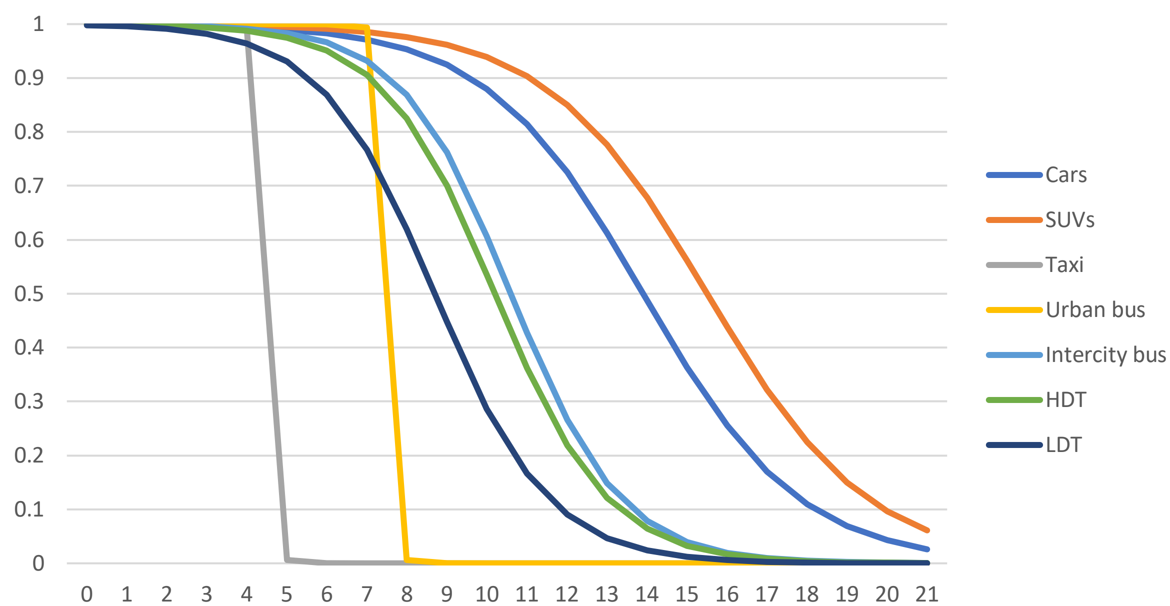


Figure 5-1 Survival rates of vehicles

(Modified from Zheng etc., 2019 and Lu et al., 2018)

5.3.3.2 VKT

The results of the study on Chinese light vehicle mileage data vary widely. BTI (2017) reviewed the Beijiing annual driving distance and found it decreased from 25,472 km in 2003 to 11,990 km in 2017. (Zheng et al., 2019) estimated vehicles over different passenger vehicle ages and found the passenger vehicles VKT decay from 100% in the first three years to 75% in year four to nine and further decreased to 45% afterwards. Ou et al. (2020) analyzed the VKT for vehicles in different provinces for different passenger vehicles sizes and found that it varies much in different provinces and cities and having been decreasing over the past decade. We adopt the 11,615 km for cars and 14,797 km for SUVs from Ou et al. (2020) and the VKT decay from Zheng et al. (2019) for light duty vehicles. The VKT of the trucks are adopted from CATARC (2017).

5.4 Scenarios setting

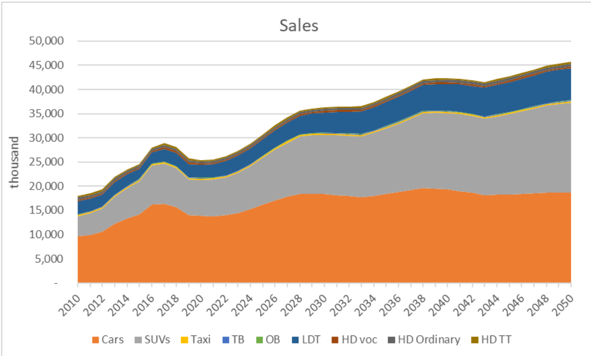
5.4.1 Stock and Sales Scenarios

Besides the aging society scenario results, we also estimate another strong economic growth and vehicle ownership growth scenario to reflect the IMF economic growth rates we adopted in the truck growth projection.

Separating the vehicles into LDV and HDV groups, we project the vehicle sales for each vehicle type based on the survival rates in section 5.3.3.1 and the following equation:

$$Sale_m = \frac{Stock_m - \sum_{j=1}^{n}[Sale_{m-j} * r(j)]}{r(0)}$$

Then we can get the projected sales in 2021-2050.



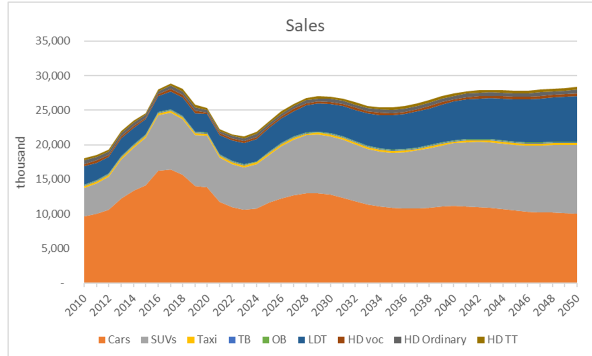


Figure 5-2 The sales results of the two scenarios

BAU scenario (on the left) and aging society scenario (on the right)

5.4.2 Electrification Scenarios

The New Energy Vehicles Development Technology Roadmap (afterward referred to as "the roadmap"), led by MIIT and developed by experts from the automobile industry in 2018 and reviewed and updated frequently afterwards, is one of the most important guidelines for the NEV development in China. In the roadmap, it estimated and projected the deployment of the energy saving and hybrid vehicles will result in higher percentages in the traditional ICE fleet, and more NEVs will be sold in the following years. The battery electric vehicles will be the dominant technology in the NEV development. The BEVs, PHEV and HEVs will take 48%, 2%, and 50% respectively in 2035.

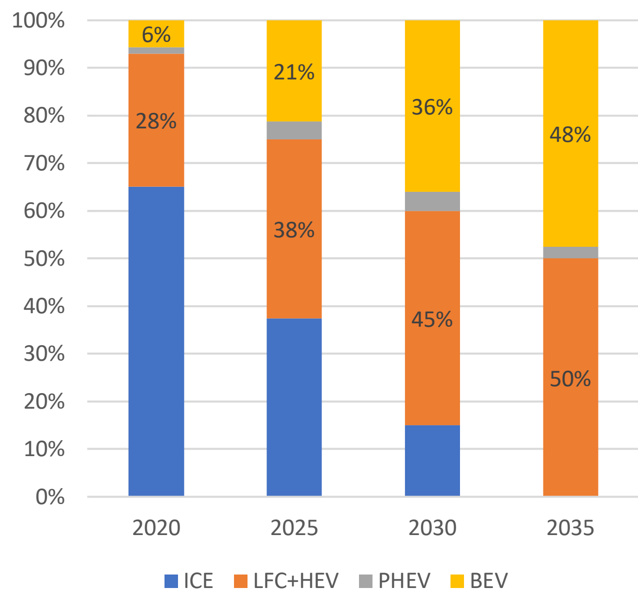


Figure 5-3 The vehicle deployment targets in 2020-2035 stated in the Technology Roadmap

As the NEV market development in 2010-2020, the cost parity between NEVs and ICEVs would be easier to reach for vehicles with smaller size. There are also more electric vehicle models available on markets with smaller vehicle size. The trend of the electric vehicle deployment in different vehicle types will be more possibly also gradually from small size vehicles to larger size vehicles. Since passenger cars take more than 80% in the vehicle sales each year, it is possible to reach the NEVs penetration target with electrification only in light-duty vehicles. Then we develop three scenarios to explore the different electrification pathways. One is all the goals will be meet by the sales of light-duty vehicles, with almost no NEV sales in heavy duty vehicles, as the NEV markets now. Another is the NEV penetration goals will be equally met by all the vehicle types. And Third is a more aggressive electric vehicle penetration in the sales market.

5.4.2.1 Scenario One: Stated Policy Scenario with only electric LDVs

As indicated in The New Energy Vehicles Development Technology Roadmap, the electric vehicle will take 40% in 2030 and 50% in 2035. For urban transit bus fleet, taxi fleet and special usage vehicles, for which the central and local governments have more authority to directly require a higher electric vehicle adoption and take the costs through fiscal cycles, the electrification would have a faster pace than the private sector. As of 2021, there are very few heavy-duty truck models available on the market. For other light-duty cars and SUVs, we set the electrification rate 5% higher to meet the fleet wise sales targets through only light-duty vehicles electrification. The roadmap also required the continuous vehicle fuel consumption efficiency improvement. We adopted the fuel consumption efficiencies accordingly in the stated policy scenario. The electrification percentages of each vehicle type can be found in the Appendix (with LDV_1 + HDV_1).

5.4.2.2 Scenario Two: Stated Policy Scenario with electric trucks

In this scenario, we require that the fleet-wise electrification targets are met by all the vehicle types equally, except for an earlier electrification schedule for taxies and transit buses. For all the trucks, the electrification will also follow the percentage penetration laid out in the roadmap. The electrification percentages of each vehicle type can be found in the Appendix (with LDV_1 + HDV_2).

5.4.2.3 Scenario Three: Higher Pace Electrification Scenario

After the national Carbon Neutrality commitment made in the United Nations Summit, the central government and some local governments have set their soft goals of meeting the carbon neutrality targets in the transportation sector earlier than the committed 2060. In the transportation sector, it means a faster full electrification for all the fleet. We generally set 5 years earlier for all the light duty vehicle electrification compared to the second scenario. The electrification percentages of each vehicle type can be found in the Appendix (with LDV_2 + HDV_2).

5.5 Electricity Power Grid

Coal power has been the most dominant source of electricity generation in China. 67.9% of electricity generation from fossil energy sources in 2020. Installed coal power has fallen from 74.7% in 2000 to 56.6% in 2020, and power generation has fallen from 82.2% to 67.9% (Figure 5-4).

China is continuously increasing its installed renewable energy capacity. By the end of 2020, China's cumulative installed renewable energy capacity will account for about 1/3 of the world, and new installations of wind power and photovoltaic will account for more than half of the world (IEA, 2020). It is expected that by 2025, the installed renewable energy power generation will account for more than 50% of the total installed capacity.

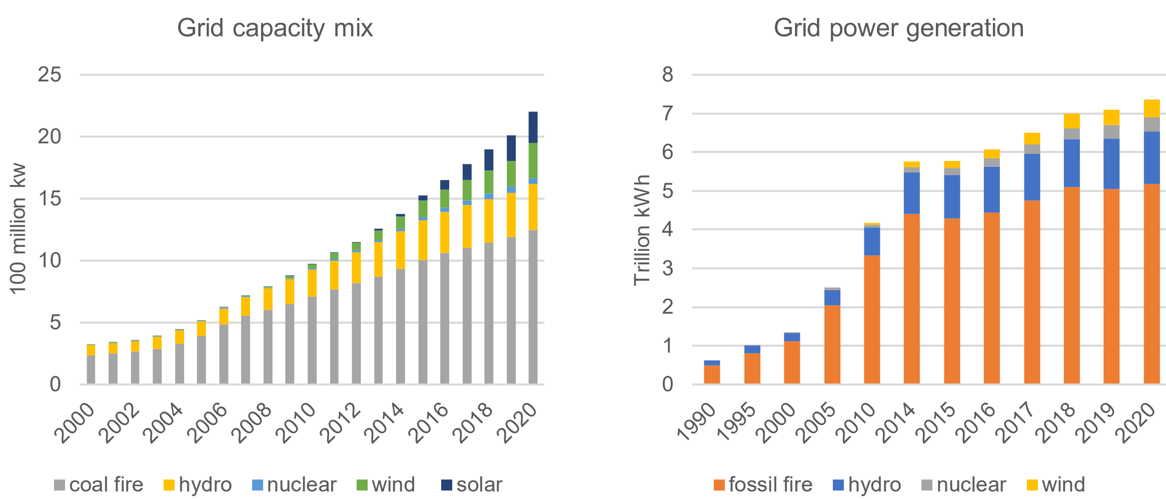


Figure 5-4 China historical grid structure

We set two scenarios for the grid development projection with more renewable energy in electricity generation (Figure 5-5). The BAU scenario (BAU Grid) is an extrapolated extension of the penetration of renewable energies in the electric production process and result in the coal power generation reduce to 25% in 2050. And the Rapid Renewable energy penetration scenario (RR

Grid) adopted from NDRC-ERI (2015) with a faster pace of coal phasing out of the power generation after 2030 with a corresponding drop to 6.8% in 2050. Even though Wang et al. (2019) estimated the RR Grid would encounter huge challenges as the required critical minerals needed for this scenario would be under shortage and supply risk, the energy and GHG result of vehicle operating with the RR Grid scenario would present important implications how the fleet emission would result amid a clean grid development.

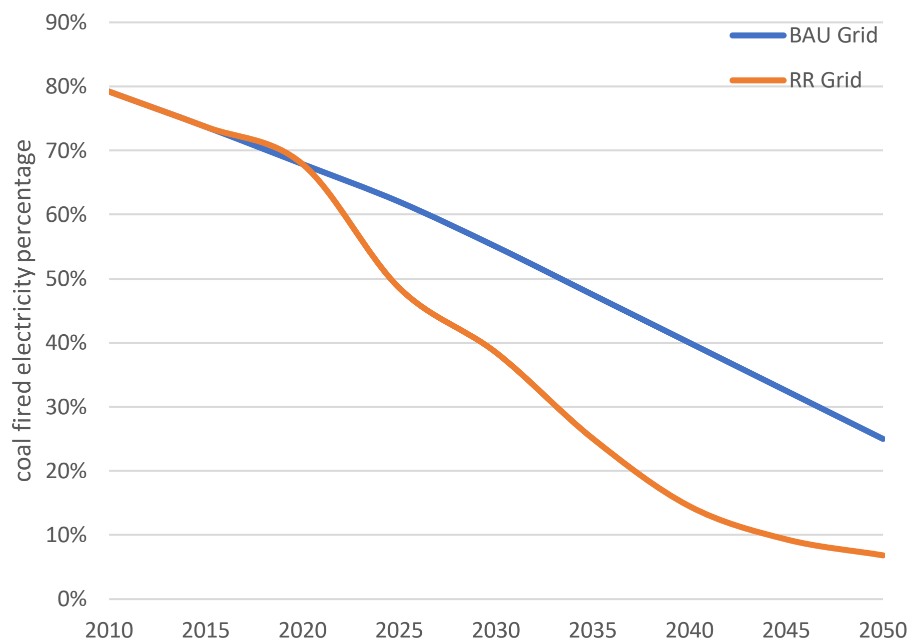


Figure 5-5 Electricity generation coal fired source percentage scenarios

5.6 Results and discussion

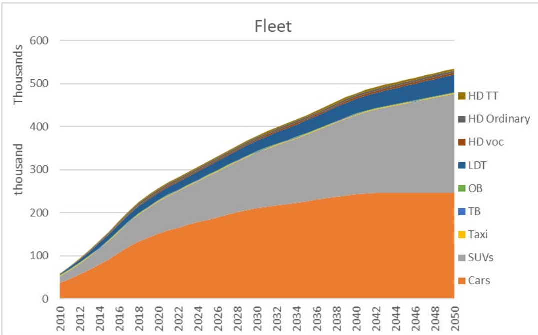
Two scenarios of vehicle fleet growth (BAU sales (BS) and Aging society sales (AS)), three scenarios of vehicle electrification (Stated policy LDV (SPL), Stated policy LDV and HDV (SPLH), higher pace LDV and HDV (HPLH)), and two scenarios of different percentage of coal in the power grid (BAU grid (BG) and Rapid Renewable Grid (RRG)) were built in the scenario setting. In this section, the results of the scenario combinations are presented and discussed.

Table 5-2 Scenario combinations

VEHICLE GROWTH	ELECTRIFICATION SCENARIO	GRID SCENARIO	COMBINATION
BAU Sales	Stated Policy LDV	BAU Grid	BS_SPL_BG
		RR Grid	BS_SPL_RRG
	Stated Policy LDV HDV	BAU Grid	BS_SPLH_BG
		RR Grid	BS_SPLH_RRG
	Higher Pace LDV HDV	BAU Grid	BS_HPLH_BG
		RR Grid	BS_HPLH_RRG
Aging Society Sales	Stated Policy LDV	BAU Grid	AS_SPL_BG
		RR Grid	AS_SPL_RRG
	Stated Policy LDV HDV	BAU Grid	AS_SPLH_BG
		RR Grid	AS_SPLH_RRG
	Higher Pace LDV HDV	BAU Grid	AS_HPLH_BG
		RR Grid	AS_HPLH_RRG

5.6.1 Results of Fleet composition

5.6.1.1 Fleet composition for BAU Sales scenario



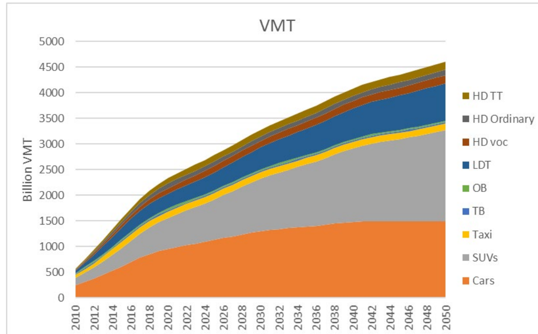


Figure 5-6 BAU Sales fleet and VMT composition

In the BAU Sales scenario, the total fleet keep growing to 535 million in 2050. Among all the vehicles, the light duty cars take the largerst portion in the fleet of 46%; larger size passenger vehicles of SUVs take another 43% in the vehicle fleet in 2050; the light-duty trucks and heavy-duty trucks take 8% and 3% respectively; other vehicle types of taxi, transit bus and other bus together take 1%. With a more intense annual driving activities, the taxies takes 3% in the total VMT in 2050, and LDT and HDT takes 16% and 8% of the total VMT respectively; the light duty cars and SUVs takes 32% and 39% in the total mileage. The total distances all the vehicles drive will rise to 4.6 trillion miles in 2050, about 8.2 times of the total driving distance in 2010.

5.6.1.2 Fleet composition for Aging Society sales scenario

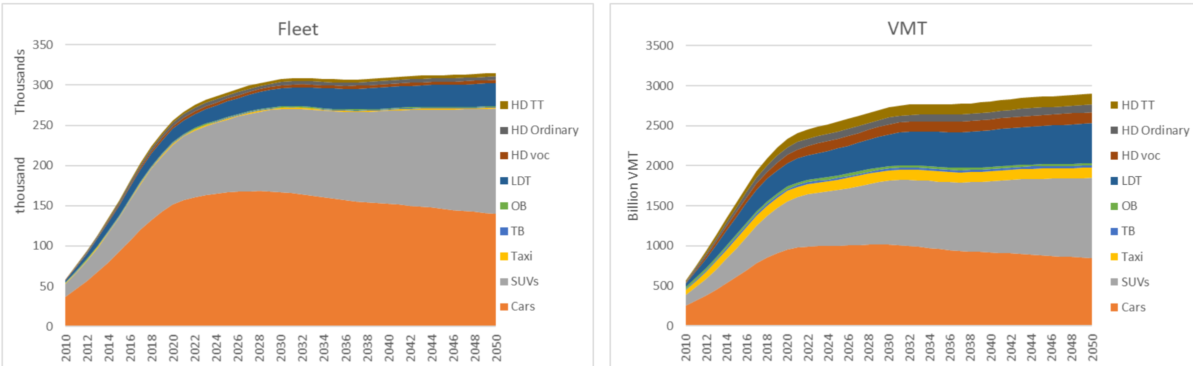


Figure 5-7 Aging society Sales fleet and VMT composition

In the aging society scenario, the total fleet growth slows down after 2020 and gradually grow to 2030, and then keep stable afterwards, reach a total fleet number of 315 million in 2050. Cars and SUVs take 44% and 41% in the total vehicle stock; LDT and HDT take another 9% and 3% respectively. The total mileage of all the vehicles travelling grow to 2.9 trillion miles in 2050, 5.1 times of the 2010 level. Among them, cars and SUVs takes 29% and 35%; taxis takes 1%; LDTs and HDTs taks 17% and 13% respectively.

5.6.2 Results of Energy Consumption

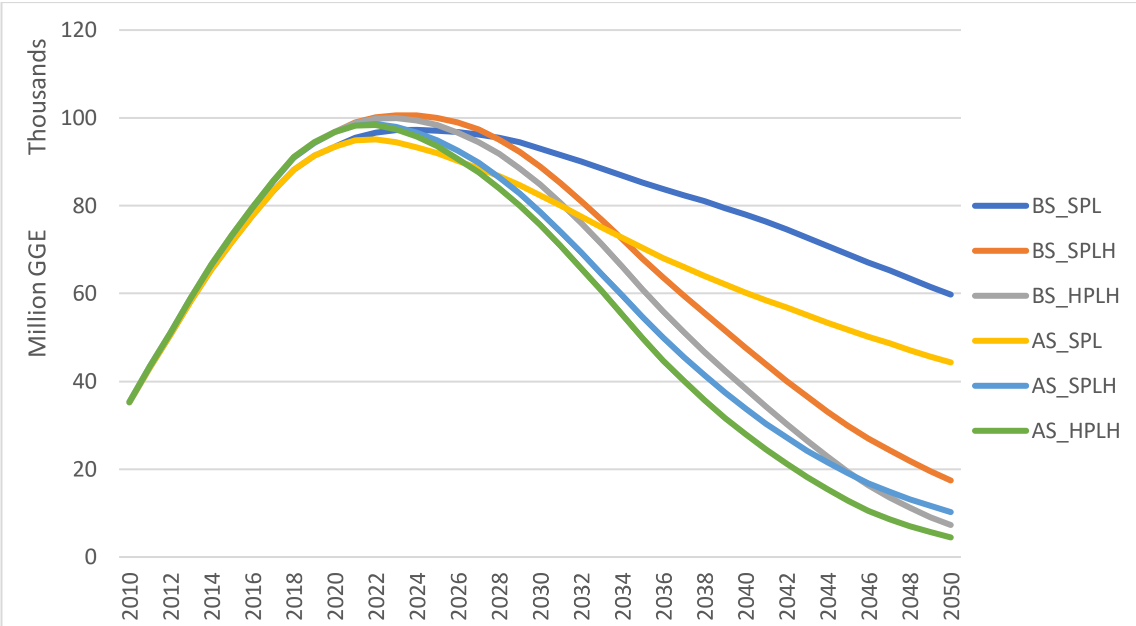


Figure 5-8 Traditional fuel (gasoline + diesel + NG) consumption in the scenarios

For all the scenarios of the sales and electrification scenarios, the traditional fuel consumption will decrease after 2025 with the improvement of the fuel consumption rates and electrifications. For the BAU sales and stated policy electrification scenario with few trucks electrified (BS_SPL), the fuel consumption will decrease the slowest, and to reach 59.7 billion GGE, the same level of the fuel consumption in 2013. In the aging society sales and stated policy electrification scenario with few trucks electrified (AS_SPL), with a stagnant total vehicle fleet and increasing fuel efficiency, the fuel consumption would decrease to 44.3 billion GGE, the same level of that in 2011. With a higher adoption rate of electric vehicles in the truck fleet, all the other four scenarios will have the fuel consumption decrease substantially, to reach less than (13-49% of) the 2010 level fuel consumption.

5.6.3 Results of GHG emission

The GHG emissions here includes the fuel stage emissions but not vehicle production stages. The carbon intensity numbers were adopted for each fuel types in each year. The electricity carbon intensity numbers are adopted from EIA. The CO2e emission results of BAU sales scenarios and the aging society sales scenarios are shown in Figure 5-9.

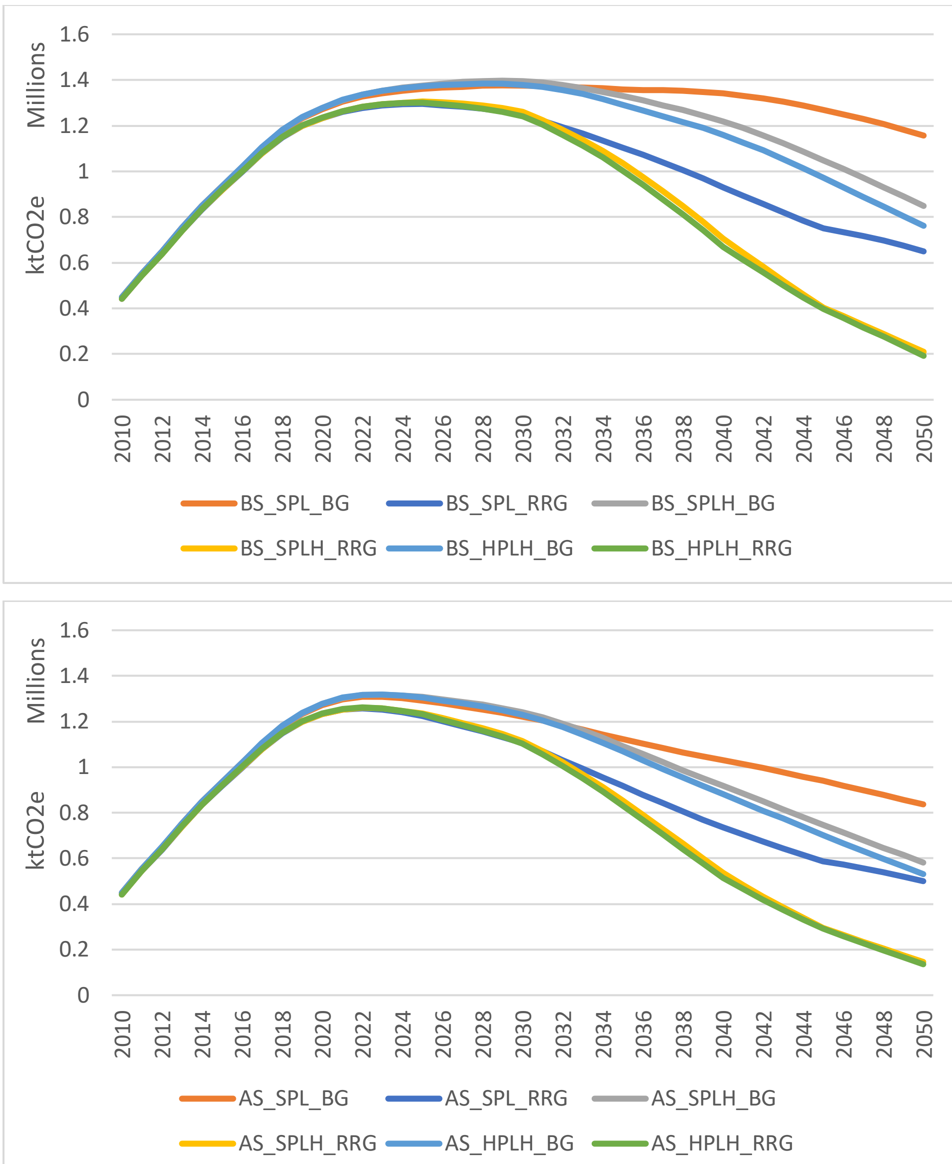


Figure 5-9 GHG emission results for different scenarios

(BAU sales scenario in the upper graph and aging society sales scenario in the lower graph)

With the continued vehicle sales and fleet growth in the BAU sales scenario, and the stated policy electrification paces with few trucks electrification (BS_SPL_BG), the total GHG emission will plateau after peaking in 2029 at 1.38 billion-ton CO_2e and decrease gradually to 1.15 billion-ton CO_2e in 2050, which is 2.58 times of the emissions in 2010. The electrification in the truck sector (BS_SPLH_BG) would bring down another 26.6% the GHG emissions in 2050 comparing to the fewer truck electrification scenario. The higher percentage of renewable energy in the power grid (BS_SPL_RRG) would reduce 43.8% GHG emissions comparing to the stated policy electrification scenario (BS_SPL_BG). With both higher electrification in LDV and HDV, and with high penetration of renewable energy in the power grid (BS_HPLH_RRG)), the GHG emissions could reduce 83.4% in 2050 compared to the stated policy electrification and stated grid power structure scenario (BS_SPL_BG) and reach a low GHG emission at about 43.5% of the 2010 level.

The aging society sales scenario GHG emissions will all peak in 2022 or 2023 with a stagnant vehicle fleet and more electric vehicles. In the stated policy electrification and stated grid power structure scenario (AS_SPL_BG), the GHG emissions will peak in 2022 with 1.31 billion-ton CO2e emissions and decrease to 0.84 billion-ton CO2e emissions in 2050, at 1.86 times of 2010 level. The truck electrification (AS_SPLH_BG) will bring another 0.25 billion-ton CO2e emissions down in 2050. The high penetration of renewable energy in the grid power and the highest electrification scenario (AS_HPLH_RRG) will bring the GHG emissions in 2050 down to 1.36 billion-ton CO2e emissions, 88.3% lower than the BAU sales, stated policy electrification and stated grid power structure scenario (AS_SPL_BG); and reach at about 30.7% of the 2010 emissions level.

5.6.3.1 Discussion

5.6.3.1.1 Conclusions

Three sets of key scenarios were developed in this study: two sales scenarios of BAU sales and aging society sales; three electrification paces of stated policy LDV electrification, stated policy LDV and HDV electrification, faster electric LDV penetration and HDV electrification; two power grid structure of stated phasing out of coal power and rapid renewable energy penetration in the power grid portfolio.

The modelling results reveals that, the electrification penetration in only LDV sector would not be enough to mitigate the GHG emission but will result in 2.58 times GHG emissions of the 2010 level in the BAU sales scenario. The electrification in the HDV sector will decrease GHG emissions by 26.6% by 2050, bringing the total GHG emissions in 2050 to about 1.89 times the 2010 level. The aging society sales scenario will have the GHG emissions decrease after 2023, but the stated policy electrification would still not enough in the emission mitigation in the long term, result the GHG emission in 2050 to 1.86 times higher than the 2010 level. The truck electrification and higher penetration of renewable energies in the power grid are critical for fleet GHG emission mitigation.

5.6.3.1.2 Uncertainties

This analysis provides a range of future vehicle sales, stock, energy consumption and GHG emission trajectory through scenario analysis. There are several trends on lifetime and VMT found but not reflected in the model estimation, as static survival curve and VMT were adopted for the modeling. First, the lifetime of the passenger vehicles has been extended over the past decades especially the recent five years. The lifetime of the vehicles is dynamic and changing with difference generations of vehicles and driving intensities. It is possible that it will be further extended in the future decades as there are more vehicles on road and the qualities of the vehicles getting better. An extended vehicle lifetime will keep the vehicle of earlier technology stay in the vehicle fleet longer and slowing down the turnover of the vehicle fleet to more efficient and cleaner technologies and may delay the GHG emission mitigation results. Second, the VMT of vehicles is getting shorter over the past decade. This may be caused by the fast growing in supply of supplement travel alternatives, like the rapid increase in the urban metro lines, supply of fast-speed rail, and cost reduction in air travel etc. Third, same survival rates and annual mileages are set for the same vehicle type with different technologies. The annual driving distance for electric vehicles could be shorter than that of a gasoline or diesel vehicle and the survival rates could also vary among vehicles with different fuels and technologies. Dynamic setting of lifetime and VMT, and different sets of lifetimes and VMTs for different vehicle technologies could be applied in future modeling work to reflect these trends.

6 Final remarks and policy recommendations

China has witnessed a soar in the population of vehicles in the past two decades. If the fast economic growth rate could be maintained, the high growth rate of vehicle ownership will keep for another decade also and gradually reach 500 million in 2050, with the vehicles total travel distance increase to eight times of the 2010 level. The demographic is changing rapidly and could potentially slowing down the vehicle growth. In the aging society scenario, the total population will peak around 2030 and decreasing afterward; the slowing down economic growth and people's consumption growth slows will result in the vehicle ownership stagnant and grow slowly to 330 million in 2050.

The Chinese government committed to industry-wide carbon peaking by 2030 and carbon neutrality in 2060. In the New Energy Vehicles technology development Roadmap, electric vehicle penetration plans have been made for automobile industry development aiming to peak GHG emission by 2028 for the vehicle sector. With the electric vehicles penetration paces stated in the Roadmap, and faster adoption of electric vehicles in the public vehicle fleet (taxis and transit buses), this study's calculations show that **it's feasible for the GHG emission from vehicles to peak in 2029, but a further reduction after the peak would be challenging**. **It requires investment in more stringent policies** such as accelerated truck electrification, higher percentage of renewable energy in electricity generation, and reduced vehicle amount and activity level to achieve the goal of carbon neutrality in the long term.

From the scenario analysis, a lower vehicle growth, high electrification and high renewable energy grid scenario would be possible to bring the GHG emission down close to carbon neutrality in 2050. The BAU scenario, with fast vehicle sales growth and stated policy electrification pace and extended renewable energy adoption in the power grid, the GHG emission will slowly decrease after 2029 and reach 1.15 billion-ton CO2e, about 2.58 times of the 2010 level.

The electrification of truck sector is essential for a significant emission reduction. If the electrification targets were only met by electrification of light-duty passenger vehicle sector and public fleet, the emission reduction would be not enough. For BAU sales scenario, with both truck and LDV electrification meet the stated policy target, the GHG emission decrease faster, emit 26.6% less GHG emission in 2050 than the scenario with only LDV electrified. **Even in the aging society with low vehicle growth, the stated policy electrification pace without truck electrification will result in a high GHG emission result in 2050 of 0.84 billion-ton CO_2e, about 1.83 times of the 2010 level.**

Through our projection and scenario analysis, a quick promotion of a high percentage renewable energy in the power grid portfolio is vital to reach the GHG emission reduction targets. Only if reducing the coal lower than 30% in the electricity generation before 2030 would be possible for the vehicle fleet emission to reach lower than the 2010 level GHG emission before 2050. The renewable energy penetration in the power grid could bring long-term GHG reduction benefits through the vehicle's operation.

From the Shenzhen case study, the electrification of the transit buses is feasible and cost-effective over the lifetime total ownership with the government subsidy. When count in the environmental benefits, the electric bus would be a more preferrable option than diesel bus without government financial support.

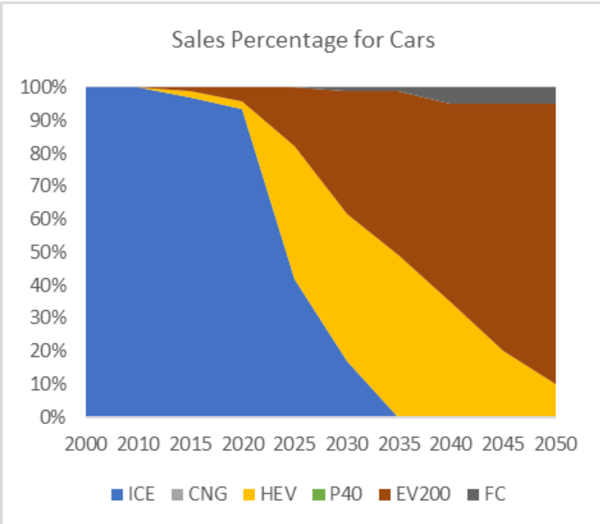
The fast vehicle growth will offset the emission reduction benefits from vehicle electrification. It is equivalently important to monitor and reduce on the total amount of vehicle ownership and driving activity, compared to the electrification of the fleet.

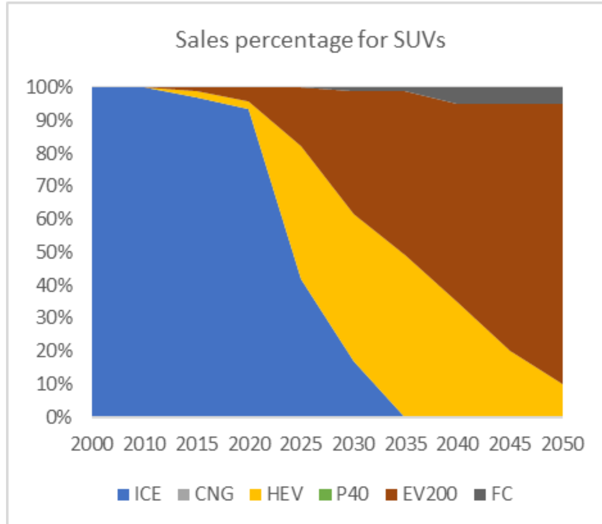
The tendency of owning larger vehicles and extending the vehicle lifetime would be a potential challenge for the decarbonization of the fleet. This analysis found the lifetime of the vehicles has extended over time with the increasing vehicle ownership. It would take more years for the vehicle fleet to turn over, which as a result, also put negative effects on the transportation sector GHG emission reduction for a delayed vehicle electrification and renewable energy adoption in the power grid. In another words, a leapfrog in the electric vehicle adoption and large percentage of renewable energy adoption will lock in tens of years of emission reduction benefits.

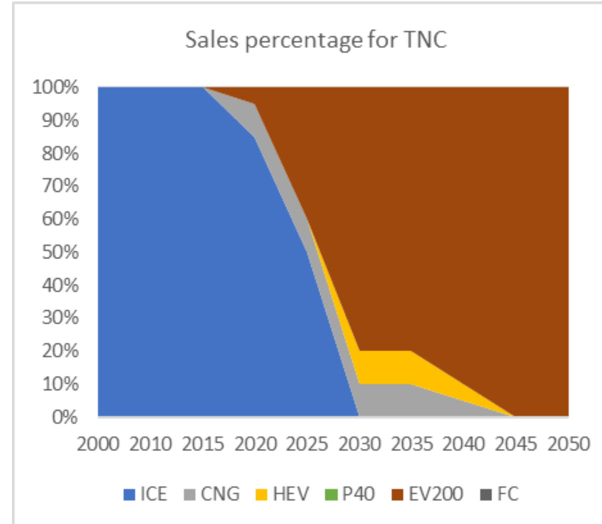
The deployment of electric vehicles has been steady increasing and the penetration rate reached 15% in September 2021. Uncertainties still exist on whether the growth rates of the electric vehicle penetration will continue steadily. As of 2021, with the rapid sales of electric vehicles, there's a supply shortage of batteries. The lithium price increased 240% over last year (Benchmark Mineral Intelligence, 2021) and consequently the battery price increased. At the same time, the GHG emission calculated in this study only included the production and operation process of the fuels and electricity consumed by the vehicles, without involvement of the production of the vehicle body or batteries. A comprehensive estimation of the lifetime GHG emissions for all the vehicles parts and batteries will result in a higher GHG emission. As a result, to reach a carbon neutral future in the road transportation sector, not only a more stringent and higher percentage of vehicle electrification and grid decarbonization are needed, the regulation and advocation of fewer vehicle ownership, less driving activity would also be important.

7 Appendix

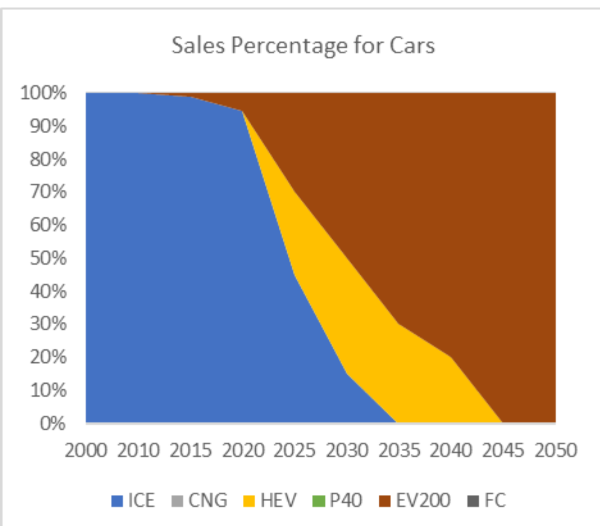
The electrification scenarios: LDV_1_Stated policy

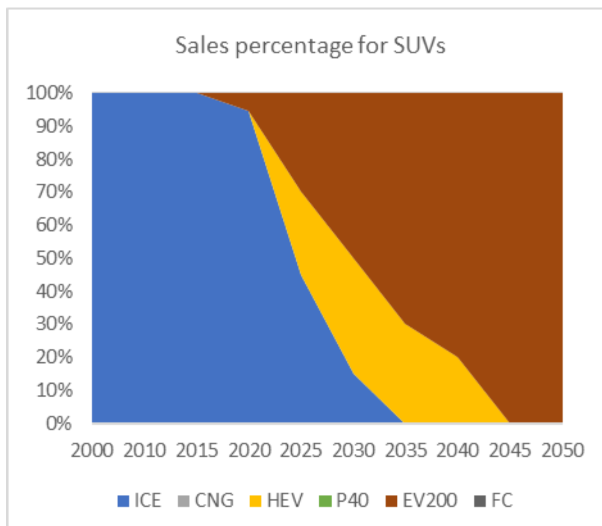


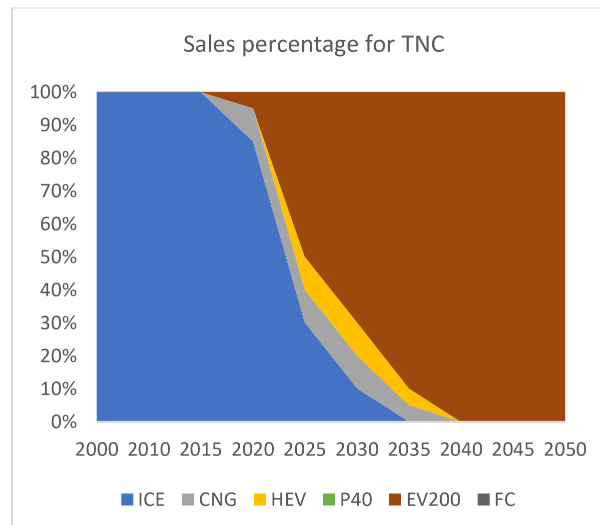




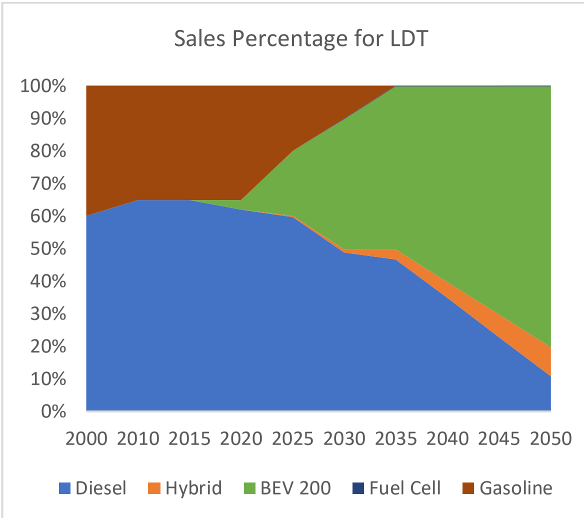
LDV_2_higher pace electrification

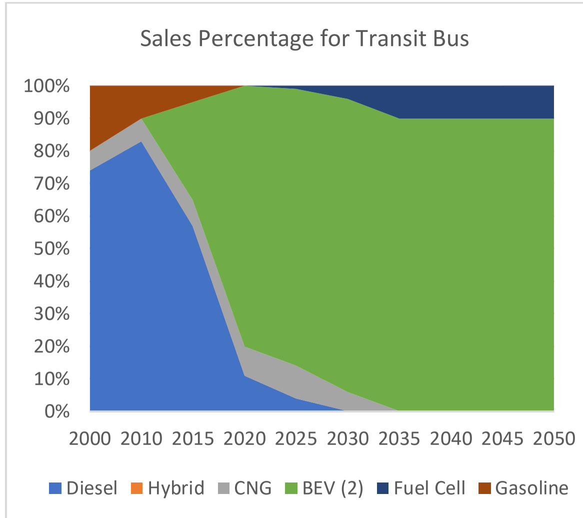


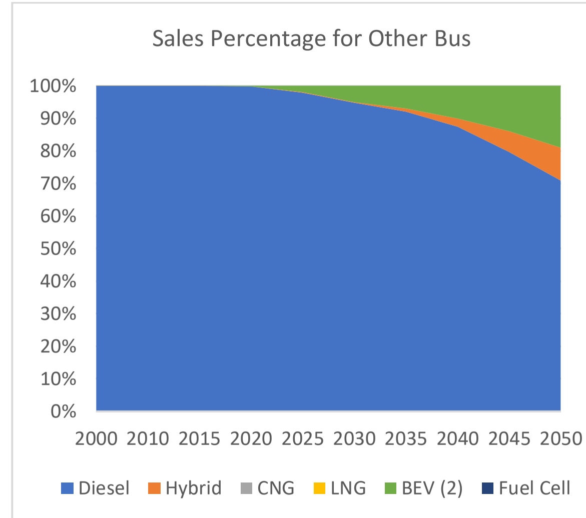


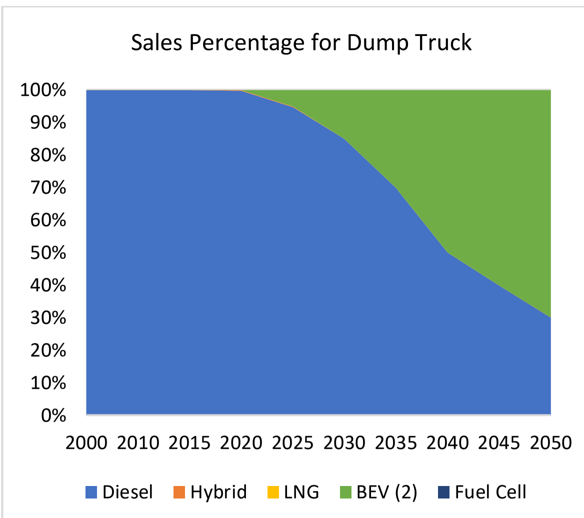


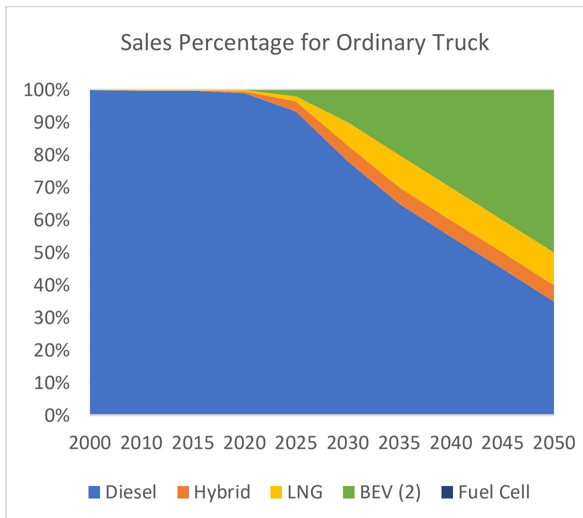
HDV_1_low EV penetration

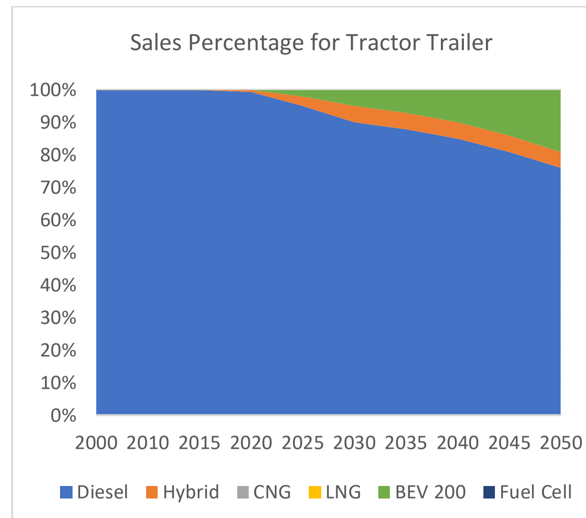




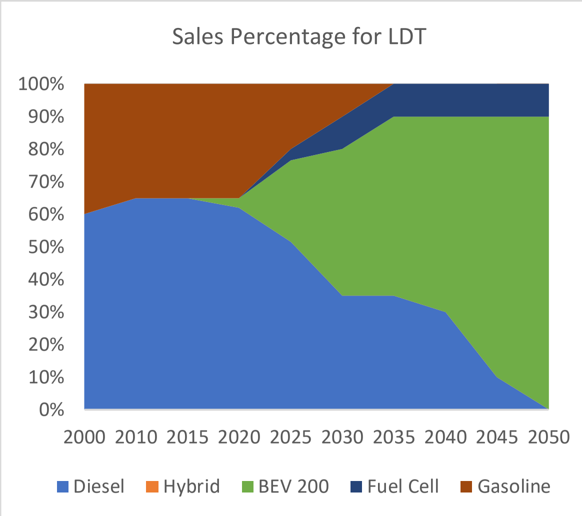


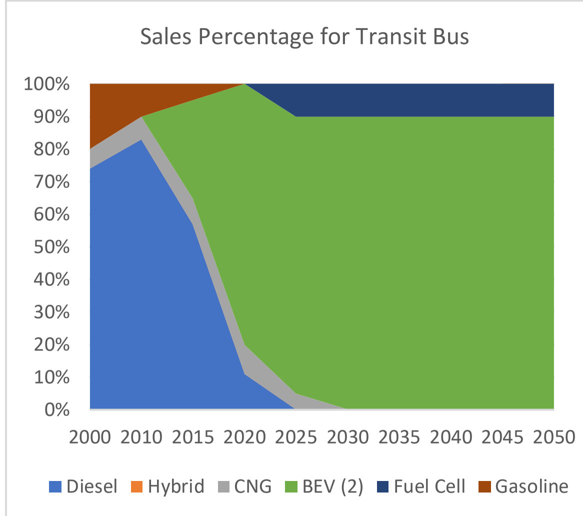


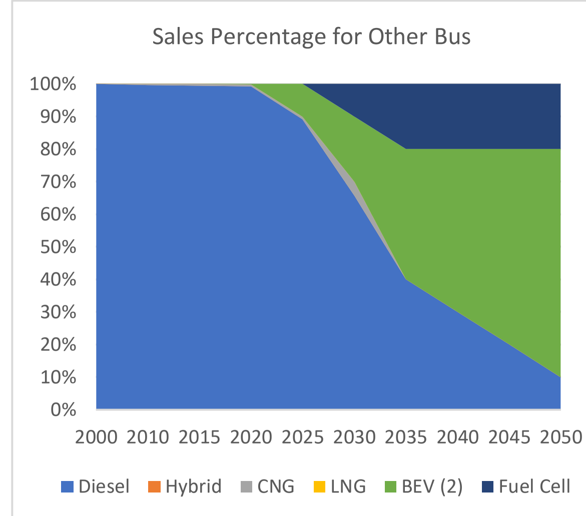


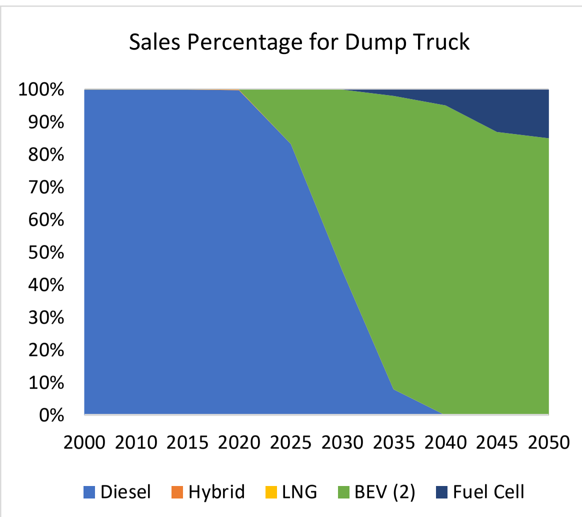


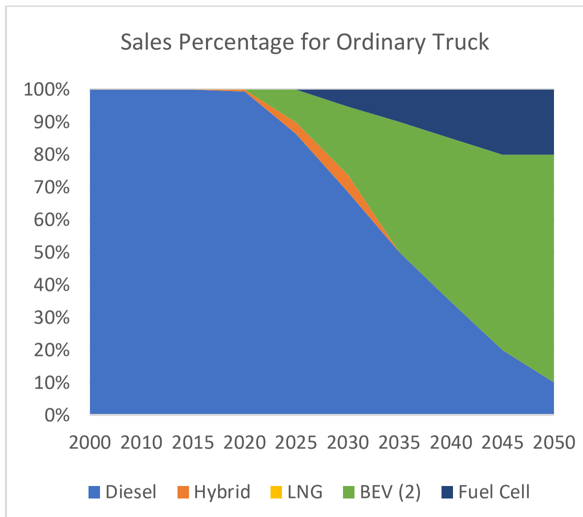
HDV_2_higher pace EV penetration

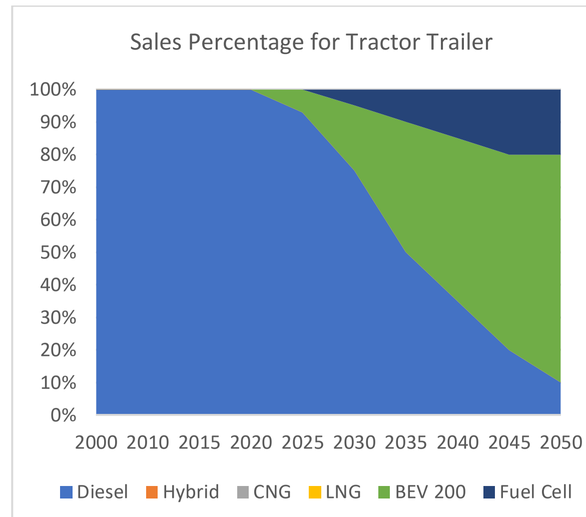












Abbreviations

BEV	Battery Electric Vehicle
CO_{2e}	Carbon Dioxide equivalent
FCV	Fuel Cell Vehicle
GDP	Gross Domestic Product
GHG	Greenhouse Gas
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
MEE	Ministry of Environment and Ecology
MIIT	Ministry of Industry and Information Technology
NEV	New Energy Vehicle
NOx	Nitrogen Oxides
PHEV	Plug-in Hybrid Electric Vehicle
$PM_{2.5}$	particulate matter with a diameter of less than 2.5 micrometers
ppm	parts per million
SSBC	State Statistical Bureau of China
VKT	Vehicle Kilometers Travel
VMT	Vehicle Miles Travel
WHO	World Health Organization
WTW	Well to Wheel
GGE	Gasoline Gallon Equivalent

Approximate Conversions from SI Units

Symbol	When You Know	Multiply By	To Find	Symbol
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
l	liters	0.264	gallons	gal
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb

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