Low-Carbon Futures for Shenzhen's Urban Passenger Transport System

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Abstract

China has established ambitious CO_2 emission reduction targets, and sustainable urban passenger transport is a key to reaching them. Shenzhen, one of China's leading cities, has the potential to be a model for achieving low-carbon development. Using an Activity–Structure–Intensity–Fuel (ASIF) framework and a human-based approach that incorporates individual transport behavior using data from a travel diary survey in Shenzhen in 2014, we model different scenarios for future urban passenger transport energy consumption and CO_2 emissions from 2014 to 2050. We find that if Shenzhen successfully constructs urban structures with greater density around the public transportation network, and finds effective ways to restrict vehicle ownership and use (either through mandatory schemes or pricing) while making substantial investments in the walking and cycling environment, it is possible for total urban passenger transport emissions to peak at 4.3 $MtCO_2$ in 2025, and individual emissions would fall by over 65% compared to its 2014 level, reaching 118 $kgCO_2$/person by 2050.

Key words: ASIF, carbon emissions, energy consumption, urban transportation, scenario analysis, transportation policy

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1. Introduction

At the 21st Conference of Parties (COP21) held in Paris in Dec. 2015, China promised to peak its total carbon emissions by 2030, in addition to setting a national target to reduce carbon intensity by 40-45% by 2020 compared to 2005. To fulfill these ambitious commitments, achieving a sustainable transport system is one of the most fundamental challenges facing cities. Cities account for 80% of greenhouse gas emissions. Transport accounts for 15% to 40% of total city CO_2 emissions and in developing countries often accounts for the greatest share of the increase in carbon emissions as many individuals aspire to own their own vehicles. It is of pressing importance to understand what the future low-carbon transport systems will look like and the role transport can play in realizing sustainable transport futures.

Given the relatively low motorization rate and underdeveloped transport infrastructure, Shenzhen, one of China's leading economic cities, has the potential to serve as a model for achieving sustainable transport while leapfrogging to a low carbon transport system. However, due to lack of availability of energy and emission statistics on Shenzhen's urban passenger transport sector, the potential for Shenzhen to realize such a future has been unclear.

Based on an Activity–Structure–Intensity–Fuel (ASIF) framework (Schipper et al., 2000), this study generates the first comprehensive estimates of Shenzhen's urban passenger transport energy consumption and CO_2 emission, with detailed travel information obtained from a travel diary survey conducted in Shenzhen in 2014. We model future energy consumption and CO_2 emissions from the present (base year is 2014) to 2050, to examine how socio-economic, technological and behavioral changes influenced by policy may contribute to reducing urban passenger transport energy consumption and CO_2 emissions in the future.

In contrast to existing studies that use vehicles as the unit of analysis, this research develops an individual-based ASIF framework by incorporating individual travel behavior into the model. This enables us to examine the environmental impact of changes in individual socio-economic factors, as well as individual responses to policy interventions. Other scholars also have included socio-economic factors in their modeling[1], but makes ad hoc assumptions about the relationship between technologies and social groups. This paper connects socio-economic factors with travel behaviors and the selection of different transport technologies, and thus, to the best of the author's knowledge, is the first to combine engineering modeling techniques at the aggregate level with econometric studies at the individual level to analyze urban passenger transport systems.

The rest of the paper is organized as follows. In section 2, we present our modeling approach and the analytical framework. Baselines for major drivers of our study are also discussed and defined. Building upon these baselines, Section 3 defines the four major

[1] For instance, Aamaas et al. (2013) grouped the distribution of different transport technologies according to socio-economic groups.

scenarios we consider and presents the main results on future outcomes associated with each scenario. A final section concludes.

2. Methodology

2.1. Overall Modeling Approach

The Activity–Structure–Intensity–Fuel (ASIF) framework has been widely used in the existing literature to model energy consumption in the transport sector (e.g., Skippon et al., 2012; Schipper et al., 2000). Under this framework, total CO_2 emissions is the product of transport activity (A, usually measured by vehicle-km per year), transport structure (S, usually measured by passenger-km per vehicle-km), energy intensity (I, usually measured by MJ per vehicle-km), and emission intensity (F, usually measured bygCO$_2$ per MJ). It is based upon transport information of vehicles rather than individuals.

Unlike previous studies, by surveying individual transport behavior in Shenzhen, we are able to incorporate individual transport information into the existing ASIF framework. As all travel decisions are actually made by individuals, the human-based approach can provide more accurate estimation of how travel demand changes with socio-economic conditions. It also makes it possible to account for individual responses to policies, which makes the scenario results more accurate and accessible.

Carbon emissions at time τ can be calculated by using equation (1):

$$C_\tau = \sum_m \sum_f DIST_{m,f,\tau} \cdot INT_{m,f,\tau} \cdot FUEL_{f,\tau} \,, \tag{1}$$

where m and f denote transport mode and fuel type, respectively. We consider 10 types of transport modes, including shuttle bus, bus, subway, taxi, private cars, vans, electric two-wheel vehicles[2], manual bicycles, walking, and others. We consider seven types of fuel technology for vehicles, including 92# gasoline, 95# gasoline, 97# gasoline, diesel, gasoline-hybrid, diesel-hybrid, and battery vehicles[3].

$DIST_{m,f,\tau}$ is the distance travelled using transport mode m and fuel type f at time τ, calculated using equation (2):

$$DIST_{m,f,\tau} = DAY \cdot POP_\tau \cdot ATRIP_\tau \cdot SM_{m,\tau} \cdot ADIST_{m,\tau} \cdot SF_{m,f,\tau} \,. \tag{2}$$

Here, DAY is the number of days per year, or 365; POP is the total population of the city, $ATRIP$ is the average number of trips per person per day, SM_m is the share of mode m in the total number of travelled trips, $ADIST_m$ is the average distance of each trip by mode m, and $SF_{m,f}$ is the share of fuel technology f in transport mode m in terms of vehicle population, assuming that the travel distances of vehicles using different fuel technology are the same.

$INT_{m,f,\tau}$ is the energy intensity of each person trip that uses transport mode m and fuel technology f, measured in terms of MJ/(100 km/person/trip), and calculated as follows:

[2] We do not consider two-wheel vehicles that use fossil fuels, since the Shenzhen government forbids use of them for security reasons. According to our travel diary survey results, none of the respondents reported travelling by gasoline/diesel/hybrid two-wheel vehicles.

[3] We distinguish between different types of gasoline, because the average levels of fuel economy for the three types of vehicles are divergent. 95# and 97# cars use 12% and 18%, respectively, more fuels than 92# cars, according to our survey results.

$$INT_{m,f,\tau} = \frac{INTV_{m,f,\tau}}{PASSENGER_{m,f,\tau}}, \tag{3}$$

Where $INTV_{m,f}$ is the energy intensity of transport mode *m* using fuel technology *f*, MJ/(100 km/vehicle). For private cars and electric two wheel vehicles, we average the reported fuel consumption per km by the respondents. For bus, subway and other types of motorized transport modes, we refer to estimates of energy use from other studies. $PASSENGER_{m,f}$ is the average number of passengers in vehicles using transport mode *m* and fuel technology *f*, based on our survey results.

Lastly, $FUEL_{f,\tau}$ is the carbon emission factor of fuel type f at time τ, measured in gCO_2/MJ.

2.2. Analytical Framework

In this study, we produce long-term scenarios for urban passenger transport energy consumption and CO_2 emissions for Shenzhen from 2014 to 2050.Below, we discuss the impact of major drivers, including population, income, vehicle technology enhancement and urban transport policies, and way in which we define different scenarios. Our study differs from the previous literature in terms of unit of analysis. Given the availability of individual travel diary survey data, we are able to consider the impact of major drivers from an individual standpoint, rather from a vehicle perspective.

2.2.1. Income and Population Growth

Basic Modeling Theory. The impact of income upon individual travel behaviors, including number of trips, travel distance and selection of travel modes, etc., has long been studied in many previous studies. For instance, Lu and Pas (1999) find that income has significant positive association with the number of household trips, travel time, and the share of trips that use cars. Similarly, we consider economic and demographic attributes as determinants of individual travel behavior. We thus estimate the following equations:

$$trip_i = \alpha_0 + \alpha_1 \cdot income_i + \sum_j \eta_j \cdot demographic_{i,j} + \upsilon_i \tag{4}$$

$$distance_{m,t} = \beta_{m,0} + \beta_{m,1} \cdot income_t + \sum_j \gamma_{m,j} \cdot demographic_{t,j} + \nu_t \tag{5}$$

$$P_{t,m} = \delta_{0,m} + \delta_{1,m} \cdot income_{t,m} + \delta_{2,m} \cdot distance_{t,m} + \sum_j \chi_{j,m} \cdot demographic_{t,j,m} + \varepsilon_{t,m} \tag{6}$$

Here, i indexes the 1015 respondents in the travel diary survey, j is a subscript for different *demographic* variables, including gender, age, education level, and t denotes the 2954 trips made by the respondents. We also control for urban districts in each regression using dummy variables. The variables used in the regressions are defined as follows: $income_i$ is the monthly income of respondent i, in yuan/month, $trip_i$ is the number of trips made by the respondent i per day, $distance_{m,t}$ is the travel distance in trip t using transport mode m, and t $P_{t,m}$ is the probability of selecting transport mode m in trip t.

Using our travel diary survey data, we are able to estimate the coefficients in equation (4) and (5) using Ordinal Least Squares (OLS) estimators, and estimate the coefficients in equation (6) using Multinomial Logit (MNL) estimators. In estimating the latter, we reduce the number of categorical choices for transport mode, m, from 10 to 4, as Hausman and Wise (1978) warn that MNL model is unsolvable when $m \geqq 5$. More specifically, the four choices we consider are public transportation (including shuttle bus, bus, subway and other), cars (including taxi, private car and van), electric two-wheel vehicles, and non-motorized transport (including man-powered bicycles and walking). The regression results are presented in Table1. With these coefficients, we are able to estimate the changes of number of trips, travel distance and selection of transport modes when incomes rise.

Table 1: impact of logged-income on transport behaviors, regression coefficients

Parameter	coefficient
Numer of trips per person per day	0.057
Distance per trip, km/trip	0.253
Probability of owning a car,	0.296
Probability of choosing:	
- Non-motorized transport	-0.013
- 2-wheel vehicle	-0.001
-Public transport	0.022
- Car	0.035

Population also directly influences transport energy consumption and CO_2 emissions at the city scale, simply because with more the residents in a city, the more travel demand there will be, as in equation (2). In addition, the structural evolution of the population, in terms of age and education, will also influence the outcomes in equation (4)-(6), which will in turn influence energy and emission levels. Lastly, there is a rich literature that points out that the quality of the population, mostly reflected by age and education structure, will also drive local economic growth and thus individual income levels. In other words, population growth is usually positively associated with economic growth.

Trends and Uncertainties. As shown in Table 2, there are many aspects of the future that are important but about which there is uncertainty. These can be grouped into the categories of economy, society, technology, environment, and urban planning. All of these dimensions of the future will influence future energy use and CO_2 emissions in Shenzhen.

China's GDP has grown rapidly by 8%~11% per year over the last two decades. However, due to weak demand in both the global and domestic market, the GDP growth rate dropped to 7.4% in 2014 and entered a so-called "New Normal" transition period. In the 13th National Five-Year Plan, the central government projected that national GDP will double by 2020 compared with 2010 levels, which indicates that GDP growth is expected to slow down and maintain a rate of about 7% per year over the next five years.

Shenzhen's economic achievements during the past three decades have been remarkable even by Chinese standards, with an average annual growth rate (at constant prices) of an amazing 24%, starting from a very low base. Not surprisingly, the growth rate has dropped over time, leveling off at around 10% over the past five years but dropping to 8.8% in 2014. The Shenzhen government has remained active in terms of promoting local demand and promoting innovation-driven industries and modern services.

China replaced the One-Child Policy with a national Two-Child Policy in October 2015. Under the new family planning policy, each family is allowed to have up to two children, which could lead to faster population growth than under the old policy. The State Council released new population projections under the new policy, predicting that the population will peak at

1.45 billion in 2030, a slight increase over earlier projections.

For Shenzhen, the rate of migration has always been the main driver of population growth. In recent years, the rate of in-migration has slowed. The population growth rate of the city fell from 4% per year during 2005 to 2010, to 1% per year from 2011 to 2014. Future population growth thus will be closely tied to the dynamism of the local economy.

The Shenzhen government also is actively seeking to upgrade the skill level of the local labor force as it seeks to play a leadership role in the growth of high-tech industries and services to sustain high rates of economic growth. It seeks to attract young and skilled professionals from all over China, and to create an environment that fosters entrepreneurship. In 2014, the Shenzhen government issued a new policy to provide generous subsidies[4] to attract high-quality talents to the city, which could also help boost population growth in coming years.

Aging of the population also poses challenges to the Chinese government. The share of of the population above age 65 increased from 6.96% in 2000 to 8.87% in 2010, and is expected to exceed 25% by 2050.[5] Shenzhen is a relatively young city dominated by migrants from all over China. Currently, it does not have a large group of elderly above age 65 (1.1% in 2000 to 1.8% in 2010)[6] but the average age of the working population is increasing as migrants settle

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[4]According to the new plan, the government will provide rent-free apartments for qualified immigrants. Besides, for all the immigrants that have bachelor and above diploma will get a subsidy of around 6000~12000 yuan per year. Data source: http://www.szjs.gov.cn/csml/rcb/xxgk_410/zcfg/201412/t20141231_2771243.htm [last access on 20151227].
[5]Data source: http://www.stats.gov.cn/tjsj/tjgb/rkpcgb/qgrkpcgb/201104/t20110428_30327.html [last access on 20151225].
[6]Data source: http://www.sztj.gov.cn/xxgk/tjsj/pcgb/201105/t20110512_2061597.htm [last access on 20151225].

down in the city for the long term.

To sum up, Shenzhen's population growth may increase to some extent in the coming years and the skill level of the population is likely to grow. The workforce will continue to age, but the share of elderly in the population will remain much lower than for China as a whole. All of these population factors may influence Shenzhen's transportation patterns.

Table 2: Trends and Uncertainties in Shenzhen's Future Development

Trends and Uncertainties
Economy and governmental
Economic growth rate (GDP)
Globalisation, international trade and investment
Manufacturing and service sector growth, including motor vehicle manufacturing
Becoming a centre for innovation and high-skilled manufacturing and services
Socio-demographics
Rural to urban migration (Hukou system reform) and population growth
Age profile (influenced by the Two-Child Policy and ageing population)
Aspirations and culture – 'western consumption' or 'other' model
Social equality, social welfare, urban-rural balance
Technologies
Technological innovation
Electric vehicle technologies
Energy and power supply – renewable sources
Environmental
Climate change
Improvement in environmental quality
Urban issues and transport planning
Environmental issues – stewardship, extent of 'seriousness' of policy making and implementation
Urban design quality
Extent of urban sprawl
Aspirations towards sustainable travel, investment in public transport, walking and cycling environment
Extent of car dependency
Smart city

Baseline Description. In this study, we consider two different baselines for future population and income growth in Shenzhen. As show in Figure 1, in the low baseline (L in the figure), Shenzhen continues the trend of a decreasing population growth rate despite the generous subsidy policy, and is further influenced by the "New Normal" economic environment. As a result, the population reaches 18 million in 2050 and the per capita income reaches 200,000 yuan/year (in 2014 prices). Our baseline population projection for Shenzhen is different from some other studies. For instance, Kang (2014) assumes a constant population growth rate of about 4% and forecasts that the population will increase rapidly and reach 20 million by 2020. However, with growth and population slowing in recent years, such a high population growth rate seems unlikely to be sustainable in the longer term. To account for the possibility that Shenzhen is able to maintain its economic dynamism and divert considerable effort and resources to implement attractive policies for migrants, we also consider a high scenario in which the population growth rate is higher (H in the figure). Under this scenario, population gradually increases to 25 million and income per capita peaks at 400,000 yuan per year (in 2014 prices) in 2050.

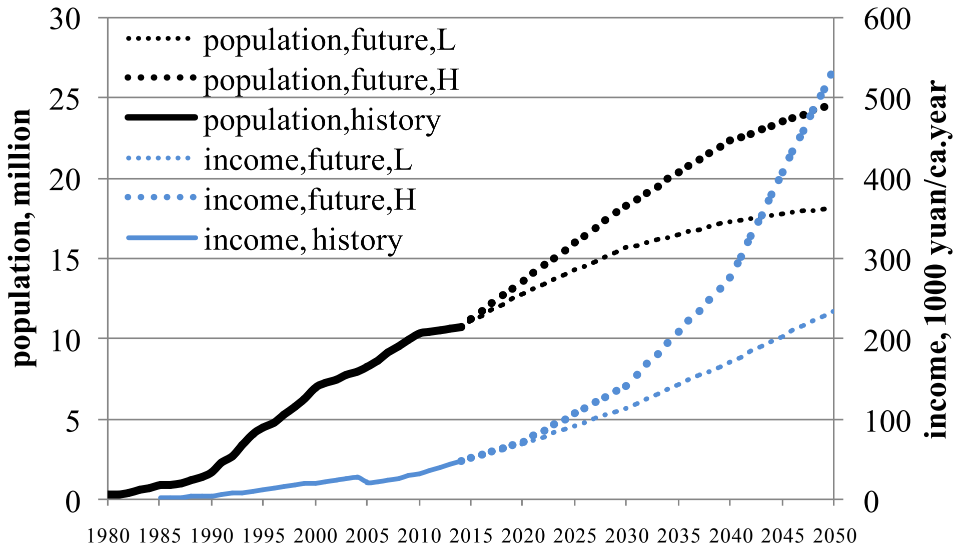

Figure 1: Population and income: historical and projections for high and low baselines, 1980-2050

2.2.2. Technological Advancement

As shown in Table 2, besides previously discussed socio-economic factors, technological factors also are likely to have a significant impact on low-carbon futures.

Energy consumption of urban passenger transport naturally varies with the energy performance of the vehicles used. Future improvements in energy performance due to expected advances in transport technologies have been well studied, so we construct our technology baselines based upon the forecasts of previous studies. The expected energy performance of major technologies is shown in Figure 2. Energy used by diesel buses is expected to fall from around 1100 MJ/100km[7] in 2014 to 600 MJ/100km in 2050 in the low baseline (L in the figure). The gasoline used by cars should fall from around 280 MJ/100km in 2014 to 120 MJ/100km

[7]The range of fuel use for bus is between 1000 MJ/(100km.vehicle) (Zhang, 2010) to 1200MJ/(100km.vehicle) (Cai et al., 2012) in existing literatures. We use the middle number of the range.

in 2050[8] in the high baseline (H in the figure).

In both low and high baselines, the fuel intensity, measured in liters of gasoline per 100 km per vehicle, will drop by more than 50% compared with current levels, which will make a tremendous contribution to energy conservation and emissions reduction in the future urban passenger transport sector.

Carbon emission coefficients for different energy types are key for calculating CO_2 emissions. In this study, we assume carbon emission coefficients for gasoline and diesel remain constant, and focus attention on the change in the emissions coefficient for electricity. Many studies (e.g. Ou et al., 2010; Shen et al., 2012; etc.) argue that the electricity structure, which refers to the mix of fuels from which electricity is generated, has a significant impact on the life-cycle emissions level of EVs. Considering that electricity in China is mainly generated from coal, EVs are not necessarily less carbon-intensive than other vehicle alternatives. However, the national energy targets are ambitious about increasing the use of non-fossil fuels for electricity generation.

Following ERI (2014), we consider two electricity baselines in our study. As shown in Figure 3, the emissions coefficient of electricity is expected to decrease from 2.1 tCO_2/tce in 2014 to 1.2 tCO_2/tce in 2050, when around 50% of the electricity in China is generated from non-fossil fuel energies in the low technology baseline (L in the figure). In the high baseline

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[8]According to the survey results, the average fuel use per car is 9 L/100km, which equals approximately to 280 MJ/100km. Based on it, we consider the national fuel economy advancement rate projected by ERI (2014) for fuel use per car in Shenzhen in future.

(H in the figure), 58% of the electricity is from non-fossil fuel sources and the corresponding coefficient will be only 1.06 tCO2/tce in 2050.

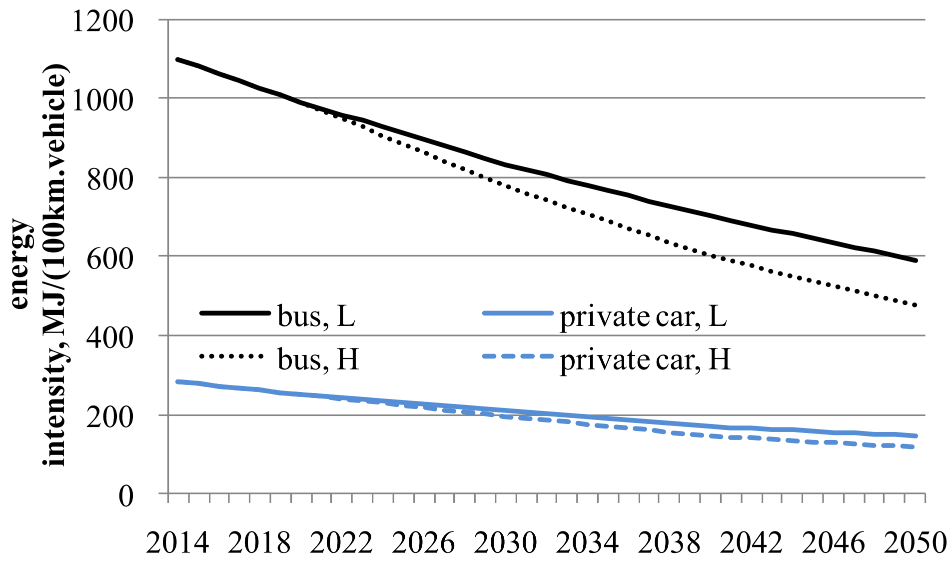

Figure 2: Fuel intensity of buses and cars in baseline cases
Source: Cai et al., 2012; Zhang, 2010; Skippon, 2012; ERI, 2014.

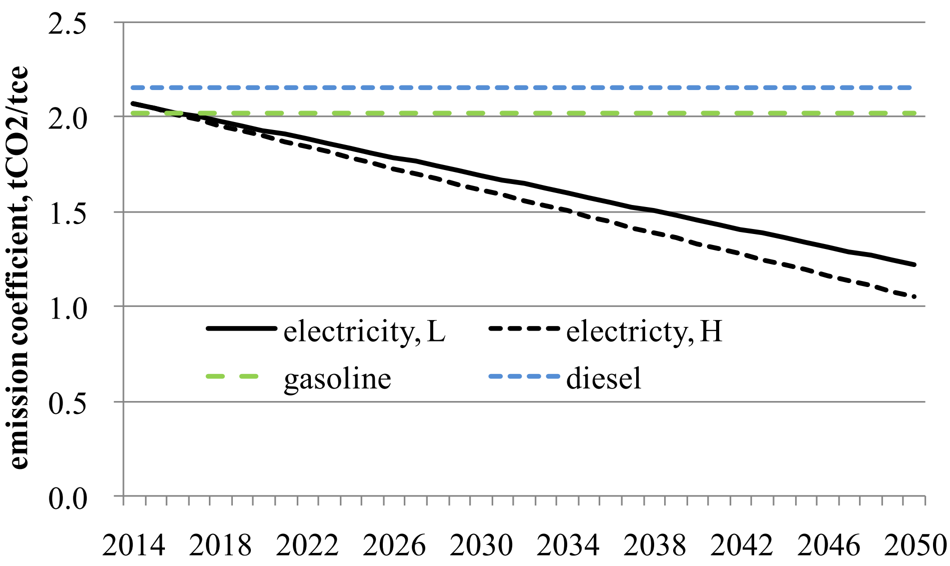

Figure 3: Emissions coefficients of different energy types
Source: CPI, 2012; ERI, 2014.

2.2.3. Transport Policy Packages

As shown in Table 2, environmental restrictions increasingly influence individual travel activities. Education to increase environmental awareness also may play a role in influencing travel behavior. Policies to promote the use of non-fossil fuels also are of vital importance. For instance, government subsidies for battery electric vehicles (BEV hereinafter) aim to increase BEV's share in the total vehicle population (SF in equation (2)). Another example is car-sharing policies, such as priority vehicle lanes for shared cars, which aim to increase the number of passengers riding in each vehicle ($PASSENGER$ in equation (3)).

***Trends and Uncertainties*.** Shenzhen plays a leading role in China's low-carbon development, especially for the transport sector. The city is the pilot city for various programs, such as promoting electric vehicles (EV, hereafter). Before discussing different policies packages applicable to Shenzhen's future, we review briefly existing transport policies in Shenzhen and their effectiveness and problems.

Transport policies in Shenzhen follow three major directions. First, the government promotes the use of public transportation in various ways. On the one hand, the government increases the supply of public transport services dramatically. Subway service was not provided in Shenzhen until 2004, and the length of subway lines increased rapidly over the past decade to reach 177 km in 2014 (SBSZ, 2015). Another 15 subway lines, whose combined total length will be approximately 540 km, are either under construction or planned (UPSZ, 2012). As a result, the per capita subway length will reach 2.3 cm/ca. by 2030. In our study, we assume continued subway construction after 2030, with per capita subway length peaking at 3.0 cm/ca. in 2050, which would be equal to that of Hong Kong in 2014 (SBHK, 2015). Similarly, the number of buses in service in Shenzhen increased from 6,050 in 2000 to 15,074 in 2014. We assume continued increase in supply of bus services, with the per capita number of buses rising from 1.4 buses per 1000 persons in 2014 to 2.8 in 2050, which is the 2014 level for Hong Kong (SBHK, 2015).

On the other hand, the government also provides subsidies to both service suppliers and users in Shenzhen to promote the use of public transport. The Shenzhen government developed the local subsidy scheme in 2008[9], by which the net profit of service providers is maintained at 6% to guarantee that service quality could be maintained under various unforeseen circumstances such as oil price fluctuations, etc. The total amount of the subsidy increased quickly from 1.7 billion yuan in 2009 to 5.7 billion yuan in 2013. For service users with a Pass Card, a price discount policy has been applied since 2007. Specifically, subway passengers receive a flat discount rate of 5%. For bus passengers, a discount rate scheme that varies by distance is applied, and an additional 0.4 RMB subsidy is given for each trip.

A park-and-ride scheme, which was proven to be effective in restraining the use of private

[9]Data source: http://www.docin.com/p-801548856.html [last access on 20150720].

cars and encouraging the use of public transport in London (Parkhurst, 2000) and Hong Kong (Lam et al., 2001), was also introduced in Shenzhen in 2012. 1089 parking spaces are provided and incentives such as cash coupons from the railway service provider are provided. However, the system did not work well. Only 10% of the provided parking spaces have been used each day over the past two years, and only 50% of those who use the parking spaces actually park and then ride the subway.

However, the extent to which such policies will persuade citizens to shift from private transport modes to public ones is debatable. For example, in Beijing the share of private car trips in total passenger trips increased much faster than that of public transportation during the past decade. However, in Hong Kong, the share of private car trips in total passenger trips was stable at 5% in 2002 and 2011, with the share of subway trips increasing from 11% in 2002 to 23% in 2011, compensated by a decreased in the share of bus trips from 27% to 15% during the same period. In Shanghai, Cervero and Day (2008) find no significant association between car use and public transport accessibility. They conclude that as incomes rise, people increasingly drive cars no matter what.

The second main policy direction is to encourage less use of cars, and if one must use a car to encourage the use of more energy efficient cars. In order to slow down the growth of the car population, the Shenzhen government launched a car quota policy on December 29, 2014, which establishes an annual quota of 100,000 new cars in each of the following five years.

According to the policy, 20% of the quota is allocated for electric cars by lottery, 40% for conventional cars by lottery, and the remaining 40% for conventional cars by auction. There are many concerns about the transparency of the policy procedures and equity (affordability) problems associated with the auction system (Chen and Zhao, 2013). There is also concern that will try to purchase more expensive vehicles, since the policy increases the relative utility of having luxury cars to that of having cheap cars, which will increase fuel consumption. Generally, researchers find that car quota policies cannot properly address the complex relationship between ownership and use of vehicles (e.g., Phang et al., 1996, Wang, 2010, etc.). Of course, it is the use of vehicles, not their ownership, which creates energy and environmental problems.

The government promotes the use of energy efficient vehicles in three ways. First, it introduces fuel economy standards, which improve the overall energy performance of vehicles on the road (Feng, 2009). Second, it encourages the purchase of small engine-size cars instead of larger ones through financial incentives. China charges various taxes that vary with engine size. For manufacturers, a higher consumption tax is charged for sales of larger engine-sized cars, which produce widen price differences that generate incentives for purchasing smaller vehicles. For consumers, an annual license fee, or "Chechuan" Tax is assessed, which increases with the engine size of the car. In Shenzhen, the rate for vehicles with engine size bigger than 4L is 4500 RMB/year, which is 25 times higher than that for vehicles no larger than 1L, for which the tax is only 180 RMB/year. The third way is to promote the use of alternative energy vehicles, especially EVs. The policies in Shenzhen cover all parts of the value chains (including production, purchase, and use) for EVs, and both command-control and market-based instruments are employed. The central and local governments jointly provide generous subsidies for the purchase of EVs, which are about RMB 1 million for battery buses and RMB 100,000 for battery private cars, with half subsidies provided for hybrid buses and cars. In addition, the government not only requires installation of chargers in parking lots but also provides various incentives, such as exemption of the annual license fee and electricity subsidies. In addition, the New Energy Vehicle (NEV) Credit Account is a very innovative instrument that is worth mentioning. The account calculates the CO_2 emissions reduction according to the charging records of the electric vehicle. The government establishes a fund financed by local fiscal revenues to provide a subsidy to vehicle owners based on the amount of CO_2 reduction. Generally, the more one uses electric vehicles, the more subsidies he or she will obtain.

The government launched various measures to reduce the use of private cars in Shenzhen. It forbid the use of Yellow-Labeled Vehicles (YLV)[10] and introduced odd-even license plate number limits on all motor vehicles since 2005 during the afternoon (15:00 to 19:00) on several major roads. Whether the limits will be applied in the future to all of Shenzhen is yet to be

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[10]YLVs refer to gasoline vehicles below the National I Emission Standard and diesel vehicles below the National II Emission Standard and are attached with yellow labels by the local transportation department. Since 2011, the definition of YLV for diesel vehicles changed to those below the National III Emission Standard.

determined. The effectiveness of driving limits on reducing car use is generally regarded as a short-term solution only (e.g., Gallego et al., 2014; Cantillo and Ortuzar, 2014; etc.). For example, when Beijing introduced city-wide driving restrictions based on license plate numbers for different days of the week starting with the Olympics in 2008, the congestion index, the higher of which indicates worse traffic conditions, decreased from 7.95 in 2007 to 5.93 in 2009, and went back to 7.80 in 2010 (Wang and Liu, 2014). Instead of turning to public transportation on restricted days, drivers purchased a second car or used cars more intensively during unregulated periods (Davis, 2008; Gallego et al., 2014).

To provide a market-based incentive, the government introduced a fuel tax since 2009. The fuel tax rate in China in 2015 is 1.4 yuan/L for leaded gasoline, 1.4 RMB/L for unleaded gasoline, and 1.1 yuan/L for diesel, which are much lower than in Hong Kong, where leaded petrol is taxed at 6.82 HK$/L and unleaded petrol at 6.06 HK$/L. However, contrary to expectations (e.g. Sterner, 2007), the Fuel Tax did not greatly influence the use of vehicles in China. According to a survey in Beijing (Chen and Lin, 2010), only 6% of car owners reduced their annual travel trips and distance significantly. More than 54% of the sample did not use their cars less than before the fuel tax policy, and for the remaining 40% there was no significant change. Another survey in Hubei province (Yuan, 2010) found that 84% of car owners said they were not influenced by the higher fuel tax.

With respect to parking policies, the government has adopted two seemingly contradictory approaches. On the one hand, the government has continuously increases the supply of parking places by raising minimum parking requirements for buildings, which will increase use of cars, as Weinberger (2012) alerts. On the other hand, the government also more than doubled the parking fee in Shenzhen in 2013 compared to 2001, which will reduce car use and congestion (e.g., Calthrop, et al., 2000, Marsden, 2006, etc.). Yet increasing the parking fee is not without problems. Glazer and Niskanen (1992) find that increasing the parking fee per unit time does not reduce car use but rather the parking time for each person, which results in more people using the parking spaces and more traffic. Shoup (2006) also states that there could be inefficiency when drivers are searching for cheap parking spaces on the street, which increases congestion and other environmental and economic costs. Last but not least, there is also severe institutional fragmentation which hampers the implementation of parking regulations (Wang and Yuan, 2013). According to the latest street parking regulations[11] in Shenzhen, the traffic management department is in charge of the design and daily management of on-street parking. Fining violations of the parking rules must be authorized by the traffic police, another city department. As a result, the average price of parking is 2.3 yuan/hour, which is lower than the lowest price guidelines established by the Shenzhen government.

The third policy direction of the government is to encourage citizens to use non-motorized transport modes, or biking and walking. First, the government increased pedestrian

[11]The Management Regulation on Motor Vehicles On-Street Parking in Shenzhen was implemented since 1st May, 2014, and is available from http://www.chinalawedu.com/falvfagui/22016/ca2014040816531716785758.shtml [last access on 20150718].

and cycling infrastructure. Many pedestrian areas were established and bicycle lanes constructed. The length of bicycle lanes will reach 2863 km by 2020, equal to 5.7% of the length of all road lanes. Bicycles parking is now provided at 40% of the subway stations to facilitate bicycle park-transit trips. The government also promotes bicycle renting services. There are 18 bicycle renting service stations in Shenzhen providing more than 1000 bicycles. Shenzhen initiated several pilot projects in Shenzhenwan, Shekou, Yantian, and Xin'an areas in 2012 to test different bicycle renting systems. The first is to have the local government establish and operated the system, as in Hangzhou. The second is to have local government established the system, then outsource operations to an enterprise, as in Zhuzhou. The third is to outsource everything to enterprises, as in Wuhan.

However, bicycling faces severe competition from alternative transport modes, especially public transportation and private cars, especially when taking into account the safety, environmental, and infrastructure concerns.

Baseline Description. To sum up, the transport policies in Shenzhen mainly aim to prioritize the use of public transportation, reduce private car use, and encourage the use of non-motorized transport. However, it should be noted that all transport modes are interconnected due to their competition with each other. As a result, it is difficult to clearly distinguish the impact of a single policy. In this study, we evaluate different policy packages that are combinations of policies implemented at different levels, and generate transport mode choices based on the the joint impact of all the policies. The effect magnitudes are determined by reference cases where applicable, in addition to the previously discussed econometric formulas in equation (6), which is motivated by population and income growth.

In the scenario analysis, we consider two baseline policy packages. Some alternatives are not considered because of data limitations. The fuel economy standards have been incorporated in the technological baselines and are not discussed in this section. We produce two baseline cases, one with low effectiveness and the other with high-effectiveness, the features of which are summarized in Table 3. The two cases differ with respect to major policies that have high uncertainty.

We do not distinguish in the two baselines between different outcomes related to the supply of public transportation services because the services are mostly government-driven and so are expected to have low uncertainty. For instance, according to current plans, the length of new subway lines will reach 540 km by 2030. If smoothly implemented, the plan will ultimately establish a comprehensive subway network. The per capita subway length will be around 4cm/ca., considerably exceeding the average level of Hong Kong (3cm/ca.), a city well-known for its efficient public transport system. As a result, we assume in both baselines that the subway and bus service supply will increase according to government plans and eventually reach the same levels of buses and subway length per capita as in Hong Kong.

However, we do consider different structures of bus fleets for the two baselines, because

EV buses are one of the focuses for Shenzhen as a pilot city for the national EV promotion programs. We assume that Shenzhen will outperform the national EV promotion goal by about 20 percentage points in 2050 in the low-effectiveness baseline, in which case EV buses will account for 40% of the local vehicle population. In the high-effectiveness baseline, we assume that the government will take more ambitious actions and the share will reach 70%, far exceeding the national average goals for 2050. We also consider enhanced public transport services in the high-effectiveness baseline as information technologies advances, which will enable providers to increase services during rush hours and reduce them when there is limited demand.

For private cars, in the low-effectiveness baseline, we assume that even with a car quota policy, citizens who aspire to own and drive cars will find ways around the constraint, for instance by using cars that are not registered in Shenzhen. As a result, on-road cars will increase dramatically from 1.5 million in 2014 to 8.2 million in 2050, even accounted for the rising cost of owning and using cars. In addition, as a pilot city for EV promotion, we assume that Shenzhen will maintain its leading role in EV use, especially for buses and taxis. However, there will remain great uncertainty about the extent to which individuals will be willing to purchase private EVs, which makes the future market share of EVs uncertain. In 2015, a quota of 20,000 EVs was assigned to Shenzhen to be allocated by auction, but only 2,146 were used[12].

[12]Data source: http://sz.southcn.com/content/2015-08/10/content_130313480.htm [last access on 20151227].

Thus in the low effectiveness baseline, we provide conservative estimates of the future EV share in Shenzhen and assume it will be equivalent to the national average goals in 2050. Following Beijing, the license plate number-based driving limits will be used throughout the city, reducing the on-road vehicle numbers. For parking policy, the government will continue struggling with the contradiction of increasing parking supply and raising parking fees, so we assume that the policy will reduce congestion problems in highly developed areas of the city but will not reduce the overall use of vehicles in the entire city.

In the high-effectiveness baseline, Shenzhen will enjoy enhanced environmental governance. The car-quota policy will be strictly implemented and the vehicle population effectively controlled. We do not reduce the quota number over time considering the increasing aspiration of local residents to own cars. As a result, the private car population will increase from 2.5 million in 2014 to 6.1 million in 2050. For EV promotion programs, as noted above, we assume that the EV share in Shenzhen is 30 percentage points higher than that of the enhanced national goal of 28.7% (ERI, 2014), which will require the Shenzhen government to maintain its active role in subsidizing the purchase of EVs and constructing EV infrastructure. In addition, we assume that the government is even more determined in the high-effectiveness baseline and launches an odd-even number driving limit policy (allowing cars to drive during only half of the workdays). With respect to parking policy, parking fees will be raised continuously while the supply of parking spaces will be restricted. A last promising opportunity for low-carbon transport is the sharing of car use. Recently, the number of people sharing car rides has increased with the use of various smart-phone apps. In the high-effectiveness scenarios, we project a continued trend of increased sharing of car rides.

Figure 4 presents the vehicle information in the two baselines. In the low-efficiency baseline (L in the figure), private car ownership will reach 764 cars/1000 persons and the EV population will reach 2.8 million in 2050, while in the high-efficiency baseline (H in the figure), the private car ownership will stay at 272 cars/1000 persons, slightly higher than the current level, and the EV population will reach 3.6 million in 2050.

For non-motorized transportation, we focus on policies affecting bicycle use. As discussed above, the park-transit policy for bicycles in Shenzhen does not work well. In the low-effectiveness baseline, since public transportation and private cars continue to be highly competitive alternatives, the attractiveness of park-transit trips will remain low, despite the increased supply of bicycle lanes and parking areas near subway stations. A similar logic applies to the bicycle renting system. According to our survey results, only 9% of respondents rented a bike in Shenzhen in the past three months. In fact, bicycles are used mainly used occasionally for entertainment or exercise, or to run errands, and rarely for routine purposes like commuting. On the contrary, in the high-effectiveness baseline, bicycling becomes more popular and users of the park-transit scheme and the renting system will increase considerably so that both systems are used up to their service capacity.

Table 3: description for major baselines of different policies

Policy packages		Baselines	
		Low-effectiveness	High-effectiveness
Subway construction		4cm/ca., exceeds Hong Kong level	
Bus fleet		30buses/10000ca., reaches Hong Kong level	
Public transport service management		The same as now	Enhanced, intelligent
Car-quota policy		Non-Shenzhen cars unregulated	Strictly implemented
EV pilot program	Bus and Taxi	Achieve the pilot city goal	Outperform the pilot city goal
	Private car	Exceed basic national goal	Exceed enhanced national goal
Driving limits		Plate-number limits	Odd-even limits
Parking policy		Contradictory, increasing supply and raising fees	Consistent, raising fees while controlling supply
Car sharing policy		Not adopted	Booms facilitated by information technology advancement
Biking promotion	Bicycle lane	Following the government plans	
	Park-transit	Not-well used	Fully used
	Renting system	Temporary users only	Successfully promoted

To sum up, in the low-effectiveness baseline, the implementation of the existing policies and the environmental governance of Shenzhen as a whole are improving as expected, which can be regarded as a business as usual baseline. In the high-effectiveness baseline, more efforts have been made in various dimensions to achieve enhanced goals.

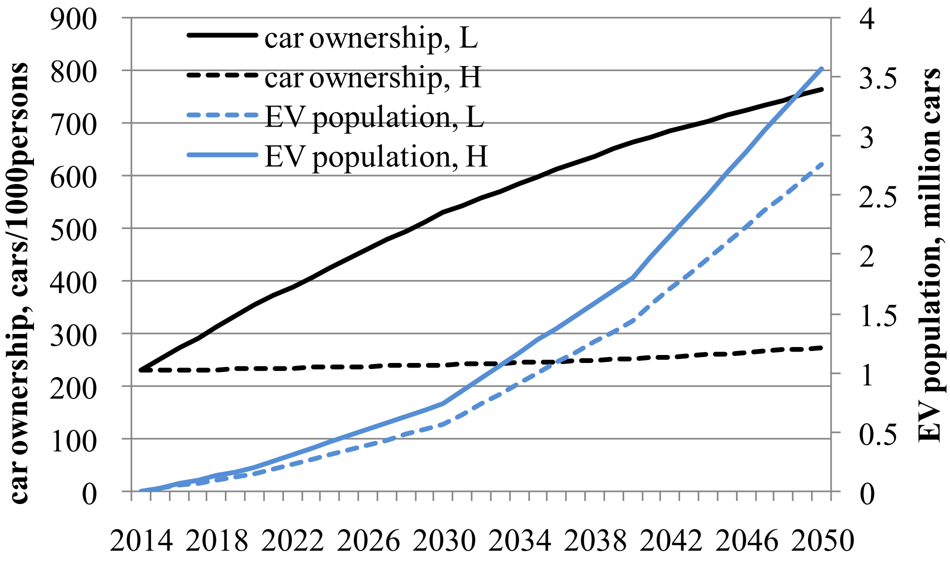


Figure 4: vehicle ownership and EV population in different baselines

3. Results

3.1. Emissions in the Base Year

As previously mentioned, the base year of our study is 2014, the year in which the individual travel diary survey was conducted. Some important socio-economic and urban passenger transport-related parameters used in the analysis are shown in Table 4.

The calculated final energy consumption of the urban passenger transport system in Shenzhen in 2014 is 1.34 million toe (Mtoe hereafter), including 1.30 Mtoe gasoline and diesel use and 484 GWh electricity use. The corresponding CO_2 emissions is 3.91 million tCO_2 ($MtCO_2$ hereafter). Personal energy consumption and CO_2 emissions for urban passenger transport in Shenzhen is 124 kgoe/person and 363 kgCO2/person, respectively. The energy consumption level is approximately double the Chinese average[13] but still much lower than the U.S. level (Jia et al., 2010). Since there are no corresponding statistics for Shenzhen, we compare our results with the latest data from other sources, and find that they are roughly consistent.

Table 4: Key model parameters for Shenzhen in 2014

parameter	value	Unit
Metropolitan area	1997	km^2
Population	10.78	Million
Population density	540	Persons/km2
GDP per capita	21357(149497)	US$(yuan)/person
GDP growth	8.8%	-
Income of urban residents	48672	Yuan/person
Length of subway lines	177	Km
Vehicle population		
-Private cars	2492400	Vehicles
-Buses	15074	Vehicles
-Taxis	16275	Vehicles
-Private car ownership	231	Vehicles/1000person
Mode share*		
-Bus	21.3%	-
-Subway	7.4%	-
-Car	16.0%	-
-Motorized two-wheel	5.5%	-
-Manpower bike	4.6%	-
-Walk	45.2%	-
CO_2 reduction target	National target to reduce carbon intensity by 40% to 45% by 2020 compared to 2005 levels, and peak the total carbon emission by 2030.	
Energy consumption*		
-Total consumption	1.34	Mtoe
-Per capita value	124	kgoe/person
CO_2 emission*		
-Total emission	3.91	$MtCO_2$
-Per capita value	363	kgCO2/person

Note:*, the numbers are calculated results of our energy and emission model based on the travel diary survey.
Data source: SBSZ, 2015.

[13] According to Jia et al.(2010) estimation, the Chinese average transport energy consumption is 257 kgoe/person and only less than 7% of the USA level. In addition, 60% of the energy consumption is for good transports and 10%~20% is for between-city passenger transportations. As a result, the Chinese average urban transport energy consumption is approximately 51~77 kgoe/person.

Gasoline and diesel sales in Shenzhen in 2012 reached 2.90 Mtoe (Wulan, 2013), of which 0.30 Mtoe was used in manufacturing (SBSZ, 2015). As a result, the gasoline and diesel use for vehicles in Shenzhen was approximately 2.6 Mtoe in 2012. If we assume half is used to transport goods, then the gasoline and diesel consumption for urban passenger transport in Shenzhen in 2012 was 1.30 Mtoe, which is equal to our estimate based on the travel diary survey data.

Total electricity consumption for all the 3173km of subway lines in China is 9400 GWh (CAM, 2015). If we assume electricity use for Shenzhen's subway system is proportional to the length of Shenzhen's subway line (177km) as a share of the length of all subway lines in China, then electricity use for Shenzhen's subway system would be about 524 GWh in 2014. However, CAM (2015) reports that Shenzhen is more energy efficient in its subway operation than other cities. So the actual electricity used by the subway system should be lower than the above estimate, and so is close to our estimation.

3.2. Emissions of Different Scenarios

Based on the previous discussion, we calculate projections for four major scenarios which combine different baselines for different drivers, as shown in Figure 5.

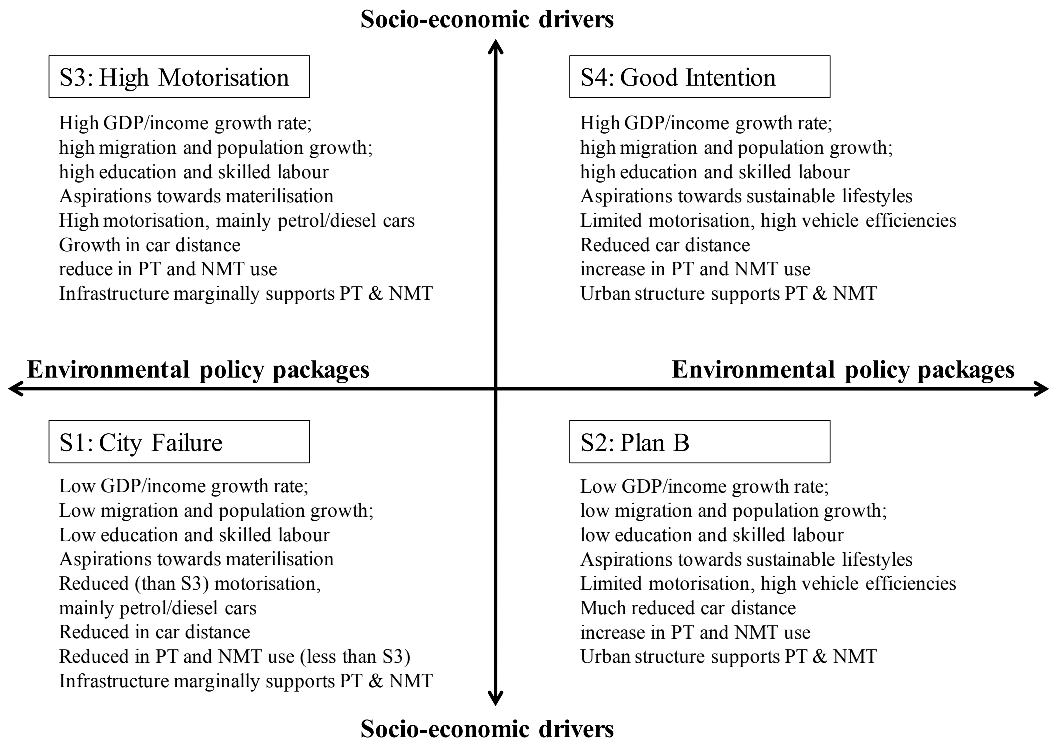
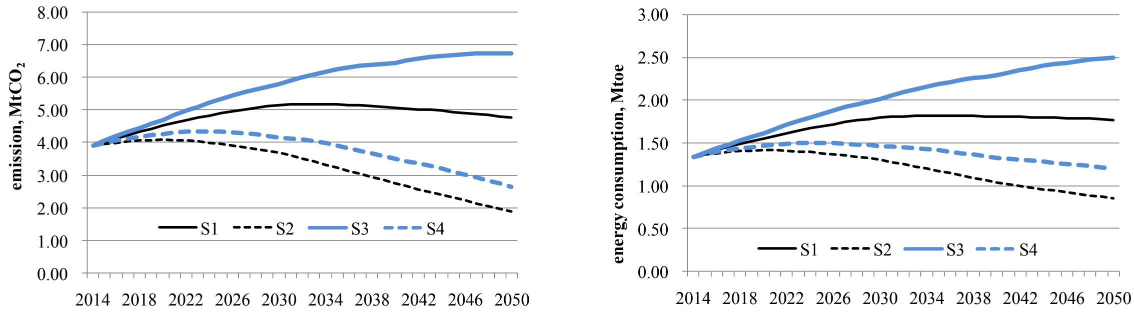


Figure 5: Definition of different scenarios

Note: Detailed baselines of both ends of the arrows are described in detail in section 2.2.



a) CO2 emission b) Energy consumption

Figure 6: Shenzhen CO_2 emissions and energy use under different scenarios , 2014 to 2050

The projected energy consumption and CO_2 emissions under different scenarios are displayed in Figure 6. Under the high growth scenario with less effective policy interventions (S3 in the figure), both energy and emissions will increase continuously and reach 2.5 Mtoe and 6.7 $MtCO_2$, respectively, by 2050. Thus, if the economy performs well, current policies may be insufficient to realize the city's CO_2 emissions targets.

Strengthened and active low-carbon policies can contribute a lot to energy conservation and reducing emissions. In scenario S4, with highly effective policies (see section 2.2.3), energy consumption and CO_2 emission will peak in 2025 at 1.5 Mtoe and 4.3 $MtCO_2$, respectively. Energy consumption and CO_2 emissions in 2050 will fall by 10% and 32%, respectively, compared to 2014, and will be 50% and 60% less than the levels in 2050 under scenario S3.

The tremendous saving potential is achieved through multiple improvements. First, the share of private cars in total passenger trips does not increase, in contrast to when the vehicle population grows rapidly (as in the low effectiveness case). As shown in Figure 7, the share of private cars levels off at around the 2014 level in 2050, due jointly to the slow growth of car ownership under the rigid car quota policy and to strengthened parking policies, which make cars less attractive. Second, EVs dominate the vehicle population, which leads to much more efficient energy use. After the country greens its electricity fuel mix and replaces half of its coal use with non-fossil fuels in electricity generation, EVs also become attractive alternatives for dealing with the problem of CO_2 emissions. As a result, the share of electricity in energy consumption increases from 10% in S3 to 30% in S4, as shown in Figure 8. Third, although individual travel distance nearly doubles in 2050 compared to 2014 due to rising incomes, the distance travelled by private cars decreases from 13.1 km in S3 to 10.5 km in S4, as shown in Figure 9, which also contributes to much lower energy consumption and CO_2 emissions.

Now let's turn to the low growth scenarios. Influenced by the "New Normal" economic environment, fewer immigrants are attracted and move to Shenzhen, and income growth slows down noticeably to be only half the rate of growth in 2050 that is assumed in S4. Slower population and income growth results in a drop in transport activities, and thus, transport energy consumption and CO_2 emissions. As shown in Figure 6, under this scenario, energy consumption and CO_2 emissions (S1 in the figure) peaks in 2030 at 1.8 Mtce and 5.2 MtCO2, respectively, even without highly effective policy packages. That is to say, with low growth Shenzhen has the potential to achieve the national goal of peaking carbon emission at 2030 under a business-as-usual scenario.

With low growth, strengthened policy packages (S2) will help energy consumption and CO_2 emission peak as early as 2020 at a level of 1.4 Mtoe and 4.1 $MtCO_2$, respectively.

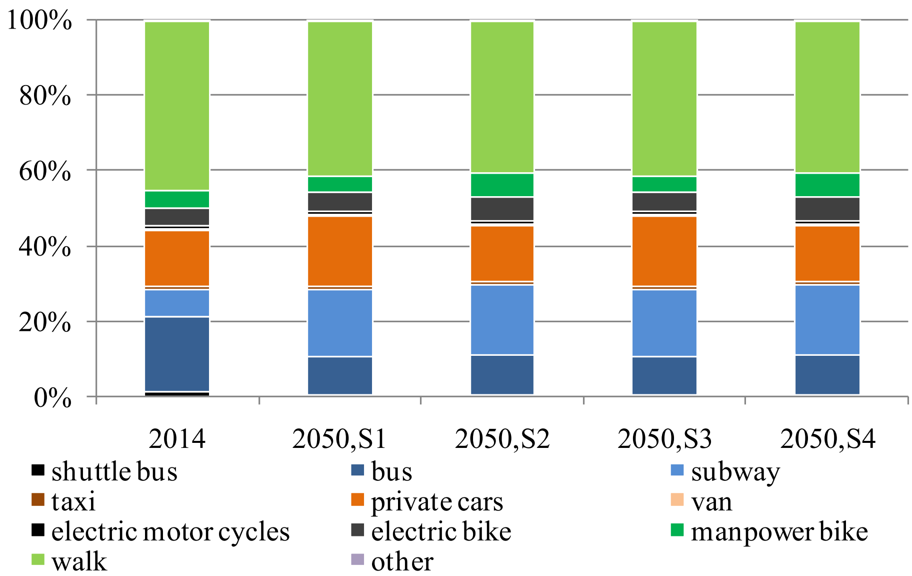


Figure 7: mode split of passenger trips in different scenarios

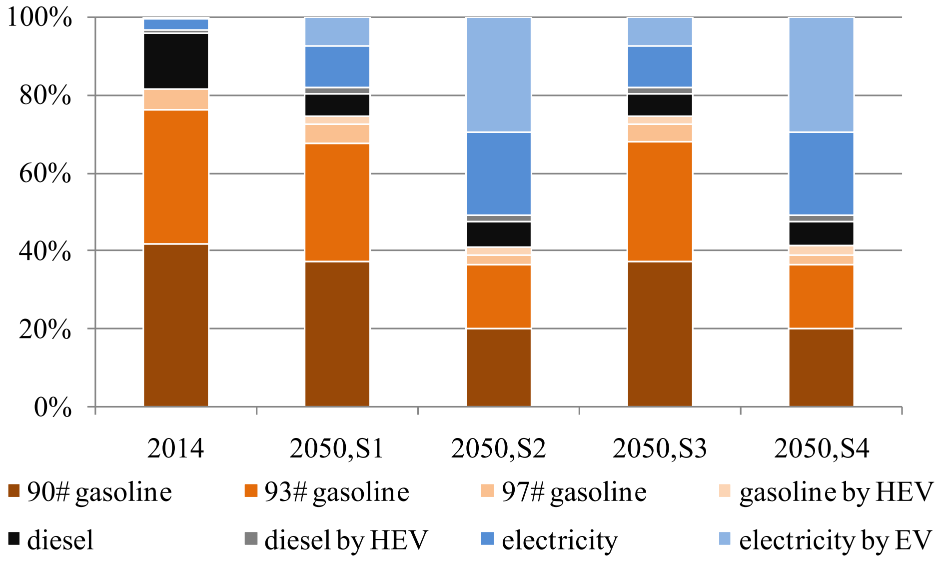
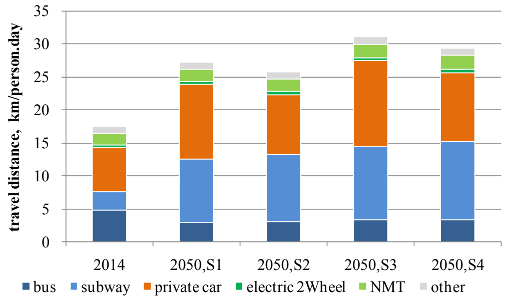
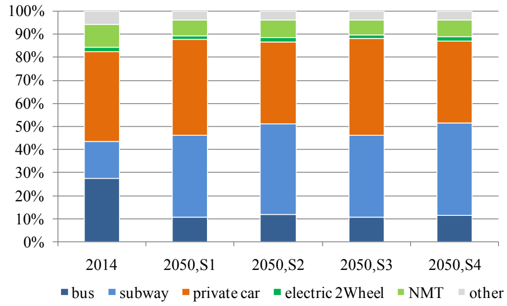


Figure 8,: fuel mix of energy consumption in different scenarios



a) absolute numbers



b) shares

Figure 9: individual travel distance by different mode in different scenarios

4. Conclusion

Building a low carbon transport system in China is an immense task, but also a great opportunity. At one level China can learn lessons from experiences in the West, but it also might be the case that China will devise even more effective strategies, focusing on societal gains, and also have sufficient funds to invest in major projects. The history of urban development in China suggests that, just as before, new and leading practices may emerge organically. Urban reconstruction often has occurred on a grand scale, with strong administrative leadership, often at breathtaking speed and involving great economic and social complexity (Ma, 2009).

Scenario analysis provides us with an indication of the different futures that might be possible given current trends and potential uncertainties. Scenarios, with a quantitative and empirical underpinning based on individual travel diary information, take us beyond the generic general emphasis on 'restricting growth in motorization and investing in public transport" to show the potential detailed changes in distance by mode, vehicle emissions, motorisation rates and resulting transport CO_2 emissions that can be achieved under different intervention strategies.

According to our scenarios, Shenzhen has the potential to achieve the goal of peaking its urban passenger transport emissions by 2030, either at a lower income growth rate scenario without significant enhancement of current transport policy strategies, or at a much higher income growth rate if it can adopt more aggressive policies and implement them effectively.

Based on these results, we conclude that an effective sustainable transport strategy that will enable Shenzhen to realize its climate change targets even with more rapid economic growth is likely to include the following features over the period 2015-2050:

1) The share of car trips in total passenger trips remains at levels similar to today (S4), rather than increasing 25% (S3) over current levels; at the same time, the share of non-

motorized transport remains above 45%.

2) Individual travel distance reduces by about 2 km/day, which mainly results from reduced travel distance driving in private cars. At the same time, non-motorized travel distance per person per day increases by around 20%.

3) Car ownership remains at levels similar to today, which is 250 vehicles/1000 persons (S4), rather than the higher level of 700 to 1000 vehicles/1000 persons, thanks to vehicle registration and pricing mechanisms (increased the cost of car ownership and use) and car parking supply constraints;

4) Private car use becomes more efficient with average energy consumption below 120 MJ/100km. Electric vehicles dominate the vehicle population with the share of EVs increasing from less than 1% in 2014 to nearly 60% in 2050.

5) Electricity supply becomes cleaner, with 58% of energy used to produce electricity sourced from non-fossil fuels.

6) Total energy consumption and emissions peak in 2030 at 1.5 Mtoe and 4.3 $MtCO_2$, respectively, while per capita emissions reduce continuously from 363 $kgCO_2$ in 2014 to 118 $kgCO_2$ in 2050.

To achieve the aspirations of scenario S4 will mean building an urban structure with higher densities around the public transportation network, strictly controlling vehicle ownership and use (either through mandatory schemes or pricing), and substantial investment in the walking and cycling environment. The motor industry also has a critical role to play in designing and supplying low emission vehicles at a market price that is cheaper than petrol equivalents. These types of futures can help overcome problems of congestion, traffic safety and local air pollution, as well.

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