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Future energy use and CO_2 emissions of urban passenger transport in China: a travel behavior and urban form based approach

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HIGHLIGHTS

- Developed an improved ASIF using empirically derived personal travel activity and built environment variables
- Per capita urban passenger transport energy use increases as city size expands
- Behavior targeting policies have national mitigation effects
- National guideline on city transport policies should have spatial and temporal priority

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ABSTRACT

Work on comparing cities in terms of their transport energy consumption and CO_2 emissions in the urban passenger transport sector has rarely been done using detailed travel activity data that takes into account city level differences in terms of economic development, population, and urban form. A personal activity based approach is necessary to better reflect travel behavior change results from different social, economic, urban form, technical, and transportation policy situations in the future. The present study extends the existing activity, modal share, energy intensity, fuel/carbon intensity (ASIF) modeling framework by disaggregating travel activity into key structural components and city-specific factors for 288 prefectural level cities in China. Testable econometric modeling systems were built to link mode split and mode specific travel distances with local economic and urban form characteristics in four different population sizes and two urban form types, based on 187 travel surveys in 108 Chinese cities in the past two decades. Scenarios of energy use and carbon emissions between 2010 (baseline) and 2050 were developed. Results showed that in 2010 urban passenger road transport in China generated 396 Mt CO_2 emissions and per capita urban passenger transport energy use increased as city size expanded. By 2030, under business as usual scenario assumptions, energy use in the urban passenger transport sector comprised 23.2 Mt of gasoline, 1.72 Mt of diesel, 3.36 billion M^3 of natural gas, and 0.62 billion kWh of electricity. While national policies targeting travel behavior change have been shown to mitigate emissions to some extent, urban transport policies targeted at specific spatial and temporal drivers of energy demand and emissions may be more effective in meeting policy goals. Short-term policies that promote car-pooling and ride sharing and medium-term policies that increase the cost of driving and promote public transport (such as transit oriented development, walkable neighborhood design, and parking pricing/restraint in city centers) help stabilize carbon emissions over the long term. However, the decision of building polycentric cities might have less significant impact on mitigating urban passenger transport in big cities. Moreover, large-scale promotion of electric vehicles should be designed from a long-term perspective rather than from a short-term one to achieve balanced carbon emissions in regard to the decarbonization process of electricity generation in China.

Keywords: Energy use; CO_2 emissions; Urban passenger transportation; ASIF; Scenario analysis

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1. Introduction

Urban passenger transportation has received increasing concern for its impact on global warming, urban pollution, physical (in)activity, and human health [1-4]. The United Nations Framework Convention on Climate Change (UNFCCC) estimated that 7.0 Gt CO_2 eq of greenhouse gas (GHG) emissions were generated in 2010 from the transport sector globally, of which 72.06% was from the road sector [5]. Transport is perceived as the most challenging sector to mitigate emissions worldwide [6, 7]. Efforts have been made to alleviate fast increasing energy use from passenger transport sectors, including technological improvements and transportation demand management (TDM). Over the past decades, TDM has increasingly been discussed as a way to contribute to a low-carbon society, as urban human mobility and energy use are largely interdependent [8, 9]. For example, spatial planning that creates compact living and working environments helps reduce individuals' travel distances and encourages trip sharing and chaining [10-12]. City polices such as tax incentives for lower engine displacement gasoline vehicles or new energy vehicle purchases, priority for new energy vehicles, or improved frequency and service quality of public buses (PB) help urge travelers to use public transit or cleaner private vehicles (PV). These policies have been widely practiced in cities in different contexts across the globe. Although urban passenger transport policies have been enacted at the local level, a large number of them are promoted based on national standards or action plans as part of an international commitment to reduce global warming.

The impact of local behavior change policies on national scale energy consumption and CO_2 emissions of urban passenger transport is generally not well understood using existing evidence and approaches. On the one hand, aggregated national approaches, either top-down or bottom-up from provinces, use vehicle numbers or odometer data to estimate general vehicle activities. These methods have good responses to the change of the vehicle parameter itself (such as engine fuel efficiency); however, they overlook how the vehicles are utilized (such as the frequency and travel distance of passengers, how people are loaded, and shifting between other modes). Thus, they provide less information on how behavior targeting policies could result in energy and emission changes in urban passenger transport sectors. On the other hand, many recent studies have started to explore travel behavior, urban form and transport infrastructure, and demand management's effects at a more local level, including analytical approaches involving TRANUS [13], long-range energy alternative planning (LEAP) [14], logarithmic mean divisia index approach (LMDI) [15], Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) [16, 17] and the Gompertz model [18]. These studies have higher accuracy in reflecting the effects on urban transport energy consumption from spatiotemporal change. However, the demanding detail of land use and traffic flow data make it difficult to estimate national effects, especially for less developed regions.

In China, fast-paced economic growth, auto industry development, infrastructure investment, and higher spatially dispersed cities have simultaneously spurred the need and capability of owning and using cars for ordinary urban households. As the Chinese government commits to reducing its carbon emissions before 2030, transportation, especially passenger transport is important when referring to emissions reduction [6, 11, 19, 20]. Existing literature provides a wide spectrum of approaches and angles to evaluate energy consumption and CO_2 emissions from the transport sector. This has enhanced the missing official released data on energy consumption of transportation. According to the yearbook of energy use in China, transportation energy use data was combined with 'storage, post, and communication' information [20-22]. As further discussed in the next section, these studies collectively suggested that data resolution and collection methods need to be further improved in a national scale energy study. Disparity of city populations, economies, and spatial layouts need to be considered as these influence motorized travel intensity and structure, and they might have substantial effects on national energy consumption and emissions, which need to be evaluated.

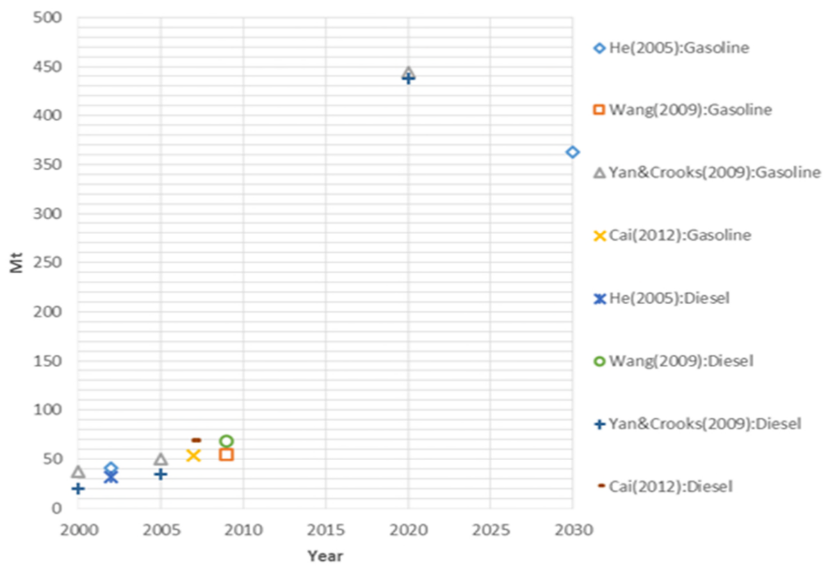
The present study attempts to develop a city level national energy consumption and CO_2 emissions framework based on personal travel activity. It contributes to the existing literature in the following aspects: 1) It creates a nationwide energy and CO_2 emissions modeling framework that allows urban travel demand policies to be evaluated in terms of travel reductions and mode shift. This is realized by a detailed decomposition of vehicle kilometre traveled (VKT) into passenger trip generation, passenger mode choice, and passenger distance traveled based on an adjusted activity, modal share, energy intensity, fuel/carbon intensity (ASIF) approach. 2) It provides statistical estimation rather than approximation in two main motorized travel elements: mode split and travel distance. Based on 166 travel surveys in Chinese cities conducted after 2000, these two elements were associated with local economic or land use characteristics.

They are examined in five modes (PV, PB, taxis (TX), motorcycles (MT), and E-bike (EB)), four city sizes (mega, big, medium, and small), and two urban forms (monocentric and polycentric). 3) An outlook towards 2050 is provided. Nine scenarios with different economic and policy backgrounds such as different economic growth, transit-oriented-development, TDM, E-haul, new energy, and low displacement vehicle promotion were compared. None of this can be accomplished by an aggregate vehicle-based approach using a single VKT value.

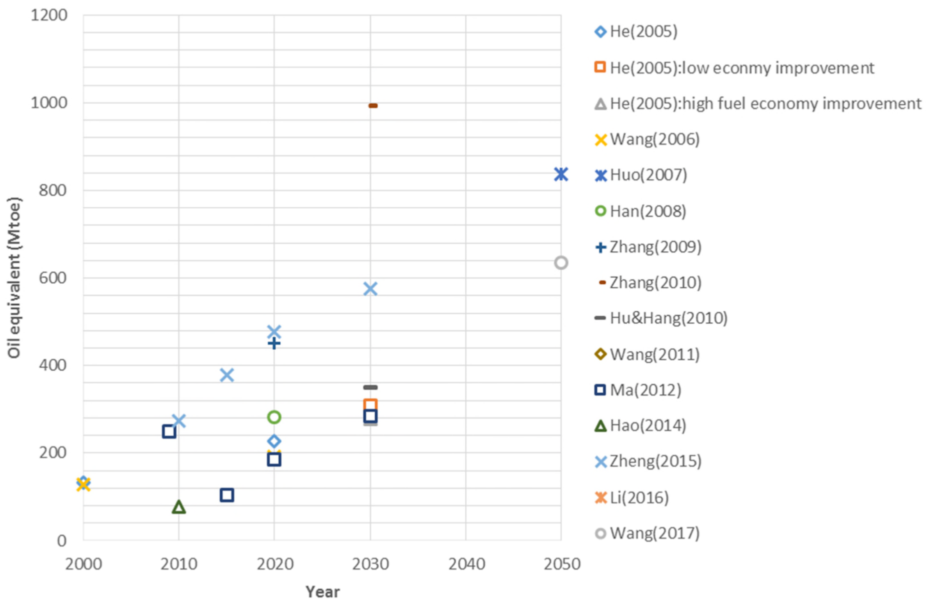
The remainder of the paper consists of four parts. First, it provides a review of various studies using a decomposition approach to study energy use and CO_2 emissions, focusing on China's road transport sector. Second, it presents the adopted research framework, methodology, and data. Third, it provides baseline and scenario results on the energy consumption and CO_2 emissions of urban passenger transport with different economies and policy backgrounds. Finally, it presents the results of a comparative analysis using different scenarios of future development in China before concluding with implications for policy and urban planning.

2. Previous work on China

Different approaches have been applied to provide estimations or projections of passenger transport's energy consumption or CO_2 emissions in China, based on various data structures and characteristics. According to Loo and Li [23], approaches could generally be categorized into distance-based (includes aggregate and disaggregate approaches) and fuel-based (includes bottom-up and top-down approaches). Fig.1 presents results of national energy consumption (gasoline, diesel, and oil equilibrium) and CO_2 emissions in the road transport sectors using these methods.

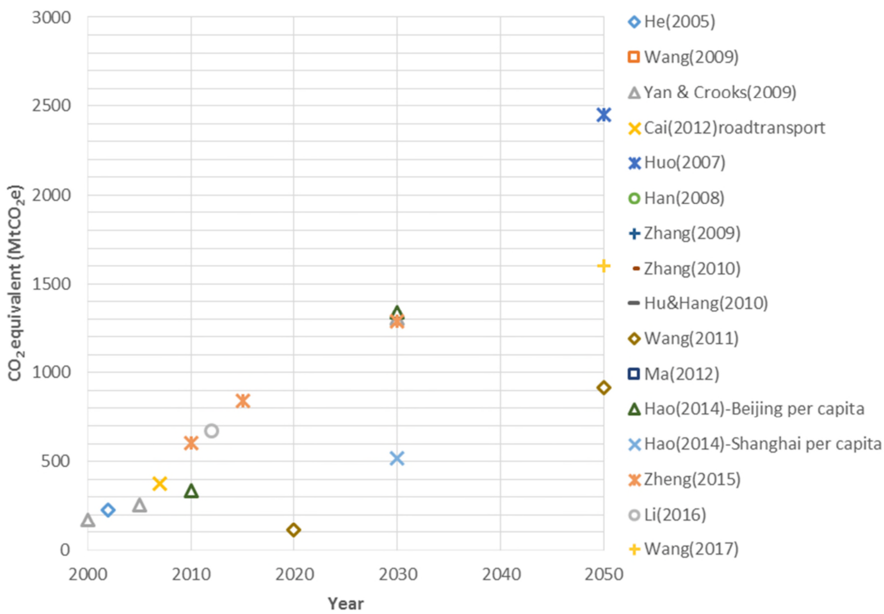


a. Energy consumption (gasoline and diesel)



b. Energy Consumption (tonnes of oil equivalent)

Zhang, Mu [24], Hu, Chang [25],Ma, Lou [26],



c. Carbon emissions of China's road transport sector (in Million tonnes of CO_2 equivalent)

Fig. 1. National energy consumption and CO_2 emissions of China's road transport sector

For distance-based methods, the disaggregate approach distinguishes different passenger transport modes such as PV, PB, TX, and MT. Therefore, it enables mode specific effects such as average speed, distance, loading factor, energy, or emission intensity to be taken into consideration; however, consequently becomes data demanding. Studies using the disaggregate distance-based approach generally multiply passenger turnover volume, regularly measured by passenger kilometer, with energy or emission factors for different modes. These components are then summed as total energy consumption or CO_2 emissions for passenger transport sector. Based on this method, He, Huo [27] estimated from national level data that road vehicles consumed 72.51 Mt oil (gasoline and diesel combined) and generated 229.04 Mt CO_2 emissions in 2002. Loo and Li [23] estimated from provincial level data that average CO_2 emissions for road transport was approximately 250 Mt on average in 2009. Taking into account the full lifecycle of energy production and use (Well-To-Wheel, WTW) it has been estimated that road transport accounted for around 1,000 Mt (WTW) CO_2 emissions, compared to around 750 Mt (Tank-To-Wheel [TTW]) in 2015[6]. In comparison, using the aggregate distance-based approach CO_2 emissions from passenger cars were estimated at about 91.4 MtCO_2 in China in 2005[28]. Although it does not provide mode split results, the present study was able to consider locally specified VKT for passenger turnover volume, which provides valuable evidence on regional disparity.

Compared to the distance-based method, the fuel-based method has the advantage of yielding higher accurate fuel specific results, and avoids uncertainty in differences in the 'real world' operation of vehicles such as driving style and topography [29]. There are two types of fuel based methods: top-down and bottom-up. The top-down approach directly applies consumption or sold fuel data from certain inventories. This method has its legitimacy, especially in China, owing to its extreme oligopoly status in oil supply [29]. Results of Cai, Yang [29] showed that using fuel based methods produce 68% (for gasoline) and 73% (for diesel) lower value in results compared to the distance based method. The bottom-up method determines the source of different types of fuels and explores patterns of fuel usage. One of the popular bottom-up approaches is the LEAP system developed by the Stockholm Environment Institute in 1997 [30]. This approach links energy demand with demographic and macroeconomic characteristics, and enables scenario analysis on technology effects to the bottom level factors. The LEAP modeling approach has been widely applied to access energy consumption and emission data for road transport [11, 14, 30]. Using the LEAP system model, Yan and Crookes [11] were able to measure the dynamic change of existing vehicle stock using sales data and estimated that road transport in China increased its GHG emissions from 168.6 Mt CO_2 in 2000 to 254.9 Mt CO_2 in 2005. Another modeling approach is the ASIF approach developed by [31, 32]. This approach is more suitable to estimate regional level carbon emissions and better reflects human activity, and thus has been widely applied in studies paying special attention to how vehicle will be used by humans [20, 33, 34]. Many recent studies have further integrated the ASIF with the disaggregate distance-based method by breaking the vehicle activity into different modes' activities. Using an adapted ASIF framework, Hao, Geng [33] measured components of different transport modes using a range of fuels. These components included vehicle population, loading factor of vehicles and intensity of vehicle use, energy, and carbon emissions. Using provincial level data, they were able to provide regional disparity regarding vehicle modes and fuel types. For example, generating national urban passenger transport by adopting the GHG emission per capita of Beijing (high PV ownership and public transport use) and Shanghai (more PV ownership than public transport use) would result in 822 Mt CO_2 emission difference in national aggregated results in 2030.

Most of the previous decomposition studies separated vehicle activity into vehicle population and average annual mileage of vehicle (measured for the majority of the time by a single VKT number) in different inventory. This risks omitting or underestimating passenger mode shifting or transportation intensity change effect [35], which targets the change to key elements of VKT from a social perspective. In recent years, city level research, with the benefit of detail human mobility, land use, transport infrastructure, and traffic information, started to evaluate the effects from the built environment and TDM on transport energy growth via individuals' travel behavioral change [16, 17, 19, 36, 37]. Four major analyzing tools have been identified in recent studies to access the dynamic relationships between transport energy use and emissions to various defined driving forces, especially human activities: the LMDI (one of the Index Decomposition Analysis (IDA) approaches), the STIRPAT, the ASIF, and the TRANUS. These modeling approaches generally allow human activities to be taken into consideration. LMDI was widely applied in recent studies [12, 15, 23, 36] owing to its lower requirement on weight function normalization, avoidance of zero-value problems, and easy application [38, 39]. Using this method, Luo, Dong [36] found in Shanghai (1995, 2004, 2009) that mode shifting to high emission vehicles contributed greater than 50% of the emission gain in the road transport sector, followed by trip generation increase and population increase (35% combined). Whereas, Wang, Liu [16] found in Beijing (2000–2012) that increased vehicle-use intensity was one of the main driving forces behind CO_2 emissions and promoting individual travel behavioral change played an important role in mitigating urban transport emissions. In a national level study (1949–2009), Loo and Li [23] also verified that contributions from increased transport intensity and modal shifts occurred after income growth, the effects of which had regional disparity. The STIRPAT model is not based on the Kaya identity to develop its framework, and thus has more flexibility in allowing different driving forces. Using this method, Wang, Liu [16]were able to place urban forms, transportation networks, and technology factors into driving force analysis. They found in four megacities in China (Beijing, Shanghai, Guangzhou, and Tianjin) from 1990 to 2010 that the significant impacts were from the urban spatial structure and how transportation is organized. Using the same modeling approach, Zhou and Liu [17] augmented the data scale to the provincial panel during a similar period (1990–2012) and discovered that human activities have varying effects on environmental impacts. The TRANUS model allows very detailed inspection of spatial, temporal, and economic effects of land use on transport. Zhou, Lin [13] utilized a TRANUS model to study the relationship between transport energy consumption and resident settlement morphology in the southeast coastal city of Xiamen. They involved detailed real estate availability and land use type from a traffic analysis zone level to help estimate location and interaction between activities, which allowed a more accurate estimation of activities.

These studies, however, did not verify the scale differences across cities having different population sizes. Those studies that did explore size differences did not take into account travel behavior or urban form factors. Moreover, neither national aggregate or provincial specific analysis take into account the difference between urban and rural areas. Although transport in rural areas has also experienced an unprecedented increase in growth rate, urban area transport contributes a substantially larger share in terms of energy consumption and emissions from a regional perspective. As rapid urbanization continues, this proportion is going to continue to increase [17, 40]. A more specific analysis on city level urban passenger transport would not only tackle changes in urbanization on transport energy and emissions, but would also explore the effect of empirically verified significant factors (income, population, travel behavior, and urban form) in smaller size cities more effectively. In the present study, we therefore advance the body of knowledge by integrating the distance-based and fuel-based approaches. This is accomplished by adapting the ASIF approach. The vehicle activities are not estimated by vehicle population or average mileage data, but instead by personal motorized travel intensity.

3. Approach and modeling framework

The ASIF method was first introduced by Schipper, Marie-Lilliu [32] as an approach to estimate regional carbon emissions and environmental impacts from human activities, as shown in equation (1):

$$G = \sum_i A \times S_i \times I_i \times \sum_j F_{i,j} \tag{1}$$

where, G is the dependent variable (either carbon emissions or energy use); A is the intensity of activity, often represented by VKT, S is the mode split of vehicle fleet of mode *i*, the multiplication of A and S_i denoted the travel intensity of different types of vehicles; I is the energy intensity of mode *i*, and $F_{i,j}$ is the carbon intensity of fuel type *j* for each mode of transport. When solely aggregated $\sum_i A \times S_i \times I_i$ together, it becomes the energy consumption of different modes in a certain geographical scale. A typical ASIF decomposition relationship is presented in Fig. 2.

In the present study, instead of calculating motorized activity intensity by vehicle activity intensity, we transformed the equation by using resident motorized travel intensity. Therefore, the traditional vehicle population, vehicle distance, and passenger turnover normally utilized to model vehicle activity intensity were replaced with trip generation, mode choice, mode specific travel distance, and loading factors to estimate activity-based intensity. This is shown in equation (2):

$$E_{i,j,k} = \sum_i \sum_j A_{i,j} \times \sum_i \sum_k I_{i,k} \qquad (2)$$

where, $E_{i,j,k}$ denotes the energy consumption in China's urban passenger transport sector; *i* is one of the five motorized transport modes, including PV, PB, TX, MT, and EB; j is the 288 cities in China, including 284 prefectural level cities and 4 provincial level cities; k is the four energy types, including petroleum, diesel, natural gas, and electricity; and $A_{i,j}$ denotes the intensity of travel demand. Instead of estimating vehicle activity using VKT and mode split, as introduced in the ASIF model, here it refers to the intensity of residents' motorized travel with different modes in a certain city, as further illustrated in equation (3):

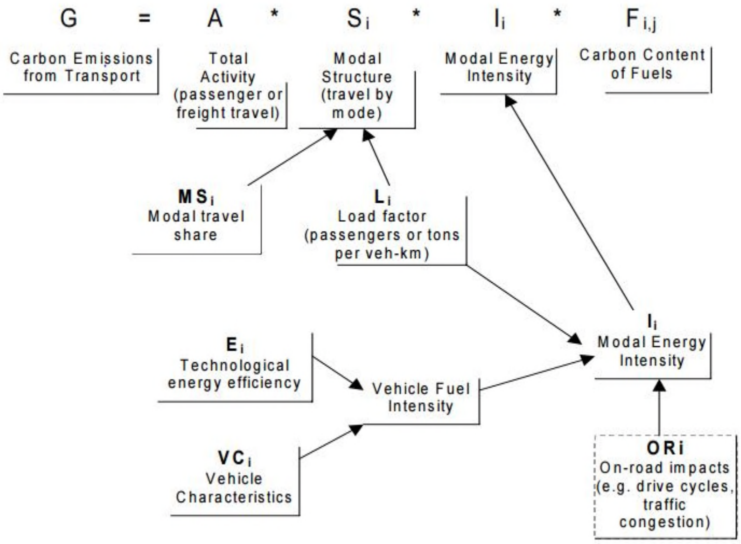


Fig 2. A typical ASIF decomposition relationship
Source: Schipper and Marie-Lilliu [31], Schipper, Marie-Lilliu [32]

$$A_{i,j} = \frac{Pop_j \times TR_j \times NT_j \times MS_{i,j} \times AD_{i,j}}{LF_{i,j}} \qquad (3)$$

Compared to applying vehicle data such as odometer readings or car sales data that are regularly utilized in popular methods such as LMDI, this adapted ASIF method reflects future economic, social, and land use changes, which concerns most economies in the era of globalization. In equation (3), $Pop_{i,j}$ is the urban residential population (in 10 thousand) in city *j*; $TR_{i,j}$ is the rate of population in city *j* who travel; $NT_{i,j}$ is the number of daily trips in city *j*; $MS_{i,j}$ is the rate of the travel population using mode *i* in city *j*; $AD_{i,j}$ is the daily average distance when using mode *i* in city *j*; $LF_{i,j}$ is the average loading factor of mode *i* in city *j*. $I_{i,k}$ denotes the energy intensity of different energy types or engine displacement within the different modes. The gross travel demand in a certain city estimated for a certain mode *i* is assigned to vehicles with different types of energy or engine displacement, proportional to their market share or ownership structure in the national portfolio. This is based on assumption that each vehicle in a certain mode is used to bear travel demand identically. The 1-to-1 mapping is an approximation applied due to the lack of disaggregate data needed on detail variation of vehicle types (fuel type, age, size) and ownership (private vs. company/fleet market), which have influence on vehicle mileage travelled [41, 42]. Although utilization of specific vehicles have these variations, this design allows national level assessment on fuel-specific energy demand changes when certain nationwide energy/engine displacement-based tax/fee incentive/burden is put forward. The same national consequences can also be evaluated when provincial or even city different policies are stipulated.

4. Data and methods

Using the above modeling framework, we utilized economic, travel, land use, and automobile data in China to estimate baseline energy consumption and CO_2 emissions and assess energy and CO_2 emission consequences in response to different scenarios over the short, medium, and long term. This involved five main steps: (1) empirical examination of travel demand based on city travel surveys, (2) city level motorized mode specified travel demand evaluation, (3) mapping travel activity onto different vehicle technologies, (4) national aggregation from city level energy estimation, and (5) scenario analysis.

In the first step, we undertook empirical examination on travel demand based on city travel surveys. To estimate travel elements in equation (3), namely TR_j, $NT_{i,j}$, $MS_{i,j}$, $AD_{i,j}$, and $LF_{i,i,}$, public accessible city travel survey results published in official reports (main results released from local cities' government websites), media coverage after a particular survey, and academic literature in and after 2000 were collected. There were a total of 187 travel survey results containing information on at least one of these five elements, as presented in Appendix A. These results originate from 108 cities, of which 84 are prefectural cities and 24 are county level cities. Surveys were conducted in the urban area of the cities. County level cities were included owing to our attempt to evaluate the generic empirical relationship linking travel behavior to the local economy, urban form, built-up areas, and population in the general Chinese urban context. The geographical location and boundaries of these cities is shown in Fig.3.

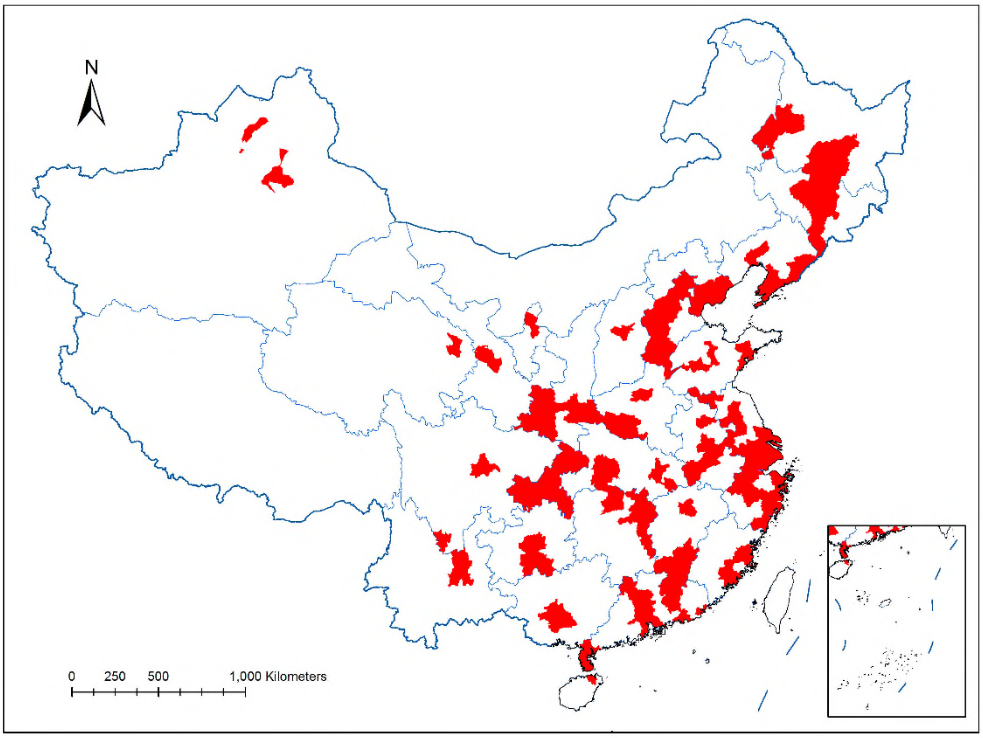


Fig.3. Geographical location and boundaries of the 108 survey cities

In total, there were 10 survey results reported for trip rate (TR) (Appendix B.1) and 34 surveys for number of daily travel (NT). The average value of 84.49% was applied to generate the travel rate for each city. Daily trip generations within capital cities in most provinces were generated for all cities in that province (Appendix B.2). For mode share (MS) and daily average travel distance (AD) of the five motorized modes, detailed statistical regression groups were constructed. MS was regressed with the natural logarithm transformed local gross domestic product (GDP) per capita while AD was regressed with urban built-up areas. Assumptions regarding these relationships were founded on extensive agreement within the literature on the relationships between motorized travel choice and regional economic development, as well as urban sprawl and motorized travelling distance [43-45]. Although in recent decades there has been discussion on the saturation of car use in developed countries and some found a decoupled pattern with economy [46-48], it might still be reasonable to expect continuous PV ownership and usage growth in Chinese cities before reaching equivalent levels of urbanization (around 80%) with developed economies by 2050 [49]. The natural logarithm transformed local GDP per capita considers saturating motorization due to diminishing marginal utility of economic growth in the long term. Moreover, continuous urbanization might lead to spatial urban expansion. As a result, a substantial number of inhabitants might be dispersed from the city center to the suburbs, which provides continuing incentive for higher levels of car use [50, 51].

Bivariate linear regression (ordinary least squares) method was applied to estimate these relationships. A linear relationship was assumed for MS evaluation for three reasons. First, the majority of the motorized modes quantity will increase as non-motorized modes decrease. Non-motorized travel still accounts for a large portion of transport in China. Second, a referred mode (generally walking or whole non-motorized mode) share is required in a discrete approach that is regularly utilized for mode split evaluations. Estimating the non-motorized quantity of travel for every city is not feasible in such a baseline study. Finally, a linear approach also helped to apply the survey information to a greater extent, as many of the survey results only reported certain mode(s).

To evaluate travel choice and distance traveled in smaller sized or polycentric cities, sample cities were categorized into four size groups: megacities (population larger than 5 million), big cities (1–5 million population), medium cities (0.5–1 million population), and small cities (less than 0.5 million population), based on urban non-agricultural population of each city during the baseline year (2010) [52]. Mega and big cities are further divided into monocentric and polycentric urban forms. Monocentric urban forms refer to a single agglomeration of economic activities, spatially displayed as high density of development, while polycentric urban forms refer to more than one concentration of urban economic activities. City urban forms were decided by two steps. First, the websites of local city governments or planning departments were visited to identify their cities' urban form stated in the introduction or master planning document. Second, Google Earth™ satellite images were utilized to graphically examine the number of concentrated inhabitant centers that either had high density or were separated by green space. Local economic data including GDP and GDP per capita were collected from the local Economic and Social Development Report during the survey year. The regression results of different modes are presented in Appendix B.3.1–3.5.

In the second step, motorized passenger transport intensity was estimated for each of the 288 cities using equation (3), based on each city's population, economy, and land use characteristics. Hong Kong, Macau and Taiwan were not included due to different transport and statistical systems. Cities with different sizes and urban forms utilized specific regressions (presented in Appendix B.3.1–3.5) to calculate the mode split. Grouping results are found in Appendix C. There were 12 mega cities (6 polycentric vs. 6 monocentric), 115 big cities (44 polycentric vs. 71 monocentric), 108 medium cities, and 53 small cities. With the baseline year set in 2010, population and economic data of each city in 2010 were acquired from the Chinese city statistical yearbook [52]. Urban form types were decided utilizing the same method as for the sampled cities. Built-up areas were calculated using provincial specified regressions based on city populations as described by Zhao [53].

The third step involved the mapping of transport intensities onto vehicle categories and technologies proportional to their national market share (or structure of the local ownership portfolio, if available). For PVs, we further specified their gasoline engine displacement into 1.6 L or less, and greater than 1.6 L to split travel demand assigned to PVs, so that the models could evaluate collective national effects of policies encouraging lower displacement engines purchased instead of higher ones. The Chinese government has been frequently using 1.6 L displacement and electric types of vehicles as benchmarks for promoting tax/fee benefit in an effort to slow vehicle fleet fossil energy consumption growth in the country. Examples include a reduced 10% off purchase tax (implemented nationwide during much of 2009; and from late 2015 to the end of 2016) and a 25% purchase tax rebate (implemented nationwide during 2010 and from then again in 2017) [54-57]. The market share of gasoline vehicles with engine displacement of 1.6 L or less has been relatively stable. It increased from 63.5 % in 2005 to 69.6% in 2009 and dropped to 66.7% in 2014 [58, 59]. While the market share of new energy and diesel vehicles were both at a very low level, the new energy received high policy priority[60]. It is important in observing the effect of shifting energy type from fossil to new energy methods. Therefore, new energy vehicles are involved as part of the assigned PV fleets. Ownership of new energy vehicles in 2010 was around 10,000, compared to more than 70 million in PV ownership [61]. With the fast development of new energy vehicles in Chinese cities taken into account, 0.35%, 69%, and 30.65% are assigned as new energy, 1.6 L or less engine displacement, and greater than 1.6 L engine displacement PV, respectively, in the baseline analysis. Travel demands using MT and EB are assigned on 100-125cc engines and lead-acid batteries, respectively, due to their dominant share in the market (market share of 100-125cc motorcycles was 78.4% in 2009 and 80.0% in 2010[62]; market share of lead-acid batteries for e-bike was 97.5% in 2010 [63].

For public transport, the vehicle fleet combination is more locally based as it is regularly calculated as public investment and has higher dependence on local policy and development priority. In the present study, we utilized data from the 2012 China Yearbook of Transportation and Communication, which provides official information on the PB fleet energy structure of 57 prefectural level cities [22]. Major energy types recorded include conventional diesel as well as new/clean energy such as electricity, hybrid of gasoline and electricity, liquefied natural gas, and compressed natural gas. The 288 cities were divided into four groups, based on proportion (0%, 0–20%, 20–50%, and 50% and above) of new/clean energy buses in the current fleet in the particular city. The 0% of new/clean energy group was assigned to 231 cities that had no new/clean energy bus fleet data. In the baseline calculations for 2010, for the remaining 57 cities, bus travel demands were assigned based on the listed proportion of different energy type buses. For the other 231 cities, bus travel demands were all assigned to diesel buses. Mapping of TX travel demand was proportional to vehicle energy structure, which further depended on city scales. Based on the 2012 China Yearbook of Transportation and Communication, natural gas powered TX use 60% in megacities and provincial capitals, 30% in other mega and big cities, 20% in medium cities, and 5% in small cities. Loading factors of the five modes are presented in Appendix B.3.1-3.5.

In the fourth step, we aggregated city level energy estimations to the national level. In each city, after the travel demands of different modes were mapped onto vehicles with different propulsion systems, they were multiplied with the corresponding fuel intensities (as explained in Appendix B.3.1–3.5). This step yielded urban passenger energy consumption under different energy types. The aggregation of each city’s consumption became the result of the national level of consumption at the baseline year.

In the final step (5), nine scenarios were developed for the years 2015, 2020, 2025, 2030, 2040 and 2050. Each scenario represented different policies with different promotion/penetration rates. Using the same procedure as in the baseline year level, the business as usual (BAU) was first calculated based on future population and economy with designated growth rates. Vehicle and energy structures remained identical to the current level. Other situations were estimated by amending key parameters in response to policy design. A brief conversion of all energy use into CO_2 emissions was then conducted to provide a comparison between scenarios and to other studies. Policy implications were addressed at the end of this process. The development of the bassline and future scenarios is described next.

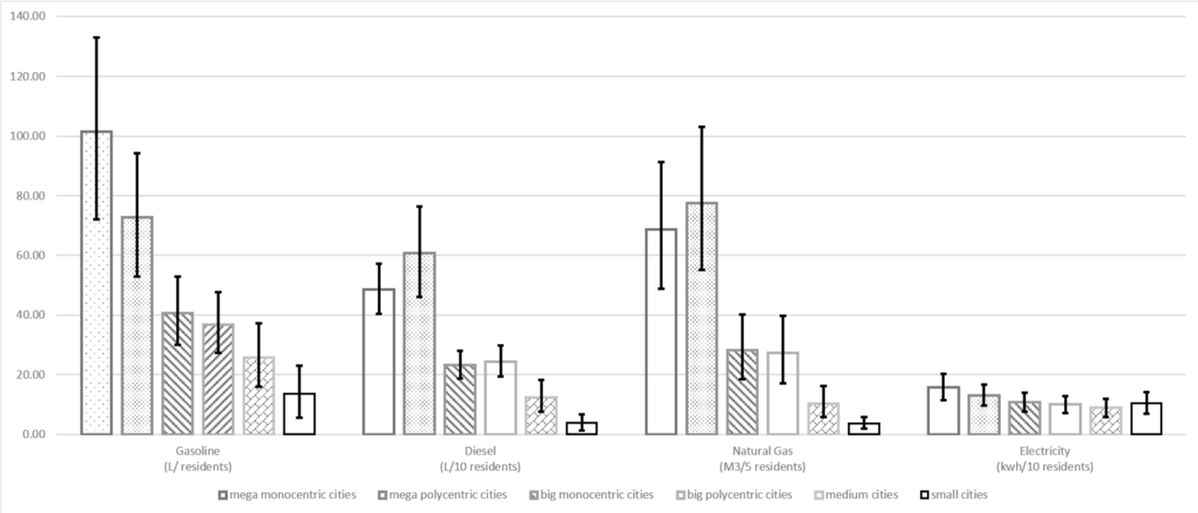
5. Baseline results and scenario development

5.1. Baseline results for the year 2010

The results of the baseline daily urban transport energy consumption, as a result of the fourth step in section 4 above, are shown in Table 1. These take different modes, energy types, city population scales, built-up areas, and urban forms into account. An estimation of the average energy consumption level is also presented in Fig.4. The per capita result shows that per capita energy consumption increased substantially as city size increased. Per capita energy consumption in megacities is much higher than in big and smaller cities in our model. This is due to higher motorized mode choice and travel distance in average motorized trips, which was associated with much higher GDP per capita and larger built-up areas. When affluent people cluster in fast sprawling, national central cities such as Beijing, Shanghai, and Guangzhou, the multiplier effect of higher population, higher motorized choice, and longer travel distances leads to an aggregated urban passenger transport energy usage of a single megacity larger than tens of smaller sized collectively. When we examine the different urban forms, it appears that for big cities the energy consumption among the monocentric and polycentric urban forms are similar. However, for megacities, per capita gasoline consumption (mostly consumed by PV and TX) is 36% higher in monocentric cities than polycentric cities, whereas diesel and natural gas (mostly consumed by PB and TX) are 24% and 13% higher in polycentric cities than in monocentric cities.

Table 1. Annual baseline (2010) disaggregate city level energy consumption

		mega cities	**mega cities**	**big cities**	**big cities**	**medium cities**	**small cities**		
		Mono Centric N = 6	Poly Centric N = 6	Mono Centric N = 71	Poly Centric N = 44	Mono Centric N = 108	Mono Centric N = 53	weighted average	
Private Vehicle	Gasoline (10,000 L): by engine displacement ⩽1.6 L	46,209 (34610-58503)	26,989 (19775-34590)	3,831 (2956-4776)	3,718 (2841-4667)	1,060 (695-1461)	270 (121-436)	3,485 (2579-4458)	
	Gasoline (10,000 L) by engine displacement >1.6 L	27,917 (20909-35345)	16,305 (11947-20897)	2,315 (1785-2885)	2,246 (1716-2820)	640 (420-883)	163 (73-263)	2,105 (1558-2693)	
	Electricity (100 kwh)	594 (445-752)	347 (254-444)	49 (38-61)	47 (36-60)	13.64 (8.95-18.8)	3.48 (1.56-5.61)	44 (33-57)	
Public Buses	Diesel (10,000 L)	3,836 (3058-4694)	3,916 (3150-4720)	291 (223-369)	243 (151-353)	88 (50-136)	14 (3-29)	306 (226-397)	
	Natural Gas (100 M^3)	207 (159-258)	188 (156-223)	66 (53-81)	13.47 (7.89-20.36)	2.21 (1.18-3.5)	0.49 (0.09-1.01)	27.73 (21.44-34.78)	
	Electricity (100 kwh)	0 (0-0)	0 (0-0)	1.98 (1.27-2.81)	0.22 (0.17-0.28)	1.38 (0.78-2.1)	5.83 (3.54-8.54)	2.11 (1.28-3.09)	
Taxi	Gasoline (10,000 L)	3,614 (2565-4821)	3,323 (2357-4419)	704 (441-1027)	652 (406-956)	278 (158-433)	154 (84-245)	550 (348-799)	
	Natural Gas (10,000 M^3)	10,649 (7559-14205)	9,793 (6946-13021)	856 (544-1239)	945 (593-1379)	146 (83-228)	27 (14-42)	841 (561-1177)	
	Electricity (100 kwh)	0 (0-0)	0 (0-0)	2.26 (1.56-3.08)	0 (0-0)	0 (0-0)	3.15 (2.18-4.29)	1.14 (0.79-1.55)	
Motorcycle	Gasoline (10,000 L)	3,690 (1492-6314)	3,541 (1459-5966)	452 (167-829)	449 (164-829)	137 (46-265)	64 (21-126)	394 (149-710)	
E-bike	Electricity (10,000 kwh)	633 (452-815)	500 (353-646)	124 (85-162)	129 (88-169)	48 (32-64)	24 (16-32)	96 (66-126)	
		Annual energy consumption by city scale, form, and energy type							**Total**
Gasoline (10,000 L)		77,817 (57012-100163)	46,836 (33182-61454)	6,599 (4909-8492)	6,415 (4721-8318)	1,839 (1162-2610)	498 (215-825)	5,985 (4286-7862)	16.2 million ton (10.4-22.7)
Diesel (10,000 L)		3,836 (3058-4694)	3,916 (3150-4720)	291 (223-369)	243 (151-353)	88 (50-136)	14 (3-29)	306 (226-397)	0.84 million ton (0.57-1.16)
Natural Gas (100 M^3)		10,857 (7718-14463)	9,982 (7102-13244)	923 (598-1321)	958 (601-1399)	149 (84-232)	27 (15-43)	869 (582-1211)	2.5 billion m^3 (1.68-3.49)
Electricity (10,000 kwh)		1,228 (897-1567)	847 (607-1091)	177 (126-230)	177 (125-229)	63 (42-85)	36 (23-50)	144 (101-188)	0.41 billion kwh (0.28-0.55)



* Values in parenthesis represent 95% confidence interval.

Fig.4. Per capita annual energy consumption of urban passenger transport by energy types, city scale, and urban form
Upper and lower limits for each bar present 95% confidence interval.

5.2. Scenario development and analysis

Once the baseline results were derived, we developed nine alternative, multi-dimensional scenarios for potential future developments in Chinese cities: a BAU scenario; two optimistic/pessimistic economic growth scenarios; two techno-centric, commercial, and policy scenarios that emphasized the deployment of low carbon/energy and smaller engine sized vehicles; two planning, policy, and commercial scenarios focusing on mode shift to public transport; and two policy scenarios that encouraged higher vehicle occupancy such as successful implementation of car pool lanes or e-haul business. These scenarios were designed in response to discussions of potential economic, social, institutional, and technical changes in the coming decades. We evaluated each of the scenarios carefully with alternative extents and timelines to provide readers with different parameter changes over multiple years. The long-term period from 2030–2050 was also projected to examine future trends and to verify the feasibility of reaching an energy or carbon emissions peak by 2030, which China has formally committed to by 2030 or earlier, as well as efforts to reduce carbon intensities by reaching 60–65% below 2005 levels by 2030 [64]. Each scenario was based on a BAU case for a certain year, controlling the change of elements other than the interest parameters. The main scenario assumptions are shown in Table 2.

Table 2. The main scenario assumptions

Scenario	**Altered parameters**	**2010–2015**	**2015–2020**	**2020–2025**	**2025–2030**	**2030–2040**	**2040–2050**
Business - as -Usual*	Annual pop growth	1.115%	0.058%	0.035%	0.035%	0.01%	0.01%
	Annual econ growth	8.5%	7%	6%	5%	4%	3%
Economic growth							
Optimistic	Annual econ growth	8.5%	7%	6.5%	6%	5.5%	5%
Pessimistic	Annual econ growth	8.5%	6%	5%	4%	3%	2%
New energy and low displacement vehicle promotion							
Slow	See Appendix D						

Fast	See Appendix D						
TDM + TOD	bus mode split annual change (on top of BAU change)	3%	2.5%	2%	1.5%	1%	0.5%
	car mode split annual change (on top of BAU change)	-1%	-1%	-1%	-1%	-1%	-1%
TDM + TOD + Polycentric urban form promotion	Urban form -polycentric	Baseline portfolio	Baseline portfolio	+ all mega cities	+ all mega cities	+ all big cities	+ all big cities
	bus mode split annual change (on top of BAU change)	3%	2.5%	2%	1.5%	1%	0.5%
	car mode split annual change (on top of BAU change)	-1%	-1%	-1%	-1%	-1%	-1%
E-Haul promotion							
Positive effect	Loading factor for private vehicles	2%	5%	8%	10%	15%	20%
	Occupancy rate for taxi	5%	8%	10%	13%	15%	20%
Adverse effect	Trip rate increase (from 2010 level)	2%	3%	4%	5%	5%	5%
	Private vehicle mode split (from 2010 level)	2%	5%	10%	15%	15%	15%

* Population and economic growth rate use the medium scenario introduced by Zhao [53]. Unless otherwise noted, population and economic growth rates in different scenarios follow the BAU setting.

** TOD = transit oriented development

Business as usual (BAU)

Based on the original demographic data from 2010, we evaluated energy consumption for the years 2015, 2020, 2025, 2030, 2040, and 2050 to observe possible intensity of structure and quantity aligned with the current pace of development. Annual population and economic growth is presented in Table 2. The results are shown in Appendix E.

Prospect of economic growth

In recent years, there has been great concern about the sustainability of the rapid economic growth occurring in China. Two economic development scenarios were applied to model both optimistic and pessimistic economic growth expectations [65-67], as shown in Table 2.

New energy and low displacement vehicle promotion

Expanding cities, especially megacities such as Beijing, Shanghai, Guangzhou, and Shenzhen, have started to provide local incentives for residents to purchase new energy-rated vehicles. These incentives include exemptions for lottery licenses, purchases and tax discounts, and parking/road priority [68]. Although many metropolitan governments have planned to reduce benefits in subsequent years, there would still be potential for growth in smaller cities [69]. At a national level, policies have been put forward to offer tax benefits to purchases of 1.6 L or less displacement vehicles, as introduced in the previous section. In addition, there has been rapid increase in the number of city governments who are planning to facilitate natural gas and public electric buses. Several megacities have even set goals to increase the proportion of new energy PB to more than 50% before 2020 [70]. Therefore, it was essential that these factors be taken into account in our scenarios. Appendix D illustrates detailed fleet upgrade designs for different modes and energy types under two different speeds (slow and fast).

TDM, TOD, and polycentric urban form promotion

TDM has frequently been introduced by Chinese metropolitan governments to tackle urban congestion and pollution. This includes plate license acquiring controls (Beijing, 2011; Shanghai, 1994; Guangzhou, 2012; Shenzhen, 2014; Tianjin, 2013; Guiyang, 2011; Hangzhou, 2014) and vehicle travel restrictions (Beijing 2010; Shanghai 2002; Guangzhou 2010; Shenzhen 2014; Xiamen 2015). More policy practices enacted in western cities have increasingly been introduced to many Chinese metropolises, or have been written into their long-term or short-term urban development plans, such as building right-of-lanes or designing signal priorities for Bus Rapid Transit or carpooling use [71-76]. In response to policies aimed at lowering transit costs and increasing car use costs, we designed increases in mode split for PB and decreases for PV. The remaining modal split went to non-motorized travel, as a credit for successful transit oriented development, walkable neighborhood development, social initiatives, or entrepreneurships such as dockless bike sharing schemes ofo and MoBike in China.

Urban form has widely been discussed as a potential factor associated with energy consumption [77-81]. Although the effects of urban forms such as monocentric or polycentric cities on urban transport energy consumption are inconclusive, many local Chinese administrations have included polycentric-guided master planning as a strategy for long-term urban growth. It is necessary to evaluate the effect and to what extent this will change future national energy use in the passenger transport sector. In the present study, we designed a gradual change into polycentric cities for mega and large cities towards 2050, paralleled with the mode split change effect under transport policy, as shown in Table 2.

Impact of higher vehicle occupancy

E-haul businesses, which provide smartphone based online platforms to match car use supply and demand in cities, are rapidly emerging and developing in China. Lifestyle changes under new business modes or policy nudging influence inhabitants' mode choices and travel preferences, which contributes to the low carbon economy [82]. In this scenario and in response to these emerging businesses and conventional carpooling incentive policies, average loading factors change for PV and occupied rates for TX are designed to grow, shown as a positive effect in Table 2. Another scenario was designed to see if over-subsidizing drivers and passengers resulted in the generation of more motorized travel or if it shifted from other modes such as transit, cycling or walking, as have been anecdotally discussed. This scenario provided a PV mode split and trip rate increase, as summarized in the adverse effect in Table 2, parallel with the positive effect.

6. Results and discussion

6.1 BAU

Gasoline consumption is, and will continue to be, the main source of energy for urban passenger transport, unless there is long-term, persistent promotion of new energies and low displacement vehicles.

In 2010, CO_2 emissions from the urban passenger transport sector in China were 396 Mt when 2.31 kg CO_2 as carbon intensity for 1 liter of petrol, 2.56 kg CO_2 as carbon intensity for 1 liter of diesel, and 2.03 kg CO_2 as carbon intensity for 1 cubic meter of natural gas were adopted. These TTW carbon intensity values were suggested by the UK Department of Energy and Climate Change [83]. Although electric vehicles do not produce CO_2 emissions on the road (i.e. from TTW), the generation process of electricity used in these vehicles does produce emissions. Therefore, it is necessary to consider WTW emissions at least for electric vehicles in transportation emissions evaluations. The cleanliness of different resources in electricity generation is different and the structure of these energies have different results on urban passenger transport sectors when observed from a life-cycle perspective [84, 85]. There have been a number of research papers and reports that have attempted to project carbon intensity of electricity generation in China based on fuel changes. The International Energy Agency projected that electricity generation using coal as a raw material in China will drop from 75% of current levels to less than 45% by 2040 [86]. Fridley [87] proposed 0.49 kg CO_2/kWh and 0.24 kg CO_2/kWh for carbon intensity of electricity generation in 2020 and 2030, respectively, where the level of coal dropped from 64% in 2020 to 50% in 2030. The UK National Energy Foundation [88] suggested 0.75 kg CO_2/kWh for the average Chinese grid compared to 0.41 kg CO_2/kWh in the UK where coal shares in electricity would slightly exceed 10%. Combining carbon intensity of China's coal-fired electricity, which will drop slightly from around 0.9 kg CO_2/kWh to 0.85 kg CO_2/kWh under the Intended Nationally Determined Contributions (INDCs), we designed a gradually declining rate of carbon intensity for electricity generation. The calculation of future CO_2 emissions from electric vehicles was based on these values. Results for carbon emissions trends with a BAU setting are shown in Table 3. However, these results should be interpreted cautiously, as the "carbon emissions factor of China's CO_2 is substantially different with that from IPCC" [29].

Of the total quantity of over 7 billion tons of CO_2 emissions in all sectors in 2010 estimated by the International Energy Agency (IEA) [89], urban passenger road transport sectors were only 5.91% of total CO_2 emissions in China. In

2030, under a BAU scenario, energy use in the urban passenger transport sector would use 28.56 Mt of gasoline, 1.72 billion Mt of diesel, 3.36 billion m^3 of natural gas, and 0.62 billion kWh of electricity. Combined, these equal approximately 6801 Mt of CO_2 emissions, which is 71.9% higher than in 2010. In addition, CO_2 emissions from urban passenger road transport will double to 809 Mt by 2050 compared to 396 Mt in 2010.

Table 3. CO_2 emissions conversion of urban passenger transport energy consumption (BAU)

Fuel Type	type	carbon intensity	unit	2010	2020	2030	2040	2050	Unit
Gasoline	TTW[1]	2.305	Kg CO_2/L	16.18	23.21	28.56	31.88	34.37	Mt
Diesel	TTW	2.564	Kg CO_2/L	0.84	1.33	1.72	1.94	2.11	Mt
Natural Gas	TTW	2.028	Kg CO_2/m^3	2.50	3.03	3.36	3.48	3.57	billion m^3
Electricity	WTT[2]	0.752	kg CO_2/kWh	0.41					billion kwh in electricity
		0.650			0.53				
		0.528				0.62			
		0.412					0.67		
		0.370						0.71	
TOTAL CO_2 emissions (Mt)				395.87	558.57	680.55	754.05	809.22	

1. TTW: Tank-to-Wheel, indicating average carbon content during engine operating.
2. WTT: Well-to-Tank, indicating average carbon content during energy production process.

A comparison of CO_2 emissions from the present study to the BAU scenarios of other studies is shown in Table 4, which highlight a large variation in energy use. Two reasons for this are: first, there were different scopes in defining road transport. Some studies estimated passenger transport, including aviation and waterways; some estimated intercity transport only; some calculated both passenger and freight travel [27]; and some included rural travel [90]. The second reason is because of the type of energy involved. The majority of studies on road transport energy use estimated petrol, with only a few studies specifying diesel [11, 27, 29] and natural gas.

Table 4. CO_2 emissions (BAU). Unit: Mt

	Scope		2010	2020	2030	2050
	Passenger	Freight				
This study	PV, BS, TX, MT, EB		396	559	681	809
Huo, Wang [90]	PC, BS, MT, RR	TR				1,900-3,000
Han and Hayashi [91]	PC			281		
Yan and Crookes [11]	BS, CA, MT, MV	TR			1304	
Wang, Fu [92]	PC			450	730	
Cai, Yang [29]	PC, MT, TV, LSA	TR	376 (2007)			
He, Liu [34]	PC, TX			340[1]		
Zheng, Zhang [6]	PV, MT, BS, RR	TR	600[1]	930[1]	1050[1]	
Mittal, Dai [93]	PV, BS, EB/MT, UR		143			475

PC: passenger cars; TR: truck; BS: bus; MT: motorcycle; RR: rural vehicles; CA: cars; PV: private vehicles; TX: taxies; EB: e-bikes; MV: minivan; TV: three-wheeled vehicles; ICL: internal combustion locomotive; AIR: aircraft; SHP: ship

1. Estimated from figure, this value is TTW not WTW.

6.2 Alternative policy scenarios

The trends of different scenarios on fuel-specific energy consumption and CO_2 emissions compared to the baseline in 2010 are presented in Fig.5 and Fig.6, respectively, with detailed baseline and scenario results provided in Appendix E.

With the assumed parameter changes indicated in Table 2, policies aimed at mitigating energy usage considered in the present study contribute to both gasoline consumption and CO_2 emission reduction on a national scale. However, the effects might be different. For gasoline, this gap ranged from 0.7 Mt in 2015 to 7.6 Mt in 2030 to 20.8 Mt in 2050; for

CO_2 emissions, this increased from 12.6 Mt in 2015 to 98 Mt in 2030 to 319 Mt in 2050. Compared to BAU, promoting new energy and low engine displacement strategy brings 12% and 43% less gasoline growth from 2010 to 2020 and to 2030, respectively. Under this scenario, gasoline and diesel consumption from urban passenger transport sector will peak in 2025 and natural gas will peak in 2030, which is earlier than in other scenarios. However, when referring to CO_2 emissions mitigation, the effect of this strategy does not stand out in the short and medium terms.

In the short term (2010 to 2020), promoting car sharing, new energy and low displacement vehicles, and transit helped mitigate CO_2 emissions growth by approximately 5–7% compared to BAU. Car sharing promotion without causing substantial trip rates and PV usage increases stands out in these scenarios. In the medium term (2020 to 2030), strategies promoting both transit usage and polycentric urban forms stand out by helping to achieve 14% less CO_2 emission growth on a national scale. In the long run (to 2050), electrifying vehicle fleets on a large scale, when road and electric charging infrastructure are ready, might substantially mitigate general energy use and CO_2 emissions. This helped mitigate 21% CO_2 emission growth from 2010 to 2030 when compared to BAU, with this growth mitigation effects increased to 61% by 2050. This is consistent with the previous finding that electrification and fuel blending will have limited influence from 2010 to 2035 until electricity generation is further decarbonized [6].

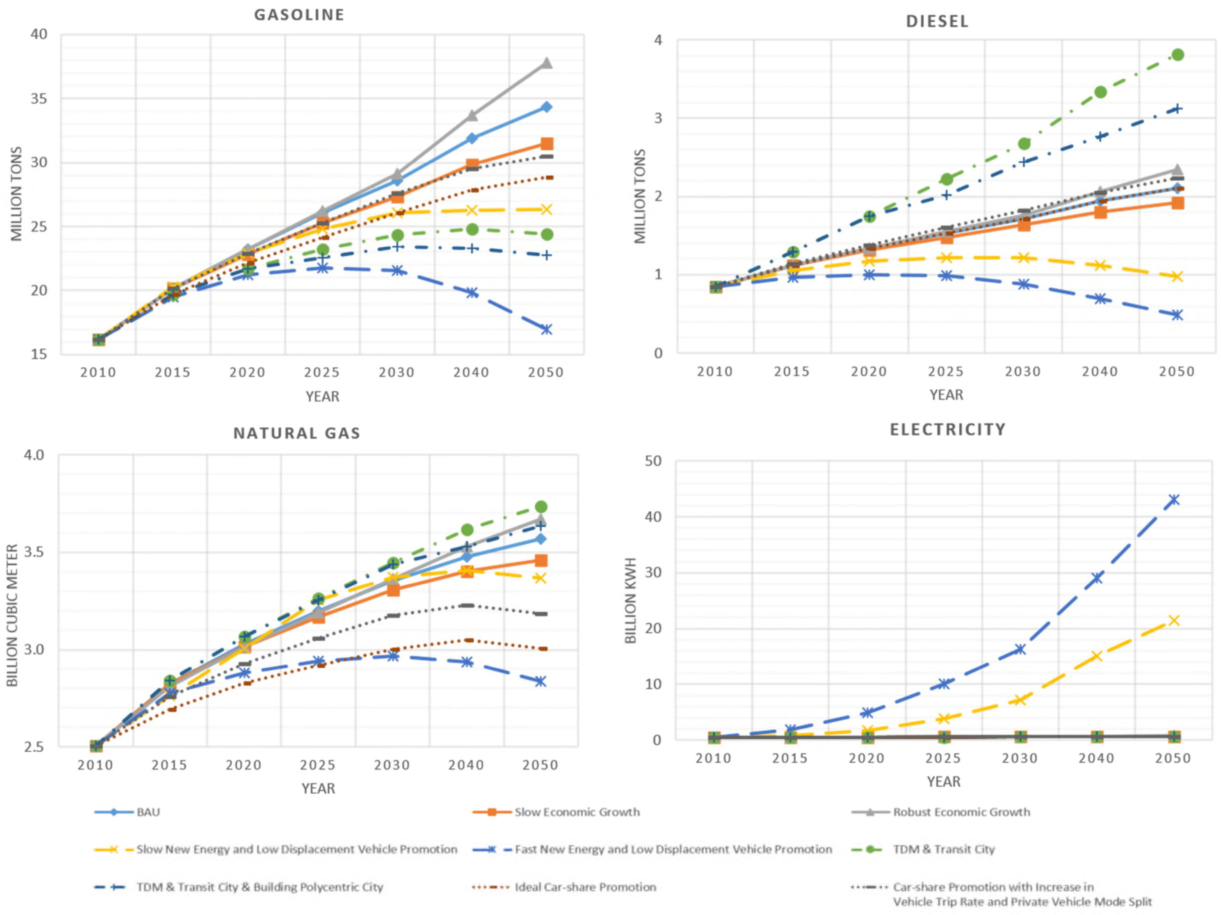


Fig.5. Annual energy consumption for baseline and future scenarios

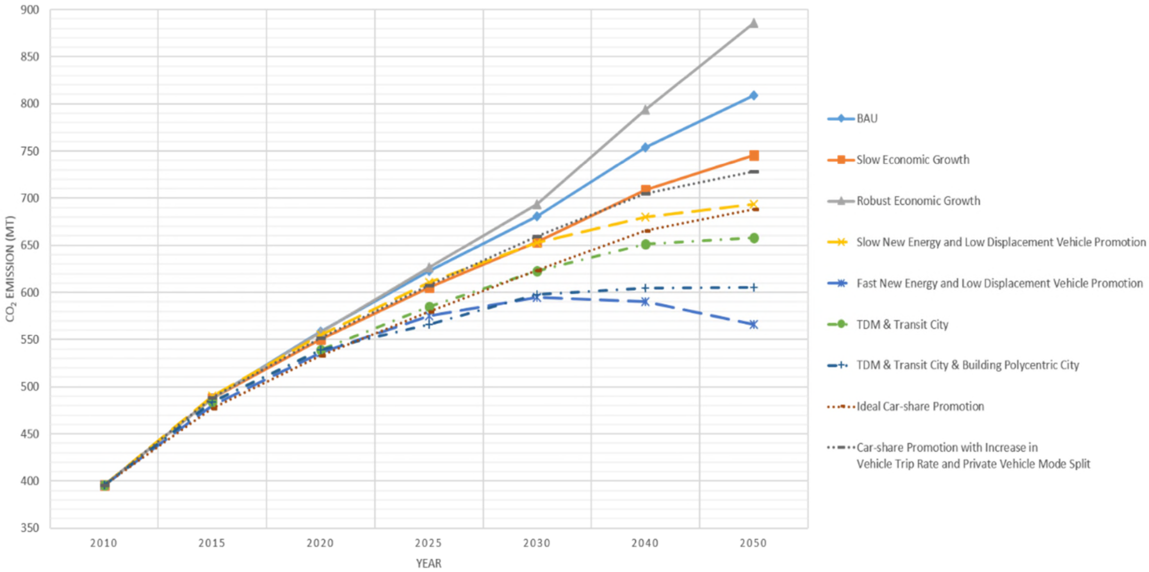


Fig.6. CO_2 emissions for baseline and future Scenarios (unit: Mt)

When integrating spatial city disparity with temporal effects of different scenarios in urban passenger transport energy consumption and CO_2 emissions, two policy implications could be cautiously generated for real applications.

First, vehicle update incentives, TDM, and appropriate spatial planning could be synergized to mitigate GHG emissions. A clear temporal priority might further enhance the reduction effect nationwide. When considering long-term strategies for electrifying vehicle fleets, it is necessary to take into account the environmental cost of electricity generation from a life-cycle perspective. Countries such as Norway, the Netherland, Germany, India and France have designed timetables to stop or substantially reduce selling of gasoline and diesel consumed vehicles by 2025, 2030 or 2040 [94, 95]. In China, the Ministry of Industry and Information Technology has recently started designing timetables for ceasing the production and selling of convention energy powered vehicles[96]. According to the scenario results, electrifying vehicle fleets should be promoted gradually. Only when carbon intensity for electricity generation dropped below 0.6 kg CO_2/kWh after 2025 could environmental benefits be achieved with large scale vehicle electrification. If GHG intensity of electricity generation in China can be reduced to less than 0.4 kg CO_2 eq/kWh, as proposed by IEA's BLUE Map scenario, vehicle electrifying could be accelerated [97].

Considering, however, that coal is still cost-efficient in China, a good short to medium term strategy might be to promote land use and transport policies that create a reasonable amount of travel in space-efficient ways. Our results extend recent large sized cities studies in that significant impact from urban spatial structure could influence nationwide urban passenger transport carbon emissions as well. The comparison between transit city and greener vehicle promotion scenarios indicated that although substantially increasing diesel and natural gas, appropriate TDM and transit promotion might be useful in curbing carbon emissions. This might have resulted from higher efficiency in utilizing vehicles either by reducing private car use or shifting demand to public transit.

Second, city disparity needs to be taken into account when developing national guidelines for urban low carbon development. For example, monocentric megacities have higher per capita gasoline consumption but lower diesel and natural gas consumption than polycentric megacities; however, this difference is not significant for big cities. This indicates that PV might be required more in huge built-up urban areas with single economic cores. Developing self-contained, transit oriented suburban new towns and strictly restricting urban sprawl might be more useful for megacities in mitigating growth of CO_2 emissions in the transportation sector than in smaller sized cities. This extended result regarding size specific situations. In addition, since megacities have substantially higher per capita consumption of fossil fuels whereas small sized cities have much lower levels, it might be reasonable to prioritize vehicle electrification in megacities while allowing conventional fuel powered but less engine displacement vehicles tax benefits to continue in small cities. While on the other hand, policies and planning that promote non-motorized travel, shorten travel distances, and increase loading factors could be promoted nationwide. These include a mixed use of housing, jobs, and services in both city master planning and community design to shorten job-housing distances and increase walkable proportion of non-work trips. Appropriate car-sharing or bicycle-sharing schemes might also reduce the inclination for car ownership.

6.3 Limitations and further work

There are two limitations to the present study. First, a lack of socio-demographic data across the country. Non-income demographics and urban form factors such as household structure and employment, in much of the existing literature, influenced car ownership, mode choice with different trip purposes, and trip distances. City-level built environments, measured by development or land use density, diversity or accessibility, road capacity, commuting parking spaces in the CBD, and feasibility between residential areas to working sites have high potential to affect travel preferences and patterns for urban residents, which also helps to facilitate higher accuracy of inhabitants' general mobility. Currently, energy use studies applying these data are on a local level due to data constraints. National level research needs consistent city level measurements with advanced data mining techniques. Second, a proportional disaggregation of travel demand to vehicle ownership structure. As mileage travelled also depends on what type of vehicle (fuel type, age, size) is owned by whom (private vs. company/fleet market), we may be over or underestimating CO_2 emissions depending on how the fleet (ownership) evolves over time in the scenarios. Detail information on city disparity in private vehicle ownership, sociodemographic variation in vehicle ownership/use preference, as well as vehicle type (fuel type, age, size) variation in vehicle use in Chinese context might help to create a more meticulous travel demand mapping in the third step.

7. Conclusions

Urban passenger transport has contributed a higher share of GHG emissions globally. Different approaches have been applied to evaluate local or national trends of future urban passenger transport under different circumstances. Although travel behavior has been empirically studied as having an impact on energy consumption, there has been an inadequate attempt to evaluate the effects of behavioral change policies in a national scale. In China, with rapid economic growth in the past two decades, many behavioral targeting policies have been put forward in cities in an attempt to curb increased private motorization usage and shorten travel distances. National urban passenger transport energy studies based on vehicle activities have limited capability in response to passenger mode choice and travel distance, which are the decomposed elements of the VKT. Local studies examining behavioral change effects under different spatial planning and transport demand management policies have overlooked smaller sized cities. The present study attempted to propose a social response framework to evaluate energy consumption and CO_2 emissions on a national level. Passenger activities were evaluated empirically based on local population, economy, urban forms, and their relationship to travel behaviors collected from 187 travel surveys in Chinese cities conducted after 2000. This serves as part of the adjusted ASIF approach. An outlook to energy use and CO_2 emissions in the short-term (2020), mid-term (2030), and long-term (2050) was provided. Results showed that, in 2010, urban passenger road transport in China generated 396 Mt of CO_2 and per capita energy consumption increased substantially as city size increased. Polycentric urban forms created gasoline energy saving effects in mega cities; however, were similar to monocentric forms cities in cities with smaller built-up areas. In 2030, under a BAU development, energy use in the urban passenger transport sector would use 23.2 Mt of gasoline, 1.72 Mt of diesel, 3.36 billion M^3 of natural gas, and 0.62 billion kWh of electricity. Behavioral targeting policies in the cities were shown to contribute to CO_2 emissions mitigation in China. However, in real applications, a more delicate spatial and temporal prioritizing of different policies might further promote mitigation. When life cycling of energy emissions was considered, promoting electric vehicles at a large scale could help reduce dependence on petrol and diesel. However, large-scale promotion might have to be postponed until the late 2020s, by which time electricity generation might be cleaned up and decarbonized to 0.6 kg CO_2/kWh or below. When the city level disparity was considered, spatial planning aimed at mode shift to transit or non-motorized modes, as well as creating shorter travel distances for various purposes of travel via transit orient development and mixed land use could be promoted in all level of cities. However, the decision to build more polycentric cities might have less significant impact on mitigating urban passenger transport in big cities.

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Appendix A

Summary of travel survey results

Size	Urban form	City	Survey year	MS PV	MS PB	MS TX	MS MT	MS EB	AD PV	AD PB	AD TX	AD MT	AD EB	Source
mega	**mono**	Beijing	2000	0.072	0.154									[98]
			2005						11.323		9.300			[53]
			2007	0.236	0.213									[99]
			2012						13.720					[53]
		Chengdu	2000	0.079	0.102									[100]
			2005	0.083	0.147						3.800			[100]
			2009							4.480				[101]
			2010								5.600			[102]
			2013			0.065								[103]
		Guangzhou	2003						7.680	6.810	6.250			[104]
			2005	0.106	0.239	0.048								[105]
		Shantou	2011	0.071	0.123	0.018	0.308							[106]
		Shanghai	2004	0.178	0.208	0.062	0.012	0.043						[107]
			2005		0.185					8.400	7.200			[108]
			2006		0.235									[105]
			2009	0.200	0.129	0.066		0.152						[109]
			2012						11.913					[53]
			2014	0.192	0.134	0.07	0.003	0.202						[110]
		Xi'an	2009							3.710				[101]
			2010	0.119		0.015	0.032							[111]
			2012						11.780					[53]
			2013	0.250								10.00		[112]
		Zhengzhou	2000		0.065		0.054							[108]
	poly	Nanjing	2003	0.0077	0.241									[113]
			2005	0.0302	0.226									[113]
			2007	0.082	0.215									[113]
			2009		0.191									[113]
			2014							16.300				[114]
		Chongqing	2002	0.047							8.300	8.210		[115]
			2007	0.082	0.051									[116]
			2008	0.093	0.059									[116]
			2009	0.101	0.064									[116]
			2010	0.115	0.067									[90]
			2011							7.200				[91]
			2014		0.089	0.048								[89]
			2015	0.135	0.171									[117]
		Tianjin	2000	0.012	0.051									[118]
			2005		0.152						5.100			[105]
			2006	0.031	0.152	0.025								[119]

			2011		0.160									[92]
			2012	0.272										[120]
		Wuhan	2003		0.086									[121]
			2008		0.235									[93]
			2009							3.990				[101]
			2012						13.554					[94]
		Shenyang	2004		0.188						4.400			[108]
big	**mono**	Changchun	2009	0.037	0.25	0.083	0.018							[122]
		Changde	2001	0.035								5.623		[123]
		Changzhou	2005	0.047	0.084							8.000		[124]
			2016											[125]
		Caohu	2003	0.026										[123]
		Foshan	2004									3.750		[105]
			2010	0.164										[126]
			2013	0.273						9.400				[127]
		Fuqing*	2003	0.038	0.084									[128]
		Harbin	2006			0.014								[129]
			2009							3.790				[101]
		Haikou	2016	0.218	0.096									[130]
		Handan	2001	0.032										[131]
		Hefei	2001	0.045	0.039									[121]
			2002		0.039									[132]
			2010	0.214										[133]
		Huzhou	2004		0.061			0.083						[123]
			2013	0.205	0.101	0.070	0.010	0.092						[134]
		Huaian	2013	0.086	0.137	0.046								[135]
			2014	0.098	0.144	0.047								[135]
		Jilin	2013	0.145	0.164		0.032	0.049	7.045	5.230	4.840	4.130	1.200	[136]
		Jinan	2012	0.150										[137]
			2013	0.173	0.177					13.700				[137]
		Kunming	2005								3.000			[53]
			2010	0.175		0.021								[138]
			2011	0.197		0.021								[138]
			2012	0.215	0.218	0.021	0.010							[138]
			2014	0.217	0.235									[138]
			2015	0.221	0.252									[138]
		Kunshan*	2001		0.068	0.012		0.069				8.000		[123]
			2002				0.110							[108]
			2013	0.170	0.082									[134]
		Nan'an*	2006	0.061	0.063									[128]
		Nantong	2003		0.093			0.124				7.240		[123]
		Nanyang	2014	0.120	0.078	0.016	0.109							[139]
		Ningbo	2008	0.151										[140]
			2011	0.179	0.133									[141]
			2013							11.100				[53]
		Putian	2009	0.047	0.057	0.0088	0.1803							[140]
		Qingdao	2010	0.113	0.221									[108]
		Ruian*	2012		0.083									[142]
		Suzhou	2000		0.064							5.624		[121]
			2013	0.162				0.210						[134]
		Taian	2016		0.2118									[143]
		Tonghua	2010	0.016		0.027		0.005						[144]
		Wenling*	2003		0.105			0.057						[145]
			2005	0.064	0.082	0.017		0.048						[146]
		Wenzhou	2011		0.124		0.044	0.060						[147]
		Wujiang	2001	0.029										[123]
		Xuzhou	2003	0.012								5.522		[108]

	Yangzhou	2013	0.121	0.125	0.061		0.090						[148]
	Yixing*	2015	0.267				0.253						[149]
	Changchun	2009	0.102										[122]
	Zhongshan	2015	0.103										[150]
	Zhuhai	2013		0.193	0.025								[151]
	Zibo	2014	0.185	0.060			0.175						[152]
	Handan	2001	0.032										[153]
poly	Baoji	2014	0.117	0.346									[154]
	Changsha	2007	0.097										[155]
		2009		0.230									[156]
	Dalian	2012		0.45									[157]
	Dongguan	2005		0.021									[105]
	Fuzhou	2002		0.110									[158]
		2005	0.075	0.173									[158]
		2008	0.092	0.167									[158]
		2013							4.700				[53]
	Guiyang	2001											[118]
	Hangzhou	2000		0.222	0.015								[118]
		2003	0.049	0.237	0.012								[159]
		2005	0.091	0.214	0.008								[105]
		2010	0.138	0.235				8.190	7.040	7.560	4.640	1.620	[160]
		2011								5.600			[53]
	Lanzhou	2015	0.125			0.021							[161]
	Nanchang	2002	0.040	0.093									[162]
		2010	0.080			0.081	0.119						[163]
		2013							7.000				[164]
		2016					0.164						[163]
	Nanning	2011				0.072							[163]
		2016				0.016							[163]
	Shenzhen	2006		0.180									[105]
		2010	0.187	0.154	0.016								[165]
	Shijiazhuang	2000		0.043									[166]
		2007		0.072	0.008								[105]
	Taizhou	2014		0.113									[167]
	Taiyuan	2005								4.000			[53]
		2014		0.29									[168]
	Urumqi	2006	0.081										[169]
		2010	0.211	0.449	0.030	0.018							[170]
		2014	0.186	0.300	0.066								[170]
	Xining	2000											[121]
		2015	0.058	0.428		0.011					5.730	1.300	[171]
medium	Anqing	2005	0.016	0.092									[123]
		2013	0.109	0.107	0.015	0.102	0.086						[134]
	Benbu	2001	0.013								5.867		[123]
		2016	0.102	0.228			0.201						[172]
	Donggang*	2012		0.178									[173]
	Feixian*	2013	0.058			0.108							[174]
	Ganzhou	2010	0.037	0.109									[175]
	Hanzhong	2011	0.048	0.141									[176]
	Ji'an	2004		0.070							8.000		[177]
	Jiaxing	2004	0.026			0.127							[178]
		2009								4.000			[53]
	Jiaozhou*	2007	0.082										[178]
	Jinzhou	2012		0.289									[173]
	Panzhihua	2010	0.120	0.270	0.030								[179]
	Puyang	2002	0.076										[123]
	Qidong*	2004	0.049	0.149		0.218	0.050						[146]

	Qianan*	2014			0.008	0.023					[180]
	Qinhuangdao	2004	0.067						5.670		[123]
		2013	0.145	0.121	0.028	0.042	0.098				[134]
	Qingyuan	2013	0.152	0.170	0.020	0.136	0.089				[134]
	Shanwei	2012	0.020	0.040		0.250	0.060				[181]
	Shangluo	2016		0.230		0.073					[182]
	Taishan*	2012						4.400			[53]
	Taicang*	2002					0.182				[146]
	Xingtai	2015			0.022						[183]
	Yinchuan	2005	0.019	0.207			0.030				[108]
	Yingkou	2010	0.205	0.179	0.050	0.047					[108]
	Changxing*	2013	0.262								[184]
	Zhuzhou	2014	0.130	0.217	0.073	0.038	0.049				[185]
Small	Anning	2009	0.091								[186]
	Dangyang*	2004	0.004								[128]
	Deqing*	2005	0.095								[123]
	Duyun*	2011	0.056								[187]
	Heyuan	2011			0.012			4.400			[188]
	Jiangmen	2009	0.046	0.041		0.364					[106]
	Jishou*	2012				0.200					[189]
	Karamay	2013								1.600	[190]
	Longgang*	2008	0.105	0.039							[178]
	Shengze*	2005	0.075	0.015							[128]
	Tonglu*	2011	0.129			0.037	0.149				[191]
	Tongling	2004	0.025								[123]
		2013	0.096	0.109			0.130				[134]
	Xinyi*	2006	0.040	0.01	0.01	0.13					[140]
	Yidu*	2002	0.003								[128]
	Zhangjiagang*	2002	0.072	0.053						1.500	[123]
		2005	0.116	0.058			0.222				[146]

* indicate county level cities

Appendix B

*B.1 Trip Rate of Urban Population (TRi,j)**

The trip rate of sampled cities and relevant economic data **

City	Surveyed Year	Urban Trip Rate	GDP in 100 million Yuan	GDP per capita in Yuan
Suzhou	2000	98.00%	1541	26692
Tianjin	2006	91.30%	4463	41163
Shanghai	2008	88.00%	14070	66932
Beijing	2005	84.30%	6970	45993
Changsha	2009	84.21%	3745	56620
Hangzhou	2000	82.80%	1383	22342
Guangzhou	2005	80.90%	5154	53809
Xi'an	2008	79.39%	2318	27794
Jinhua	2011	81.00%	2447	52317
Jilin	2013	75%	2617	60877

* Trip rate in a city denotes the percentage of urban residents who has the capability or need to move
**With factors other than GDP or GDP per capita explain most of the urban trip rate, we applied average value 84.49% in estimating trip rate.

*B.2. Number of Daily Trips (NTi,j)**

Province**	NT[1]	**Source**	**Province**	**NT**	**Source**
Tianjin	2.47	Tianjin Travel Survey,2011	Heilongjiang	2.23	Harbin Travel Survey, 2006
Shanghai	2.46	Shanghai Travel Survey,2006	Shanxi	2.18	Taiyuan Travel Survey, 2004
Beijing	2.75	Beijing Travel Survey,2014[192]	Xinjiang	2.8	Urumqi Travel Survey, 2006
Jiangsu	2.78	Nanjing Travel Survey,2006	Hunan	2.4	Changsha Travel Survey, 2009
Zhejiang	2.78	Avg Hangzhou &Ningbo Travel Survey, 2005	Qinghai	2.76	Xining Travel Survey, 2000
Inner Mongolia	1.91	Avg Shenyang (2004), Qiqihar(2014) [193]	Henan	2.46	Zhengzhou[123]
Guangdong	2.68	Avg Zhanjiang (2014) [194], Guangzhou (2005),Shenzhen(2010)	Hainan	2.69	Haikou Travel Survey, 2016
Liaoning	2.43	Shenyang Travel Survey, 2004	Jiangxi	2.59	Nanchang Travel Survey, 2010
Fujian	2.45	Avg Quanzhou (2010) [195]and Putian (2009)	Sichuan	2.56	Chengdu[123]
Shandong	2.1	Jinan Travel Survey, 2013	Guangxi	2.67	Nanning[123]
Jilin	2.3	Changchun Travel Survey,2010	Anhui	2.58	Hefei Travel Survey, 2002
Chongqing	2.25	Chongqing Travel Survey, 2010	Tibet	1.62	Lanzhou Travel Survey, 2000
Hubei	2.41	Wuhan Travel Survey, 2008	Gansu	1.62	Lanzhou Travel Survey, 2000
Hebei	2.3	Shijiazhuang Travel Survey, 2007	Yunnan	2.35	Kunming Travel Survey, 2015
Shan'xi	1.95	Xi'an Travel Survey, 2000	Guizhou	2.49	Guiyang [123]
Ningxia	1.95	Xi'an Travel Survey, 2000			

1. Number of daily travel

*. Daily trip generation of capital cities in each province is applied to different cities.

**For provinces that cannot match any capital city data, we use data from provinces that are geographically close or share similar GDP per capita.

B.3.1 Private Vehicle travel

Mode split							
City Scale		**Urban Form**	**Sample Number**	**Description**			**Private Vehicle mode split Association with GDP per capita (in natural logarithm)**
				Private Vehicle mode split		medium survey year	
				average	medium		
Mega cities	5million+	Monocentric	11	14.42%	11.90%	2007	y = 0.0824x - 0.7294 R^2 = 0.562
		Polycentric	12	8.40%	8.20%	2007	y = 0.0828x - 0.7667 R^2 = 0.352
Big cities	1-5 million	Monocentric	41	12.27%	12.00%	2010	y = 0.0776x - 0.7011 R^2 = 0.464
		Polycentric	15	10.85%	9.20%	2010	y = 0.0765x - 0.7060 R^2 = 0.615
Medium cities	0.5-1 million	Monocentric	20	8.68%	7.15%	2010	y = 0.1039x - 0.9801 R^2 = 0.552
Small cities	<0.5 million	Monocentric	14	6.81%	7.35%	2006	y = 0.0365x – 0.3138 R^2 = 0.642

Travel distance		
Samples number	Medium survey year	Private Vehicle mode split Association with urban built-up area
8	2012	Y=0.00528x+7.236 R^2 = 0.515
Loading factors	1.2587*	

Current energy structure			
	≤1.6L L/100km	>1.6L L/100km	Electric kWh/100km
Current Structure[1]	70%	29.65%	0.35%
Energy Intensity	5.6[2]	8[2]	12.6[3]

* Most of the travel survey data did not provide loading factors. In this study we use 1.2587 for the private vehicle from the 2005 Beijing Travel Survey [196]

1. Diesel ICE and hybrid electric (HEV) passenger cars were not considered in this study for their low percentages in the existing fleet.

2. Based on various source. Such as 7.78L/100km [197]; 5.2L/100km to 11.9L/100km for vehicles with displacement 1.6L or less [198]; 8.1L/100km,

9.0 L/100km, 11.5 L/100km and 14.0 L/100km for Petrol private cars engine size less than 1000cc, 1001-1500cc, 1501-2500cc and 2501-3500cc respectively [199]
3.[200]

B.3.2 Public Buses travel

Mode split

City Scale		Urban Form	Sample	Description			Public Buses mode split Association with GDP per capita (in natural logarithm)
				Private Vehicle mode split		median survey year	
				average	median		
Mega cities	5 million +	Monocentric	11	16.12%	15.05%	2005	y = 0.0858x - 0.7201 R^2 = 0.839
		Polycentric	17	14.95%	16.00%	2007	y = 0.0852x - 0.7209 R^2 = 0.428
Big cities	1-5 million	Monocentric	32	12.39%	10.10%	2012	y = 0.0932x - 0.8660 R^2 = 0.573
		Polycentric	8	21.56%	21.40%	2008	y = 0.1107x - 0.9692 R^2 = 0.439
Medium cities	0.5-1 million	Monocentric	17	16.45%	17.00%	2012	y = 0.0765 - 0.6080 R^2 = 0.486
Small cities	<0.5 million	Monocentric	7	4.64%	4.10%	2006	y = 0.0265x - 0.2069 R^2 = 0.468

Travel distance

Samples number	**Sample**	Medium survey year	Public bus travel distance associates with urban built-up area
Mage-monocentric	4	2005	Y=0.0127x-1.280 R^2 = 0.973
Other monocentric	5	2013	Y=0.0244x-0.210 R^2 = 0.399
polycentric	7	2012	Y=0.0192x-0.329 R^2 = 0.735

Loading factors Megacities and big cities: 60 Medium and small cities: 40

Current energy structure*

	Diesel L/100km	LNG M^3/100km	CNG M^3/100km	Hybrid L/100km	Electric kWh /100km
Current Structure[1]	48%	31%	22%	32%	9%
Energy Intensity	37	35	42	29	70

*vary by cities, sample averages are provided. Data was retrieved from the 2012 China Yearbook of Transportation and Communication, which provide official information of public bus energy structure of 62 prefectural level cities. [22]
1. only three cities used gas and electricity hybrid bus (Ningbo: 4.86%; Changchun: 4.42%; Hohhot: 10.75% in 2012), only one city use ethanol gasoline (Changchun: 8.71% in 2012), and only on city use CBM (Changzhi: 48.23% in 2012).

B.3.3 Taxi travel

Mode split

Samples number	Medium survey year	Taxi mode split in association with GDP per capita (in natural logarithm)
28	2010	Y=0.0474x-0.467 R^2 = 0.722

Travel distance

Samples number	Medium survey year	Taxi travel distance in association with urban built-up area
17	2005	Y=0.00551x+3.359 R^2 =0.440

Taxi mileage utilization rate*

Samples number	Medium survey year	Taxi mileage utilization rate in association with GDP (in natural logarithm)
10	2005	Y=0.0504x+0.1588

Loading factors **1.7****

Current energy structure***

	Petrol L/100km	Natural Gas L/100km	Electric kWh /100km
Current Structure	77%	22%	0%
Energy Intensity	5.6	11	12.6

* The average distance calculated are the distance that utilized by travellers. Energy consumption is not included in the result for empty taxi running without passengers.
** it should be noticed that loading factors including taxi driver are 2.7, but in that case, drivers will be calculated repeatedly. In order to avoid this, we use passenger loading factors
***[22]

B.3.4 Motorcycle travel

Mode split		
Samples number	Medium survey year	Average motorcycle mode share*
26	2012	7.87%
Travel distance	Medium survey year	Motorcycle travel distance in association with urban built-up area
12	2004	Y=0.00606x+5.436 R^2 =0.144
Loading factors	1.2	
Current energy structure	Current structure: 100% 125cc; Energy Intensity: 2.6 L/100km	

* In this study, no model is appropriate in describe relation between motorcycle mode split and GDP per capita with acceptable fitting precision. We therefore use the 7.87% as national average.

B.3.5 E-bike travel

Mode split		
Samples number	Medium survey year	E-bike mode share in association with GDP per capita
29	2012	Y=0.0882x-0.831 R^2 =0.500
Travel distance	Medium survey year	Average e-bike travel distance
5	2013	1.444
Loading factors	1.2	
Current energy structure	Current structure: 100% Lead-acid batteries; Energy Intensity: 1.2 kWh /100km*	

* Electric Bicycles- General technical requirement of P.R.C: GB 17761-1999

Appendix C

Categorization of the 288 prefectural level cities in China (2010)

Megacity		**Big city**		**Big city**		**Medium city**		**Medium city**		**Small city**	
Province	**City**	**Province**	**City**	**Province**	**City**	**Province**	**City**	**Province**	**City**	**Province**	**City**
Beijing	Beijing[A]	Fujian	Fuzhou*[+]	Guangxi	Nanning*[+A]	Liaoning	Benxi	Hunan	Zhuzhou[C]	Anhui	Tongling
Tianjin	Tianjin*		Xiamen[C]		Liuzhou		Dandong[A]		Xiangtan[B]		Huangshan
Liaoning	Shenyang*[+B]		Putian[B]		Qinzhou		Jinzhou[B]		Hengyang	Fujian	Sanming
Shanghai	Shanghai[A]		Quanzhou[A]		Guigang		Yingkou		Shaoyang		Nanping[A]
Jiangsu	Nanjing*[+]	Jiangxi	Nanchang*[+]		Yulin		Fuxin		Zhangjiajie		Longyan
Henan	Zhengzhou*[+]		Yichun*		Hezhou		Liaoyang[A]		Chenzhou		Ningde
Hubei	Wuhan*[+]		Fuzhou*		Laibin		Panjin	Guangdong	Shaoguan	Jiangxi	Jingdezhen
Guangdong	Guangzhou[+A]	Guangdong	Shenzhen*[B]	Hainan	Haikou[+B]		Chaoyang		Zhaoqing[B]		Yingtan
	Shantou		Zhuhai[B]	Shaanxi	Baoji*		Huludao		Shanwei		Shangrao
Chongqing	Chongqing*		Foshan		Ankang*	Heilongjiang	Jixi		Yangjiang	Henan	Xuchang[A]
Sichuan	Chengdu[+]		Jiangmen	Gansu	Lanzhou*[+]		Hegang		Qingyuan		Sanmenxia[B]
Shaanxi	Xi'an[+]		Zhanjiang		Tianshui*		Yichun		Jieyang	Hubei	Huanggang
			Maoming*		Wuwei*		Jaimusi	Guangxi	Guilin[C]	Hunan	Huaihua
Big city			Huizhou*[B]	Sichuan	Zigong*		Qitaihe		Wuzhou		Loudi
Province	**city**		Dongguan*		Luzhou*		Mudanjiang		Beihai	Yunnan	Yuxi
Hebei	Shijiazhuang*[+C]		Zhongshan[A]		Mianyang*		Suihua		Fangchenggang		Lijiang
	Tangshan*[B]	Zhejiang	Hangzhou*[+A]		Suining*	Zhejiang	Jiaxing	Hainan	Sanya[C]		Simao
	Handan[C]		Ningbo[C]		Neijiang*		Shaoxing	Sichuan	Panzhihua		Lincang
	Baoding[C]		Wenzhou		Leshan		Jinhua		Deyang	Tibet	Lhasa[+]
	Taiyuan*		Huzhou		Nanchong*		Quzhou		Guangyuan[C]	Shaanxi	Yan'an
	Datong		Taizhou*		Yibin		Zhoushan		Meishan	Gansu	Jiayuguan
Inner Mongolia	Hohhot*[+C]	Henan	Luoyang*[A]		Guang’an	Jiangsu	Lianyungang	Guizhou	Zunyi		Jinchang
	Baotou*		Pingdingshan*		Bazhong*		Taizhou		Anshun		Jiuquan
	Chifeng*[B]		Anyang		Ziyang*	Anhui	Bengbu	Yunnan	Qujing		Qingyang
Liaoning	Dalian*		Xinxiang	Guizhou	Guiyang*[+]		Ma'anshan		Baoshan		Dingxi

	AnShan		Luohe		Bijie*		Anqing		Zhaotong	Ningxia	Shizhuishan
	Fushun		Nanyang	Yunnan	Kunming[+]		Chuzhou	Ningxia	Yinchuan[+]		Wuzhong[A]
Jilin	Changchun[+B]		Shangqiu	Qinghai	Xining*[+]		Chizhou	Shaanxi	Tongchuan		Guyuan
	Jilin[A]		Xinyang*	Xinjiang	Urumqi*[+]		Xuancheng		Xianyang		Zhongwei
Heilongjiang	Harbin[+C]	Hubei	Yichang[A]	**Medium city**		Fujian	Zhangzhou[B]		Weinan	Xinjiang	Karamay
	Qiqihar[B]		Xiangfan*	**Province**	**City**	Jiangxi	Pingxiang		Hanzhong	Guangdong	Meizhou
	Daqing[B]		Ezhou	Hebei	Qinhuangdao		Jiujiang		Yulin		Heyuan
Jiangsu	Wuxi		Jingzhou		Xingtai		Xinyu		Shangluo[A]		Chaozhou
	Xuzhou	Hunan	Changsha*[+]		Zhangjiakou		Ganzhou	Gansu	Baiyin		Yunfu
	Changzhou[B]		Yueyang		Chengde	Shandong	Dongying[B]		Zhangye	Guangxi	Baise
	Suzhou		Changde		Cangzhou[A]		Weihai		Pingliang		Hechi
	Nantong[A]		Yiyang		Langfang		Dezhou		Longnan		Congzuo
	Huai,an		Yongzhou*		Yangquan		Binzhou		Small city	Sichuan	Dazhou
	Yancheng	Shandong	Jinan[+B]		Changzhi	Henan	Kaifeng	Hebei	Hengshui[A]		Ya'an
	Yangzhou		Qingdao[B]		Shuozhou		Hebi		Jincheng	Guizhou	Liupanshui
	Zhenjiang[A]		Zibo		Jinzhong		Jiaozuo		Lvliang		Tongren
	Suqian		Zaozhuang*		Yuncheng		Puyang	Inner Mongolia	Ordos[C]		
Anhui	Hefei[+B]		Yantai*		Xinzhou		Zhoukou		Hulinbuir		
	Wuhu		Weifang		Linfen		Zhumadian		Ulanqab		
	Huainan		Jining	Inner Mongolia	Wuhai	Hubei	Huangshi	Liaoning	Tieling		
	Huaibei		Tai,an		Tongliao		Shiyan	Jilin	Liaoyuan		
	Fuyang		Rizhao		Bayannur		Jingmen		Tonghua		
	Suzhou[A]		Laiwu	Jilin	Siping		Xiaogan	Heilongjiang	Shuangyashan		
	Liu,an		Linyi*[B]		Baishan		Xianning		Heihe		
	Bozhou		Liaocheng[B]		Songyuan		Suizhou	Zhejiang	Lishui		
			Heze		Baicheng						

* Indicates polycentric cities (50 cities as in 2010)
\+ Provincial capitals
A indicates cities with 0-20% of new/clean public buses (21 cities as in 2010);
B indicates cities with 20-50% of new/clean public buses as in 2010 (24 cities as in 2010);
C indicates cities with 50% or above of new/clean public buses as in 2010 (12 cities as in 2010).

Appendix D. Scenarios design for two speeds of new energy vehicle promotion for modes and years

		2015		2020		2025		2030		2040		2050	
		Slow	fast	Slow	fast	Slow	fast	Slow	fast	Slow	fast	Slow	fast
Private Vehicles	<=1.6L	73.60%	79.20%	74.40%	78.00%	72.20%	75.00%	68.40%	72.00%	60.80%	59.00%	57.00%	45.00%
	>1.6L	26.00%	20.00%	24.00%	17.00%	23.00%	13.00%	22.00%	8.00%	20.00%	6.00%	18.00%	5.00%
	EIEC	0.40%	0.80%	1.60%	5.00%	4.80%	12.00%	9.60%	20.00%	19.20%	35.00%	25.00%	50.00%
Public Buses CPNE*=0%	DISEL	95.00%	88.00%	86.50%	75.50%	78.00%	66.00%	70.50%	52.50%	60.50%	37.50%	48.00%	25.00%
	HYBRID	0.00%	2.00%	1.00%	3.50%	2.00%	5.00%	2.00%	5.00%	2.00%	5.00%	2.00%	5.00%
	CNG	0.00%	0.00%	0.00%	1.00%	0.00%	1.50%	0.00%	2.50%	0.00%	3.00%	0.00%	5.00%
	LNG	0.00%	0.00%	5.00%	7.50%	10.00%	12.50%	15.00%	15.00%	17.50%	17.50%	20.00%	15.00%
	ELEC	5.00%	10.00%	7.50%	12.50%	10.00%	15.00%	12.50%	25.00%	20.00%	37.00%	30.00%	50.00%
Public Buses 0%<CPNE<=20%	DISEL	87.00%	78.00%	82.50%	69.00%	73.00%	57.50%	63.00%	45.00%	43.00%	25.00%	33.00%	15.00%
	HYBRID	2.00%	2.00%	2.00%	3.50%	2.00%	5.00%	2.00%	5.00%	2.00%	5.00%	2.00%	5.00%
	CNG	5.00%	10.00%	5.00%	10.00%	5.00%	7.50%	5.00%	7.50%	5.00%	5.00%	5.00%	5.00%
	LNG	5.00%	5.00%	7.50%	10.00%	15.00%	20.00%	22.50%	30.00%	30.00%	30.00%	30.00%	30.00%
	ELEC	1.00%	5.00%	3.00%	7.50%	5.00%	10.00%	7.50%	12.50%	20.00%	35.00%	30.00%	45.00%
Public Buses 20%<CPNE<=50%	DISEL	52.00%	48.00%	52.50%	41.50%	53.00%	35.00%	48.00%	30.00%	38.00%	25.00%	33.00%	10.00%
	HYBRID	2.00%	2.00%	2.00%	3.50%	2.00%	5.00%	2.00%	5.00%	2.00%	5.00%	2.00%	5.00%
	CNG	15.00%	10.00%	10.00%	10.00%	5.00%	10.00%	5.00%	7.50%	5.00%	5.00%	5.00%	5.00%
	LNG	30.00%	35.00%	32.50%	37.50%	35.00%	40.00%	37.50%	45.00%	30.00%	35.00%	25.00%	30.00%
	ELEC	1.00%	5.00%	3.00%	7.50%	5.00%	10.00%	7.50%	12.50%	25.00%	30.00%	35.00%	50.00%
Public Buses 50%<CPNE	DISEL	19.50%	15.00%	22.50%	10.00%	18.00%	5.00%	15.50%	5.00%	13.00%	15.00%	13.00%	20.00%
	HYBRID	2.00%	5.00%	2.00%	5.00%	2.00%	5.00%	2.00%	5.00%	2.00%	0.00%	2.00%	0.00%
	CNG	25.00%	20.00%	15.00%	15.00%	15.00%	15.00%	10.00%	10.00%	10.00%	5.00%	10.00%	5.00%
	LNG	52.50%	55.00%	57.50%	62.50%	60.00%	65.00%	62.50%	65.00%	50.00%	50.00%	40.00%	25.00%
	ELEC	1.00%	5.00%	3.00%	7.50%	5.00%	10.00%	10.00%	15.00%	25.00%	30.00%	35.00%	50.00%
Taxies	Petrol	55.00%	43.00%	53.00%	36.00%	51.00%	29.00%	52.50%	29.00%	52.00%	27.00%	49.00%	26.00%
	CNG	42.00%	42.00%	42.00%	39.00%	42.00%	36.00%	40.00%	33.00%	38.00%	31.00%	36.00%	29.00%
	ELEC	3.00%	15.00%	5.00%	25.00%	7.00%	35.00%	7.50%	38.00%	10.00%	42.00%	15.00%	45.00%
Motor	Petrol	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
E-bike	ELEC	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

*CPNE: percentage of new/clean energy public buses in the cities' current fleet. Public bus fleets were further divided into four sub-groups, according to different proportion of new/clean energy powered public buses in the fleet (Yearbook of China Transportation and Communication, 2012). 288 prefectural level cities were accordingly categorized into four groups:

A. no new/clean energy public buses currently listed in the yearbook (231 cities),
B. 0-20% of new/clean public buses (21 cities);
B. 20-50% of new/clean energy public buses (24 cities);
C. 50% or above of new/clean energy public buses (12 cities).
D. no new/clean energy public buses listed in the yearbook in 2010 (231 cities),

Appendix E. Outcome of scenarios, compared with current level, by energy type

Gasoline (Annual consumption, in million tons)	2010	2015	2020	2025	2030	2040	2050
BAU	16.2 (11.5-21.4)	20.1 (15-25.9)	23.2 (17.8-29.3)	26 (20.4-32.3)	28.6 (22.7-35)	31.9 (25.9-38.5)	34.4 (28.3-41.1)
Slow Economic Growth	16.2 (11.5-21.4)	20.1 (14.6-24)	22.8 (17-26.9)	25.2 (19.2-29.5)	27.3 (21.1-31.7)	29.8 (23.5-34.3)	31.5 (25.1-36)

Robust Economic Growth	16.2 (11.5-21.4)	20.1 (15-25.9)	23.2 (17.8-29.2)	26.2 (20.5-32.5)	29.1 (23.3-35.6)	33.7 (27.6-40.4)	37.8 (31.6-44.6)
Slow New Energy and Low Displacement Vehicle Promotion	16.2 (11.5-21.4)	20.3 (14.1-27.5)	22.9 (16.5-30.3)	24.8 (18.4-32.2)	26 (19.6-33.5)	26.3 (20.2-33.3)	26.3 (20.5-33)
Fast New Energy and Low Displacement Vehicle Promotion	16.2 (11.5-21.4)	19.5 (13.7-26.2)	21.2 (15.5-27.8)	21.8 (16.4-28)	21.5 (16.4-27.5)	19.9 (15.3-25.1)	17 (13.1-21.6)
TDM & TOD	16.2 (11.5-21.4)	19.7 (13.4-27.1)	21.7 (15.2-29.3)	23.2 (16.5-31)	24.3 (17.5-32.3)	24.8 (18-32.8)	24.4 (17.6-32.3)
TDM & TOD & Building Polycentric City	16.2 (11.5-21.4)	19.7 (13.4-27.1)	21.7 (15.2-29.3)	22.5 (15.9-30.3)	23.4 (16.6-31.4)	23.3 (16.5-31.2)	22.8 (16-30.6)
Ideal Car-share Promotion	16.2 (11.5-21.4)	19.7 (14.7-25.4)	22.1 (16.9-27.9)	24.2 (18.9-30)	26 (20.6-32)	27.9 (22.6-33.7)	28.8 (23.6-34.6)
Car-share Promotion with Increase in Vehicle Trip Rate and Private Vehicle Mode Split	16.2 (11.5-21.4)	20.2 (15-26)	22.9 (17.5-28.9)	25.3 (19.8-31.4)	27.6 (21.9-33.9)	29.5 (23.9-35.7)	30.5 (25-36.6)

Diesel (Annual consumption, in million tons)	2010	2015	2020	2025	2030	2040	2050
BAU	0.84 (0.62-1.1)	1.12 (0.86-1.41)	1.33 (1.05-1.65)	1.53 (1.23-1.87)	1.72 (1.39-2.08)	1.94 (1.6-2.32)	2.11 (1.75-2.51)
Slow Economic Growth	0.84 (0.62-1.1)	1.12 (0.86-1.36)	1.31 (1.03-1.57)	1.48 (1.18-1.76)	1.63 (1.32-1.93)	1.8 (1.47-2.11)	1.91 (1.57-2.23)
Robust Economic Growth	0.84 (0.62-1.1)	1.12 (0.86-1.36)	1.33 (1.05-1.6)	1.55 (1.24-1.83)	1.76 (1.43-2.06)	2.06 (1.71-2.4)	2.34 (1.96-2.7)
Slow New Energy and Low Displacement Vehicle Promotion	0.84 (0.62-1.1)	1.05 (0.77-1.32)	1.17 (0.88-1.44)	1.22 (0.93-1.49)	1.22 (0.95-1.48)	1.12 (0.88-1.34)	0.97 (0.77-1.16)
Fast New Energy and Low Displacement Vehicle Promotion	0.84 (0.62-1.1)	0.97 (0.71-1.21)	1 (0.75-1.23)	0.98 (0.75-1.2)	0.88 (0.68-1.06)	0.7 (0.55-0.84)	0.49 (0.39-0.58)
TDM & TOD	0.84 (0.62-1.1)	1.29 (0.97-1.6)	1.75 (1.37-2.11)	2.22 (1.78-2.63)	2.68 (2.19-3.14)	3.34 (2.78-3.88)	3.82 (3.21-4.41)
TDM & TOD Building Polycentric City	0.84 (0.62-1.1)	1.29 (1.04-1.6)	1.75 (1.44-2.11)	2.02 (1.67-2.42)	2.44 (2.04-2.89)	2.76 (2.32-3.25)	3.12 (2.64-3.65)
Ideal Car-share Promotion	0.84 (0.62-1.1)	1.12 (0.91-1.36)	1.33 (1.1-1.6)	1.53 (1.28-1.82)	1.72 (1.45-2.02)	1.94 (1.65-2.26)	2.11 (1.81-2.45)
Car-share Promotion with Increase in Vehicle Trip Rate and Private Vehicle Mode Split	0.84 (0.62-1.1)	1.14 (0.88-1.39)	1.38 (1.09-1.65)	1.6 (1.29-1.9)	1.82 (1.47-2.14)	2.05 (1.69-2.4)	2.23 (1.85-2.59)

Natural Gas (Annual consumption, in billion M3)	2010	2015	2020	2025	2030	2040	2050
BAU	2.5 (1.68-3.49)	2.82 (1.94-3.87)	3.03 (2.11-4.11)	3.2 (2.26-4.3)	3.36 (2.4-4.47)	3.48 (2.52-4.59)	3.57 (2.61-4.68)
Slow Economic Growth	2.5 (1.68-3.49)	2.82 (1.94-3.87)	3.01 (2.1-4.09)	3.17 (2.23-4.27)	3.31 (2.35-4.43)	3.4 (2.45-4.52)	3.46 (2.51-4.58)
Robust Economic Growth	2.5 (1.68-3.49)	2.81 (1.93-3.86)	3.02 (2.1-4.09)	3.19 (2.26-4.29)	3.36 (2.41-4.48)	3.53 (2.58-4.64)	3.67 (2.72-4.77)
Slow New Energy and Low Displacement Vehicle Promotion	2.5 (1.68-3.49)	2.76 (0.42-5.98)	3.01 (0.6-6.29)	3.26 (0.8-6.58)	3.37 (0.98-6.59)	3.41 (1.15-6.42)	3.37 (1.25-6.19)
Fast New Energy and Low Displacement Vehicle Promotion	2.5 (1.68-3.49)	2.78 (0.43-6)	2.88 (0.63-5.95)	2.94 (0.81-5.82)	2.97 (0.97-5.67)	2.94 (1.08-5.42)	2.84 (1.12-5.13)
TDM & TOD	2.5 (1.68-3.49)	2.84 (0.46-6.01)	3.07 (0.63-6.3)	3.27 (0.79-6.52)	3.45 (0.94-6.74)	3.62 (1.15-6.84)	3.73 (1.29-6.91)
TDM & TOD & Building Polycentric City	2.5 (1.68-3.49)	2.84 (0.46-6.01)	3.07 (0.63-6.3)	3.25 (0.78-6.51)	3.44 (0.93-6.73)	3.53 (1.07-6.75)	3.63 (1.2-6.8)
Ideal Car-share Promotion	2.5 (1.68-3.49)	2.69 (1.85-3.69)	2.83 (1.97-3.83)	2.92 (2.07-3.92)	3 (2.15-4)	3.05 (2.22-4.02)	3.01 (2.21-3.94)
Car-share Promotion with Increase in Vehicle Trip Rate and Private Vehicle Mode Split	2.5 (1.68-3.49)	2.76 (1.89-3.78)	2.93 (2.04-3.97)	3.06 (2.17-4.11)	3.18 (2.27-4.23)	3.23 (2.35-4.26)	3.18 (2.34-4.17)

Electricity (Annual consumption, in billion kwh)	2010	2015	2020	2025	2030	2040	2050
BAU	0.41 (0.29-0.54)	0.48 (0.35-0.61)	0.53 (0.4-0.67)	0.58 (0.44-0.72)	0.62 (0.48-0.76)	0.67 (0.53-1.36)	0.71 (0.56-0.86)
Slow Economic Growth	0.41 (0.29-0.54)	0.48 (0.13-0.21)	0.53 (0.15-0.24)	0.57 (0.17-0.26)	0.6 (0.19-0.28)	0.64 (0.21-1.24)	0.66 (0.23-0.32)
Robust Economic Growth	0.41 (0.29-0.54)	0.48 (0.35-0.61)	0.53 (0.4-0.67)	0.58 (0.44-0.72)	0.63 (0.49-0.77)	0.7 (0.55-1.47)	0.76 (0.62-0.91)
Slow New Energy and Low Displacement Vehicle Promotion	0.41 (0.29-0.54)	0.77 (0.41-1.2)	1.64 (1.01-2.4)	3.77 (2.65-5.09)	7.12 (5.4-9.08)	15.06 (12.0-16.2)	21.4 (17.2-26.1)
Fast New Energy and Low Displacement Vehicle Promotion	0.41 (0.29-0.54)	1.89 (0.73-3.43)	4.92 (2.65-7.82)	10.06 (6.37-14.7)	16.22 (11.3-22.16)	29.05 (22.12-30.7)	43.11 (34.1-53.48)
TDM & TOD	0.41 (0.29-0.54)	0.47 (0.32-0.63)	0.51 (0.36-0.67)	0.55 (0.39-0.71)	0.58 (0.42-0.74)	0.6 (0.44-1.27)	0.62 (0.46-0.78)
TDM & TOD & Building Polycentric City	0.41 (0.29-0.54)	0.47 (0.32-0.63)	0.51 (0.36-0.67)	0.54 (0.39-0.7)	0.57 (0.41-0.73)	0.59 (0.43-1.26)	0.6 (0.44-0.77)
Ideal Car-share Promotion	0.41 (0.29-0.54)	0.48 (0.35-0.61)	0.52 (0.39-0.66)	0.56 (0.43-0.7)	0.6 (0.46-0.74)	0.63 (0.5-1.33)	0.66 (0.52-0.8)

Car-share Promotion with Increase in Vehicle Trip Rate and Private Vehicle Mode Split	0.41 (0.29-0.54)	0.49 (0.36-0.62)	0.54 (0.4-0.68)	0.59 (0.45-0.73)	0.63 (0.49-0.78)	0.67 (0.53-1.4)	0.7 (0.55-0.85)

Values in the parenthesis present confident interval with 95% in confidence level.

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