Estimation of Vehicle Home Parking Availability in China and Quantification of Its Potential Impacts on Plug-in Electric Vehicle Ownership Costs

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Abstract

China has become the world's largest plug-in electric vehicle (PEV) market. One major barrier to greater consumer acceptance of PEVs is the lack of home parking spaces for charging outlets. This study developed a methodology to estimate the residential parking ratios (parking spaces vs household numbers) and project the residential community-weighted parking availabilities (home parking availabilities) in China, by area and by province, through data mining from several major real estate trading network platforms. The results show that the home parking availabilities from 2015 to 2050 vary by geographic areas and building life expectancy. A method was developed to quantify the shadow values of home parking impacting on PEV ownership costs and combined with Monte Carlo simulation to address estimation uncertainty. Depending on the PEV type and all-electric range, the value of home parking space to a PEV owner, measured by the reduced vehicle ownership cost, ranges from $2,399 USD to $10,802 USD. The total incremental shadow value, relative to the 2015 situation, of the home parking availability for PEV owners increases over time due to both improvement in home parking availability and increase in the PEV population, and is estimated to reach over $2.51 billion USD by 2025 (U.S. dollars in 2015 level).

***Keywords*:** China's vehicle market; home parking availability; data mining; vehicle ownership cost; Monte Carlo simulation; electric vehicle charging.

1. Introduction

China has become the world's largest market in both all vehicles and the plug-in electric vehicles (PEVs) (Ou et al., 2017). According to the China Automotive Technology and Research Center (CATARC), the total vehicle stock in China reached over 151 million in 2015, and the passenger vehicle population increased to around 130 million units, most of which were sold in the urban areas (CATARC, 2018). Studies anticipate that, by 2050, the vehicle stock in China will reach to 400 ~ 700 million (Huo et al., 2007; Huo and Wang, 2012). The explosive growth of the vehicle market in China has inevitably raised issues in the economic, energy security, air pollution, and urban planning (Ou et al., 2017; Wang et al., 2011). Therefore, the PEVs, including both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), are viewed as a solution for national energy security and air pollution problems in highly congested urban areas (Zheng et al., 2012). After implementation of a range of favorable policies, in 2015, China became the world's largest light-duty PEV market with annual sales of 191,000 units (Ou et al., 2017).

As urbanization and motorization develop in China, the availability of vehicle parking becomes an increasingly severe problem in neighborhoods and communities in urban areas. Vehicle owners fret to find empty parking spots while pedestrians and cyclists are annoyed by streets congested with vehicles (The Economist, 2016). Meanwhile, more people are moving into cities: the urbanization rate in China has reached 55.61% by the end of 2015 with a 3.05% annual rate of change (2010-2015 estimation) (The World Bank, 2015). The conflict between urbanization and motorization constantly intensifies. According to the Ministry of Housing and Urban-Rural Development of China, the ratio of the parking spaces to vehicles is about 0.8 in the megacities, and is just 0.5 in small cities (Information Office of the State Council, 2015). The government reckons China has a shortage of roughly 50 million parking spaces, and its target is 1.3 parking spaces per vehicle (including both public and home parking) (Information Office of the State Council, 2015).

Insufficient parking space for electric vehicle charging infrastructure has become a critical bottleneck to the large-scale adoption of PEVs (Franke and Krems, 2013). Specially, as found by Smart. et al in 2012, during early adoption of PEVs, most vehicle charging took place at homes using residential PEV charging equipment (Smart and Schey, 2012), demonstrating the importance of home parking spaces for promoting PEV acceptance by consumers. In the meantime, because of the generous government subsidies and vehicle purchase privilege for PEVs, most PEV sales occur in highly congested metropolitan areas such as Beijing and Shanghai (Ou et al., 2017). This brings a critical problem to some PEV owners: no home parking spaces for vehicle home-charging.

The Chinese government has stated commitments to investing more in residential and public parking lots for urban residents to meet the parking and charging demands. In the *2016 Report on the Work of the Government*, the premier of the State Council promised to speed up construction of urban parking lots and PEV charging infrastructure (Li, 2016). The *Guiding Opinions on Accelerating the Construction of Urban Parking Infrastructure* issued by the National Development and Reform Commission in 2015 requires all new residential parking lots to provide the infrastructure for PEV charging facility installation (General Office of the State Council, 2015).

The planning and management of the vehicle parking is a challenge in other places as well. In some developed countries/regions, such as Europe, parking space is a scarce resource in urban context; this situation is intensified when electric vehicle charging facilities are needed in the parking spaces. For example, Faria et al. constructed a methodology to quantify the economic feasibility of deploying the electric vehicle parking spaces in urbans (Faria et al., 2014). Vehicle parking still needs a strategic planning even in areas with a low population density, such as the U.S. The urban planners set minimum parking requirements to satisfy the peak demand for free parking, which might increase the implicit cost to vehicle owners and bring unnecessary expenses (Guo, 2013; McDonnell et al., 2011; Shoup, 1999). In the developing countries, the insufficient home parking availability aggregates the extra economic burden to vehicle buyers (Liu, 2002; Wang, 2011). Because of its influences on the PEV charging infrastructure and street congestion (Liu, 2002), the insufficient residential parking substantially affects the commuter behaviors, vehicle kilometers traveled (VKT), and emissions (Weinberger et al., 2009). However, few published studies have investigated current situations of residential parking availability in China or quantified its potential impacts on the PEV ownership.

This study quantifies the residential community-weighted average parking availabilities by province/region and by urban type in China from 2005 to 2050, explores the relationship of the residential community-weighted average parking availability with other exogenous variables such as economic level, geographic position, urban planning etc., and built a method to estimate the impacts of the home parking on PEV ownership with Monto Carlo simulation by @Risk®. The term - "home parking availability" - will be used for describing the residential community-weighted average parking availability in following context. Admittedly, the policies pursuing the high parking availability to meet the demands by the rapid vehicle ownership growth might bring some traffic and urban design problems (Manville and Shoup, 2005), but the evaluation of the parking policies or PEV promotion policies is out of this study scope. Nevertheless, the methods and results achieved in this study can supply the policy makers and researchers a reference for their policy evaluation.

The vehicle residential parking ratio (γ) is defined as the ratio of the vehicle residential parking spaces to the households in the residential communities. The number of "households" in this study means the number of houses or apartments in a residential community. The home parking availability (R) is a weighted average value calculated from the parking ratios (γ) of the residential communities, and it is used for evaluating the residential parking conditions in the urban areas in China.

The following questions are raised and addressed:

- What are the home parking availabilities in first-tier, second tier, third-tier cities respectively by province?
- What will the home parking availability be like in the future in China?
- What is the relationship between the home parking availability with economic level, geographic position, urban planning etc.?
- What is the invisible cost of the residential parking space on the PEV ownership?

This paper consists of five sections. The first section presents the motivations and objectives, and it reviews the related background and literature. The second section presents the processing of the data analysis and assumptions for the home parking availability model. The third section clarifies the methodology and equations. Section four focuses on the analyses of the home parking availabilities and quantifies its influences on the PEV ownership. The last section presents the conclusions. The yearly average currency exchange rate of $ 1.0 USD = 6.489 CNY in 2015 is used (U.S. Internal Revenue Service, 2017), and money is at 2015 level.

2. Data

To investigate the residential parking circumstances in different levels of urban areas by province, three tiers of areas are classified (Tier 1, Tier 2, Tier 3) in 31 provincial regions in mainland China (excluding Taiwan, Hong Kong, and Macao) based on their administrative partitions by the Chinese government. As shown in Table 1, Tier 1 areas include the urban areas in the direct-controlled municipalities (Beijing, Chongqing, Shanghai, and Tianjin), the capitals of the provinces (e.g., Changsha, Nanchang), and the sub-provincial municipalities (e.g., Dalian, Qingdao). Tier 2 refers to the suburban areas in the direct-controlled municipalities and the prefectural level cities in provinces. Tier 3 includes the urban areas in the county or township levels in each province.

Table 1. Classification of the area type in China.

Classification	Area types (n)	Example
Tier 1	The urban areas in the direct-controlled municipalities	Haidian, Beijing
	The provincial capitals	Nanjing, Jiangsu
	Sub-provincial municipalities	Qingdao, Shandong
Tier 2	The suburban areas in the direct-controlled municipalities	Baoshan, Shanghai
	The prefectural level cities	Yueyang, Hunan
Tier 3	The urban areas in the county or township levels	Weng'an, Guizhou

To achieve the parking ratios, accurate and comprehensive information is vital. Information on both household and residential parking spaces are rarely collected by the authorities. However, the dramatic development of real estate transactions in China spurs Chinese real estate transaction platforms to glean abundant information of pre-owned and new residential communities and present them online to the customers. Through data mining, this study collected residential community information from the largest real estate transaction internet platforms (fang.com, lianjia.com, anjuke.com) in China. Fig. 1 shows the information structure of the data obtained. Totally, 852 samples of residential community information, covering over 100 cities across 31 provinces, are collected. Recognizing the potential limitation of the collected data, the following assumptions are made:

- Only the residential parking in the urban areas is studied, and it includes the parking garages, street parking spaces, and open parking grounds in the residential communities.
- For simplicity, the residential communities belong to the same tier area (as shown in Table 1) within a province/region are assumed to be homogenous on geographic characteristics, economic level, and population density.
- The vehicle parking ratios in the residential communities built at the year 2050 are assumed to meet the government target (Ministry of Housing and Urban-Rural

Development of China, 2015), which is about 80% in Tier 1 area, and 85% in Tier 2 and Tier 3 areas.

- Despite the diligent efforts, data collected in some provinces/regions are still incomplete. Thus, the parking ratios in some areas are used for some other areas without enough data, based on their feature similarities in geography, economic level and population density. For example, it is assumed that the parking ratios in Tibet are the same as in Xinjiang, which is a neighboring region to Tibet.

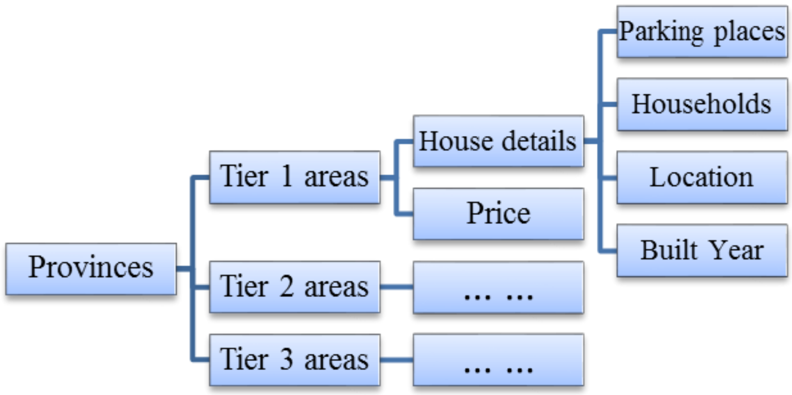

Fig. 1. Information structure of a sample.

Based on data from CATARC, we estimated the PEV's sales-weighted energy consumption metrics in China in 2015. As shown in Table 2, L_E is the all-electric-range (AER) (km); c_f is the fuel consumption in charging-sustaining mode (L/100km); and c_e is the electricity consumption in charging-depleting mode (kWh/100km).

Table 2. PEV sales-weighted energy consumption in China in 2015.

Type	Technology	L_E (km)	c_f (L/100km)	c_e (kWh/100km)
Sedan	BEV-150 (AER<150km)	83	-	13.9
	BEV-250 (150≤AER<250km)	157	-	13.5
	BEV-350 (250≤AER<350km)	277	-	16.6
	BEV-400 (AER≥350km)	400	-	20.5
	PHEV-50 (AER<70km)	58	4.40	13.0
	PHEV-70 (AER≥70km)	70	6.28	19.9
SUV	BEV	150	-	21.1
	PHEV	84	8.74	20.5

3. Assumptions and Methodology

3.1. Home parking availabilities

The home parking availability (R) in year $Y(j)$ is the residential community-weighted average value calculated from the parking ratio (γ) of the residential communities built in different decades (i) by their proportion at the year $Y(j)$, $Y(j) \in \{2005, 2015, 2025, 2050\}$. The residential communities are segmented into four groups based on their built years:

(1) Communities I: all the residential communities built before 2005, and the parking ratios of these communities are labeled as γ_1;
(2) Communities II: the new residential communities built between year 2005 and 2015, and their corresponding parking ratios are labeled as γ_2;
(3) Communities III: the new residential communities built between year 2015 and 2025, and their parking ratios are labeled as γ_3;
(4) Communities IV: the new residential communities built after 2025, and their parking ratios are labeled as γ_4.

The parking ratios (γ_i) by residential community within one province/region and within one Tier are presented in Table 3. The values for Communities I, Communities II and Communities III in Table 3 are the median values for the parking ratios of the residential communities built in the same period, which are investigated using the data from the real estate transaction websites. As assumed in Section 2, the parking ratio γ_4 in the residential communities built after 2025 is 80% in Tier 1, and 85% in Tier 2 and Tier 3 urban areas.

Eqn. (1) shows the calculations for the home parking availabilities (R) by considering the proportions of these four groups of residential communities (I-IV) in year 2005, 2015, 2025 and 2050.

$$\begin{cases} R_{Y(j)}^{m,n} = \sigma\left(\sum_{i=1}^{j} P^{m,n}(i,j)\gamma_i^{m,n}\right) \\ \sum_{i=1}^{j} P^{m,n}(i,j) = 100\% \end{cases}, \quad i,j \in \{1,2,3,4\} \tag{1}$$

where, R is the home parking availability at year $Y(j)$; m refers to the provincial region in China; n refers to the area type which includes Tier 1, Tier 2 and Tier 3. Since the calculations are the same for all provinces and urban areas, the superscripts (m and n) are ignored in the following text. σ is a parking space multiplier which considers the possibility of renovating existing residential communities to build extra parking spaces to meet the parking demands. σ is assumed to be 110% in this model. $P(i,j)$ (≤ 100%) is the proportion of the Communities i over all residential communities at the year $Y(j)$. γ_i is the parking ratio of the Communities i. For example, "$P(1,2) = 20\%$" means that the proportion of the Communities I over all four residential communities (I-IV) at year ($Y(2) = 2015$) is 20%.

Table 3. The parking ratios (γ) of the residential communities by built year. (Ratio unit: %)

Region \ Area type	Communities I			Communities II			Communities III			Communities IV		
	Tier1	Tier2	Tier3	Tier1	Tier2	Tier3	Tier1	Tier2	Tier3	Tier1	Tier2	Tier3
Anhui	32.8	28.6	31.4	54.6	54.1	58.9	82.0	71.4	78.6	80.0	85.0	85.0
Beijing	38.6	21.3	23.5	60.0	53.4	58.7	101.6	90.3	99.4	80.0	85.0	85.0
Chongqing	29.1	24.6	27.0	54.6	46.0	50.7	72.8	61.4	67.5	80.0	85.0	85.0
Fujian	26.6	27.4	30.1	49.8	51.3	56.4	66.4	68.4	75.3	80.0	85.0	85.0
Guangdong	43.5	26.7	29.4	81.5	50.0	55.0	108.7	66.7	73.4	80.0	85.0	85.0
Gansu	21.1	28.9	31.8	39.5	58.3	59.7	52.7	72.3	79.6	80.0	85.0	85.0
Guangxi	34.4	27.9	30.7	64.5	52.4	57.6	85.9	69.9	76.9	80.0	85.0	85.0
Guizhou	38.4	35.1	38.6	72.0	65.8	72.4	96.1	87.8	96.6	80.0	85.0	85.0
Henan	37.4	21.7	31.5	70.1	40.6	59.0	93.5	71.5	78.7	80.0	85.0	85.0
Hubei	18.6	30.5	33.5	34.8	57.2	62.9	46.4	76.2	83.8	80.0	85.0	85.0
Hebei	22.0	26.5	29.1	41.3	49.7	54.6	55.1	66.2	72.8	80.0	85.0	85.0
Heilongjiang	18.7	10.3	20.3	35.1	19.4	38.0	46.7	46.1	50.7	80.0	85.0	85.0
Hunan	26.7	19.1	21.0	50.0	35.9	39.4	66.7	47.8	52.6	80.0	85.0	85.0
Hainan	32.6	17.7	19.5	61.1	33.2	36.5	81.5	44.2	48.7	80.0	85.0	85.0
Jilin	17.1	13.5	14.8	32.0	25.3	27.8	42.7	33.7	37.1	80.0	85.0	85.0
Jiangsu	35.1	29.2	32.1	65.7	54.7	60.2	87.6	72.9	80.2	80.0	85.0	85.0
Jiangxi	27.2	30.7	33.8	51.0	57.5	63.3	68.0	76.7	84.4	80.0	85.0	85.0
Liaoning	31.7	18.1	19.9	59.4	33.9	37.3	79.2	45.2	49.7	80.0	85.0	85.0
Inner Mongolia	28.4	24.0	26.4	53.2	45.0	49.5	71.0	60.0	66.0	80.0	85.0	85.0
Ningxia	34.0	29.8	32.8	63.7	55.9	61.5	85.0	74.5	82.0	80.0	85.0	85.0
Qinghai	33.2	27.0	29.7	62.2	50.6	55.7	82.9	67.5	74.3	80.0	85.0	85.0
Sichuan	36.0	28.3	36.4	67.5	53.0	68.3	90.0	82.8	91.0	80.0	85.0	85.0
Shandong	30.9	27.7	30.5	57.9	52.0	57.2	77.2	69.3	76.2	80.0	85.0	85.0
Shanghai	4.8	4.3	5.3	46.4	52.2	51.1	84.5	95.0	92.9	80.0	85.0	85.0
Shaanxi	28.9	15.4	17.0	54.1	28.9	31.8	72.1	38.5	42.4	80.0	85.0	85.0
Shanxi	30.9	30.0	33.0	57.9	56.3	61.9	77.2	75.1	82.6	80.0	85.0	85.0
Tianjin	20.7	36.0	22.7	51.7	90.0	56.8	72.2	81.2	79.4	80.0	85.0	85.0
Xinjiang	28.6	24.7	27.2	53.6	46.3	50.9	71.5	61.7	67.9	80.0	85.0	85.0
Tibet	28.6	24.7	27.2	53.6	46.3	50.9	71.5	61.7	67.9	80.0	85.0	85.0
Yunnan	28.6	23.7	26.1	53.6	44.4	48.9	71.4	59.2	65.1	80.0	85.0	85.0
Zhejiang	37.7	29.7	32.7	70.7	55.7	61.3	94.3	74.3	81.7	80.0	85.0	85.0

3.2. Life expectancy of residential communities in China

The residential community proportion $P(i,j)$ varies by year, which is caused by two conditions: (a) all residential communities have a life expectancy, and the aged ones are demolished gradually; and (b) the total number of residential communities (N) is still growing up to meet the demands from the new urban residents in the rural-urban migration. Fig. 2 is a schematic diagram shown the proportion of Communities i varying by year. The total number of all residential communities in year $Y(j)$ varies with the life expectancy of the residential communities, which determines the proportion of each Communities i.

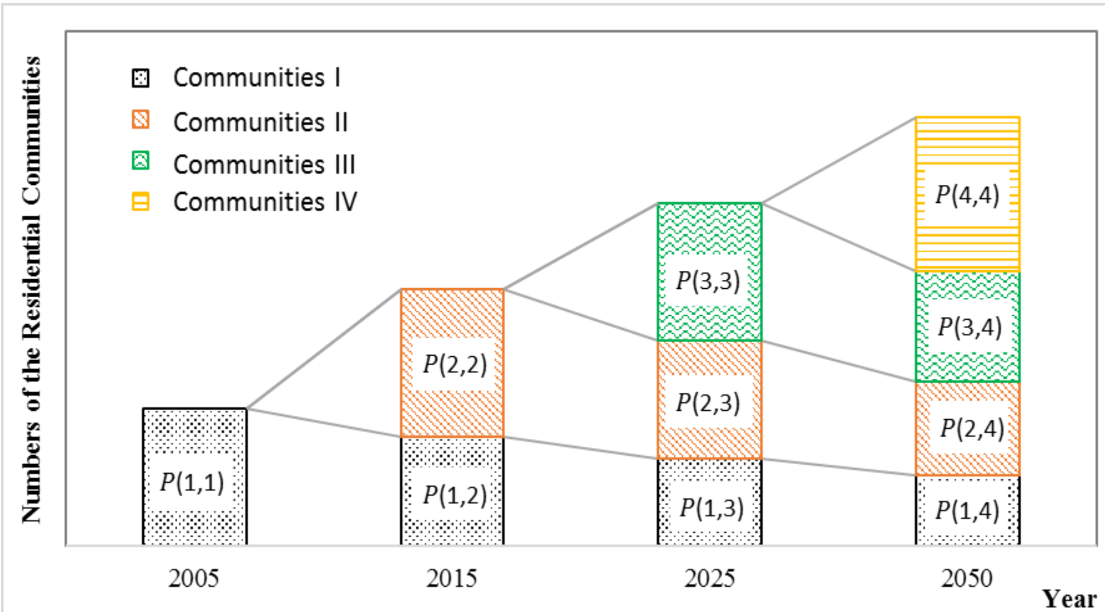

Fig. 2. The schematic diagram of the proportions of the residential communities by year.

The building survival rate, which is the percentage of the buildings with a particular age are in use, is a critical factor in deciding the proportion $P(i,j)$. A few have studied on the building's life expectancy or obsolescence rate (OR) in China. Ouyang et al. 2008 estimates that the average life expectancy of the residential buildings is 25.5 years in the 1960s, 35.7 years in the 1970s, and 40.4 years in the 1980s in China (Ouyang and Ren, 2008). Per the report by the State Information Center, current average life expectancy of buildings is 25-30 years (Liu, 2015). Accordingly, for these residential communities built between 2000 and 2050, it is assumed that 50% of the residential communities survive at 30 years old, and about 10% residential communities' life expectancy is about 40 years.

This study employs the Weibull distribution to model China's residential OR, as shown in Eqn. (2). Weibull distribution is widely used for the reliability of lifetime analysis (Huo and Wang, 2012). In general, $a_i^{Y(j)}$ is the average age of the Communities i at year $Y(j)$. Considering the life expectancy of buildings at 30 years, it assumes that the average age $a_1^{Y(1)}$ of Communities I is 15 years. Considering the oldest buildings after year 2005 is at age of 10 years in 2015, and the youngest buildings after year 2005 is at age of 0 year in 2015, the average age $a_2^{Y(2)}$ of the Communities II is assumed of 5 years in 2015. Similarly, the residential communities in the Communities III are assumed to have an average age $a_3^{Y(3)}$ of 5 years in 2025.

$$OR(a) = 1 - e^{-(a/\lambda)^{\tau}} \tag{2}$$

$$SR(a) = 1 - OR(a) = e^{-(a/\lambda)^{\tau}} \tag{3}$$

where, SR is the survival rate of the residential communities at age of a, $\tau > 0$ is the shape parameter of the Weibull distribution and $\lambda > 0$ is the scale parameter of the Weibull distribution. Based on these assumptions, λ is calculated to be 32.8, and τ is 4.18. Fig. 3 shows the fitting survival rate of the residential communities in China derived by the Weibull distribution.

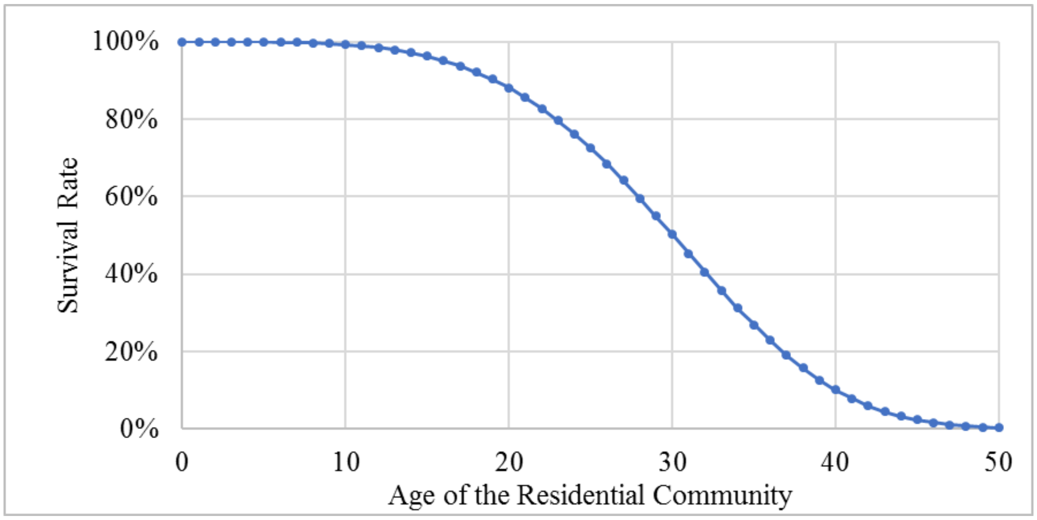

Fig. 3. The assumed survival rate of residential communities by the Weibull distribution.

3.3. Urbanization in China

Urbanization rate (U), describing the percentage of the population in urban areas to total population in China (Eqn. (4)), is driven by two forces: rural-urban migration; and suburbanization transformation of towns and villages (Kamal-Chaoui et al., 2009). Though the number of residents in a residential community varies, the capacity of residents in most urban residential communities is believed to be designed in a reasonable range, to simplify the calculation, this study assumes the average number of residents in an urban residential community as a constant (P_{RC}). Therefore, the increase of the urbanized residents leads to the growth of the residential community numbers (N), instead of residential community sizes, as derived in Eqn. (4).

$$\begin{cases} U = \dfrac{P_U}{P_T} \\ N = \dfrac{P_U}{P_{RC}} \end{cases} \tag{4}$$

where, P_U is the population in urban areas, and P_T is the total population. Gao et al. in 2013 concluded that the urbanization rate in China will be approximately 60.34% by 2020, 68.38% by 2030, 75.37% by 2040, and 81.63% by 2050 (Gao and Wei, 2013). The urbanization rates by year are presented in Table 4.

Urbanization and population growth cause demands upon residential communities. In the developing countries, the urbanization is positive correlated with the new homes in cities (UN and UNCHS, 2001). When the total population remains unchanged, only the growth of the urbanization rate will incent the new urban residential communities to be built; or in other words, the numbers of urban residential communities (N) could be linearly positive-correlated with the urbanization rate (U), as shown in Eqn. (5). Meanwhile, will the total population in China remain a stable level in next decades? If the total population level in China is assumed at a baseline of 1.000 in 2005. According to the total population projections by the World Bank (DataBank, 2017), the population levels are calculated and given by Table 4. In fact, these numbers show that only a very small fluctuation of the population in China will be in years from 2005 to 2050. The urbanization is expected to be the major reason that leads to the urban residential communities in China. Thus, it is OK to assume the total amount of urban residential communities to be linearly correlated with the urbanization rate.

$$U = \frac{P_{RC}}{P_T} \cdot \mathrm{N} \tag{5}$$

Table 4. The explanations of the symbols.

Year, $\boldsymbol{Y(j)}$	**2005**	**2015**	**2025**	**2050**
Urbanization rate, $U^{Y(j)}$	42.52% (The World Bank, 2015)	55.61% (The World Bank, 2015)	64.36%*	81.36% (Gao and Wei, 2013)
Population level, $\rho^{Y(j)}$ (DataBank, 2017)	1.000	1.052	1.081	1.027

* Linear interpolation of the projected urbanization rates in 2020 and 2030 from Reference (Gao and Wei, 2013).

Although the exact number of residential communities in a particular year is unknown, based on the assumptions mentioned earlier, the proportion of the Communities i over all Communities (I-VI) at year $Y(j)$ can be calculated from the urbanization rates, as shown in Eqn. (6).

$$\begin{cases} P(j,j) = 1 - \sum_{t=1}^{j-1} P(t,j) \\ P(i,j) = \dfrac{\dfrac{SR\left(a_i^{Y(j)}\right)}{SR\left(a_i^{Y(i)}\right)} P(i,i)\rho^{Y(i)} U^{Y(i)}}{\rho^{Y(j)} U^{Y(j)}}, i < j \end{cases}, \quad i,j \in \{1,2,3,4\} \tag{6}$$

where, $\rho^{Y(j)}$ is the population level at year $Y(j)$; and $U^{Y(i)}$ is the urbanization rate at year $Y(i)$. Notably, $P(1,1)$ denotes all the residential communities in 2005, which is 100%, as shown in Fig. 2.

3.4. Potential values of home parking on PEV ownership

The quantified shadow value impacted by the home parking on PEV ownership in China is derived in this section. The value considered in this study includes the costs paid PEV drivers and also externally contains the invisible expenditures by the government, the auto companies, or the society.

First of all, the vehicle lifetime kilometers (L) is estimated by Eqn. (7).

$$L = \sum AVKT/(1+DR)^i \ , i \in Y_{PEV} \tag{7}$$

where, $AVKT$, the annual VKT, is 19,681 km, or 53.92 km as the daily vehicle kilometers travelled ($DVKT$) mean (M_n) (CATARC, 2014); DR is the discount rate which is assumed to be 7%; Y_{PEV} is a perceived lifetime used in calculation of energy costs (Lin and Greene, 2011). Some scholars believe that consumers highly discount future energy savings and recommend 2~4 years for calculation, while some others believe consumer full valuation of fuel economy and recommend 14~16 years, close to the average lifetime of a vehicle (Xie and Lin, 2017). 10 years as a commonly used middle point value is adopted.

The variation of $DVKT$ is characterized as a Gamma distribution, which has been validated using real-world GPS travel data (Lin et al., 2012). The daily commute drive round trip is approximately 16.22 km, which is assumed as the $DVKT$ mode (M_d) (CATARC, 2014). The shape parameter of Gamma distribution (k) and scale parameter of Gamma distribution (θ) are two important metrics to shape the Gamm distribution $p(x)$ which are estimated based on Eqn. (8) and (9).

$$k \cdot \theta = M_n \tag{8}$$

and

$$(k-1) \cdot \theta = M_d \tag{9}$$

If the PEVs are always charged at home, and no electric range extension daily, the daily electric VKT (EVKT) is estimated by Eqn. (10) (Lin, 2014).

$$EVKT = \int_0^{L_E} xp(x)\,dx + L_E \int_{L_E}^{+\infty} p(x)\,dx \tag{10}$$

where, x is the random $DVKT$ (km) that follows a Gamma distribution probability density function $p(x)$; L_E is the electric range of a PEV (km).

Home Parking Impacts on BEV Ownership

C_{BEV} is the home parking shadow value (USD) for the BEV drivers who have no home parking place for charging outlet installation and is estimated of the difference between $C_{w/oR,BEV}$ and $C_{wR,BEV}$, as shown in Eqn. (11). $C_{w/oR,BEV}$ is the costs (USD) for the BEV drivers without home parking places, and $C_{wR,BEV}$ is the costs (USD) for the BEV drivers with home parking places. Because of lacking the home parking place with charging outlet, several ways the BEV owners have to think about for their vehicle charging: (a) find a workplace charger; or (b) find a public charging outlet (includes ubiquitous on-street charging spaces–priced and managed, shops, charging stations), which brings the inconvenience and extra fees to the BEV owners. According to the investigation on BEV charging locations in five cities in China by SHEVDC (SHEVDC, 2017), the probabilities of charging locations (α) are assumed as they are shown in Table 5. Considering the charging inconvenience, it is assumed that the BEV owners do not charge the vehicles until the unused electric range is shorter than $EVKT$, and the BEVs are always fully charged in every charging. $C_{w/oR,BEV}$ and $C_{wR,BEV}$ are calculated as shown in Eqn. (12) and (13).

Table 5. The assumed possibilities of charging locations based on (SHEVDC, 2017).

Locations	**Drivers with home-charging (α_{wR})**	**Drivers without home-charging ($\alpha_{w/oR}$)**
Home parking	60%	0%
Public-charging	20%	60%
Workplaces	20%	40%

$$C_{BEV} = C_{w/oR,BEV} - C_{wR,BEV} \tag{11}$$

$$C_{w/oR,BEV} = \frac{Y_{PEV} \cdot 365}{int\left(\frac{L_E}{EVKT}\right)} \cdot \left(\alpha_{w/oR,P} \cdot c_{P,BEV} + \alpha_{w/oR,W} \cdot c_{W,BEV}\right) \tag{12}$$

$$C_{wR,BEV} = \frac{Y_{PEV} \cdot 365}{int\left(\frac{L_E}{EVKT}\right)} \cdot \left(\alpha_{wR,R} \cdot c_{H,BEV} + \alpha_{wR,P} \cdot c_{P,BEV} + \alpha_{wR,W} \cdot c_{W,BEV}\right) + P_{st} \tag{13}$$

where, $int\left(\frac{L_E}{EVKT}\right)$ represents the number of days between two consecutive charging events. α is the charging probability by location. For example, $\alpha_{wR,P}$ is the possibility of public-charging for the BEV drivers who have home parking. As shown in Table 5, the BEV owners with home-charging might have three places (home parking places, workplaces and public) for vehicle charging. The BEV owners without home-charging might have only two places (workplaces and public) for vehicle charging. $c_{H,BEV}$ is the home-charging cost per full charging (USD). $c_{P,BEV}$ is the public-charging cost per full charging (USD). $c_{W,BEV}$ is the workplace-charging cost per full charging (USD). P_{st} is the home-charging pile purchase and installation cost.

P_{st} is the fixed cost invested into home-charging place by the BEV drivers, and it is estimated to be $500-$1,200 USD. In fact, the subsidies for home-charging pile purchase and installation make the BEV drivers' actual expenses much smaller than the P_{st} estimation. This is because these costs are partially covered by the auto companies or the government financial supports. Therefore, P_{st} is a full cost without any subsidies.

The home-charging cost for those who have home parking are calculated by Eqn. (14). This cost consists of two parts: electricity cost and charging pile installation cost.

$$c_{H,BEV} = P_{He} L_E \frac{c_e}{100} \tag{14}$$

where, P_{He} is the residential electricity price in 2015, which is \$0.044-0.110 USD/kWh with a median price at 0.079 USD/kWh (CATARC, 2018). c_e is the electricity consumption (kWh/100 km) and is given in Table 2.

The public-charging cost is calculated by Eqn. (15). This cost consists of two parts: electricity cost, and inconvenience cost calculated based on driver's time value. Two types of public charging are considered in the estimation: fast-charging, and slow-charging.

$$c_{P,BEV} = \varphi_{FC}\left[V_T(t_T + t_{FC}) + (P_{Pc} + P_{Fs})L_E\frac{c_e}{100}\right] + \varphi_{SC}\left[2\omega V_T t_T + (P_{Pc} + P_{Ss})L_E\frac{c_e}{100}\right] \quad (15)$$

where, φ_{FC} is the possibility of fast-charging which is assumed to be 0.26 (the ratio of fast-charging piles/total public charging piles in China in 2015), φ_{SC} is the possibility of slow-charging with 0.74 (CATARC, 2018). V_T is the driver's time value assumed to be \$2.31-5.39 USD/hour (National Bureau of Statistics of China, 2017). t_T is the estimated time for the round trip traveling from home to the nearest available public charging outlets, which is assumed to be 15-25 mins if the average distance is about 2 km (Liu, 2012). Some drivers might consider the PEV charging as a detour (e.g., charging on their way home), it is hard to find out the average detour distance of the drivers, but there is a consensus that the inconvenience costs are caused on the way to the public-charging. Thus, 2 km is deemed as an acceptable range for evaluating these costs. t_{FC} is assumed to be 20-40 mins for fully charged with fast-charging (Liu, 2012); P_{Pc} is the public charging electricity price, which is 0.051-0.224 USD/kWh with a median price at 0.135 USD/kWh in year 2015-2016 in our investigation with CATARC (CATARC, 2018); P_{Fs} is the fast-charging service fee, which ranges from \$0.061 to 0.279 USD/kWh with a median fee at 0.154 USD/kWh in year 2015-2016 (CATARC, 2018; State Grid, 2017). In the slow-charging scenario, it assumes that the drivers wait at home till the PEVs are fully charged, and thereby will have two round trips to the public charging stations. ω is the travel annoyance multiplier and assumed to range from 1.2 to 2.0. P_{Ss} is the slow-charging service fee, which is \$0.061-0.279 USD/kWh with a median fee at 0.108 USD/kWh in year 2015-2016 (CATARC, 2018). The service fee can cover most costs of operating a public charging station (according to the estimation by (Li, 2017), the break-even service fee is about 0.230 USD/kWh).

The workplace-charging cost is calculated in Eqn. (16). Workplace could be a favorable place for vehicle charging: on one hand, encouraging the PEV use, workplace charging is often free to the employees; on the other hand, the workplace-charging brings no inconvenience costs to the drivers only if they find places for vehicle charging. However, this "cheap" charging mode is just because the cost of charging infrastructure and electricity use in workplace are transferred to the society or the employers. Therefore, the workplace-charging cost is still counted into the shadow value calculation. This cost consists of two parts: electricity cost, and infrastructure cost, as shown in Eqn. (16). Electricity price in workplace is the same as it is in public-charging (P_{Pc}), since they are both classified as commercial/industrial use in China.

$$c_{W,BEV} = (P_{Pc} + P_I)L_E\frac{c_e}{100} \quad (16)$$

where, P_I is the infrastructure cost (USD/kWh). It is hard to achieve the employer private PEV charging infrastructure cost, but according to the knowledge of the break-even cost to run a public charging station, it could be very close to be 0.230 USD/kWh (Li, 2017). Thus, the possible range of P_I is assumed to be the same as the slow-charging service fee in public-charging, and its median is at 0.230 USD/kWh.

Home Parking Impacts on PHEV Ownership

C_{PHEV} is the home parking shadow value for PHEV drivers who have no home parking place with charging outlet installed. Because of lacking the home parking places with charging outlets, and to avoid the inconvenience, the drivers have to run the PHEV in a charging-sustaining mode only. $C_{P,PHEV}$ can be calculated based on Eqn. (17).

$$C_{PHEV} = \frac{EVKT}{M_n} L \frac{c_f}{100} P_f - \left(\frac{EVKT}{M_n} L \frac{c_e}{100} P_{He} + P_{st} \right) \quad (17)$$

where, P_f is the average gasoline price in 2015, which is \$0.872-1.106 USD/Liter (Feng, 2016).

If all the home parking spaces are qualified for charging outlet installation, the incremental shadow value on PEV ownership in market impacted by the growth of home parking availability, $V_{i,PEV}$, can be calculated by Eqn. (18).

$$V_{i,PEV} = (R_j - R_{2015}) N_j^{i,PEV} \cdot C_{i,PEV}\ , \qquad C_{i,PEV} \in [C_{PHEV}, C_{BEV}] \quad (18)$$

where, R_j is the home parking availability in year $Y(j)$; R_{2015} is the home parking availability in year 2015 which is a benchmark for comparison; $N_j^{i,PEV}$ is the total units of individually-owned PEV i in year $Y(j)$; $C_{i,PEV}$ is the home parking shadow value of PEV i. To consider the influences of the extreme values for shadow value of home parking on PEV ownership, the probabilities of the parameters are assumed to be triangular-distributed, while the peak values in distributions are the most likely values. The model for quantifying the shadow value of the home parking impacting on PEV ownership costs is constructed and run with @Risk® with the Monte Carlo simulations.

4. Results and Discussions

4.1. Trends of home parking availabilities in China

Based on the methodology in Section 3, the estimated results of the home parking availabilities are obtained for three urban area types in 31 provinces/regions. Fig. 4 shows the home parking availabilities in Tier 1 in 2005, 2015, 2025, and 2050 respectively. The home parking availabilities in each province for all three urban areas are given in Table 6.

As shown in Fig. 4, all the home parking availabilities are improved national widely. The home parking availabilities are small almost everywhere in mainland China in 2005, especially in the metropolitan cities such as Beijing and Shanghai. For example, based on the calculations, it is found that the home parking availability is about 42.5% in central area in Beijing in 2005, when more than half of the households had no parking places and most households had no cars. Nevertheless, by 2025, the home parking availability in Beijing's central urban area is estimated to be 82.8%, about 1.9 times over the 2005 level.

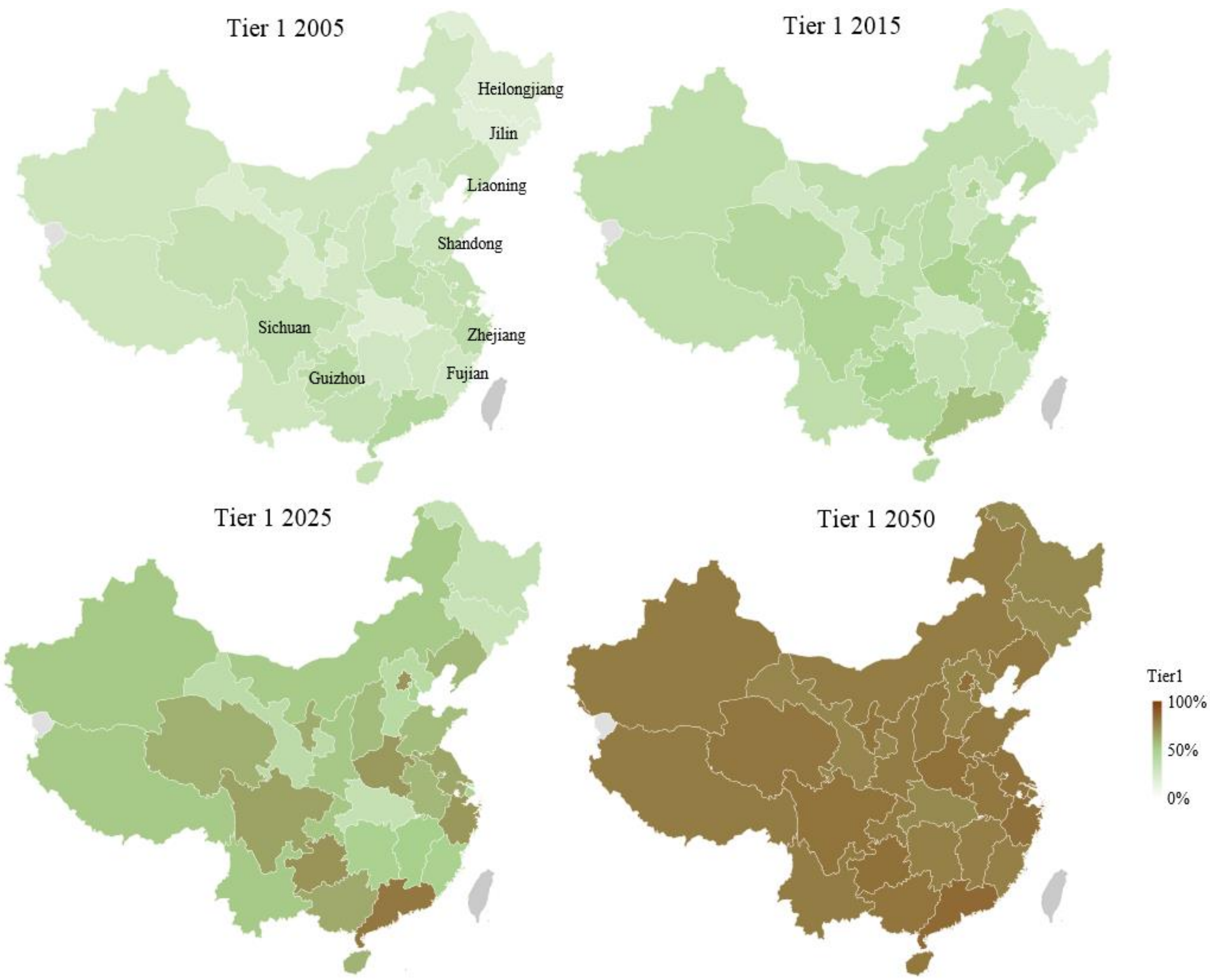

Fig. 4. Estimated home parking availabilities in mainland China.

Table 6. The home parking availabilities (R) by year (Unit: %).

Area Type	2005			2015			2025			2050		
	Tier1	Tier2	Tier3	Tier1	Tier2	Tier3	Tier1	Tier2	Tier3	Tier1	Tier2	Tier3
Anhui	36.1	31.4	34.6	46.9	44.1	48.3	69.9	63.5	69.7	87.5	89.5	91.2
Beijing	42.5	23.5	25.8	53.1	39.4	43.4	83.2	71.5	78.6	91.9	93.5	95.6
Chongqing	32.0	27.0	29.7	44.7	37.7	41.5	64.5	54.4	59.9	85.6	87.1	88.6
Fujian	29.2	30.1	33.1	40.8	42.0	46.2	58.9	60.6	66.7	84.0	88.8	90.4
Guangdong	47.8	29.4	32.3	66.8	41.0	45.1	96.4	59.1	65.1	94.2	88.4	90.0
Gansu	23.2	31.8	35.0	32.4	46.4	48.9	46.7	65.7	70.5	80.8	89.9	91.5
Guangxi	37.8	30.7	33.8	52.8	42.9	47.2	76.2	61.9	68.1	88.7	89.1	90.8
Guizhou	42.3	38.6	42.5	59.0	53.9	59.3	85.1	77.8	85.6	91.1	93.4	95.5
Henan	41.1	23.8	34.6	57.4	33.3	48.3	82.9	56.8	69.7	90.5	89.1	91.2
Hubei	20.4	33.5	36.9	28.5	46.8	51.5	41.1	67.6	74.3	79.3	90.7	92.5
Hebei	24.2	29.1	32.0	33.8	40.7	44.7	48.8	58.7	64.6	81.3	88.3	89.8
Heilongjiang	20.6	11.4	22.3	28.7	15.9	31.1	41.4	33.2	44.9	79.3	82.9	84.5
Hunan	29.3	21.0	23.1	41.0	29.4	32.3	59.1	42.4	46.6	84.1	83.9	85.0
Hainan	35.9	19.5	21.4	50.0	27.2	29.9	72.2	39.2	43.1	87.7	83.0	84.1
Jilin	18.8	14.8	16.3	26.2	20.7	22.8	37.8	29.9	32.9	78.4	80.5	81.3
Jiangsu	38.6	32.1	35.3	53.8	44.8	49.3	77.7	64.7	71.1	89.1	89.9	91.6
Jiangxi	29.9	33.8	37.1	41.8	47.1	51.8	60.3	68.0	74.8	84.4	90.8	92.6
Liaoning	34.8	19.9	21.9	48.6	27.8	30.5	70.2	40.1	44.1	87.1	83.2	84.3
Inner Mongolia	31.2	26.4	29.0	43.6	36.9	40.5	62.9	53.2	58.5	85.1	86.8	88.2
Ningxia	37.4	32.8	36.1	52.2	45.8	50.3	75.3	66.0	72.7	88.5	90.2	92.0
Qinghai	36.5	29.7	32.7	50.9	41.5	45.6	73.5	59.8	65.8	88.0	88.6	90.2
Sichuan	39.6	31.1	40.1	55.3	43.4	55.9	79.8	68.8	80.7	89.7	91.9	94.2
Shandong	34.0	30.5	33.5	47.4	42.6	46.8	68.5	61.4	67.6	86.6	89.0	90.7
Shanghai	5.3	4.7	5.8	26.0	28.6	28.6	62.6	70.2	68.8	87.8	94.5	94.0
Shaanxi	31.7	17.0	18.7	44.3	23.7	26.0	63.9	34.2	37.6	85.4	81.6	82.6
Shanxi	34.0	33.0	36.3	47.4	46.1	50.7	68.4	66.6	73.2	86.6	90.4	92.2
Tianjin	22.7	39.6	25.0	38.2	66.5	42.0	61.4	84.4	67.6	85.3	92.9	91.3
Xinjiang	31.5	27.2	29.9	43.9	37.9	41.7	63.4	54.7	60.2	85.3	87.2	88.7
Tibet	31.5	27.2	29.9	43.9	37.9	41.7	63.4	54.7	60.2	85.3	87.2	88.7
Yunnan	31.4	26.1	28.7	43.9	36.4	40.0	63.3	52.5	57.7	85.2	86.6	88.0
Zhejiang	41.5	32.7	35.9	57.9	45.6	50.2	83.6	65.8	72.4	90.7	90.2	92.0
Nationwide	**33.5**	**27.6**	**31.4**	**47.0**	**39.3**	**44.4**	**68.7**	**58.7**	**65.1**	**86.8**	**88.5**	**90.1**

4.2. Inequality of home parking availabilities in China

Inequalities of home parking availabilities exist among provinces and area types. For instance, it shows that the home parking availabilities in the three northeastern provinces (Heilongjiang, Jilin, and Liaoning) are generally smaller than other provinces/regions in the same year, as referred to Table 6. The 2005 home parking availabilities in Tier 1 areas in these provinces are 20.6%, 18.8%, and 34.8% respectively, which, except Liaoning province, are much smaller the national average home parking availability of 33.5%. Historically, the urbanization in northeastern China occurred much earlier than in other areas. As shown in Fig. 5(a), the urbanization rates were already much higher than other areas before 2000, but there were few demands for residential parking lots from the urban residents. Consequently, many residential communities built in earlier decades were not designed with enough parking lots. After the automotive age arrived in China in the 2000s, urbanization rate moved slowly in these provinces when their economic growth fell behind others (Gao and Wei, 2013), which retarded the improvement of home parking conditions in these regions.

On the other hand, most developed regions, specifically the coastal areas, have greater home parking availabilities than the less developed regions. Shown in Fig. 4, home parking availabilities in coastal provinces such as Fujian, Shandong, and Zhejiang are higher than the national average, and the developments of home parking availabilities in the three area types are well-balanced. This shows that economic and urbanization levels could positively influence the home parking availabilities.

Economic level is not the only determinant. Home parking availabilities in the prosperous metropolitan areas are not always higher than other areas. Fig. 5(b) reveals the home parking availabilities of China's three major cities (Beijing, Shanghai, and Tianjin). Shanghai's home parking availabilities in 2005 are less than 10%, which are the lowest values among metropolitan cities nationally. This might be attributed to the historically full-blown streets and blocks and costly land prices in Shanghai. Nevertheless, the rapid growth of home parking availabilities in Shanghai helps the home parking availabilities to be over 60% in Shanghai by 2025. At the flip side, the second-mover advantage plays a critical role in helping the less developed regions. As shown in Fig. 4, Guizhou and Sichuan provinces perform better in the home parking availability than most of other provinces. Three major factors possibly contribute to this phenomenon: (a) the rapid economic growth in recent years motivates the increase of new urban residents and new urban residential communities in these regions; (b) the second-moved provinces are able to learn the urban planning experience in preparation for parking space issues; and (c) the cheaper land prices in these second-movers generate less economic pressure on building parking lots in the populated urban areas.

Home parking availabilities are also different among the area types. The home parking availabilities in the Tier 2 areas are generally smaller than they are in Tier 1 and Tier 3 areas. As shown in Table 6, the average national home parking availability is respectively 46.2% in Tier 1 and 43.6% in Tier 3; however, is 38.6% in Tier 2 area in 2015. There are three possible reasons: (a) the car owner population density in Tier 2 is smaller than it is in the Tier 1 urban areas (Wu et al., 2012); (b) compared to the experienced urban planners in Tier1, the urban planners in Tier 2 might have insufficient consideration to parking issues when designing residential communities in early years; and (c) Tier 3 areas with their second-mover advantage and inexpensive land prices make higher parking availabilities compared to Tier 2. Nevertheless, the disparity among area types will decrease as the time goes by, as shown in Table 6.

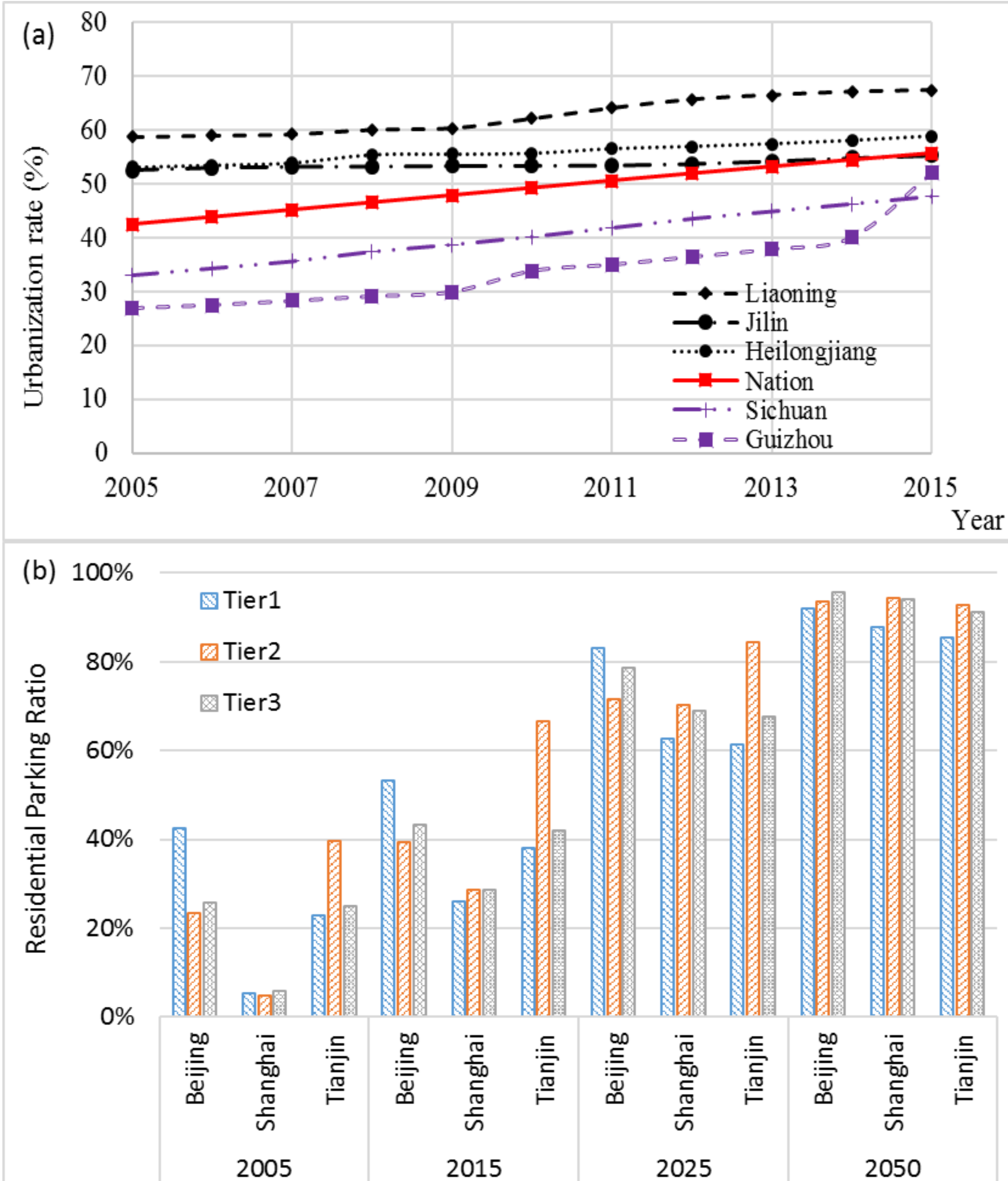

Fig. 5. (a) The urbanization rates by province (National Bureau of Statistics of China, 2017; The World Bank, 2015); and (b) the home parking availabilities in metropolitan cities (Beijing, Shanghai, and Tianjin).

4.3. Impacts of home parking availabilities on PEV ownership costs

As shown in Fig. 6(a), the quantifiable shadow value of the home parking on PEV ownership are estimated. The mean value ranges from $2,376 to $10,687 USD, which will be a considerable factor deciding the consumer preferences in the PEV market. For example, the highest mean value of home parking is $10,687 USD for the BEV-150 sedan in the model, since the BEV-150 sedan owners have to look for vehicle charging more frequently if they have no home parking spaces for home-charging. Meanwhile, the sales-weighted MSRP (Manufacturer Suggested Retail Price) of a BEV-150 sedan is $17,248 USD in China in 2015 (CATARC, 2018), which is approximately $7,000 USD more than the shadow value of the home parking. Considering the central government subsidy to BEV-150 sedan at $6,935 USD in 2015, the shadow value from the home parking to the BEV-150 sedan is almost the same as their actual purchase price in the estimation.

In the BEV segment, the impacts of the home parking on ownership costs are decided by two determinants: BEV's AER; and BEV's total electricity consumption. In general, the dependence of the home parking gradually declines as AER increase, however, the BEV's total electricity consumption becomes the major factor in the value of home parking when AER is large enough. As shown in Fig. 6(a), the BEV-400 sedan owners have to suffer more electricity cost with larger total electricity consumption, thus the lowest shadow value of the home parking at $4,973 USD is from BEV-350 sedan instead of BEV-400 sedan.

In the PHEV segment, however, the shadow values affected by the home parking increase only with the growth of AER. This is because the PHEV drivers have to run their PHEVs in charge-sustaining mode when they have no home parking; A larger AER indicates a larger shadow value. The mean value of home parking to a PHEV owner is at least $2,376 USD in 2015 according to the simulation results.

The incremental shadow values impacted by the home parking on vehicle ownership in China's PEV market vary along with the availability changes of home parking and PEV ownership. Huo et al. project that the stock of the individually-owned light-duty vehicles in China will range from 251.7 to 289.3 million by 2025 (Huo and Wang, 2012). Referring to the *Technology Roadmap for Energy Saving and New Energy Vehicles*, the PEV sales share is expected by the Chinese government to be 15% in 2025 and over 40% in 2030, the annual sales of PEVs are expected to be 2 million and the PEV stock is to be 5 million by 2020 (The Strategic Advisory Committee and SAE-China, 2016). Accordingly, the study assumes the PEV share of total vehicle stock to be 2%-7% by 2025. Comparing to the benchmark of year 2015, the incremental shadow values impacted by the home parking on vehicle ownership in the Chinese PEV market are calculated in Eqn. (18). If the external conditions of workplace and public-charging remain the same as they are in 2015, the incremental shadow values impacted by the home parking on vehicle ownership could reach over $2.51 billion USD in the PEV market by 2025, with 90% possibility ranging between $6.86 billion and $26.53 billion USD, as shown in Fig. 6(b). Therefore, along with the growth of home parking spaces and the PEV home-charging accessibility, home parking availability impacts PEV ownership costs becomes increasingly critical to consumer decisions to purchase PEVs. Notably, as the development of PEV technology, the AERs in PEVs and the fuel economies are expected to become better. All these changes are likely to reduce the shadow values. However, the improvement of AER only is hardly to completely eliminate the shadow values impacted by the home parking in a foreseeable future.

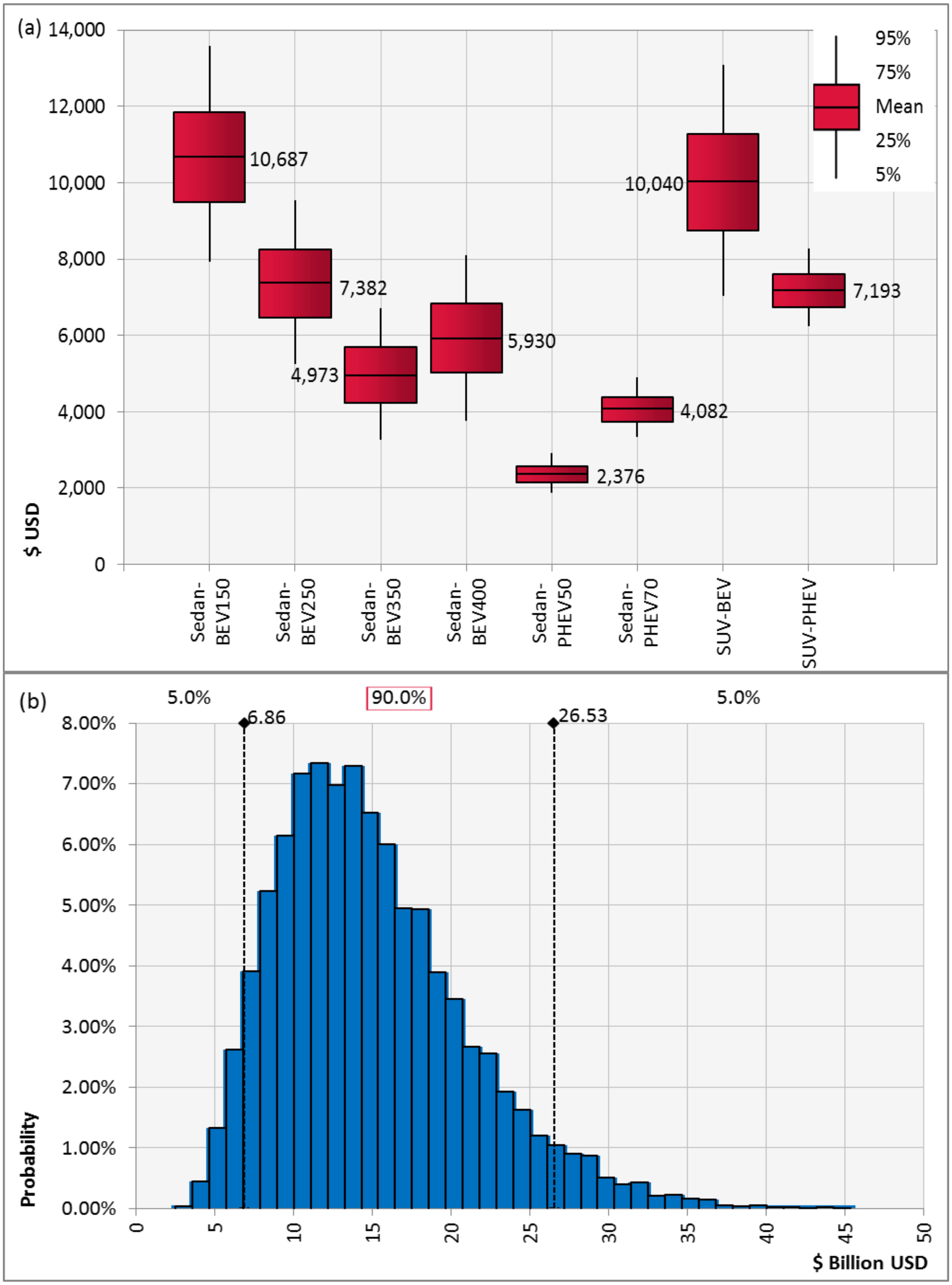

Fig. 6. (a) The shadow values of home parking by vehicle type for PEV owners who have no home parking places in 2015; and (b) the estimated incremental shadow values of home parking on vehicle ownership in Chinese PEV market in 2025.

5. Conclusions and Future Work

The objective of this paper is to quantify the effects of home-parking availability improvement over time on PEV ownership. Toward this, we estimate the home parking availabilities by province and by urban area type in China, project such availabilities in the long run, and construct a method to estimate the potential economic shadow value of home parking on PEV ownership.

The findings of the study may contribute insights to the understanding of: 1) current and future status of the home parking availability in China, 2) allocation of resources for public charging or home parking/charging under certain projections of home parking improvements, 3) future PEV incentive needs and policies in light of projected home parking improvements, and 4) the potential effect on PEV ownership of land use policies that could significant divert the baseline projection of home parking improvement.

The home parking availabilities in 31 provinces by three urban area types in China from 2005 to 2050 are estimated, and the shadow values created by the home parking growth on PEV ownership are calculated. The raw data were achieved by data mining from the estate trading websites and used for calculating the home parking availability by considering the house lift expectancy and urbanization, which are shown in Section 3. The results show that the home parking availabilities vary within provinces and within area types. Our qualitative analysis suggests that parking availabilities across cities and provinces are correlated with the economic level, urbanization rate, motorization and urban planning. The less developed areas have the second-mover advantage in the development of the residential parking lots. By quantifying the PEV recharging inconvenience for drivers without residential parking spaces, this study constructs a methodology to estimate the shadow value of the home parking availabilities to the PEV ownership. It shows that the mean value of a home parking space with a range from $2,376 USD to $10,687 USD, with the upper bound close to the subsidized price of some PEV models. The total incremental shadow values of the home parking are estimated to be over $2.51 billion USD in 2025, representing a significant co-benefit of the projected home parking improvement for the PEV market. Overall, it is concluded that the home parking availability is an important factor affecting PEV market penetration.

The methodological contribution of this study is the development of a method to quantify the shadow value of home charging availability. The method is considered coherent and seems to produce logical results: by investigating the driving patterns and use costs of home-charging, workplace charging and public charging in China, the shadow value was estimated by PEV AER and shown in Fig 6. Apparently, the different shadow values by AER can affect consumer choices between PHEVs and BEVs, among different AERs, and even between PEVs and gasoline conventional vehicles. Thus, the better estimate of the aggregate impact of home charging available should be conducted by linking the above method dynamically with a consumer choice model, which has been considered for our future research.

The empirical contributions of this study include characterization and projection of Chinese home parking availability with regional heterogeneity and the found significance of the home parking value for PEV owners. Desirable improvements for future studies include more scenario analysis with respect to land use constraints, urbanization process, PEV policies and PEV technological progress.

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