Optimal range of plug-in electric vehicles in Beijing and Shanghai

Yan Xing, Alan T. Jenn, Yunshi Wang, Chunyan Li, Shengyang Sun, Xiaohua Ding & Siwen Deng

Mitigation and Adaptation Strategies for Global Change
An International Journal Devoted to Scientific, Engineering, Socio-Economic and Policy Responses to Environmental Change

ISSN 1381-2386

Mitig Adapt Strateg Glob Change
DOI 10.1007/s11027-020-09912-7

Springer

Mitigation and Adaptation Strategies for Global Change
https://doi.org/10.1007/s11027-020-09912-7

ORIGINAL ARTICLE

Optimal range of plug-in electric vehicles in Beijing and Shanghai

Yan Xing, et al. *[full author details at the end of the article]*

Received: 29 April 2019 / Accepted: 10 January 2020/[redacted]

Abstract

Both China's national subsidy policies for plug-in electric vehicles (PEVs) purchasers and passenger cars corporate average fuel consumption and new vehicle credit regulation (dual-credit policy) favor long-range 300+ km battery electric vehicles (BEVs) and 80+ km plug-in hybrid electric vehicles (PHEVs). However, these electric vehicles tend to have lower energy efficiency and higher purchase and operation costs. Vehicle with larger batteries can also be less equitable because the subsidies are often provided to more expensive vehicles and wealthier owners. This study takes advantage of a novel dataset of daily driving data from 39,854 conventional gasoline vehicles in Beijing and 4999 PHEVs in Shanghai to determine the optimal range of BEVs and PHEVs within their respective cities. We simulate a model to explore ranges with which PEVs emit less GHGs than that of a baseline hybrid and conventional gasoline vehicle while ensuring that all daily travel demands are met. Our findings indicate that in both cities, the optimal ranges to balance cost and travel demand for BEVs are 350 km or less and for PHEVs are 60 km or less in Beijing and 80 km or less in Shanghai. We also find that to minimize carbon dioxide (CO_2) emissions, the ranges are even lower 10 km in Beijing and 30 km in Shanghai. Our study suggests that instead of encouraging long-range PEVs, governments should subsidize PEV models with shorter ranges. Parallel efforts should also be made to both increase renewable energy over fossil fuels and expand charging facilities. Although individual mobility demand varies, the government could reduce occasional long-distance driving by subsidizing alternative transportation choices. Providing week-long driving trials to consumers before their purchases may help decrease the demand of very long range PEVs by alleviating the range anxiety through a learning process.

Keywords China's national subsidy policy · Plug-in electric vehicles · Optimal range · Travel demand · Carbon emission reduction

1 Introduction

Plug-in vehicles (PEVs) are promoted worldwide as an important solution to mitigate climate change in the transportation sector. One major barrier to their adoption is related to concerns

---

SI: PEV technology and market assessment for the United States and China regarding the battery ranges of battery electric vehicles (BEVs) compared to the range achievable by conventional internal combustion engine (ICE) vehicles. However, it is possible that longer range batteries have the potential to achieve greater electrification of vehicles miles traveled (VMT) (Tal et al. 2014). Both China's national subsidy policies for PEV purchasers and passenger cars corporate average fuel consumption and new energy vehicle credit regulation (dual-credit policy) favor long-range PEVs (300 km BEVs and 80 km PHEVs). As shown in Table 1, the subsidies for BEVs with a range of less than 300 km have been continuously reduced or entirely eliminated while for those greater than 300 km have been increased. Moreover, the dual-credit policy, which is similar to a combination of the United States (US) Corporate Average Fuel Economy (CAFE) standards and the US state of California's Zero Emission Vehicle (ZEV) regulations provides additional credits to BEVs with longer ranges.

Meanwhile, China's subsidy policy also favors longer range plug-in hybrid electric vehicles (PHEVs), which can drive using either electricity (charge depleting mode, CD) or gasoline (charge sustaining mode, CS). Longer-range PHEVs are subsidized without any fuel efficiency requirement, while a high level of fuel efficiency is required for PHEVs with a range less than 80 km. For these shorter range PHEVs, the full amount of subsidy is only awarded after the fuel consumption in CS mode is proven to be less than 60% of that of a gasoline car with the same curb weight.

In response to the subsidy policy, the market shares of both long-range BEVs and PHEVs have increased rapidly in the Chinese market. According to the China Ministry of Industry and Information Technology (MIIT) monthly catalogs of Recommended PEV Models (vehicles which are eligible for subsidies), nearly 80% of new BEV models had an electric-range longer than 300 km (Fig. 1) and about one-third of the PHEV models in the catalogs had a range of at least 80 km at the end of October 2018.

Since vehicle range can be boosted simply by adding low energy density batteries into a vehicle, the government required additional improvements in battery energy density: no subsidies are provided to PEVs with an energy density less than 105 Wh/kg (watt-hour per kilogram). Furthermore, a vehicle with an energy density between 105 and 120 Wh/kg received 40% less subsidies while batteries with an energy density above 120 Wh/kg received 20% more in subsidies. Unfortunately, larger battery packs that enable longer ranges are considerably heavier and thus decrease the energy efficiency of the vehicle. Since the battery pack is the heaviest and most expensive component of a PEV, if it is not fully utilized during operation, it is a waste of energy and money to employ a heavier battery than is necessary. The importance of vehicle curb weight in

Table 1 China nationa wide subsidies for PEVs since 2013

	Range (km)	2013	2014	2015	Range (km)	2016	2017	After June 11, 2018	Increase (%)
BEV	$80 \le R < 150$	3.5	3.33	3.15	$100 \le R < 150$	2.5	2		
	$150 \le R < 250$	5	4.75	4.5	$150 \le R < 200$	4.5	3.6	1.5	− 58%
	$250 \le R$	6	5.7	5.4	$200 \le R < 250$	5.5	3.6	2.4	− 33%
					$250 \le R < 300$		4.4	3.4	− 23%
					$300 \le R < 400$		4.4	4.5	+ 2%
					$R \ge 400$		4.4	5	+ 14%
PHEV/REEV	$50 \le R$	3.5	3.33	3.15	$50 \le R$	3	2.4	2.2	− 8%

Unit: 10,000 Yuan

Source: Notice of adjusting and improving the financial subsidies policy for the promotion and application of new energy vehicles, published by the Ministry of Finance, the Ministry of Industry and Information Technology, and the Ministry of Science of Technology on February 13, 2018. https://www.d1ev.com/news/zhengce/62776

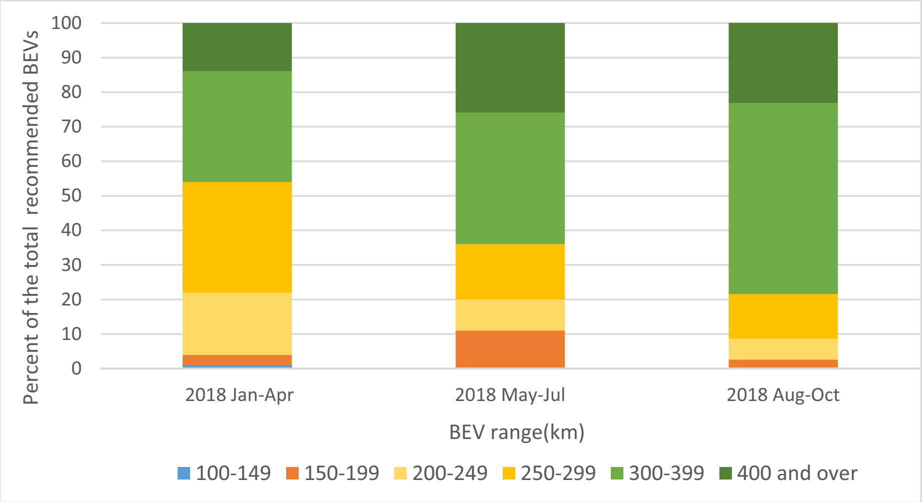

Fig. 1 Shares of the BEV models by range in the first 10 months in 2018 by the China MIIT. Source: 470 BEV data were collected from the monthly catalogs of recommended BEV models by the MIIT from January through October in 2018.

energy consumption has been studied in previous research: a 10% reduction in vehicle weight reduces fuel consumption by about 7% (Cheah 2010). Since consumers face a higher price premium for longer ranges, social equity becomes an issue since more subsidies are provided to higher priced, longer-range PEVs which are generally purchased by wealthier individuals. Therefore, it is critical to find a range for PEVs that not only benefits the environment and society, but also helps the Chinese government make better decisions regarding their subsidy policies.

Several studies have already explored the carbon emission mitigation potential and the optimal electric ranges of PEVs. Plötz et al. (Plötz et al. 2017) conducted research on the greenhouse gas mitigation of PEVs from real-world operating data in the US and German and found that PHEVs lead to higher carbon emission reductions than BEVs. Lin optimized BEV ranges for heterogeneous US drivers and suggests that unless battery costs are reduced to below $100/kWh, over half of US drivers would want BEVs with a range of less than 100 mile in the US (Lin 2014). Pearre et al. (Pearre et al. 2011) employed the daily driving patterns of 484 ICE vehicles in the US to infer the range requirements of BEVs. They found that a limited-range (e.g., a 100-mile range) BEV would meet daily travel demands if drivers made some adaptations such as recharging during the day, borrowing a gasoline vehicle for longer trips, or grouping errands. Suggestions of optimal range of PHEVs have also been proposed in previous literature. For example, according to Shiau and Michalek, the minimum greenhouse gas emissions (GHGs) are achieved with a mix of PHEVs sized for 25–45 miles (40–72 km) of electric travel (Shiau and Michalek 2010). An electric range of 16 miles (25.6 km) of PHEVs for commuters was determined to minimize the social cost of the technology (Kontou et al. 2015). Another study showed that the optimal PHEV electric range should be approximately two thirds of a typical daily driving distance, which minimizes the costs of the battery, gasoline and electricity fuel costs, and the hassle of refueling for US drivers (Lin 2012). These studies provide a foundation for the methods employed in this paper, where we obtain optimal ranges of PEVs that minimize the cost of ownership along with costs from externalities such as carbon emissions.

Several studies focusing on PEVs in China have explored relationships among different ranges of PEVs, energy consumption, and carbon emissions. For instance, in one study, Yuan et al. (Yuan et al. 2015) analyzed the impacts of driving patterns (e.g., speed and frequency of stops) and found that BEVs with ranges shorter than 250 km in China achieved climate benefits. However, the influence of travel demand was neglected (Yuan et al. 2015). Another study argues that a battery size of 20 kWh is optimal for PHEVs in Shanghai to minimize the total cost, but this result was based on operating data from a limited sample size of only 50 PHEVs (Xia et al. 2018). Our study builds on the idea that a PEV will meet daily travel demand with less energy consumption and carbon emissions than that of a hybrid vehicle or a conventional gasoline vehicle. The purpose of this study is to provide a reference for policy makers to make appropriate decisions regarding the subsidies and credit policies for PEVs based on their electric range.

2 Data

2.1 Active daily travel data in Beijing and Shanghai

Although census data provides an overview of China's nationwide or citywide transportation system (average vehicle kilometers traveled (VKT), mode share, and average number of daily trips), details regarding the distribution of vehicle travel are still lacking. We employ a novel real-time, large-scale data in this study collected through on-board diagnostic (OBD) devices. In Beijing, 39,854 gasoline vehicles were randomly chosen to install data loggers. The daily travel information of these vehicles from May 1, 2017 through April 30, 2018 were collected and analyzed. Similarly, 4999 PHEVs were selected randomly from the total PHEV population in Shanghai. The daily travel data of these vehicles from January 1, 2017 through December, 31, 2017 was provided by Shanghai Electric Vehicle Public Data Collecting, Monitoring and Research Center. The daily vehicle kilometers traveled (VKT) by each vehicle was recorded in both samples. The real-time data of Beijing records a total of 7,447,360 days of daily travel of 39,854 ICE vehicles and the Shanghai data includes 991,447 days of daily travel of 4999 PHEVs. Daily VKT of each vehicle during weekdays, weekends, and holidays was categorized in each sample according to the recorded date when trips were made that day. Note that in China, some weekend days are shifted to workdays to make long continuous holidays, e.g., people were required to work at weekends of January 22 and February 4 due to a 7-day public holiday of Chinese New Year from January 27 through February 2, 2017. The real-time data of Beijing includes a total of 7,447,360 days of daily travel distances made by 39,854 ICEs and Shanghai data includes 991,447 days of daily travel by 4999 PHEVs (Table 2).

2.1.1 Average daily VKT distribution of Beijing vehicles

The average daily VKT distributions during weekdays, weekends, and holidays of 39,854 ICE vehicles in Beijing are presented in Fig. 2. We find that the daily travel distribution does not

Table 2 Summary of daily VKT of the sample vehicles by city

AVKT (km) (standard deviation)	Weekdays	Weekends	Holidays	Average	Number of vehicles	Total driving days
Beijing	57.48 (400.27)	61.44 (83.13)	81.60 (128.04)	60.17 (334.48)	39,854	7,447,360
Shanghai	60.61 (72.17)	62.42 (75.32)	78.13 (108.76)	62.06 (75.65)	4999	991,447

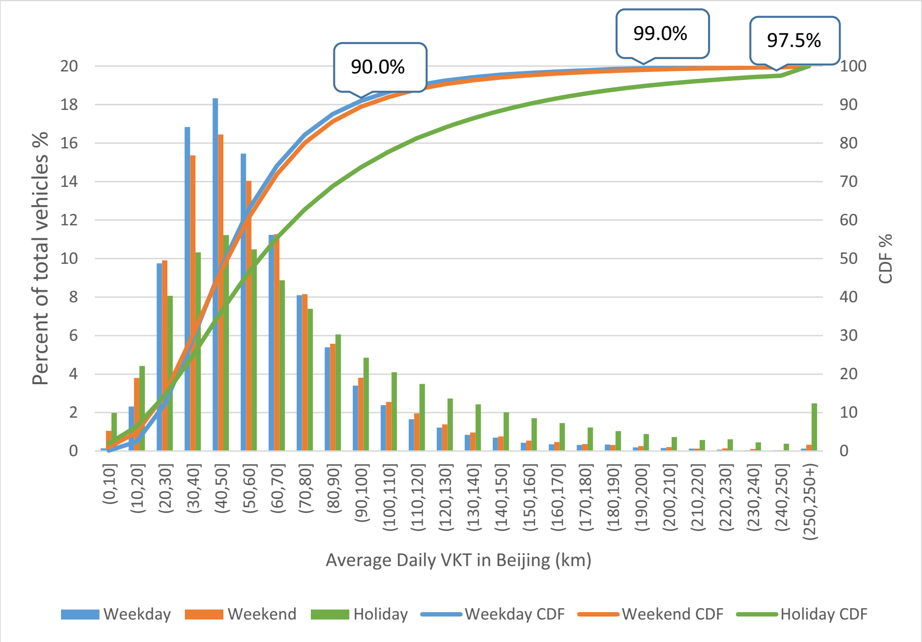

Fig. 2 Average daily VKT distribution and cumulative distribution of the vehicles in Beijing. Ninety percent of the population drive less than 100 km/day and 99% of the population drive less than 200 km/day. However, 2.5% of people drive more than 250 km/day during holidays

differ much during weekdays and weekends. However, the distribution of longer trips differed substantially during holidays compared to weekdays and weekends. The highest percentage of people in Beijing travel 40 to 50 km every day during weekdays, weekends, and holidays. The red dots on the cumulative density function (CDF) curve in the figure show that about 90% of people travel no longer than 100 km every day. Additionally, more than 99% of people's average daily VKT is shorter than 200 km. However, about 2.5% people's daily trips are longer than 250 km during holidays.

2.1.2 Average daily VKT distribution of Shanghai vehicles

The average daily VKT distributions during weekdays, weekends, and holidays of 4999 PHEVs in Shanghai are shown in Fig. 3. Similarly, while the weekday and weekend travel distributions do not differ substantially, people tend to travel longer distances during holidays. During weekdays, 90% of the total drivers travel less than 110 km; more than 99% of the total drivers have an average daily VKT shorter than 210 km; only 0.8% of drivers record their daily trips longer than 250 km during holidays.

Compared to Beijing, Shanghai drivers travel longer distances during weekdays and weekends but shorter distances over the holidays. Because most trips on weekdays are for work, this difference may be explained by longer commutes in Shanghai compared to Beijing. Although more Beijing drivers travel for short or medium commuting trips, a greater percentage of people in Beijing drive longer than 250 km in holidays, which aligns with a recent finding that most long-distance intercity travel during the weeklong spring festival of 2019 were made by Beijing citizens (National Big Data Aliance of New Energy Vehicles 2019). It is

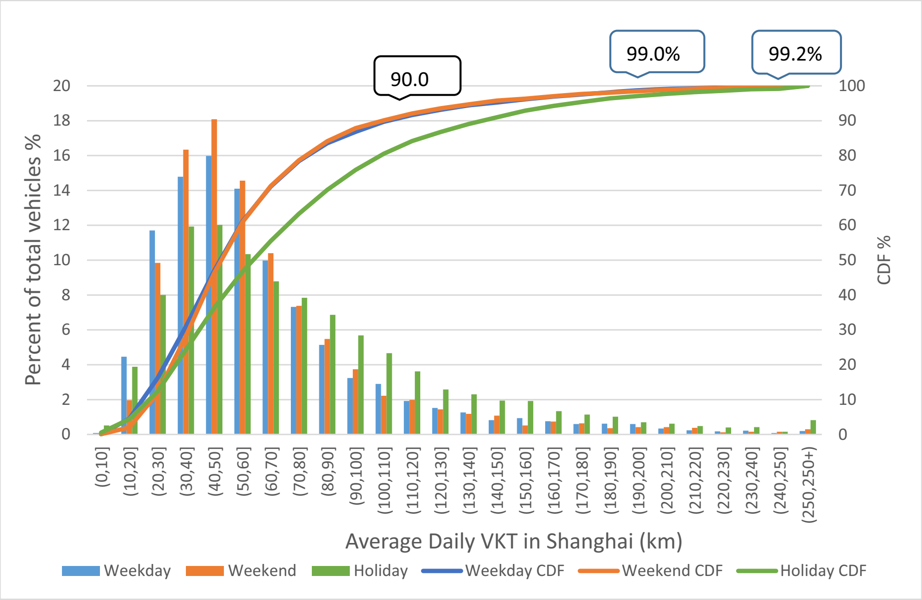

Fig. 3 Average daily VKT distribution and cumulative distribution of the vehicles in Shanghai. Ninety percent of the population drives less than 110 km/day and 99% of the population drives less than 210 km/day. Only 0.8% of drivers exceed 250 km/day during holidays

also possible that the percentage of Beijing natives is smaller than that of Shanghai, thereby more Beijing immigrants drive long distances back for family gathering during holidays. It is also possibly associated with different local culture that Beijing people are more inclined to long-distance travel.

2.2 Attributes of best-selling PEVs in China market

The data for this analysis also includes attributes of 50 of the best-selling BEVs and 40 of the best-selling PHEVs in the Chinese 2018 PEV market (China Passenger Car Association 2018). We collected the data from the monthly catalogs of recommended PEVs published by the MIIT. Because the attributes of some models were missing, the final dataset contains 45 BEV models and 34 PHEV models. The sales of these models account for about 91% of the total sales of BEVs and 88% of PHEVs in 2018 market, respectively. The vehicle attributes include the PEV model names, electricity consumption rate (in CD mode for PHEVs), and gasoline consumption rate in CS mode for PHEVs, and electric range. The summary of these attributes is displayed in Table 3. We assume that the PHEVs chosen by consumers represent the current level of energy efficiency of PEVs in China market.

3 Methods

For BEVs, this study aims to optimize ranges by minimizing GHGs while satisfying the constraint of travel demand obtained from empirical travel data in Beijing and Shanghai. However, for PHEVs (which lack a range constraint) the optimal ranges are determined by

Table 3 Attributes of best-selling PEVs in 2018 China market

		Minimum	Maximum	Mean	Std. deviation
BEV	Electricity consumption rate (kWh/km)	0.10	0.21	0.14	0.02
	Range (km)	150	450	296.31	80.38
	N	45			
PHEV	Gasoline consumption rate (l/km)	0.04	0.08	0.06	0.01
	Electricity consumption rate (kWh/km)	0.16	0.24	0.20	0.03
	Range (km)	50	100	67.05	14.77
	N	34			

reaching a battery size where the PHEV emits less GHGs than that of an equivalent hybrid vehicle or a gasoline vehicle that meets the 2020 the Corporate Average Fuel Consumption (CAFC) target. Below, we first introduce our calculation of utility factors for PHEVs and method of calculating GHGs. We then describe our method of minimizing GHGs from PEVs.

3.1 PHEV Utility factor

The utility factor (UF) of PHEVs is defined by the Society of Automotive Engineers (SAE) J1711 as the ratio of the electric distance traveled to the total distance traveled by a specific vehicle in 1 day, and later developed by SAE J2841 as the average of a fleet of vehicles' UFs (SAE, 1999, 2009). In the United States, the standard UF is calculated by employing the daily travel data of the US light duty vehicle fleet, as captured by the 2001 National Household Transportation Survey (NHTS). This UF is calculated to measure the performance of PHEV fleets. It reflects the statistical probability of the average US PHEV fleet driven less than, or equal to, its electric range during a given driving day.

We adopt the standard method of the SAE J2841 to calculate the utility factors in the two cities but provide an improvement in the travel behavior data by employing longitudinal one-year real-time daily travel data in Beijing and Shanghai. Equation (1) describes our calculation for the aggregate average UF in each city over 365 days following the method demonstrated by Wu et al. (Wu et al. 2015). Note that the content of the UFs for PHEV fleets was expanded to include both PHEVs and BEVs. For BEVs, the value of the UF is always equal to 1.

$$\text{UF distance (RCD)} = \frac{\sum_{i=1}^{N} min(d_i, R_{CD})}{\sum_{i=1}^{N} d_i} \tag{1}$$

Where:

R_{CD} is the e-range in km of a BEV or a PHEV in CD mode;
d_i is the daily travel distance of the ith day;
N is the number of recorded travel days;

3.2 Greenhouse gas emission calculation

Following the method of UF calculation, we assume that:

(1) All vehicles start their trips with fully charged batteries and are only charged once during the day
(2) Every PHEV is powered by electricity first and then by gasoline after the battery is fully depleted
(3) The energy consumption of a blended PHEV drivetrain, i.e., gasoline, is used to supplement battery or electric motor power in CD mode, is neglected in this study
(4) Heterogeneous charging behavior and charging infrastructure deployment in the cities were not considered in this study due to the lack of data.

The daily GHGs of a single BEV or a PHEV can be calculated as

$$q_{i\ CO_2}(\mathrm{R}_{CD}) = u_i(R_{CD}) \cdot d_i \cdot \gamma_{e,CD} \cdot \delta_{e\ CO_2} + (1 - u_i(R_{CD})) \cdot d_i \cdot \gamma_{g,CS} \cdot \delta_{g\ CO_2} \tag{2}$$

Where:

$q_{i\ CO_2}$	indicates the GHGs of a PEV in day i;
u_i ($\mathrm{R_{CD}}$)	is the UF of the *i*th day calculated from formula (1), equals to 1 for BEVs;
R_{CD}	is the electric range in km of the BEV/PHEV in CD mode;
$\gamma_{e,\ CD}$	is the electric efficiency (kWh/km) of the BEV/PHEV in CD mode;
$\gamma_{g,\ CS}$	is the gasoline efficiency (L/km) of the PHEV in CS mode;
$\delta_{e\ CO_2}$	is the electricity carbon-dioxide-equivalent GHG emission factor in kg/kWh;
$\delta_{g\ CO_2}$	is the gasoline carbon-dioxide-equivalent GHG emission factor in kg/l.

The corresponding total amount of GHGs (Q) was calculated following the formula below:

$$\mathrm{Q}\ (\mathrm{R}_{CD}) = \sum_{n=1}^{N} q_{i\ CO_2}(\mathrm{R}_{CD}) \tag{3}$$

We employ a life-cycle analysis (LCA) CO_2 equivalent emission factor for gasoline at the national level of 2.95 kg CO_2-eq/l of gasoline (Wang 2017). We assume an LCA grid emission factor (which includes both upstream and emissions associated with fuel production) at the provincial level for Shanghai of 0.564 kg CO_2-eq/kWh and for Beijing of 0.617 kg CO_2-eq/kWh (National Center for Climate Change Strategy and International Cooperation 2016). These parameters were used as constants to calculate the CO_2 emissions of the PEVs in this study.

3.3 Optimal ranges of PEVs

We assume that a PEV is required to both meet its daily travel demand and emit less carbon emissions than that of equivalent hybrid or a gasoline vehicle in order to reach a carbon emissions reduction goal. Our baseline gasoline vehicle is a CAFC compliance model that meets the 2020 passenger car fleet efficiency target with an average fuel economy of 5 l/100 km (Ministry of Industry and Information Technology 2015). Additionally, a more fuel-efficient hybrid model operating with a fuel efficiency of 4.65 l/100 km, which represents current hybrid technology in China market, serves as another more stringent baseline. The fuel efficiency of this hybrid model is derived from two representative hybrid models: the Toyota Prius and Kia Niro hybrid, both of which are among the most fuel efficient hybrids by size.

The former is a mid-size car with the fuel efficiency of 4.3 l/100 km, the latter is a Sport utility vehicle (SUV) with a fuel-efficiency of 4.9 l/100 km as reported by the MIIT. We weighted the Kia Niro 58.1% and the Toyota Prius 41.9% in order to mirror the fleet mix of the 34 best-selling PHEVs for a fair comparison.

For BEVs, the estimation of GHGs is based on the formula (2). Because $u_i(R_{CD})$ equals to 1 for BEVs, formula (2) can be rewritten as follows. This formula shows that the GHGs of a BEV are determined by its daily travel distance, vehicle energy consumption rate, and local electricity carbon-dioxide-equivalent GHG emission factor.

$$q_{i\ CO_2}(\mathrm{R}_{CD}) = d_i \cdot \gamma_{e,CD} \cdot \delta_{e\ CO_2} \tag{4}$$

To ensure that the GHGs of an EV model do not exceed than the baseline model, we create a requirement as follows:

$$\begin{gathered} q_{i\ CO_2}(\mathrm{R}_{CD}) = d_i \cdot \gamma_{e,CD} \cdot \delta_{e\ CO_2} \le q_{i\ CO_2}(\text{Baseline model}) = d_i \cdot \gamma_{g,Baseline\ model} \cdot \delta_{g\ CO_2}, \\ \text{So} : \gamma_{e,CD} \le \gamma_{g,Baseline\ model} \cdot \frac{\delta_{e\ CO_2}}{\delta_{e\ CO_2}} \\ \text{Let}\ \frac{\delta_{e\ CO_2}}{\delta_{e\ CO_2}} = C_0, \text{then}\ \gamma_{e,CD} \le \gamma_{g,Baseline\ model} \cdot C_0 \end{gathered} \tag{5}$$

where C_0 is the ratio of gasoline equivalent CO_2 emission factor to electricity equivalent CO_2 emission factor, we refer to this as the gasoline-electricity ratio. The formula (5) indicates that the electric consumption rates of BEVs needs to be smaller than the product of the gasoline consumption rate of the baseline model and the gasoline-electricity ratio, i.e., $\gamma_{g,\ Baseline\ model} \cdot C_0$, to guarantee a smaller amount of GHG emissions than that of the baseline model.

To find the optimal range of BEVs that benefits the environment and climate, we employ a linear regression of electricity consumption on vehicle electric range. The data of the best-selling BEVs in the 2018 market was collected to explore the relationship between the vehicle electricity consumption rate and electric range. The electric range of the vehicle proxies for both the size and weight of the battery, for which there is a lack of information in the Chinese market. Since the range is increased at higher battery capacities, which lead to greater battery mass, we know that battery weight and range are highly correlated (Berjoza and Jurgena 2017). The relationship between the electricity consumption rate and the vehicle electric range is expressed as follows:

$$\gamma_{e,CD}(\mathrm{R}) = \underset{(p=0.000)}{0.0903} + \underset{(p=0.000)}{0.0002^{*}\,\mathrm{R}_{CD}} \tag{6}$$

We find that a 100-km increase in vehicle electric range leads to an electricity consumption increase of 0.02 kWh/km. Furthermore, the GHGs of BEVs can be calculated with the following formula:

$$q_{i\ CO_2}(\mathrm{R}_{CD}) = d_i \cdot (0.0903 + 0.0002{*}\mathrm{R}_{CD}) \cdot \delta_{e\ CO_2} \tag{7}$$

This indicates that the electricity consumption rate of EVs increases with greater electric range, as does the amount of GHGs. Our results imply that while longer-range BEVs may relieve range anxiety, they are not necessarily better for environment. To find the optimal electric range, the function of electricity consumption rate of R was then combined with eq. (5):

$$\mathrm{R}_{CD} \leq \frac{\gamma_{g,Baseline\ model} \cdot C_0 - 0.0903}{0.0002} \tag{8}$$

Equation (8) reveals that the optimal ranges are determined by fuel efficiency of the baseline model and the emissions from the local electricity grid. The higher the fuel efficiency (better fuel efficiency) of the baseline model and carbon intensity of the local grid (dirtier gird) are, the shorter the ranges of BEVs are needed to be cleaner than the baseline model.

For PHEVs, we modify eq. (2) and assume that both the electricity consumption rate in CD mode, $\gamma_{e,\ CD}$, and the gasoline consumption rate, $\gamma_{g,\ CS}$, are functions of the electric range R_{CD}.

$$q_{i\ CO_2}(\mathrm{R}_{CD}) = u_i(R_{CD}) \cdot d_i \cdot \gamma_{e,CD}(\mathrm{R}_{CD}) \cdot \delta_{e\ CO_2} + (1 - u_i(R_{CD})) \cdot d_i \cdot \gamma_{g,CS}(\mathrm{R}_{CD}) \cdot \delta_{g\ CO_2} \tag{9}$$

Again, to simplify the question, we employed linear regressions to explore the relationship between the two energy consumption rates and the electric range respectively. Based on the data of the best-selling PHEVs in China 2018 PEV market, both the electricity and gasoline consumption rates are explained by the electric range. The two final linear models are expressed as follows:

$$\gamma_{e,CD}(\mathrm{R}_{CD}) = \underset{p=0.000}{0.137} + \underset{\substack{p=0.034 \\ R^2=0.198}}{0.001^{*}\mathrm{R}_{CD}}$$

$$\gamma_{g,CS}(\mathrm{R}_{CD}) = \underset{p=0.000}{0.043} + \underset{\substack{p=0.055 \\ R^2=0.121}}{0.0002^{*}\mathrm{R}_{CD}}$$

Two scenarios were considered in order to calculate the GHGs of a PHEV. Under the first scenario, the daily kilometers traveled by a PHEV is equal to or shorter than its electric range, i.e., $d_i \leq R_{CD}$. Then, the amount of GHGs is calculated as below,

$$q_{i\ CO_2}(\mathrm{R}_{CD}) = d_i \cdot \gamma_{e,CD}(\mathrm{R}_{CD}) \cdot \delta_{e\ CO_2}$$

Combined with the function of electricity consumption rate of range, the amount of GHGs monotonically increases as R_{CD} increases within the range of travel distance from 0 to R km.

$$q_{i\ CO_2}(\mathrm{R}_{CD}) = d_i \cdot (0.137 + 0.001{*}\mathrm{R}_{CD}) \cdot \delta_{e\ CO_2} \tag{10}$$

Under the second scenario, the daily kilometers traveled by a PHEV is longer than its electric range, i.e., $d_i > R_{CD}$. Assuming that a driver drives the PHEV in CD mode first and after the electricity is fully depleted, the driver keeps driving in CS mode. Then, the amount of GHGs is

$$q_{i\ CO_2}(\mathrm{R}_{CD}) = \mathrm{R}_{CD} \cdot \gamma_{e,CD}(\mathrm{R}_{CD}) \cdot \delta_{e\ CO_2} + (d_i - \mathrm{R}_{CD}) \cdot \gamma_{g,CS} \cdot \delta_{g\ CO_2}$$

Finally, combining the two functions of electricity and gasoline consumption rate, the GHGs of a PHEV can be calculated as

$$q_{i\ CO_2}(\mathrm{R}_{CD}) = \mathrm{R}_{CD} \cdot (0.137 + 0.001{*}\mathrm{R}_{CD}) \cdot \delta_{e\ CO_2} + (d_i - \mathrm{R}_{CD}) \cdot (0.043 + 0.0002{*}\mathrm{R}_{CD}) \cdot \delta_{g\ CO_2} \quad (11)$$

We employ formulas (10) and (11) to calculate the total GHGs based on the real-time daily travel data.

4 Results

4.1 City utility factor derived from the real-time data

We follow the SAE J2841 method introduced above to calculate the electric utility factors, i.e., the ratio of daily electric distances to the total daily travel distances, of fleets of PHEVs in both Beijing and Shanghai based on the real daily VKT data (Fig. 4). The daily VKT distributions of Beijing and Shanghai reveal that longer daily trips are generated due to a variety of travel demands during holidays and weekends. We find that the values of UF over the holidays are the smallest relative to weekends and weekdays. Additionally, the UFs of PHEVs in Shanghai are greater than those of Beijing, implying a higher fraction of electric kilometers traveled in Shanghai PHEV fleet, likely due to the smaller area of Shanghai. Based on eq. (1), longer electric range PHEVs have a corresponding greater UF. We note that the estimated Beijing UF is smaller than that in a recent study (Zhang and Wang 2014). However, their data includes only 112 *volunteer* passenger cars during the period of June 2012 through March 2013 in Beijing. However, our data is both larger and randomly selected, which likely better represents the population of drivers in the city.

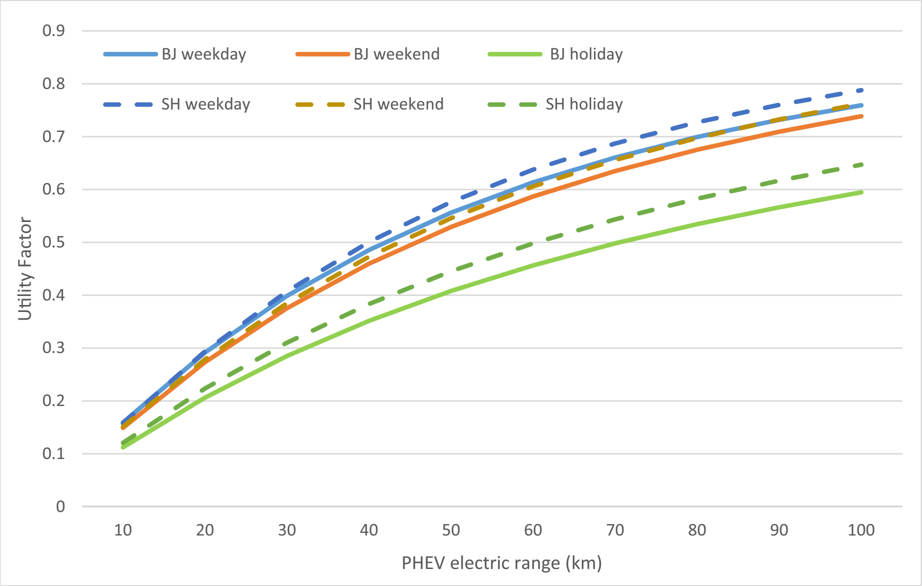

Fig. 4 Utility factors of PHEV derived from real 1-year DVKT data collected in Beijing (BJ) and Shanghai (SH)

4.2 Optimal ranges of BEVs

We establish critical electricity consumption rates (labeled as "Critical Value" in Table 4) of BEVs in different regions which represent the rate in which local BEVs produce less carbon emissions than the baseline 2020 CAFC compliance model. According to formula (5), the electricity consumption rate is decided by a gasoline-electricity ratio, which depends on the carbon intensity of the electricity grid. Table 4 shows some examples of critical values of electricity consumption rates, e.g., 23.9 kWh/100 km in Beijing and 26.2 kWh/100 km in Shanghai, respectively. This means that the energy consumption rate of a BEV needs to be less than 23.9 kWh/100 km in Beijing and 26.2 kWh/100 km in Shanghai to be cleaner than the 2020 CAFC compliance model. If the local electricity grid is dominated by coal, the city's electricity CO_2 equivalent emission factor would be higher, which in turn requires an even smaller electricity consumption rate by BEVs. For example, in Hebei Province, the electricity CO_2 equivalent emission factor is the highest (at 0.903 kg/kWh) among all the provinces in China in 2016 (National Center for Climate Change Strategy and International Cooperation, 2016). An electricity efficiency rate of 16.4 kWh/100 km is required for BEVs in the Hebei province to emit less CO_2 than a 2020 CAFC compliant ICE vehicle. We find that all of the 50 best-selling BEVs in 2018 would be cleaner than the 2020 CAFC baseline model. However, in Hebei Province, about 7% of the best-selling BEVs in China 2018 PEV market would emit more GHGs than the 2020 CAFC compliance model due to the high carbon intensity of its electricity grid.

The optimal range of BEVs must also meet daily travel requirements. The real-time daily travel data in the two cities shows that more than 99% of city dwellers travel no more than 200 km in Beijing and 210 km in Shanghai during weekdays and weekends. We assume that a range of 210 km would satisfy the daily travel demand of the vast majority of drivers in both cities.

According to eq. (8), BEVs with ranges shorter than 845 km in Beijing and 974 km in Shanghai are cleaner than the baseline CAFC compliant vehicle. Even compared to a more fuel efficient hybrid baseline model, BEVs with 750 km or less in Beijing and 880 km or less in Shanghai are cleaner than the average hybrid fleet. Figure 5 compares the average BEV GHG emissions as a function of the range of the vehicle with the baseline CAFC compliant vehicle and the hybrid vehicle based on the real-time daily travel data in the two cities. We find that all the BEVs reduce significantly more GHGs than the average of 2020 passenger vehicles in both Beijing and Shanghai. Because the electricity consumption and GHG emissions rate of BEVs increase with greater electric range, shorter the electric ranges benefit the environment more.

Based on the real-time data, about 90% of individuals' daily travel distances are shorter than 100 km in Beijing and 110 km in Shanghai during weekdays and weekends. Additionally, more than 99% of people travel less than 200 km in Beijing and 210 km in Shanghai,

Table 4 Critical values of BEV electricity consumption rate

City/ province	Electricity grid CO_2 emission factor (kg/kWh)	Gasoline-electricity ratio (C_0)	Critical value (kWh/ 100 km)	Dirty BEVs (%)[a]
Shanghai	0.564	5.23	26.2	0
Beijing	0.617	4.78	23.9	0
Hebei	0.903	3.27	16.4	6.7

[a] BEVs in China's 2018 PEV market that emit more GHGs than the 2020 CAFC compliance model due to high carbon intensity of the local electricity grid

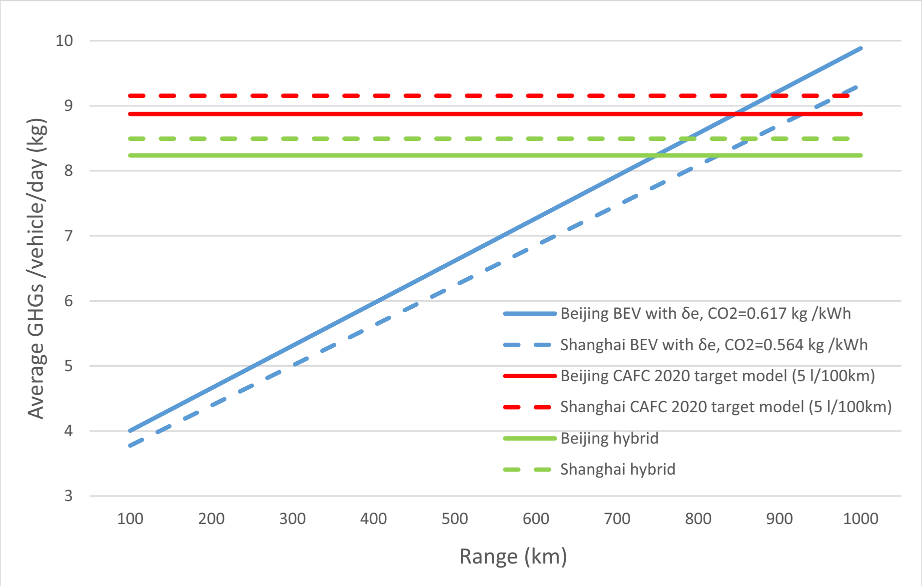

Fig. 5 Average GHGs by BEV models and the baseline models based on real-time daily travel

respectively, during weekdays and weekends. In an ideal situation, a 110 km BEV and a 210 km BEV can meet 90% and 99% of individuals' most daily travel demand, respectively during weekdays and weekends, if they are fully charged every day. However, in the real world, a great percentage of battery capacity drops due to weather conditions. A study by Yuksel and Michalek indicates that during the coldest wintertime weather, real world ranges of BEVs may decrease by 30% of their tested ranges (Yuksel and Michalek 2015). Similarly, an EV test conducted by China Automotive Technology and Research Center (CATARC) in 2017 reveals that the range of a popular electric vehicle, BYD Qin EV, decreased by about 30% under very low temperature (China Clean Transportation Partnership 2018). Even adding additional 10% for extra loads and hilly topography etc., a 183-km range BEV and a 350-km range BEV would be capable of meeting 90% and 99% daily travel demand during weekdays and weekends in Beijing and Shanghai.

4.3 Optimal ranges of PHEVs

Based on the real-time data in the two cities, four PHEV models with different ranges from the same OEM were selected to compare the amount of GHGs emitted in both cities. We also selected the CAFC 2020 baseline compliance model and the baseline hybrid model as additional models for comparison. Following the assumptions described in 3.2, we calculate the average GHGs per vehicle model per day (Fig. 6). The estimates of GHGs for the four PHEV models are shown in Fig. 6. Surprisingly, the 100-km range Tang vehicle model emits more GHG emissions than both the CAFC 2020 compliance and the hybrid model. Figure 6 reveals that longer electric-range PHEVs may actually be dirtier than the CAFC baseline model.

We then adjusted the battery size to calculate the amount of GHG emissions of PHEV fleets representing current level of energy efficiency in the Chinese market by employing real-time daily travel patterns in Beijing and Shanghai. The aggregate amount of GHGs in each city was

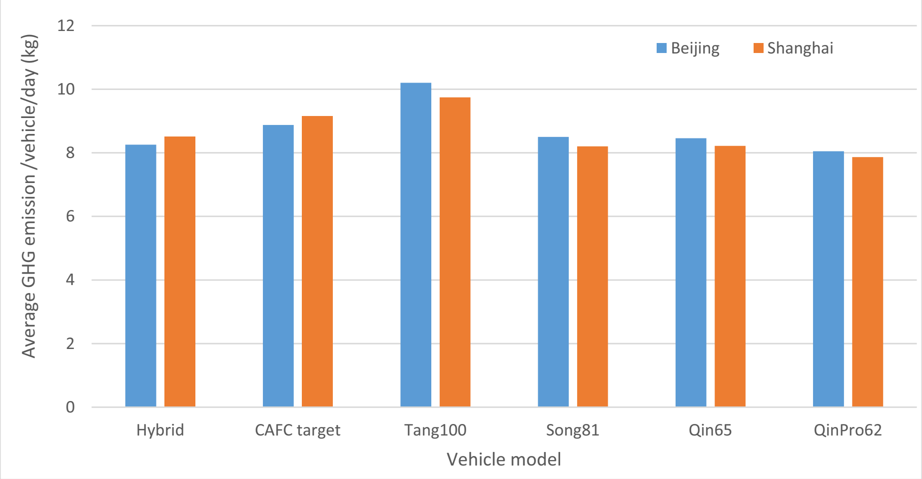

Fig. 6 Average amount of GHG emissions per vehicle per day by model. Note: the number following the model is the vehicle electric range such as Tang100 and Song81

calculated by summing up all the emissions generated from all daily trips by PHEVs with a variety of electric ranges. Figure 7 shows the amount of GHGs emitted per vehicle per day from PHEVs with ranges from 0 to 150 km based on the real-time daily travel distance in each city. We find a non-linear, convex relationship between GHG emissions and vehicle range. The increase in electric range (corresponding to a higher UF) decreases GHGs as more electricity is employed to travel. However, there is a tradeoff resulting from the increased capacity which results in heavier batteries and thus lowers the energy efficiency of both the electric and gasoline

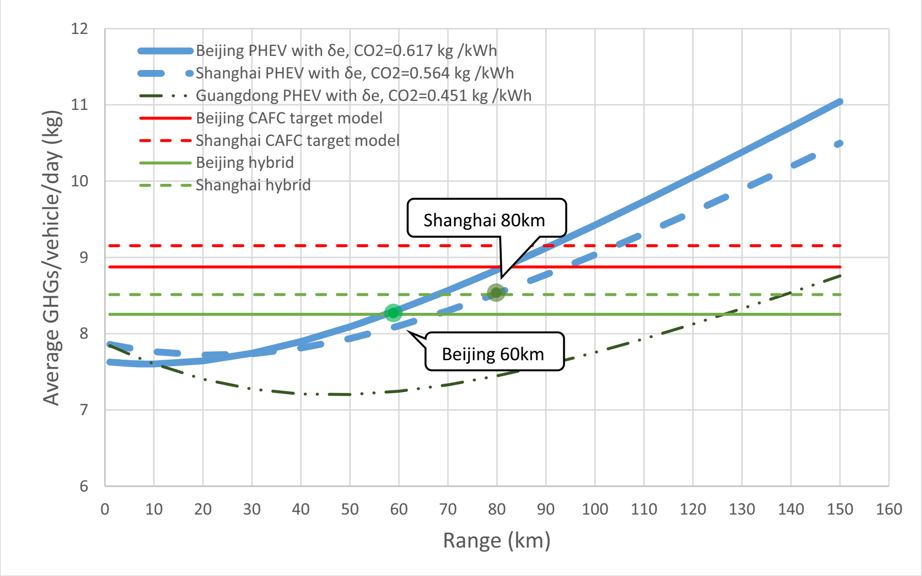

Fig. 7 Average GHGs by PHEV models and the baseline models by city with different carbon intensity based on real-time daily travel. Note: the green points pointed by the text boxes are the net-benefit points where PHEVs within a range that emits less GHGs than that of the baseline hybrid model

drivetrains. Ultimately, this leads to an initial decrease in overall GHGs but the efficiency losses gradually rise and eventually takeover, leading to an increase in overall GHGs. Therefore, there exists a point at which GHG emissions can be minimized as a function of the range of the vehicle, which is the ideal lowest-carbon range for PHEVs in each city. Based on the daily VKT of the vehicles in each city, the ideal ranges that minimize GHG emissions of PHEVs are 10 km and 30 km in Beijing and Shanghai, respectively. We are also able to perform sensitivity analysis with the carbon intensity of the electricity grid within the city. Using Shanghai real-time data but with the grid carbon intensity of the city of Guangdong (which is lower than that of Shanghai) we show that the ideal PHEV range would be about 50 km. This illustrates that the idea that the ideal PHEV range increases as carbon intensity of a city grid decreases. The ideal low-carbon optimal range should function as a long-term target and a reminder to the grid must decrease its carbon intensity to improve transportation emissions.

Nevertheless, we also consider a constraint in which PHEVs only need to improve their emissions rate to be less than that of the baseline gasoline and hybrid vehicles (rather than minimizing carbon emissions). In this case, PHEVs with ranges of less than 60 km in Beijing and 80 km in Shanghai are superior to the average hybrid fleet in GHG emissions reduction while PHEVs with range over 80 km in Beijing and 105 km in Shanghai will emit more GHGs than that of the CAFC compliance model. This finding helps explain why the BYD Tang, a long-range PHEV, is not as clean as expected in Fig. 6. Similarly, the figures demonstrate that a city with less carbon-intense grid can accommodate PHEVs with longer optimal ranges, partly because that the amount of GHGs resulting from fuel inefficiency of larger batteries is offset by a cleaner city grid.

The findings of this study indicate that relatively shorter-range PHEVs can benefit the environment more than the suite of currently available vehicle models in the Chinese market. An electric range of 60 km or lower in Beijing and 80 km or lower in Shanghai would be superior to a hybrid fleet in reducing GHGs. Additionally, the study indicates that a clean city grid leads to a longer optimal range. The subsidy policies favoring long-range-battery PHEVs may actually be creating an adverse incentive to create vehicles with longer ranges that are both more expensive and higher emitting.

5 Discussion and conclusions

Our study highlights the importance of energy efficiency requirements for BEVs. While we find that popular BEV models emit far less GHGs than their gas-powered counterparts in Beijing and Shanghai, we discover a counterintuitive flaw in Chinese policies favoring long-range vehicles. The results of our analysis indicate that longer-range BEVs generate more GHGs than shorter-range ones, and while BEVs up to a range of over 800 km are cleaner than our baseline gasoline vehicle, a mere 350-km range can meet vast majority of daily travel demands in the two cities. However, it is important to note that the marginal travel demand from drivers who have occasionally travel longer than 210 km, especially during holidays, remains unaddressed in our work. Pearre et al. (2011) indicated that if people can make adaptations only a few days per year by substituting alternative transportation or charging during the day, BEVs could meet the travel needs of an absolutely large fraction of population. Thus, is it possible that the government could find ways to subsidize other alternatives (Didi, e-bikes, public transit or high-speed rail) for their emergency travel needs? It is also possible to subsidize urban charging infrastructure, enabling shorter-range BEVs to meet greater travel demand requirements. This begs the question of whether incentivizing additional charging stations and cleaning the grid may be a more effective method of accelerating PEVs compared to subsidizing larger batteries to increase vehicle range.

Our study suggests that PHEVs with electric ranges of less than 60 km and 80 km can be lower emitting than gasoline and hybrid vehicles in Beijing and Shanghai, respectively. We also find that cleaner energy sources for electricity generation in a region result can increase the "emissions competitive" range of PHEVs. Importantly, these results also indicate that long-range PHEVs may not have emission advantage over similar hybrids or even conventional gasoline vehicles in Beijing and Shanghai, thus contradicting China's favoritism towards longer range vehicles. We do note some caveats in our work: the travel patterns within Shanghai is represented by the real-time daily travel data of PHEV users. However, PHEVs are still marginal compared with ICE vehicles in the market. It is possible that daily travel trips have been overestimated because studies have indicated that PHEV users may drive longer distances than ICE drivers due to higher vehicle energy efficiency (Tal et al. 2014). Additionally, this study assumes that each vehicle is charged only once per day and starts the daily trip with a fully charged battery. It is plausible that some PEVs are plugged in more or less frequently than our assumed rate. Most importantly, the current PHEV technology varies and the models in PEV market differ much in electric powertrain designs. Our study takes averages the most recent PEV models in China without examining them individually. In future research, more detailed real-time data and vehicle operation information will be necessary to address these questions.

This study ultimately aims to provide important insights into the effects of well-meaning policy on climate outcomes. Even without strong financial support from the government as seen in China, there is a tendency to increase the battery range of PEVs globally. This can already be seen in historical sales data, for example in the US BEV ranges have increased an average 17% per year (EV Adoption 2018). The interest in longer range is driven partly by the urge to scale up the battery market so that the cost of batteries will come down more quickly and partly by OEMs' concerns that consumers will not buy vehicles ranges less than an equivalent ICE vehicle. However, in cities, extremely long-range PHEVs are not necessarily "clean", as demonstrated by BYD Tang in this study. Additionally, in cities with a dirty electricity grid, policy makers may reconsider promoting large battery BEVs, which may emit even more GHGs than an ICE vehicle. It is critical to determine the optimal range of PEVs, taking into account a variety of factors such as environmental damages, for governments to make a well-informed and balanced decision to encourage certain PEV models in the market, especially in regions that depend heavily on conventional fossil fuels for electricity generation. Our study suggests that to achieve a goal of emissions reduction, governments ought to consider the ranges that would minimize GHG emissions rather than blindly encouraging very long-range PEV models. Importantly, range anxiety could be alleviated through the learning process. A study found that 65% of electric car users in the US were no longer anxious about the range after driving their BEVs for a few months (Nichols 2019). This suggests that providing week-long driving trials prior to the purchase may help reduce the demand for long-range BEVs.

Over the past few years, many countries have committed to tackling climate change by setting ambitious goals, such as the public announcement that all new passenger cars sold must be zero emission vehicles by 2025 in Norway. However, we need to understand the way to meet greenhouse gas emission reduction targets cost-effectively. This analysis provides important insights into the effects of government subsidies and credit policies on ZEV deployment and develops a methodology to identify an optimal range for PEVs.

References

Berjoza D, Jurgena I (2017) Influence of batteries weight on electric automobile performance. Eng Rural Dev: 24–26

Cheah LW (2010) Cars on a diet: the material and energy impacts of passenger vehicle weight reductin in the U.S. (Ph D), Massachusetts institute of technology

China Clean Transportation Partnership (2018) Projects: EV-TEST tells you the real performance of EVs in China

China Passenger Car Association (2018) The sales of PHEV models. Retrieved from http://biz.touchev.com/industry_data

EV Adoption (2018) US BEV Battery Range Increases an Average 17% Per Year and 38 Miles Each Model Update Retrieved from https://evadoption.com/us-bev-battery-range-increases-an-average-17-per-year-and-38-miles-each-model-update/

Kontou E, Yin Y, Lin Z (2015) Socially optimal electric driving range of plug-in hybrid electric vehicles. Transp Res Part D: Transp Environ 39:114–125

Lin Z (2012) Optimizing and diversifying the electric range of plug-in hybrid electric Vehciles for U.S. drivers. SAE Int J Alt Power 1:180–194

Lin Z (2014) Optimizing and diversifying electric vehicle driving range for U.S. drivers. Transp Sci 48:635–650

Ministry of Industry and Information Technology (2015) Passenger car fuel comsumption explanation [Press release]. Retrieved from Ministry of Industry and Information Technology (MIIT)

National Big Data Aliance of New Energy Vehicles (NDANEV) (2019) New energy vehicle 2019 Spring Festival Travel Season big data report https://www.3mbang.com/p-4705829.html

National Center for Climate Change Strategy and International Cooperation (NCSC) (2016) Province level average power grid CO2 emission factor

Nichols, J (2019) Poll finds Americans feel electric vehicles are the future of driving [Press release]. Retrieved from https://www.media.volvocars.com/us/en-us/media/pressreleases/248305/poll-finds-americans-feel-electric-vehicles-are-the-future-of-driving

Pearre NS, Kempton W, Guensler RL, Elango VV (2011) Electric vehicles: how much range is required for a day's driving? Transp Res C. https://doi.org/10.1016/j.trc.2010.12.010

Plötz P, Funke SA, Jochem P, Wietschel M (2017) CO2 mitigation potential of plug-in hybrid electric vehicles larger than expected. Sci Rep 7:1–6

Shiau CSN, Michalek JJ (2010) Optimal plug-in hybrid electric vehicle design and allocatgion for minimum life cycle cost. J Mech Des 133(9)

Society of Automobile Engineers (SAE) (1999) Recommended practice for measuring the exhaust emissions and fuel economy of hybrid-electric vehicles. SAE-J1711. Retrieved from https://saemobilus.sae.org/content/j1711_201006

Society of Automobile Engineers (SAE) (2009) Utility factor definitions for plug-in hybrid electric vehicles using 2001 U.S. DOT National Household Travel Survey data. Hybrid Committee, SAE-J2841. Retrieved from https://saemobilus.sae.org/content/j2841_200903

Tal G, Nicholas M, Davis J, Woodjack J (2014) Charging behavior impacts on electric VMT: who is not plugging in? Transp Res Rec 2454:53–60

Wang, H (2017) Significant CO2 emission reduction from new energy vehicles. Retrieved from https://www.d1ev.com/kol/51461

Wu X, Aviquzzaman M, Lin Z (2015) Analysis of plug-in hybrid electric vehicles utility factors using GPS-based longitudinal travel data. Transp Res C 57:1–12

Xia Y, Yang J, Wang F, Cheng Q (2018) Impact of battery size and energy cost on the market acceptance of blended plug-in hybrid electric vehicles. Procedia Comput Sci 131:377–386

Yuan X, Li L, Gou H, Dong T (2015) Energy and environmental impact of battery electric vehicle range in China. Appl Energy 157:75–84

Yuksel T, Michalek JJ (2015) Effects of regional temperature on electric vehicle efficiency, range, and emissions in the United States. Environ Sci Technol 49:3974–3980

Zhang X, Wang H (2014) Utility factors derived from Beijing passenger car travel survey. Paper presented at the FISITA 2014 World automotive congress Maastricht, Netherlands

Affiliations

Yan Xing[1] • **Alan T. Jenn**[1] • **Yunshi Wang**[1] • **Chunyan Li**[2] • **Shengyang Sun**[3] • **Xiaohua Ding**[4] • **Siwen Deng**[4]

✉ Yan Xing
yxing@ucdavis.edu

Alan T. Jenn
ajenn@ucdavis.edu

Yunshi Wang
yunwang@ucdavis.edu

Chunyan Li
lichyan@gmail.com

Shengyang Sun
jummysun@qq.com

Xiaohua Ding
dingxiaohua@shevdc.org

Siwen Deng
dengsiwen@shevdc.org

[1] Institute of Transportation Studies, University of California, Davis, Davis, CA 95616, USA

[2] Beijing Transport Institute, Beijing, China

[3] The Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH, Bonn, Germany

[4] Shanghai Electric Vehicle Public Data Collecting, Monitoring and Research Center, Shanghai, China