

# Energy-saving benefits from plug-in hybrid electric vehicles: perspectives based on real-world measurements

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**Abstract** Promoting plug-in hybrid vehicles (PHEV) is one important option to mitigate greenhouse gas emissions and air pollutants for road transportation sector. In 2015, more than 220,000 new PHEVs were registered across the world, indicating a 25-fold growth during 2011–2015. However, more criticisms have been put forward against the current energy efficiency regulations for vehicles that are mostly depended on laboratory measurements. To better understand the real-world energy-saving and emission mitigation benefits from PHEVs, we conducted on-road testing experiments under various operating conditions for two in-use PHEVs in Beijing, China. Our results indicate that air condition usage, congested traffic conditions, and higher loading mass could significantly increase energy consumption and shorten actual all-electric distance for PHEVs. For example, the worst case (14.1 km) would occur under harshest usage conditions, which is lower by at least 35% than the claimed range over 20 km. In charge sustaining (CS) mode, real-world fuel consumption also presents a large range from 3.5 L/100 km to 6.3 L/100 km because of varying usage conditions. Furthermore, various vehicle users have significantly different travel profiles, which would lead to large heterogeneity of emission mitigation benefits among individual PHEV adopters. Therefore, this study suggests that the global policy makers should use real-world energy efficiency of emerging electrified powertrain techniques as criteria to formulate relevant regulations and supportive policies.

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## 1 Introduction

The continuing growth in global transportation activity has posed a challenging position to reduce road transportation greenhouse gas emissions. The Intergovernmental Panel on Climate Change (IPCC) has clearly highlighted the importance of energy transit for transportation sector in the Fifth Assessment Report (IPCC 2014). For road passenger transportation, where light-duty vehicles play a dominant role, developing electric vehicles (EVs) including battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) is an important component under the 2 Degree Scenario (IPCC 2014; IEA 2016; ICCT 2014). Many countries have adopted various supportive policies to spur the rapid growth of EVs. For example, according to the International Energy Agency, the global amount of new registered PHEVs in 2015 climbed to over 220,000, indicating a 25-fold increase just during 2011–2015. Another important observation in the global megatrend of fleet electrification is that China has played an important role along with major traditional automobile manufacturing countries (IEA 2016). In 2015, China has replaced the United States (USA) and become the largest EV market across that world, which has substantially motivated by multiple concerns including present challenges concerning energy security and air quality and ambitions to hold a leading position in the future era of electrified transportation (Ke et al. 2017; Wu et al. 2017; Zhang et al. 2014a; Gong et al. 2013; Tong et al. 2016).

Different from BEV that is purely powered by battery electricity, PHEV capable of grid recharging typically can run on battery electricity for 20 to 50 km and then operate the internal combustion engine to power the extensive range. Thus, such a powertrain category has its technical advantage of balancing energy efficiency and travel range (Zhou et al. 2015; Tong et al. 2015; Wang et al. 2015a). However, the real-world energy-saving and emission mitigation benefits from PHEVs could be more complicated compared with the BEV counterparts. It is noted that real-world emissions have become a global issue since the diesel emission scandal, because vehicle emission regulations across the world are majorly developed based on laboratory testing protocols that may not represent real-world vehicle operating conditions and could be artificially optimized (Zhang et al. 2014b; ICCT 2014). The laboratory measurements could be even artificially optimized by vehicle manufacturers. The International Council on Clean Transportation (ICCT) has noted that this road-to-laboratory discrepancy for internal combustion engine vehicles (ICEV) became significantly enlarged with increasingly stringent carbon dioxide (CO<sub>2</sub>) emission limits in Europe, from below 110% in 2000 to approximately 140% in 2014 (ICCT 2014). Previous studies have expressed similar concerns with respect to all electric ranges (AERs), fuel consumption (FC), and exhaust CO<sub>2</sub> emissions of PHEVs that could vary significantly (Karabasoglu and Michalek 2013; Millo et al. 2014; Wang et al. 2015a). Researchers have applied advanced experimental and simulation techniques to understand the effects of traffic conditions on FC of PHEVs (Fontaras et al. 2008; Marshall et al. 2013). These existing efforts have resulted in EC values closer to those of the real world but still may underscore impacts from other variables, such as air conditioning (AC), passenger load, and charging loss, as well as overall complexity (Zhang et al. 2014b, c; Paffumi et al. 2015). Therefore, since the on-road testing profiles

of PHEV are not readily available, we are motivated to measure FC of PHEVs and characterize comprehensive affecting factors from a real-world perspective.

Technically, for PHEVs, real-world evaluations of gasoline consumption (GC) in the charge-sustaining (CS) mode can be conducted in a high time resolution (e.g., second by second) by employing a portable emission measurement system (PEMS) or using on-board sensors (e.g., oxygen level, engine revolution, air intake, and fuel injection) (Zhou et al. 2016; Hu et al. 2014). In the charge-depleting (CD) mode with zero tailpipe emissions, an appropriate on-board diagnostics (OBD) decoder paired with a global positioning system (GPS) receiver can be used to collect real-time vehicular and traffic information. The complex effects of real-time travel patterns and vehicle operating conditions can be analyzed for tested PHEVs in either CD or CS mode, including state of charge (SoC), speed (Wu et al. 2015; Zhang et al. 2014d), AC usage (Faria et al. 2013), and loading mass (Zhou et al. 2016; Raslaviciusa et al. 2013). Nevertheless, trip distance is another important factor affecting real-world distance fractions of CS and CD modes for PHEVs with various battery capacities (e.g., AERs) (He et al. 2016). Thus, real-world FC evaluations of PHEVs should include all previous issues, which is a key interaction between upstream and operation stages.

In this manuscript, we aim to report real-world energy-saving benefits from in-use PHEVs, which are measured under a wide spectrum of operating conditions and analyzed based on actual travel profiles of large-sized individual drivers. We select Beijing as a case to implement our field experimental study, because Beijing is not only the city with largest vehicle population within China (Beijing Municipal Bureau of Statistics 2015) but also an important hub for China's EV deployment in the early adoption stage (Beijing Municipal Science & Technology Commission 2014). In this study, two plug-in Toyota Prius PHEV models participated in a 2-month road test campaign in Beijing, where a series of complex operating conditions were applied. In addition, thanks to detailed usage profiles of approximately five private passenger vehicles collected in Beijing (He et al. 2016), we could comprehensively present the heterogeneity of energy-saving and emission mitigation benefits among individual vehicle users. This study could suggest global regulations, and supportive policies should emphasize the real-world energy and climate benefits from emerging electrified transportation technologies.

## 2 Methodology and data

The on-road test campaign was performed in the urban area of Beijing from April to June, 2014. The key experimental conditions such as the date, ambient temperature, departure and arrival time, mode switching time (e.g., CD to CS) and trip distance, electricity consumption (EC) and GC, and designed operating conditions were carefully recorded. The vehicles were tested for a few trips (four trips per day typically) during daytime to experience as many traffic conditions as possible. Most of the road segments are flat except for one underground charging site and one tunnel. To eliminate any possible bias from different behaviors of different drivers, the total test distance over 2000 km was completed by one same driver. The data for two PHEVs were averaged to reduce the inter-vehicle bias. To explore the actual AER under real-world conditions, all the test trips started after the PHEVs were fully charged and were longer than the claimed AER value (e.g., designed as 20 km). Two fixed charging sites 14 km apart from each other were used in our field test, both located in the urban area of Beijing. In addition, we fixed the departure and destination locations

for all trips, although the entire route may be not in completely accord between various trips. As we noted above, traffic conditions, AC usage, and loading mass are major real-world affecting factors, which were covered by various experimental conditions designed in this study.

## 2.1 Key parameters of the PHEV and charging equipment

The PHEVs of a same model were originally produced in Japan, and their key parameters are listed in Table 1. The lithium-ion battery can independently power the synchronous motor to drive over 20 km as designed (i.e., AER of 20 km) after being fully charged. In terms of the electric vehicle supply equipment (EVSE), indoor household power (220 V/10 A) was used to charge the PHEVs. We recorded the total power from the local network using a handheld local network power collector (model HP 9800), which combined the charging and discharging loss. The maximum charging power was 2.3 kW, which was gradually reduced as the actual SoC increased.

The real battery SoC is designed not to fall to zero to promote driving safety and warrantee battery lifespan. On the other hand, the dashboard SoC indicator performs as follows: as the dashboard SoC reaches zero, the PHEV immediately shifts from CD mode to CS mode. Then, the SoC would remain approximately stable representing a dynamic equilibrium of frequent shifts between CD and CS modes (Samaras 2013), although all of the tests may not be absolutely the same. For example, we charged the battery right after a complete test trip. Our results indicated that the total electricity gained from local power was  $3.0 \pm 0.3$  kWh. The inter-trip and inter-vehicle discrepancy (e.g., both within  $\pm 10\%$ ) could be identified in Appendix A.

## 2.2 Fuel consumption calculation

Technically, PHEVs could operate in the CD, CS, and CD blended modes according to SoC and traffic conditions. In this study, we primarily focused on pure CD and CS modes by avoiding the blended mode, as the blended mode would not commonly occur in the urban area with lower speed limits. In the CD mode, we set two rules in the road test to keep the engine off and eliminate any blended conditions. First, the driver was required to step on pedal appropriately to avoid unnecessary boost acceleration, and second, the instantaneous speed was not higher than 80 km/h. The second rule was also in accordance with the speed limits (less than 80 km/h) for most of the urban roads in Beijing.

**Table 1** Key vehicle parameters of the PHEVs tested in Beijing

Index	Data
OEM	Toyota
Model type	Prius Plug-in Hybrid ZVW35L-BHXEBW
Gross vehicle weight (kg)	1840
Curb weight (kg)	1420
Battery capacity	21.5 Ah/207 V/4.5 kWh
Engine displacement (ml)	1798
Engine power (kW)	73
Motor power (kW)	60
Charging parameter	10 A/230 V(stable charging)
Usage time	<2 years, <10,000 km

We obtained the EC in the CD mode by recording the amount of local network charging (Eq. 1). EC in the CS mode was calculated by integrating second-by-second GC recorded by an OBD decoder (Eq. 2). The key parameters, such as the real-time speed of trips, were collected simultaneously.

$$\overline{EC}_i = 100 \times EC_i / S_{i,CD} \quad (1)$$

$$\overline{GC}_i = 100 \times GC_i / S_{i,CD} = 100 \times \int_{t_1}^{t_2} q_g dt / S_{i,CS} \quad (2)$$

where  $s_{i,CD}$  and  $s_{i,CS}$  are strictly the total distance of the CD and CS modes (km),  $EC_i$  is the total EC in the CD mode of trip  $i$  (kWh),  $\overline{EC}_i$  is distance-specific EC in the CD mode of trip  $i$  (kWh/100 km),  $GC_i$  is the CS mode total GC of trip  $i$  (L),  $\overline{GC}_i$  is the distance-specific CS mode EC of trip  $i$  (L/100 km),  $t_1$  is the shifting time of the CD mode to the CS mode,  $t_2$  is the finishing time of the CS mode (s), and  $q_g$  is the second-by-second gasoline injection quantity (ml/s).

We chose the Toyota Corolla (2014 model year) as an ICEV counterpart for comparison, which is equipped with a 1.8-l gasoline engine. Based on 767 individual car users' records through a smartphone app, the average on-road GC is  $8.24 \pm 1.22$  L/100 km (Xiaoxiongyouhao 2016). Although vehicle performance attributes of Toyota Corolla and Prius are not exactly consistent, the comparison could also provide useful reference for compact vehicles. In addition, we applied the speed correction curve for urban driving conditions (e.g., average speed lower than 70 km/h) based on previous real-world PEMS measurements for 41 gasoline ICEVs in China (Zhang et al. 2014d). The key parameters for the reference ICEV are listed in Appendix B.

### 2.3 Designed operating scenarios of on-road tests

We developed two-stage test scenarios, a benchmark scenario, and three additional scenarios of various AC usage and loading mass conditions. In the benchmark scenario, the PHEVs ran with AC off and without extraweight representing "passengers." Additional scenarios involved different operating situations with AC on and loading mass increased. For example, AC was on with the temperature set to 19 °C, and the fan set at a medium speed. The lower and upper ambient temperatures were 8–19 and 20–26 °C, respectively. A load of 300 kg represented by water buckets was added, which approximated a total weight of four adults. Four typical speed ranges indicated by average speed, free flow (40–50 km/h), light traffic (30–40 km/h), normal traffic (20–30 km/h), and heavy traffic (10–20 km/h), were investigated to evaluate the impact of traffic conditions on the FC of the PHEV (CD and CS modes separately) and the gasoline ICEV in each scenario. Equation 3 represents the speed-dependent FC models under various operating scenarios, which are best fitted with power functions. Equation 4 is used to normalize various speed points in each speed range to reduce bias.

$$\overline{FC}(c, v) = a_c v^{-b_c} \quad (3)$$

$$FC'_i(c, v) = FC_i(c, v) \times \frac{\overline{FC}(c, v_c)}{\overline{FC}(c, v)} \quad (4)$$

where  $\overline{FC}(c, v)$  is the speed-dependent FC function under scenario  $c$ , kWh/100 km (in CD mode) or L/100 km (in CS mode);  $a_c$  and  $b_c$  are the fitting parameters of speed-dependent FC curves under various scenarios;  $FC_i(c, v)$  represents the tested FC of route  $i$ ;  $FC'_i(c, v)$  is the normalized FC under the speed of  $v$ ; and  $v_c$  is the central speed of one speed range, km/h.

## 2.4 The utility factor and energy-saving benefits under typical travel patterns

In this study, the utility factor (UF) is defined as the distance fraction of the CD mode in one entire trip. Equation 5 illustrates the speed-dependent function of AERs under scenario  $c$ . The parameters  $c_c$  and  $d_c$  are two fitting coefficients. Given the trip length  $s$  (km) under scenario  $c$ , the UF is evaluated according to the actual AER and  $s$  as Eq. 6 illustrates.

$$AER(c, v) = c_c v^{-d_c} \quad (5)$$

$$UF(c, v, s) = \begin{cases} \frac{AER(c, v)}{s} \times 100\%, & AER(c, v) < s \\ 100\%, & AER(c, v) \geq s \end{cases} \quad (6)$$

Given a trip with certain traffic parameters (e.g., average speed and total length), UF can be estimated for further calculating the integrated FC of a PHEV (i.e., EC and GC combined). We consolidated the energy type for integrated comparison, and the equivalent GC was applied for convenient comparison between the PHEV and ICEV. Equation 7 shows how to convert the EC in the CD mode to GC equivalent ( $\overline{EC}_{eq}$ ) in terms of heating value. Finally, the FC of the PHEV for a given trip is calculated by Eq. 8, and the maximum FC from the replacement of the PHEV (Prius) with the ICEV (Corolla) could be simulated.

$$\overline{EC}_{eq} = \overline{EC} \times \frac{HV_e}{HV_g} \quad (7)$$

$$FC_{PHEV} = UF(c, v, s) \times \overline{EC}_{eq} + (1 - UF(c, v, s)) \times \overline{GC} \quad (8)$$

where  $\overline{EC}_{eq}$  is the equivalent EC of gasoline, L/100 km;  $HV_e$  is the heating value of electricity, 3.6 MJ/kWh;  $HV_g$  is the low heating value of gasoline, 43.11 MJ/l.

The UF and energy use profiles support the evaluation of on-road EC performance in terms of variable travel patterns. Estimation of travel characterization is usually based on the large populations of vehicle use data, for example, the National Household Travel Survey (NHTS) in the USA (Tamor et al. 2013). We analyzed vehicle usage data regarding start, stop, and trip trajectory for hundreds of personal passenger vehicles in Beijing by using portable GPS data loggers. Detailed information and results of the vehicle usage survey were documented by He et al. (2016). In summary, the vehicle owners were typically distributed according to their home location, office location, and occupation. GPS data collection for each vehicle lasted at least 1 month (note: some vehicles lasted up to 6 months) to improve the real-world representativeness of trip length, road coverage, and traffic conditions. We selected 7702 trips from approximately 500 vehicles with travel distances less than 100 km and average speeds below 60 km/h. Figure 1 illustrates a distribution of these trip candidates grouped by distance and average speed, where we create square-like bins within speed and distance intervals of 10 km/h and 10 km, respectively. The probability of bin  $k$  ( $P_k$ )

means that the fraction of total trips that has the trip parameters of  $\bar{v}_k$  and  $s_k$ , as Eq. 9 shows.

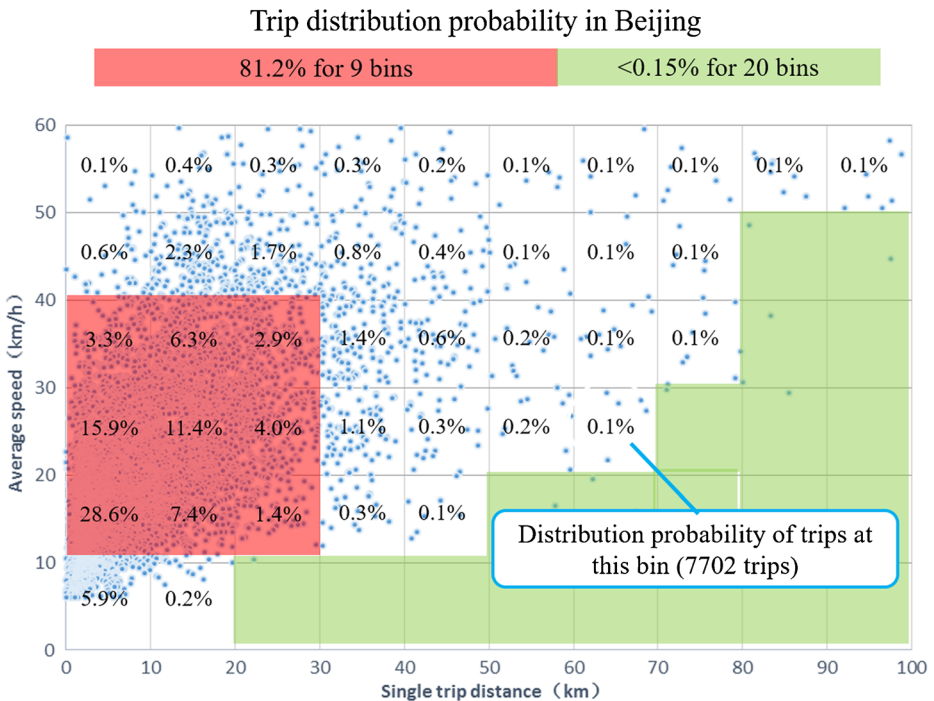
$$P_k = \frac{N_k(\bar{v}_k, s_k)}{N} \tag{9}$$

The bin with the highest distribution probability of 28.6% represents travel of less than 10 km, with a speed range of 10–20 km/h. Nine bins within the 10–40 km trips with a speed range of 0–30 km/h make up 81.2% of the selected distribution (in red, see Fig. 1). As the trip length increases, the users prefer to choose express roads with no signal light for their travel. Therefore, the average speed tends to increase accordingly. The green bins in Fig. 1 account for a total fraction less than 0.15%, which indicates that it is quite unlikely to travel a long distance while at a low average speed.

The overall FC combines the equivalent FC in each bin and its probability weight (Eq. 10). Following a similar method, ICEV EC within the Beijing travel pattern and the benefits of PHEVs in Beijing can be evaluated (Eq. 11).

$$FC_{vehicle} = \int FC_{vehicle}(k) \times P_k dk \tag{10}$$

$$\Delta = FC_{ICEV} - FC_{PHEV} \tag{11}$$



**Fig. 1** The trip distribution of 7702 trips from 200 vehicles in Beijing and the probability distribution of trip bins

### 3 Results and discussion

#### 3.1 PHEV energy consumption in the CD and CS modes

When PHEVs operate on urban roads (i.e., average speed below 60 km/h), their EC under the CD mode is generally reduced as the average speed gets increased. However, this trend becomes less significant when the average speed is over 30 km/h. Power functions could have strong correlations between EC in the CD mode and average speed for all scenarios ( $R^2 > 0.6$ ) except for the scenario of EL and AC on ( $R^2 = 0.41$ , indicating medium correlation) (see Table 2). For example, in the benchmark scenario, the average EC under the normal traffic condition (average speed of 25 km/h) is  $14.9 \pm 0.7$  kWh/100 km (Table 2). The average EC rises to  $17.0 \pm 2.0$  kWh/100 km under the heavy traffic condition, representing an increase of 14% than the normal traffic condition. The average EC of PHEVs achieves  $13.9 \pm 1.2$  kWh/100 km under the light traffic condition and  $13.8 \pm 0.9$  kWh/100 km under the free traffic condition, respectively. Furthermore, variations in EC in the CD mode due to various traffic conditions would lead to changes in real-world AERs. For example, the average AER under the benchmark scenario (i.e., normal traffic, EL, and AC off) could reach 20.4 km, which complies with the level as vehicle original equipment manufacturer (OEM) designed. When the traffic speed becomes higher (e.g., light traffic and free flow conditions in Table 2), the average AER value remains stable. However, when traffic congestion becomes increasingly serious (heavy traffic, EL, and AC off), for example, during rush hours, the average AER has difficulty reaching the designed value and deteriorates by 17%, only 16.9 km.

Although we have discerned increased EC due to congested traffic conditions, real-world EC under the CD mode for tested PHEVs is significantly less sensitive to changes in speed than that of the ICEV counterparts. For example, Zhang constructed speed-dependent functions for the EC of gasoline light-duty passenger vehicles (LDPVs) and found that the real-world EC under the heavy-traffic condition would be elevated by 43% for gasoline LDPVs (Appendix C) and by 33% for diesel LDPVs (Zhang et al. 2014d). In contrast, the EC of PHEVs in CD mode would be increased by 14% for PHEVs (Table 2). This is because the

**Table 2** Averaged fuel consumption and AER under various operating conditions

Traffic condition	Load	A/C	EC (kWh/100 km)	AER (km)	GC (L/100 km)
Heavy (ave. speed 10–20 km/h)	Empty	off	$17.3 \pm 1.7$	$16.9 \pm 1.5$	$4.5 \pm 0.6$
	Full	off	$18.5 \pm 0.4$	$16.4 \pm 0.3$	$5.3 \pm 0.3$
	Empty	on	$19.1 \pm 1.3$	$15.4 \pm 0.9$	$5.6 \pm 0.3$
	Full	on	$21.9 \pm 0.2$	$14.1 \pm 0.1$	$6.3 \pm 0.3$
Normal (ave. speed 20–30 km/h)	Empty	off	$14.7 \pm 0.5$	$20.4 \pm 1.8$	$4.2 \pm 0.4$
	Full	off	$16.7 \pm 1.6$	$18.6 \pm 0.6$	$4.7 \pm 0.5$
	Empty	on	$18.2 \pm 2.4$	$16.6 \pm 1.5$	$4.8 \pm 0.4$
	Full	on	$20.3 \pm 1.3$	$15.3 \pm 0.5$	$5.0 \pm 0.8$
Light (ave. speed 30–40 km/h)	Empty	off	$14.4 \pm 1.1$	$20.5 \pm 2.1$	$3.7 \pm 0.3$
	Full	off	$15.7 \pm 1.5$	$19.2 \pm 1.5$	$4.0 \pm 0.4$
	Empty	on	$16.6 \pm 0.4$	$17.8 \pm 0.9$	$4.0 \pm 0.3$
	Full	on	$17.7 \pm 1.7$	$16.5 \pm 0.3$	$4.3 \pm 0.2$
Free flow (ave. speed 40–50 km/h)	Empty	off	$13.8 \pm 1.0$	$20.5 \pm 2.2$	–
	Full	off	–	–	$3.6 \pm 0.2$
	Empty	on	$15.7 \pm 0.1$	$17.9 \pm 0.6$	$3.5 \pm 0.1$
	Full	on	$15.2 \pm 0.1$	$17.2 \pm 0.2$	–

The AER has been normalized by Eq. 4



internal combustion engine has a prime working area characterized by high combustion efficiency. The EC of ICEV has a significantly increasing gradient when the engine-operating conditions are apart from this area (Gao et al. 2014). For PHEV, the characteristic curve of electric motor and the brake energy regeneration allow a high and stable powertrain efficiency among traffic conditions in the CD mode.

The results of multiple scenarios indicated that the impact of AC usage on EC in the CD mode is greater than the impact of increased load mass. Compared with the benchmark scenario, AC on and FL could shorten the average AERs to 16.6 and 18.6 km, respectively, under the normal traffic condition, indicating reductions of 19 and 9% (Table 2). Evidences from other international studies could also support the significant impact of AC usage on EC and AER of electric powertrain systems. For example, Fontaras et al. (2008) and Faria et al. (2013) indicated that AC usage could reduce the AER of BEV by 12 to 17% in summer when the daytime ambient temperature ranged 25–30 °C. Farrington and Rugh (2000) used simulation methods and suggested that the AER of BEV could be reduced by 38% if increasing the AC power to 3 kW. Rugh (2010) further reported that the PHEV AER values were reduced to different extents under different driving cycles, e.g., 18% under a high-speed cycle and 30% under an urban cycle. Our experimental results suggest that, when the PHEVs were operated with AC on and a full load, their average AER would drop to 15.3 km under the normal traffic condition. This drop represents a reduction of 25% compared with the benchmark scenario. To make matters worse, if the traffic conditions are more congested (heavy traffic, FL and AC on; namely the harshest scenario in our study), the average AER for tested PHEVs could last only 14.1 km, which is only 69% of the benchmark result.

Therefore, our results indicate that attainment of the designed AER of 20 km is conditional and may not be guaranteed under some unfavorable conditions that may often occur in reality (Table 2). Logistically, the OEMs first set the AER target and later determine battery capacity accordingly. However, the opportunity to achieve the designed AER is often diminished because the driver has to maintain smooth driving, select the proper travel time to avoid congestion, and switch off on-board AC system. According to the Beijing travel pattern survey, the length of 64% of the single trips is shorter than 14 km. The users therefore have a high probability of finishing 14 km in CD mode over a wide range of combined vehicular and road conditions. The PHEV could extend the range by starting the gasoline engine. However, for a BEV equipped with similar battery and electric motor systems, the safety estimate discount of real-world AER may be 30% or higher, as noted earlier.

The GC in the CS mode falls as speed increases in the downtown area, but the speed dependence tends to be stable compared to ICEVs. Table 2 shows the GC performance in all speed ranges with different AC and loading conditions. For example, in the benchmark scenario, the average GC of the CS mode is 4.2 L/100 km (normal traffic), and the PHEV achieves 4.5 L/100 km under the heavy traffic condition. When the city traffic becomes less congested, the GC drops 10% to 3.7 L/100 km. Although less energy effective under the heavy traffic condition, the PHEV could save larger amounts of gasoline in its CS mode than the gasoline counterpart (Appendix C). In the benchmark scenario, the GC saving rates of the PHEV range from 66% (heavy traffic) to 47% (light traffic). In the CS mode, the hybrid system uses the battery as a reservoir for harsher operating conditions. When working outside the best fuel economy conditions, the hybrid system keeps the engine operating in the high-efficiency area as long as possible by using the battery to balance the residual power demand. Meanwhile, the engine can charge the battery when the engine power is beyond the demand, e.g., during braking or idling conditions.

Similar to the CD mode, added loading mass and AC usage would increase the GC in the CS mode under all scenarios. For example, under the normal traffic condition (20–30 km/h), the average GC is increased by 19% when the AC is on plus full load relative to the benchmark (i.e., 5.0 L/100 km vs. 4.2 L/100 km). Under the heavy and light traffic conditions, the harshest conditions could increase the average GC by 40 and 16%, respectively. Similar to the CD mode, AC usage is a significant contributor to extra fuel demand in the CS mode. As seen in Table 2, AC usage could increase the GC singly by 24, 14, and 8% on average under the heavy, normal, and light traffic conditions, respectively, whereas the full load could increase GC by 18, 12, and 8%. The largest difference between AC and load impact occurs in the low speed range, whereas the AC impact weakens as speed increases. However, unlike the CS mode, the AC and load impact gaps exist in most speed ranges and remain relatively stable in the CD mode, usually around 5%.

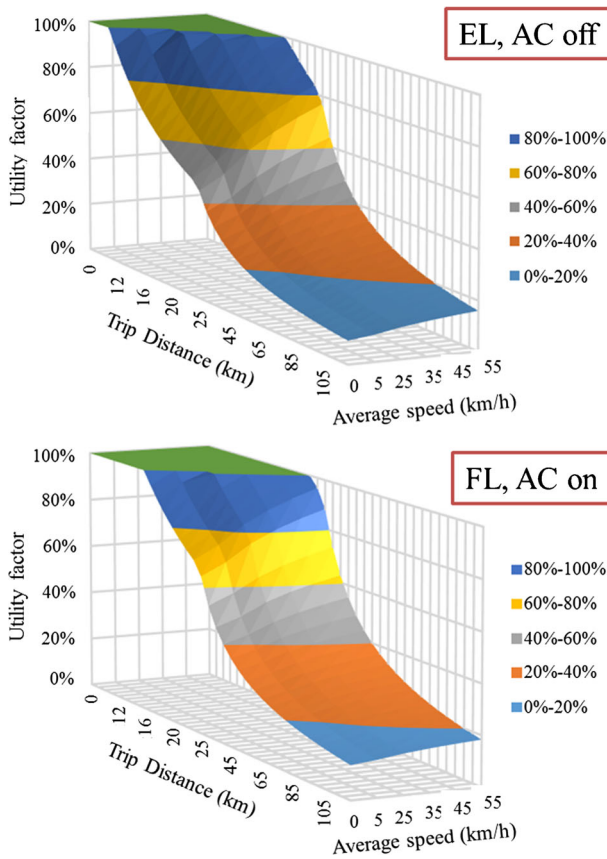
In addition, the PHEV on-road gasoline benefit decreased when the speed range exceeded the city travel pattern. We also tested the highway GC results in only the CS mode (EL, AC off) and found that the EC increases when the average speed surpasses the inflection around approximately 60 km/h. Because our previous PEMS tests provided limited data under high-speed conditions, we refer to the COPERT4 model for the speed corrections over 70 km/h (Ntziachristos and Samaras 2014). As Appendix C indicates, PHEVs could save approximately 40% of GC if the average speed exceeds 70 km/h, lower than that of the CS mode in city travel (i.e., 66% under the heavy condition, EL, AC off). Thus, considering that trip lengths of highway travels (e.g., inter-city) are very likely to exceed the AER, PHEVs tend to achieve less energy reduction relative to ICEVs when they are operated on highways rather than for urban travels.

### 3.2 The utility factor and equivalent FC of the PHEV under different scenarios

Based on the real-world travel pattern data, we evaluated the UF for urban trips for every 10 km/h from 5 to 55 km/h and every 10 through 100 km. In particular, the UF change from 10 to 25 km was calculated in a finer distance resolution of 1 km, because it represents a distance range in which the shift between CD and CS modes mostly likely occurs. As the surface shows in Fig. 2, each point in the surface represents the maximum UF of one trip (fully charged), with a certain trip length and speed under prescribed AC and loading mass conditions. Furthermore, with the UF surfaces and FC functions of the CD and CS modes, the total FC could be simulated by combining two separate parts.

Trip length and speed are proven to be two major factors in real-world maximum UF. First, under the benchmark scenario (i.e., AC off and EL), a fully charged PHEV can achieve a UF of 100% until the trip lengthens to 19 km at an average speed of 25 km/h. However, when average speed varies from 5 to 55 km/h, the longest distance to achieve a UF of 100% varies from 16 to 22 km. As the length continues to increase, the UF becomes lower as the speed decreases, indicating that the distance fraction of the trip powered by the engine tends to be greater.

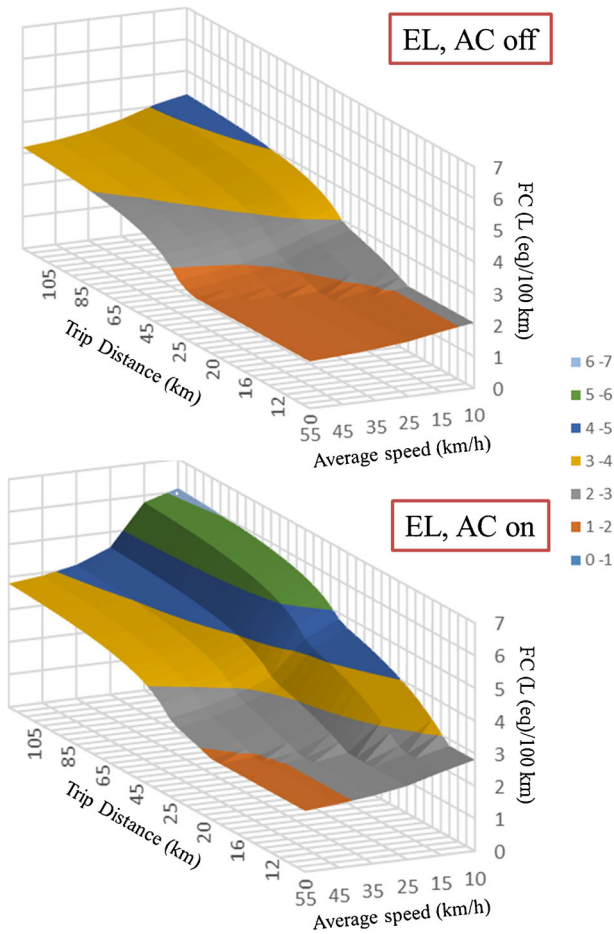
If AC, passenger load, and battery SoC are all fixed, trip length and speed would synergistically affect the on-road FC of the PHEV. The low FC domain (i.e., indicated in orange, lower than 2 L (eq.)/100 km) in Fig. 3 represents the CD mode of the PHEV, and the other part of the FC surface is mixed with the CD and CS modes. Shorter trip length is a positive factor, resulting in lower FC for PHEVs. For example, the FC of a fully charged PHEV (i.e., 25 km/h, EL, and AC off) stays at 1.7 L (eq.)/100 km before the trip distance is



**Fig. 2** The utility factor profile of certain trips under a wide range of traffic (speed) and vehicle (AC and passenger load) conditions. We controlled the initial SoC and blend CD mode situations (i.e., initial SoC at 100% and no CD blend) to simplify the cases

over 19 km (Fig. 3a). As the trip distance becomes longer, the FC would approach the result of the CS mode, and the benefit of high energy efficiency in the CD mode decreases. The overall FC (i.e., 25 km/h) increases gradually to 3.6 L (eq.)/100 km for a trip of 100 km, which is only reduced by 12% compared with the average FC in the CS mode (i.e., 4.1 L/100 km). Average speed also affects the equivalent FC significantly. For example, as the average speed changes from 10 to 55 km/h, the benchmark scenario FC to travel 19 km varies by 1.5–2.5 L (eq.)/100 km (Fig. 3a), whereby the PHEV under the heavy traffic condition (i.e., 15 km/h) has already switched to the CS mode. Therefore, short trip length and higher speed result in highly efficient PHEVs, whereas short trip length and low speed conditions bring about larger energy-saving benefits than the gasoline counterparts.

AC usage and full load reduce the highly efficient CD mode area (mostly below 2.8 L (eq.)/100 km, Fig. 4), and AC contributes more significantly to extra FC than the full load, as mentioned earlier in this paper. Compared with the benchmark scenario, the equivalent FC of a 19-km-long trip increases to 2.8 L (eq.)/100 km under the harshest conditions (i.e., 25 km/h, AC on, FL), an increase of 65%. The CD mode ends as the trip reaches 16 km, and the remainder has to be powered by the engine. As the trip extends to 100 km, the equivalent FC



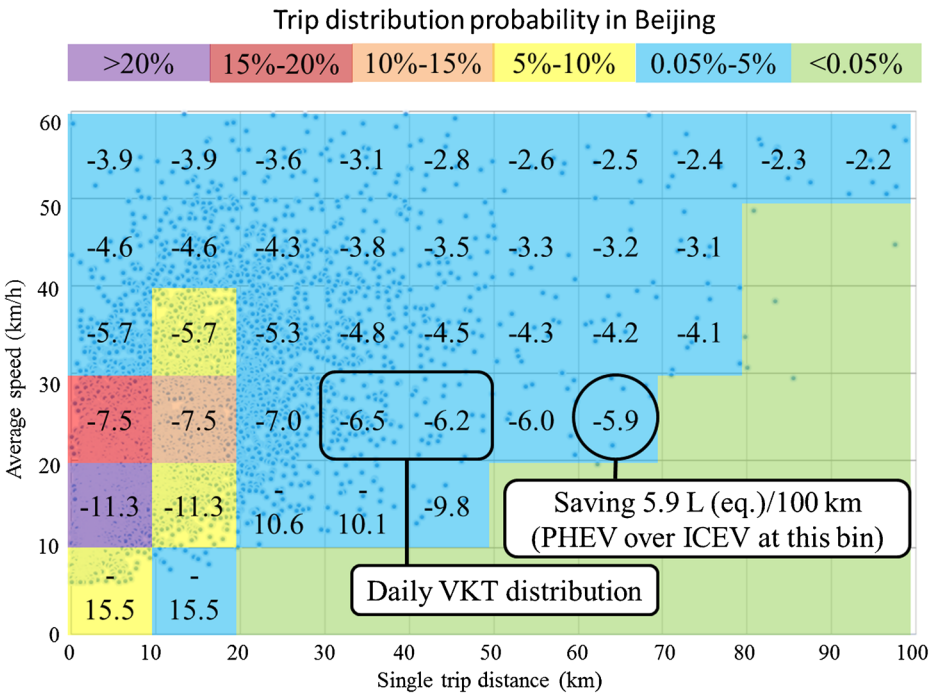
**Fig. 3** The equivalent FC of PHEV for different trip distances and speeds, AC, and passenger load conditions; a combination FC of CD mode and CS mode

rises to 4.5 L (eq.)/100 km (i.e., 25 km/h, AC on, FL), which is increased by 10% over the benchmark scenario result.

In a word, the real-world FC correction of a PHEV is not a fixed value but should be prudently derived from the test profiles and to follow a series of settings for vehicular and travel conditions. According to the Beijing travel pattern survey, drivers seldom drive long distances at a low average speed in cities (the green bins of Fig. 1). The actual UF or FC profiles tend to be smaller than the profiles shown in Figs. 2 and 3. Thus, the actual FC profile is only a portion of that illustrated (the top EC is likely to stay below 4.0 L (eq.)/100 km), and travel pattern impacts should be included to accomplish the determination of on-road FC.

### 3.3 On-road PHEV energy-saving potential: a case study of Beijing

In this section, we discuss the impact of travel patterns on real-world FC for PHEVs. To simplify the analysis, the benchmark scenario is selected with AC off



**Fig. 4** The maximum PHEV gasoline saving benefit distribution under different trip speed and length bins in Beijing (EL, AC off). The number of each bin shows the energy savings (L (eq.)/100 km) of PHEV compared to gasoline ICEVs under the same conditions; the color means different distribution probability

and no additional passengers other than one driver. The number in each bin of Fig. 4 shows the amount of equivalent gasoline saved if a PHEV replaces a conventional gasoline ICEV.

Although the PHEV have lower FC for high-speed and short-distance trips, but the energy-saving benefit relative to the ICEV is most significant for congested and short-distance trips. First, the FC gap between PHEV and ICEV narrows as the average speed increases. The FC difference drops from 11.3 L (eq.)/100 km in the domain of 0–10 km and 10–20 km/h to 3.9 L (eq.)/100 km in the domain of 0–10 km and 50–60 km/h. Then, the trip length also changes the energy-saving potential. According to Fig. 4, when the trip is lengthened to 100 km while keeping the speed stable (i.e., 50–60 km/h), the FC gap drops further to 2.2 L (eq.)/100 km. Although the longer trip increases the FC of PHEVs, these trips seldom occur in the entire Beijing travel pattern.

Combining the FC results of bins (Fig. 4), the maximum (fully charged) probability-weighted FC of PHEVs under the Beijing travel pattern is 1.9 L (eq.)/100 km. Similarly, the ICEV achieves 11.5 L/100 km, and the PHEV reduces the FC by 83%. Meanwhile, if all trips are undertaken after the dashboard SoC fell to zero, the PHEV would behave like an HEV and could save 64% of total energy use. When focusing on the nine red bins described in Fig. 1, the probability-weighted PHEV FC is 1.8 L (eq.)/100 km on average, which represents 81% of the total trip distribution and dominates the travel pattern-based EC. The total 7702 trips indicate the representative travel pattern of 24.0 km/h of average speed and 13.6 km of trip length. The 20 km of AER is not abundant for long-distance travel, but based on the travel pattern survey,

82% of the trips are shorter than 20 km. Although AC usage and higher load mass may shorten the actual AER, a fully charged PHEV may still be able to finish a major part of the first of the daily trips using electricity. Further, 77% of the total trips occurred with an average speed lower than 30 km/h and 44% under 20 km/h. Therefore, the ICEV user has few chances to drive a long distance in the most efficient fuel economy zone of their daily travel. Based on the single trip distribution, the PHEV (AER of 20 km) is a good choice to replace the ICEV in typical Chinese cities, either in the CD, CS, or combined modes.

Daily VKT consists of several single trips and has different trip distribution characteristics. According to the GPS data investigated, the probability-weighted single trip distance and daily VKT of 500 Beijing users are 13.6 and 44.0 km. However, the speed distribution for the daily VKT is more complex than the speed distribution of the single trips. Large samples and long-term observation are needed to improve the representative of travel data and the estimation accuracy of energy consumption. If the average daily travel pattern is simply defined as 44.0 km with a speed of 24.0 km/h, the white-frame bins in Fig. 4 best represent the daily travel-based energy-saving benefits on the presumption of fully charged only during nighttime. Under this circumstance, the energy-saving potential of PHEV could be up to 71% (EL, AC off) at most in the daily travel pattern. For the short AER PHEV, the CD mode could cover daily VKT partially (UF ~48%). For a PHEV equipped with a larger battery, its energy-saving benefits may be improved but accompanied by higher vehicle cost to customers, which needs further analysis to optimize.

## 4 Policy implications

Although PHEVs could achieve high energy-saving rates compared with the ICEV counterparts, their real-world energy use could be much higher than that under ideal scenarios. For example, we gathered real-world GC data for eight PHEV models available in China reported by 236 car drivers (Xiaoxiongyouhao 2016). The type-approval FC (electricity consumption excluded) values for those PHEV models range from 1.6 to 2.4 L/100 km. By contrast, their real-world GC results (note: EC data unknown) are significantly higher by 109 to 391% than type-approval values, ranging from 5.0 to 9.8 L/100 km (see Table 3). In addition, the correlation variances are distributed approximately from 30 to 40%, which are higher than their ICEV counterparts (MIIT 2016) and indicate great bias in vehicle usage conditions.

Significantly higher real-world FC of PHEVs can be primarily attributed to several major issues. The current type-approval regulation and test procedure for PHEVs in China is quite different with their real-world travel patterns. First, the EC is separately informed and not taken account into final type-approval fuel consumption results (see Appendix D) (GAQSIQ 2005). The EC is separately informed and not taken account, and the final type-approval FC level exclusively consider the GC result (GAQSIQ 2005). They set the valid tested AER (GAQSIQ 2005) and an assumed 25 km as the weight of CD and CS modes separately, and the gasoline use of CD is zero in the type-approval FC calculation. Thus, the longer the AER is, the lower type-approval FC could be achieved. For example, we tested one Prius PHEV over three consecutive NEDCs, and the first and the third ones could represent the type-approval gasoline and electricity consumption test situations for CD (or CD blended) and CS modes, respectively (see Appendix E). The GC values over the first and third NEDCs were 0.9 L/100 km and 4.6 L/100 km,

**Table 3** Real-world fuel consumption voluntarily reported by car drivers for eight PHEV models available in China<sup>a</sup>

Manufacturer	Model	Model year	Type-approval fuel consumption (L/100 km)	Type-approval AER (km)	Distance share of CD mode <sup>b</sup>	Real-world fuel consumption		Road-to-lab ratio	Number of car users
						Mean ± standard deviation (L/100 km)	Correlation variance		
BYD	Qin 1.5 T	2015	1.6	70	0.74	7.30 ± 2.16	30%	456%	6
BYD	Qin 1.5 T plus	2015	1.6	70	0.74	6.54 ± 2.44	37%	409%	39
BYD	Qin 1.5 T	2014	1.6	70	0.74	6.58 ± 1.88	29%	411%	72
BYD	Tang 2.0 T AWD	2015	2	80	0.76	9.81 ± 2.77	28%	491%	69
SAIC	Roewe e550	2016	1.6	58	0.70	6.29 ± 2.35	37%	393%	5
SAIC	Roewe 550 Plug-in	2014	2.3	58	0.70	5.78 ± 2.29	40%	251%	21
GAIC	GA5 Elite	2015	2.4	50	0.67	6.24 ± 2.50	40%	260%	10
GAIC	GA5 Exclusive	2015	2.4	50	0.67	5.01 ± 1.61	32%	209%	14

<sup>a</sup> The real-world fuel consumption data voluntarily reported by car users are gathered through the smartphone APP Xiaoxiongyouhao [39]. Because only domestic brands of PHEVs can be subsidized, therefore data for imported PHEVs and international brands of models are very limited

<sup>b</sup> The distance share of CD mode for calculating type-approval fuel consumption is estimated as the ratio of the type-approval AER and the total distance that is the sum of AER and 25 km [44]

indicating an overall weighted GC of 3.7 L/100 km as its type-approval FC according to China's current regulations. As a result, motivated by purchase subsidy policy and fuel economy standards in China (Wu et al. 2017), domestic PHEV models tend to have larger battery capacity (i.e., higher AER) and higher power rating of electric motor (or called extended range electric vehicles). Thus, the domestic PHEVs can gain low overall type-approval GC by increasing the distance allocation of CD mode (e.g., 0.67 to 0.76, see Table 3) and avoiding CD blended conditions (note: all the PHEVs have no GC in the CD mode, namely no CD blended conditions) during the type-approval AER test procedure. In addition, as we presented above, complex operating conditions such as traffic congestion, AC use, and high load mass would shorten the AER and increase GC in CS mode. More importantly, the charging infrastructures are to be developed yet (CATARC 2016), which limit the charging opportunities of PHEVs. By comparing results in Tables 2 and 3, we could conclude that a major part of existing PHEV users have not considerably utilize the battery electricity (i.e., CD mode) to power the vehicles, because their real-world GC levels are close to those fully in CS mode. PHEVs could have the opportunity to realize very low FC by using battery electricity, however, which has rarely happened according to the actual GC profiles of PHEVs. Therefore, the distance allocation of CD mode is significantly overestimated, and the weighting method may not represent the real-world travel patterns.

Since 2012, the phase III limits of fuel economy standard for LDPVs in China have introduced an overall fuel consumption bar for each vehicle manufacturer, which is the Cooperate Average Fuel Consumption (CAFC) (GAQSIQ 2011). The CAFC of each vehicle manufacturer is weighted by annual sales of each vehicle model. In 2015, the MIIT released the phase IV limits of China's fuel economy standard for LDPVs, setting a target of 5.0 L/100 km as the national average fuel consumption (NAFC) by 2020, a reduction of 28% compared with the NAFC in 2015 (i.e., 6.9 L/100 km) (GAQSIQ 2014). To promote the production of BEVs and PHEVs with AERs higher than 50 km, their annual sales will be multiplied an adjustment factor greater than 1 (e.g., adjustment factors of 5 in 2016 to 2017, 3 in 2018 to 2019, and 2 in 2020) (GAQSIQ 2011). Therefore, deployment of BEVs and PHEVs would be a very important approach by manufacturers to comply with the increasingly stringent limits of CAFC and spare more production capacity for high-profit vehicles (e.g., sport utility vehicles (SUVs)) that usually have high type-approval FC. For example, in 2015, China's annual sales of SUVs jumped to 6.22 million, an impressive increase of 52% (China Association of Automotive Manufacturers 2016). However, the real-world FC data gathered suggest that PHEVs consume much more gasoline than expected, and the adjustment factor of weighted sales would further enlarge the gap between CAFC and the actual level.

Furthermore, China's case study reflects the global challenges of designing regulations and incentives to promote EV development. A global review of supportive policies for EVs also indicates the absence of real-world usage factors when formulating relevant regulations and incentives (ICCT 2014). Either purchase subsidies or tax reductions would be determined according to vehicle specifications (e.g., battery capacity, AER) or type-approval tests (e.g., CO<sub>2</sub> emissions, fuel consumption), which have not taken into real-world impacts or individual heterogeneity into account. Although PHEVs could bring in fuel cost saving during the in-use stage, such benefits only play a minor role in total economic incentives to promote PHEVs compared with other one-time incentives. As we present in this paper, one-time purchase subsidies or tax exemptions provided by governments could not guarantee the energy-saving



benefits as global policy-makers expect. Thereby, real-world energy efficiency should be applied as criteria to develop future energy efficiency regulations and supportive policies for electric vehicle technologies. Policy-makers should encourage the usage of more advanced real-world energy efficiency monitoring techniques for emerging electrified transportation modes and switch to a policy framework (e.g., regulations, incentives) emphasizing real-world climate benefits.

## 5 Conclusions

Travel patterns affect PHEV energy consumption significantly. Travel patterns could be employed in the FC profiles to properly simulate the results in typical cities or individual trip chains. From the microperspective, we constructed the on-road EC profiles of the CD and CS modes of one type of PHEV. From the macroperspective, we collected data of the travel patterns of cities and individual trip chains using a large sample survey.

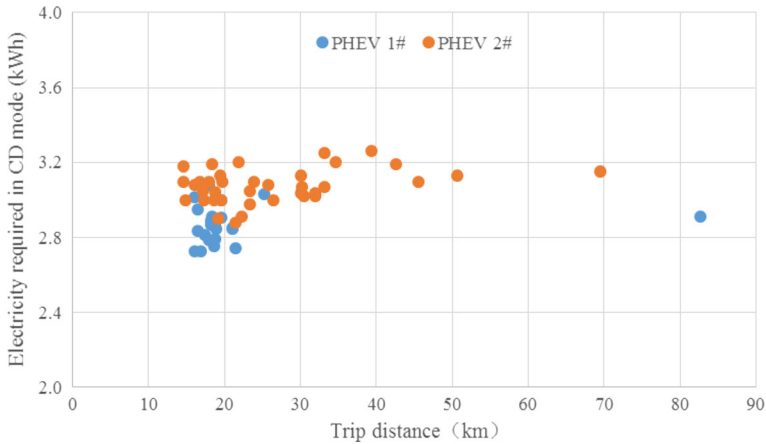
Many real-world factors affect the energy-saving benefits of PHEVs. In this Beijing test, we focus mainly on travel patterns (average speed and trip length) and vehicular conditions (AC and passenger load and the SoC condition). Correspondingly, the PHEV could achieve 20 km AER under the conditions of AC off, no passenger, and normal or better traffic conditions. However, the designed AER is shown to be the most optimistic level. Under the worst-case conditions, the users might only have a much shorter AER as low as 14 km. The safe estimation of the real-world AER discount should be over 30% of the nominal AER. Real-world energy use under both the CD and CS modes for tested PHEVs is less sensitive to changes in speed than that of the ICEV counterparts, resulted in a larger FC reduction benefit when traveling in the congested urban areas. Considering the vehicular condition factors affecting FC, AC is a more important contributor than passenger load in both CD mode and CS mode.

Combining the FC results of trip bins together, the maximum probability-weighted PHEV FC of Beijing is 1.9 L (eq.)/100 km (empty load and AC off), reducing up to 83% of the total energy consumed by the ICEV. If the SoC falls to 0%, the PHEV, considered as a grid-independent “HEV,” could also save approximately 60% of the energy. The PHEV could perform better under smooth traffic conditions but saves a larger amount of energy on a congested road because the ICEV is more speed-sensitive than the PHEV. However, in reality, users cannot be assured of the fully charged condition before every trip, so the energy-saving benefit varies between fully charged and conventional hybrid results. For example, real-world FC results for eight PHEV models in China reported by vehicle users range from 5.0 to 9.8 L/100 km, significantly higher than their type-approval results. Therefore, our real-world measurement study suggests that future energy regulations and incentives concerning global EV development use real-world energy efficiency as one important judgment aspect.

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### Appendix A CD mode energy consumption distribution of tested trips



**Fig. 5** CD mode energy consumption distribution of tested trips; the EC represents the total charging amount from local power, including the EVSE and charging and discharging loss)

### Appendix B Key parameters for the reference ICEV model

**Table 4** Key parameters for the reference ICEV model, under the urban driving conditions

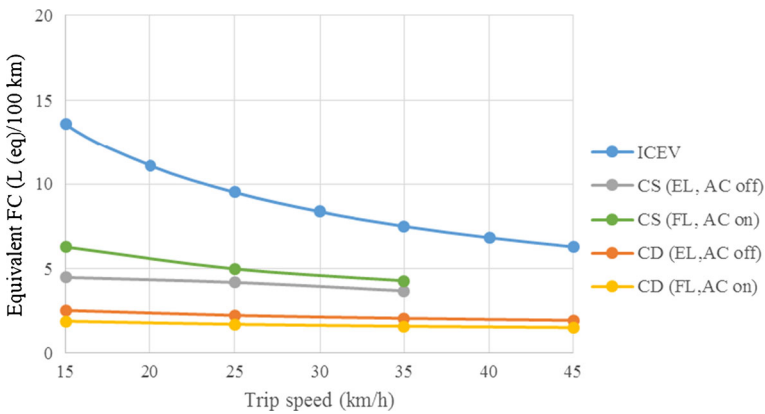
Model type	Baseline GC (l/100 km)	Relative GC of gasoline ICEV <sup>b</sup>	GC in speed ranges (l/100 km) <sup>c</sup>			
			Heavy traffic	Normal traffic	Light traffic	Free flow
Toyota Corolla (1.8 L CVT)	8.24 <sup>a</sup>	$REC_{ICEV} = 11.378 \times \bar{v}^{-0.698}$ ( $R^2 = 0.93$ )	14.2	9.9	7.8	6.6

<sup>a</sup> The baseline GC of reference Corolla was measured by averaging 767 real GC reports from Xiaoxiongyouhao (Xiaoxiongyouhao 2016)

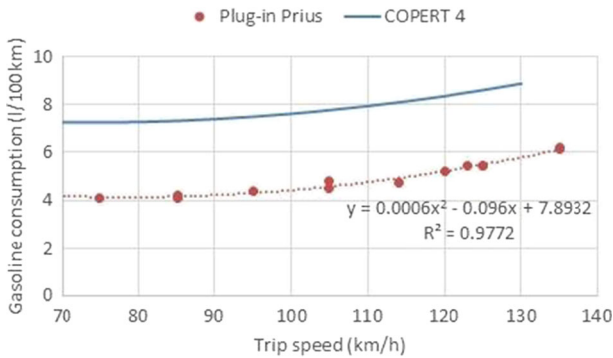
<sup>b</sup> The speed-dependent function for estimating fuel consumption is rewritten according to Zhang et al. (2014d), which is applicable to average speed lower than 70 km/h (2014)

<sup>c</sup> The average speed of heavy, normal, light, and free traffic range is 15, 25, 35, and 45 km/h

### Appendix C On-road speed corrections of PHEV and the ICEV



**Fig. 6** On-road speed corrections of PHEV and the ICEV counterpart for their urban travels, average speed lower than 45 km/h. The on-road fuel consumption for ICEV is estimated according to self-reported data by Toyota Corolla drivers (Xiaoxiongyouhao 2016) and the speed correction curve based on our previous PEMS measurement (Zhang et al. 2014d) (see Appendix B)



**Fig. 7** On-road speed corrections of PHEV and the ICEV counterpart for their high-speed travels, average speed higher than 70 km/h. The on-road fuel consumption for ICEV is estimated by using the COPERT4 model (Ntziachristos and Samaras 2014) for the category of 1.6–2.0 L Euro 4 gasoline cars

### Appendix D Calculation method of type-approval electricity and fuel consumption for PHEVs in China

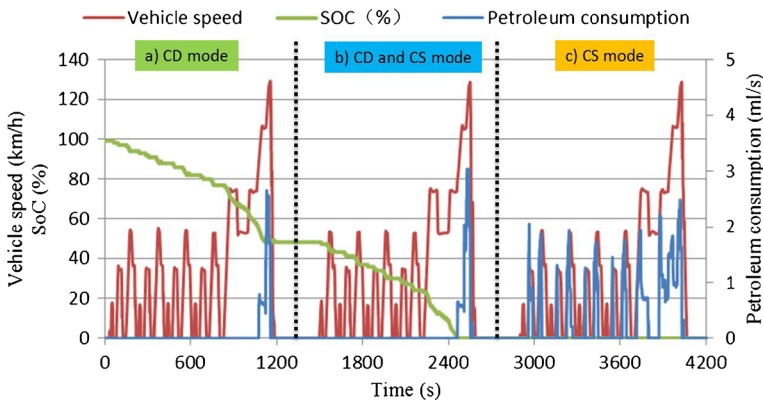
$$Gasoline\ consumption(GC) \quad C = \frac{D_e \times C_1 + D_{av} \times C_2}{D_e + D_{av}} \tag{1}$$

$$Electricity\ consumption(EC) \quad E = \frac{D_e \times E_1 D_{av} \times E_4}{D_e + D_{av}} \tag{2}$$

where  $C$  is the type-approval GC value, L/100 km;  $C_1$  and  $C_2$  are tested GC values under CD (or CD blended) and CS modes over the NEDC, L/100 km;  $E$  is the type-approval electricity consumption value, kWh/100 km;  $E_1$  and  $E_4$  are tested electricity consumption values under CD (or CD blended) and CD modes, kWh/100 km;  $D_e$  is the type-approval AER tested according to the regulation, km; and  $D_{av}$  is the assumed distance of CS mode and is fixed at 25 km (GAQSIQ 2005).

It should be noted that currently China's type-approval fuel economy for PHEVs only takes the GC ( $C$ ) of PHEVs into account for evaluations of CAFC and NAFC.

## Appendix E Second-by-second SoC conditions as well as the gasoline consumption of a PHEV in three consecutive NEDC certification driving cycles



**Fig. 8** Second-by-second SoC conditions as well as the GC of a PHEV in three consecutive NEDC certification driving cycles; the second cycle is partially powered by CD mode and the equivalent EC is between the pure CD and pure CS mode EC

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