UTILITY FACTORS DERIVED FROM BEIJING PASSENGER CAR TRAVEL SURVEY

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ABSTRACT –
This study is aimed to reveal the high sensitivity of PHEVs and BEVs utilization to real using and charging conditions in a specific region (Beijing, China). GPS loggers are adopted to collect driving data of near 10,000 km travel distance for about 4,892 trips in 2003 travel days. UFs of PHEV and BEV under various charging patterns are studied and compared. The results show that the utilization of PHEVs as well as BEVs are intensively affected by charging patterns, and constant public place charging brings more benefit compared with deploying charging infrastructures everywhere. If the CD range exceeds 100 km or AER reaches 150 km, only night charging is necessary. Cost and benefit analysis of BEV based on UF indicates AER less than 200 km is a cost-effective choice for the current Beijing passenger car travel pattern.

1. INTRODUCTIONS

China has implemented research and development programs for alternative fuel vehicles, especially for plug-in hybrid vehicles (PHEVs) and battery electric vehicles (BEVs) for 20 years to build a sustainable transportation system[1, 2]. However, due to the limitation of battery performance, BEVs and PHEVs with smaller batteries induce a shorter driving range and longer recharging time than conventional vehicles. The driving patterns are essential to understand the benefit of energy saving and emission reduction brought by PHEVs and BEVs. For PHEVs which can be fueled from liquid fuels and grid electricity, daily driving patterns are essential to estimate the contribution of both fuels[3]. For BEVs with a limited all electric range (AER), not all the trips can be substituted by a BEV, so the utilization intensity heavily depends on the daily driving range.

For PHEVs evaluation, Utility Factor(UF) is introduced to represent the portion of liquid fuel and grid electricity consumption, which is defined in SAE 2841[4] and SAE 1711[5] standard. There are many expansions and deep studies of the UF concept. Bradley T et al studied alternatives to the standard UF from the 2001 NHTS, so as to understand the sensitivity of PHEV performance to charging frequency, vehicle characteristics and other factors[6]. The UF of BEVs was proposed by Michael Duoba to represent the expected utility of electric drive capability at given BEV range[7]. In particular, the usage of PHEVs and BEVs are intensively affected by charging patterns, which has not been well studied and reflected in UF formulation. To evaluate the energy and environmental impact of PHEVs and BEVs, driving and charging patterns of a specific region should be observed and a comprehensive indicator should be developed.

There are many published studies on driving patterns, which mainly adopt the questionnaire survey and onboard instruments records (usually the GPS loggers) methods[8, 9]. However study on driving patterns and UF of China just starts[10, 11]. In order to gain more detailed and accurate data of Chinese driving patterns, the regional travel survey of Beijing passenger cars was conducted[12, 13].

UFS of PHEV under typical charging patterns are studied based on data of the travel survey. Based on the UFs, the energy consumption of PHEVs are presented to reveal the real-world situation in Beijing. UFs of BEV under charging patterns are constructed and the benefit of charging infrastructures are compared. The cost and benefit analysis of BEV are conducted to provide advice on the optimal battery size.

2. BEIJING PASSENGER CAR TRAVEL SURVEY
For the Beijing passenger car travel survey, GPS loggers were adopted to collect the data and 112 volunteer vehicles were observed from June 2012 to March 2013. A large database of near 10,000 km travel distance in 2003 travel days for about 4,892 trips were constructed.

The average results are firstly presented to reveal general features of Beijing passenger cars. For vehicles in Beijing city, the average daily driving distance was about 39 km, while the average travel mileage per trip is about 16 km. It is coordinated with the average daily travel frequency of less than 2.5 times. The average daily travel time is about 95 min, while the average single-trip travel time is about 37 min. The average daytime parking time is about 4.8 h, which may offer the possibility of workplace charging.

In order to study the UF, the distribution of daily driving range set $S$, and single trip range set $T$ are provided, as is shown in Figure 1. Let $d_i$ be a daily distance driven by a particular vehicles, $N_i$ is the total number of vehicles multiplied by the total number of driving days considered in the set $S$. In the single trip set $T$, $t_{ij}$ is the $j$th trip of the $i$th travel day. The standard UF is specifically studied with the $S$, while extended UF may involve the single trip set $T$.

$$S = \{d_1, d_2, \ldots, d_{N_s}\} \quad N_s \text{ is all the travel days}$$

$$T = \{t_{i1}, t_{i2}, t_{i3}, \ldots, t_{ij}\} \quad i \in N_s$$

![Figure 1](image_url)

**Figure 1** a distribution of daily driving range  b. distribution of single trip driving range

### 3. UF OF PHEV UNDER 3 CHARGING PATTERNS

Charging patterns including charging duration, place and frequency may have a significant impact on the utilization of PHEV. Surveys suggest that home charging at night is the most common charging mode because of the easy access of a charger and long parking durations. If a PHEV can only be charged at night, the battery will be depleted as the trip exceeds the AER then the vehicle maintains charge sustaining (CS) mode in the left of the whole day trip. However if a PHEV can be recharged at midway, it can use more grid electricity. To better describe the usage of PHEV, three typical charging patterns are studied and the corresponding UF is calculated.

#### 3.1 Standard UF under home-charging-only pattern

The first charging pattern is charging PHEV only at night/home. It is also the precondition of the SAE standard J2841, which assumes that the vehicle begins each travel day fully charged. The vehicle starts each day in the charging depleting (CD) mode, and if the trip exceeds the AER, the vehicle switch to charge sustaining (CS) mode. Based on the distribution of daily driving range $S$, the standard UF are calculated, as Figure 2 shows.

$$UF(R_{CD}) = \frac{\sum_{d_i} \min(d_i, R_{CD})}{\sum_{d_i} d_i}$$
The distribution percentage of daily driving range shows that the vast majority of daily driving distances are less than 100km and tend to short range, and the range highly concentrates in 15km-18km, accounting for 7.44%. The UF is 0.4218 at 20 km CD range and 0.7361 at 50 km CD range, which means PHEV fleet with a 20 km CD range can drive on electricity for 42.18% of the daily trips and if the CD range rises to 50 km, the percentage rises to 73.61%. However after the CD range exceeds 100 km, UF is over 0.9 and increases slowly.

3.2 UF under day & night charging pattern

As the development of fast charging technology and the deployment of public charging infrastructures, the day & night charging pattern may become common. Then vehicles can begin each day fully charged and get recharged at public places. The adding benefit of public charging should be evaluated to justify the investment of infrastructures.

To derive UF under this pattern, we assume vehicles get charged at the longest parking duration in each day. Usually people park the car at constant public places like working places or school and so on for the longest time in the daytime. The daily trips should be examined as a chain to find the maximum stop duration and the starting time of the park. Then all the trips before and after the parking duration are summed to be 2 new trips denoted as \(d_{1,1}\) and \(d_{1,2}\). The trip set \(T\) are processed to a new trip set \(S'\).

\[
S' = \{d_{1,1}, d_{1,2}, d_{2,1}, d_{2,2}, \ldots, d_{N,1}, d_{N,2}\}
\]

The starting time of the maximum parking duration and the maximum duration are shown in Figure 3. The starting time concentrates on 8, 9 and 10 a.m. with 14.52%, 20.00% and 11.98% respectively, which means nearly half of the vehicles will get charged from 8 to 10 a.m., thus causing an intensive power shock on the grid. The mean of the maximum parking duration is 5.64 hours, which ensures the PHEV can generally be fully charged even with the current charging technology.
Similar with the standard UF, the UF2 is derived with the set S' and is shown in Figure 4.

\[
UF_2(R_{CD}) = \frac{\sum d_m \min(R_{CD}, R_{CD} + d_m)}{\sum d_m}
\]

The distribution of S' shows the trips are generally less than 50 km and 29.89% of the trips are below 9 km, which is more short-range concentrated than the daily driving range. That is, the daytime charging enables vehicles to start more trips fully charged. The corresponding UF are thus higher than the standard UF, with 0.5861 at the 20 km range and 0.8296 at 50 km range.

3.3 UF of PHEV under charging everywhere pattern

Another extreme scenario is that vehicle can get charged everywhere. The public chargers or even wireless charging makes it possible. It also reflects the maximum benefit of charging infrastructures. This UF is defined by the condition that vehicles can get fully charged after each trip, so the distribution of single trips is adopted to derive the UF. Note that in our study ‘a trip’ is segmented if the stop time is over 0.5 hour. The stop time is reasonable for PHEV charging if a charger is easily accessed. The UF is shown in Figure 5 and the comparisons are below.

\[
UF_3(R_{CD}) = \frac{\sum d_m \min(t_{ij}, R_{CD})}{\sum d_m}
\]
3.4 Comparisons between UF under 3 charging patterns

The UFs of Beijing under 3 charging patterns are compared in Figure 6, which shows the utilization is highly sensitive to charging patterns. At the 20 km CD range, the gap between UF of night & day charging and standard UF is 0.1673 while that of night & day charging and charging everywhere is 0.0729. The gap indicates that public charging brings significant increase of PHEV utilization compared with night charging only phenomenon (16.73% increase at 20 km CD range). However, applying charging infrastructures everywhere, though more costly, but brings limited benefit. At the CD range of 50 km, the results are similar, but when the CD range exceeds 100 km, the three UFs converge quickly.

The implications of UF are, if the CD range is short due to the limit of batteries, constant public place charging are beneficial besides the necessary home charging. However it might not be reasonable to deploy chargers everywhere. If the CD range is large than 100 km, then public charging infrastructures will be unnecessary.

To illustrate the impact of daily driving range and charging patterns on the energy consumption, three PHEV models are selected and the energy consumption are calculated based on the data from EPA test[14].
The results are in Figure 7. Apparently, higher UF will lead to more electricity and less fuel consumption. Compared with only charged at night, a Volt will have 45.4% of fuel reduction and 11.6% of electricity increase if charged everywhere. The maximum fuel reduction is 33.2% for Prius plug-in and 49.4% for a Ford C-Max. These figures indicate the potential fuel and emission reduction for vehicles in Beijing.

![Fuel consumption of three typical PHEVs under UF](image1)

![Electricity consumption of three typical PHEVs under UF](image2)

4. UF OF BEV UNDER 3 CHARGING PATTERNS

Due to the limited AER of BEV, the trips cannot be totally satisfied by a BEV so an alternative vehicle must be retained. The BEV+ conventional vehicles (CV) usage mode is more reasonable in the real life, and the UF is essential to evaluate the total energy consumption. Three similar but not same charging patterns are examined.

As to the cost-benefit analysis, BEV is more cost-sensitive to the battery capacity. So the cost of increasing AER should be considered. The cost of owning a BEV consists of the baseline cost $C_0$ compared with a CV and the cost of battery, which is approximated linear with the AER. The benefit is mainly the saved fuel which is linear with the UF. So we would introduce the Benefit Cost Index (BCI) to represent the increase of UF brought by unit AER, thus evaluating the fuel consumption substitution benefit of BEV.

\[
\text{Fleet purchase cost} = N \cdot (C_0 - C_r + AER \cdot k_1)
\]

\[
\text{Fleet benefit} = N \cdot R_{\text{day}} \cdot 365 \cdot \text{UF}(AER) \cdot k_2
\]

\[
\text{Total revenue} = \text{Fleet benefit} - \text{Fleet purchase}
\]

\[
= N \cdot (365 \cdot R_{\text{day}} \cdot k_2 \cdot \text{UF}(AER) - k_1 \cdot AER - C_0 + C_r)
\]

\[
\text{Benefit - cost - index} = \frac{\text{UF}(AER)}{\text{AER}}
\]

4.1 UF of BEV under night charging pattern

For the home-charging-only pattern, only when the sum of the daily trips doesn't exceed the AER or the round trip is shorter than the AER, can the trips be driven by BEV. The trips whose origin and end are within a certain small scope are recognized as the round trips. The UF derivation approach is similar as that of PHEV, but each day must be examined to filter trips that can possibly be substituted by BEV.

\[
BUF_i(AER) = \frac{\sum_{t_{i,j} \leq \text{AER}} t_{i,j} + \sum t_i}{\sum_{t_{i,j} > \text{AER}} t_{i,j}}
\]

\[
\sum t_{i,j} < \text{AER } \text{ or } t_i \text{ is round trip}
\]
The UF and BCI are in Figure 8. The UF is 0.7208 at 90 km AER, which means a BEV with a 90 km AER can drive 72.08% of the daily trips. Increasing the AER can enable the BEV to meet more travel demand. However, the BCI first increase and then decrease, and the maximum BCI comes at AER 64 km, which means each 1 km AER brings 0.9% increase of the total trips driven by BEV. It is the most cost-effective point for investment on battery. When the AER is over 175 km, the BCI is below 0.005. The AER is set to meet as much as travel demand in a cost-effective way, so the indicator UF should exceed 70% while BCI keeps over 0.005. Then AER between 90 and 175 km is recommended.

![Figure 8 UF and BCI of BEV under night charging in Beijing](image)

**4.2 UF under night & day charging pattern:**

If daytime charging is supplemented. The utility of a BEV can be extended. BEV is considered to get charged at the maximum parking duration at constant public places, and the average 5.6 parking hours is enough for charging. Considering the mileage availability, any of the daily 2 trips longer than the AER should be excluded. Based on the trip set $S'$ the UF is derived as Figure 9.

$$ BUF_2(AER) = \sum (d_{i,1} + d_{i,2}) + \sum t_i $$

$$ d_{i,1} \leq AER \text{ and } d_{i,2} \leq AER \text{ or } t_i \text{ is_round_trip} $$

The UF is 0.7016 at 66 km AER, which means a BEV with a 66 km AER can drive 70.16% of the daily trips if get charged midway. The maximum BCI is 0.0132 at AER 35 km, meaning each 1 km AER brings 1.32% increase of the total trips driven by BEV. To ensure the UF is over 70% and BCI is larger than 0.005, the AER can vary from 66 to 180 km.
4.3 UF under charging everywhere.

The idealistic scenario is that a BEV can get charged both at home and out everywhere. The mileage availability should also be considered, so only if all the trips of the same day are shorter than AER, can a BEV is adopted. The UF is derived based on the trip set $T$.

$$BUF_{j}(AER) = \frac{\sum_{t_{i,j} \in T} t_{i,j} + \sum t_{r}}{\sum_{t_{i,j} \in T} t_{i,j}}$$

$$t_{i,j} < AER \ \forall j \ or \ t_{r} \text{ is \_round\_trip}$$

The UF and BCI are illustrated in Figure 10. The maximum BCI is 0.016 at 35 km AER, where UF is 0.56, meaning the BEV of 35 km AER can substitute 56% of the driving demand. In this situation, the AER from 50 to 180 km is the recommended range to maintain high UF as well as BCI.

4.4 Comparisons of BEV UFs and discussions
The UFs of BEV are compared in Figure 11, which shows the utilization of BEV is also highly sensitive to charging patterns. The gap at 50 and 100 km AER are illustrated. Daytime charging brings 16.35% and 8.74% increase of BEV utilization at AER 50 and 100 km separately compared with night charging. Charging everywhere, which seems to be an ideal scenario, brings less benefit than the day charging. If the AER exceeds 150 km, then only night charging is necessary. However, it hide the possibility that consumers might drive longer than usual if they are informed that charging infrastructure is everywhere.

Taking BCI into consideration, when the AER exceeds 200 km, the BCI is below 0.5% and continues to decrease, meanwhile three UFs tend to 0.9 and increase slightly, which indicates that the increasing AER over 200 km produces less benefits than shorter AER. Therefor the AER within 200 km is recommended as the cost-effective choice for the current Beijing passenger car travel pattern. However the consumer preference and development of battery technology may provide other considerations for the optimal AER.

5. CONCLUSIONS AND DISCUSSIONS

This study is aimed to reveal the high sensitivity of PHEVs and BEVs utilization to real using and charging conditions in a specific region (Beijing, China). GPS loggers are adopted to collect driving data. UFs under various scenarios, especially UF of BEVs are studied.

The results show that, the utilization of PHEVs as well as BEVs are intensively affected by charging patterns. Public charging brings significant increase of utilization compared with night charging only phenomenon (16.73% increase for PHEV at 20 km CD range and 16.35% increase for BEV at 50 km AER). However deploying charging infrastructures everywhere seems to be unreasonable. If the CD range exceeds 100 km or AER reaches 150 km, only night charging is necessary.
Evaluation of PHEV shows that, compared with only charged at night, a Volt will have 45.4% of fuel reduction and 11.6% of electricity increase if charged everywhere. The maximum fuel reduction is 33.2% for Prius plug-in and 49.4% for a Ford C-Max. For BEVs, the cost and benefit analysis indicates AER within 200 km is a cost-effective choice for the current Beijing passenger car travel pattern.

The limitations of this study are, the UF only considers charging patterns, while the vehicle and driver characteristics, including range anxiety, battery degradation and so on, are left unconsidered. The travel survey mainly involved conventional vehicles. Long-term observations on private or demonstrated PHEVs or BEVs should be conducted to build more detailed and reliable UF.

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