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Individual trip chain distributions for passenger cars: Implications for market acceptance of battery electric vehicles and energy consumption by plug-in hybrid electric vehicles

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HIGHLIGHTS

- We report the first ITCD profiles in an East Asian megacity based on 459 passenger cars in Beijing.
- Beijing's current travel patterns would be more favorable to the EV deployment than western cities.
- Alternative transportation and traffic restriction can increase BEV acceptance.
- Substantial heterogeneity of energy consumption exists among individual vehicles.
- 50% people can reach considerable low gasoline consumption (3.03 L/100 km) with PHEV50.

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ABSTRACT

The energy and environmental benefits of electric vehicles (EVs) are highly dependent on individual driving patterns. To characterize individual driving patterns in Beijing, a populated megacity in East Asian, GPS-based travel data from 459 private passenger vehicles were gathered covering nearly 17,000 sampling days in 2013–2015. The data were analyzed using a statistical model to produce 0.5 h, 4 h, 8 h and daily individual trip chain distributions, which were used to evaluate customer acceptance for battery electric vehicles (BEVs) based on inconvenience thresholds and to assess the energy consumption for plug-in hybrids (PHEVs). The mean daily distances travelled on weekdays and weekends in Beijing were found to be 44.6 km and 51.4 km respectively. In Beijing the mean habitual travel distance (40.4 km) is modest, the random component of travel distance is lower, and the fraction of habitual travel is higher than for cities in the U.S. and in Germany. These factors make EV deployment in Beijing more favorable than in the U.S. or Germany. We show that the estimated acceptance rate for BEVs is very sensitive to the predetermined inconvenience threshold level. The abundant public transportation alternatives and traffic management in Beijing are factors which reduce the inconvenience of BEVs and may make them acceptable without substantially increased cost for larger battery capacity. PHEVs with all-electric ranges of 50 km (PHEV50) have an ensemble utility factor (UF) and equivalent gasoline consumption estimated to be 0.55 and 4.39 L/100 km. However, for 50% of vehicle owners PHEV50s would have a UF of 0.94 and equivalent gasoline consumption of 3.03 L/100 km. Our results show that attention to heterogeneity among individuals instead of analysis at the ensemble level is essential to understanding the real-world acceptance and benefits of EVs.

Abbreviations: AER, all electric range; BEV, battery electric vehicle; CD, charging depleting; CS, charging sustaining; EV, electric vehicle; eVKT, electrified vehicle kilometres travelled; EVSE, electric vehicle supply equipment; GB, Gigabyte; HEV, hybrid electric vehicle; ICEV, internal combustion engine vehicle; IEA, International Energy Agency; ITCD, individual trip chain distribution; ML, maximum likelihood; NHTS, National Household Travel Survey; PHEV, plug-in hybrid electric vehicle; SAE, Society of Automotive Engineers; UF, utility factor; VKT, vehicle kilometres travelled.

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1. Introduction

Electric vehicles (EVs, including battery electric vehicles, BEVs, and plug-in hybrid electric vehicles, PHEVs) are widely considered as a promising alternative to internal combustion engine vehicles (ICEVs) to improve energy efficiency and utilize renewable energy (e.g., wind and solar power). The International Energy Agency (IEA) has suggested that the EV deployment is an important component of a global future technology roadmap for the on-road transportation sector under the 2 °C *Scenario*, which targets cutting CO_2 emissions more than half by 2050 compared with 2005 [1,2]. EVs can also play an important role in alleviating urban air pollution [3]. Countries in North America, Europe, and Asia Pacific have formulated fiscal policies promoting EV markets [4]. These policies have led to rapid growth in the global EV stock from 180,000 in 2012 to 665,000 in 2014 [5,6]. However, there are cities (e.g., Denver, Riverside) with substantial incentives but without proportionate EV sales [7]. An understanding of individual travel behaviors is required to inform strategies for the optimal development of EVs and associated charging infrastructure [7–9].

To derive travel behavior profiles of potential EV users, previous studies are usually based on conventional travel survey databases, notably the widely cited National Household Travel Survey (NHTS) in the U.S., and concluded aggregated information [8,10,11]. Emerging data-collection technologies, particularly the Global Positioning System (GPS) technology, have been employed to provide cost-effective and accurate recording of time and position data [12]. Since then researchers have improved the evaluations regarding daily range requirements, battery capacity optimization, and market potential [9,13–15]. GPS-based studies of individual driving patterns have been conducted in North America [9,14,15] and Europe [13,16–18] but not in Asia. East Asian megacities have higher population densities, greater passenger transportation demands, and more extensive public transportation systems than cities in western countries [19]. Formulating an optimal strategy for EV design, EV deployment, and charging infrastructure development for East Asian megacities requires detailed and individual vehicle usage data collected locally.

China is a developing country with the world's largest auto market since 2009, and Beijing is the city with the largest vehicle population (i.e., 4.4 million light-duty passenger vehicles by 2014) within China [20]. Beijing is also one of the major hubs for EV deployment in China supported by a series of policies including purchase subsides, tax exemptions, license control and driving restriction exemptions, and provision of charging infrastructure (see *Supplementary Information Section 1 and Table S1*) [21–24]. The Beijing EV market has seen rapid growth with the city's license control agency assigning approximately 60 thousand license plates to EVs making up 40% of newly registered passenger cars in 2016 [25]. Beijing has the busiest subway system (annual ridership of 3.25 billion) and the largest public bus fleet (fleet population of 24 thousand) in the world [20]. Beijing also has widely used taxis and ride-sharing services which could provide flexible travel alternatives to EV owners. Information on the travel behaviors of private car users in Beijing is of use for government stakeholders to formulate transportation policy and for vehicle manufacturers to better understand the opportunities and challenges for EVs in this important market.

Researchers have shown interest in this region, yet several critical issues remain unresolved. Wang et al. [26] collected GPS data from 112 cars in Beijing, but focused on the aggregated driving profiles and ignored the heterogeneity among individual vehicles. Cai and Xu [27,28] evaluated PHEV CO_2 emissions reductions potential and charging station allocation for taxis but travel data for taxis is not representative of that by private passenger cars. We have undertaken a two-year investigation collecting GPS data from 459 conventional private passenger cars in Beijing in 2013–2015. For each vehicle, the data collection duration lasted between one and seven months. The aim of our study is to explore the use of individual trip chain distributions (ITCDs) in terms of EV market acceptance and energy consumption analysis. This study is the first statistical characterization of ITCDs for an international megacity. We compare ITCDs in Beijing with those in cities in the U.S. and Germany. Critical deficiencies in current PHEV energy consumption test regulations both in the U.S. and China are discussed.

2. Methods

2.1. Investigation design and data collection

2.1.1. Sample method

The study spanned two years (2013–2015) with data collected from 459 conventional private cars. For each vehicle, the data collection duration lasted between one and seven months. From April 2013 to July 2013 in the pre-investigation phase, 25 vehicles are selected to calibrate equipment, check data precision, get a gross estimate of the result and improve sampling skills. In this phase, a data filter was developed to clear out raw data and a travel dairy was used to supplement and validate the GPS data. From June 2013 to April 2015, stratified sampling based on home location and work type was applied to collect data from 434 cars. Efforts are taken to ensure the sample size in the eleven major districts in Beijing was proportional to the registered residence population. Due to privacy concerns, other demographics including drivers' income, family size, etc., were not investigated. Unlike the study by Wang et al. [26] where drivers were recruited partially from six companies and the rest by convenience, we recruited drivers from dealer stores and drivers clubs for various car brands as well as via online recruitment in eleven districts of Beijing. Freelancers, unemployed, and small business owners were not included in previous investigations but are included in our study. The demographic information of investigation, including distribution of investigation time length, drivers' home location and occupation are presented in *Supplementary Information Section 2* (see *Figs. S1–S3*).

2.1.2. Equipment

The Columbus™ Multifunction model V990 GPS data logger was used for this study. The device is equipped with a MTKII 66-channels, −165 dBm highly sensitive super single chipset. The logger uses the Enhanced Positioning System technology to improve the GPS position accuracy and reduce drifting. The device is connected to the vehicle through a charging cable and functions automatically with engine on and off. The GPS data logger used a Micro SD card with storage capacity of 4 Gigabyte (GB) sufficient for several months of trajectory data. Raw data profiles contained second-by-second information including date, time, location (longitude and latitude), altitude, speed and direction.

2.1.3. Data filtration

In a small number of cases it was found that the GPS data were inaccurate because of either temporary GPS signal loss, or signal reflection by tall buildings. In the case of signal loss the data logger reported lower distances than the vehicle actually travelled. We compared the distance reported by the GPS data logger to that reported by the drivers according to their odometer and found the average error caused by temporary signal loss was 4.7%. Tall buildings can cause the GPS signal to bounce on its way between