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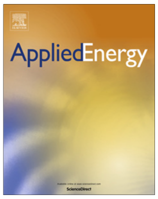

Energy consumption of electric vehicles based on real-world driving patterns: A case study of Beijing ☆

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HIGHLIGHTS

- The real-world driving cycles and driving range in Beijing are clearly studied.
- We assess energy consumptions of electric vehicles in real-world driving conditions.
- Shorter driving ranges and severe driving conditions bring EVs more fuel reduction.
- PHEVs with smaller batteries for 30–50 km CD range are preferred in Beijing.
- The impact of driving patterns on energy use of electric vehicles is quantified.

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ABSTRACT

This study assesses the energy reduction associated with Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs) and Battery Electric Vehicles (BEVs) compared to conventional vehicles (CVs) for real-world driving conditions in a specific geographic region (Beijing, China). To understand the driving patterns in Beijing, a passenger car travel survey has been conducted since 2012, including over 1000 vehicles. The initial results from driving range distribution have been calculated. In this study, first, a Utility Factor and the typical driving cycles based on 2000 days' worth of Global Position System (GPS) data are analyzed. Next, the real-world energy consumption of CVs, HEVs, PHEVs and BEVs are simulated. Finally, the fuel consumption of vehicles under different driving patterns is compared to provide data on the optimal electric vehicles and reliable test cycles for Beijing. We find that electric vehicles in Beijing, including HEVs, PHEVs and BEVs, yield more fuel reduction benefits than in the U.S. because of the severe driving conditions and short driving ranges. For PHEVs in Beijing, smaller batteries, corresponding to a 30–50 km Charging Depleting (CD) range, are preferred to meet the demands of most drivers and add less extra cost to the vehicle. We also confirm that the Chinese current suggested label values based on NEDC cycle underestimate the fuel consumption of vehicles and fuel reduction benefits of electric vehicles in Beijing. This study addresses the importance of developing and using the real-world driving cycles in designing and evaluating electric vehicles.

1. Introduction

Automotive powertrain electrification can achieve low emission and high energy efficiency to mitigate the energy shortage and air pollution brought by transportation sectors [1]. The Chinese government has implemented research, development, demonstration, and deployment programs for clean vehicle technologies for over 20 years to build a sustainable transportation system [2,3]. The national strategy highlights new energy vehicles (NEVs), including electric vehicles (EVs), fuel cell vehicles (FCVs), and plug in hybrid electric vehicles (PHEVs), with more than 2 million produced and 5 million NEVs expected to be deployed in 2020. Facing severe traffic congestion and air pollution, Beijing is actively promoting the development of new energy vehicles to reduce Particulate Matter2.5 (PM2.5) emissions from the transportation sector, which currently accounts for 25% of the emissions [4].

However, due to the limitations of Li-ion batteries, EVs and PHEVs have limited driving ranges and require longer charging time compared to conventional vehicles [5]. For such range-limited vehicles, driving patterns, including driving

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conditions and driving range, become important issues that dictate vehicle energy consumption [6], economic costs [7] and environmental impacts [8]. Driving patterns are therefore being considered more and more in vehicle optimal designs [9] and controls [10] as well as infrastructure construction [11].

Driving conditions directly determine the energy consumption of on-road vehicles, and include driving speed, acceleration, idling time, etc. To address the impact of driving conditions on fuel economy and emissions, standard driving cycles have been developed based on regional real-world driving data. In U.S., the FTP and HWFET cycles were originally developed to reflect city and highway driving conditions in the 1970s. Then, the Environmental Protection Agency (EPA) adopted the EPA-5 cycle to test conventional vehicles, as well as alternative fueled vehicles in 2006. In Europe, the NEDC cycle is supposed to represent the typical usage of a car in Europe to assess the emission levels and fuel economy. Japan adopted the JC08 cycle for vehicle testing since 2007. China has also adopted the NEDC cycle for vehicle fuel economy testing.

Driving conditions are changing rapidly and vary in different regions, mainly because of the development of vehicle powertrain technologies, increases in the vehicle population, strict regulations and traffic infrastructure. Significant deviations between the test results from standard driving cycles and real-world performance has been observed, and raise questions on the impact of the driving cycles on vehicle energy consumption [12]. Real-world driving cycles were generated based on recorded driving profiles for vehicle testing or simulation [13,14].

Driving range affects the average energy consumption of PHEVs and BEVs. For PHEVs capable of being fueled by liquid fuels and grid electricity, the daily driving range is essential to estimating the contribution from both energy sources [15]. For BEVs with a limited All Electric Range (AER), not all trips can be substituted by BEVs. Therefore, BEV utilization depends heavily on the daily driving range. The distribution of the driving range is mainly developed by questionnaires survey and onboard instrumentation records (usually GPS data loggers), and the impact of driving range on PHEV and BEV energy consumption is evaluated based on this distribution [16]. The Utility Factor (UF) is introduced to represent the percentage of electric driving range contained in the total driving range [17,18]. The National Household Travel Survey (NHTS) of the US conducted national questionnaire survey on driving patterns including average daily driving range and provides comprehensive data for transportation researchers [19]. The GPS devices were also adopted by the National Renewable Energy Laboratory (NREL) in regional travel surveys, such as the study on 407 vehicles in the greater Chicago area in 2007, and 1,325 vehicles in Atlanta in 2011 [20]. In Europe, the Danish National Travel Survey and on-board GPS data have been adopted to extract driving distances and driving time periods [21]. In China, the annual driving mileage was intensively studied [22,23], and the distribution of daily driving ranges in specific regions has been studied since 2012 [24].

The impact of driving conditions and driving range on vehicle energy consumption are closely coupled. Driving conditions directly determine the energy consumption per kilometer of driving, which will also affect the range of a BEV or the charge depleting (CD) range of a PHEV. The available electric range and the distribution of the driving range will then determine the utilization of electricity and fuel [17]. These two factors may act together or in conflict on the ability to reduce fuel usage in electric vehicles. However, as discussed above, current studies mainly focus on the evaluation of driving conditions or driving range, respectively [7,13,16,18,25]. To assess the average electricity and fuel consumption from vehicles of a specific region, the driving conditions and driving range should be obtained and evaluated together.

To understand the driving patterns in Beijing, a passenger car travel survey has been conducted since 2012. Preliminary results taken from 112 vehicles' GPS driving data have been compiled focusing on the driving range distribution [24,26,27]. This study focuses on the energy reduction potential of HEVs, PHEVs and BEVs compared with conventional vehicles based on driving patterns in Beijing. The paper is organized as follows. First, the UF and typical driving cycles based on 2000 days' worth of GPS data are analyzed and compiled. Second, the real-world energy consumption of CVs, HEVs, BEVs and PHEVs are simulated, and the coupled effect of driving conditions and driving range is examined to provide insight into PHEV battery sizing. Finally, the fuel consumption under different driving patterns are compared to provide conclusions on optimal electric vehicles and reliable test cycles for Beijing.

2. Driving patterns based on GPS survey

The driving patterns in Beijing, including the driving range, and driving conditions are studied based on systemic and real-world collected driving data. The Utility Factor is adopted to describe the usage of electricity of PHEV in the total driving range, and four representative driving cycles are built. This is the basis of evaluation on vehicle energy consumption.

In the Beijing passenger car travel survey, GPS loggers were adopted to collect travel data and 112 volunteer vehicles were observed from June 2012 to March 2013. The recorded data of 2003 travel days comprises nearly 10,000 km for 4892 trips.

2.1. UF for PHEVs and BEVs based on the distribution of the driving range

The collected data are processed to extract the distribution of the daily driving range and the single trip range, which is denoted as set S and set T separately.

$$S = \{d_1, d_2 \ldots d_{Ns}\}$$
$$T = \{t_{1,1}, t_{1,2}, t_{2,1} \ldots t_{i,j}\} \quad i = 1.2 \ldots N_s$$

In the set S, d_i is a daily driving range of a vehicle and N_s is the number of total travel days. In the single trip set T, $t_{i,\,j}$ is the j^{th} trip of a vehicle in the i^{th} travel day. The average daily driving range in Beijing is 39.6 km, and the average single trip range is 16.4 km.

2.1.1. Utility factor for PHEVs

The Utility Factor is proposed to describe the fraction of charge depleting (CD) range and charge sustaining (CS) range of a PHEV by the SAE. The SAE standard J2841 assumes that a PHEV begins each travel day fully charged, and starts out in the CD mode. When the trip exceeds the CD range, the vehicle switches to charge sustaining (CS) mode. Thus UF indicates the percentage of CD range, and (1-UF) indicates the percentage of CS range in the total driving range. Based on this assumption, the standard UF for a PHEV in Beijing (UF_{PHEV}) can be calculated, as is shown in Fig. 1.

$$UF_{PHEV}(R_{CD}) = \frac{\sum_{d_k \in s} \min(d_k, R_{CD})}{\sum_{d_k \in s} d_k}.$$

R_{CD} is the CD range of the PHEV, and d_k is from the daily driving range set S.

The distribution percentage of the daily driving range shows that the vast majority of daily driving ranges are less than 100 km and tend to be short. The UF is 0.4218 for a 20 km CD range and 0.7361 for a 50 km CD range, meaning that a PHEV with a 20 km CD range can drive solely on electricity for 42.18% of its the daily trips and if the CD range is increased to 50 km, the percentage rises to 77.06%. Compared with the UF in the U.S., the Beijing UF is larger at the same CD range, with a maximum observed difference of 23% at 50 km. This may cause a difference

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