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Charging ahead on the transition to electric vehicles with standard 120 V wall outlets ☆,☆☆

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HIGHLIGHTS

- Commercially available EVs satisfy the daily travel needs of over 85% of US drivers.
- Charging EVs with standard 120 V outlets at home only is enough for most drivers.
- With EVs over 77% of drivers will have over 60 km buffer range for unexpected trips.
- EVs meet driver needs even with terrain, high ancillary losses, and capacity fade.
- 120 V outlets in more locations is more useful than fast chargers in fewer locations.

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ABSTRACT

Electrification of transportation is needed soon and at significant scale to meet climate goals, but electric vehicle adoption has been slow and there has been little systematic analysis to show that today's electric vehicles meet the needs of drivers. We apply detailed physics-based models of electric vehicles with data on how drivers use their cars on a daily basis. We show that the energy storage limits of today's electric vehicles are outweighed by their high efficiency and the fact that driving in the United States seldom exceeds 100 km of daily travel. When accounting for these factors, we show that the normal daily travel of 85–89% of drivers in the United States can be satisfied with electric vehicles charging with standard 120 V wall outlets at home only. Further, we show that 77–79% of drivers on their normal daily driving will have over 60 km of buffer range for unexpected trips. We quantify the sensitivities to terrain, high ancillary power draw, and battery degradation and show that an extreme case with all trips on a 3% uphill grade still shows the daily travel of 70% of drivers being satisfied with electric vehicles. These findings show that today's electric vehicles can satisfy the daily driving needs of a significant majority of drivers using only 120 V wall outlets that are already the standard across the United States.

1. Introduction

Meeting multi-lateral targets for reductions in greenhouse gas emissions requires widespread electrification of transportation [1], however EV adoption has been slow[1] [2]. Uptake of EVs soon and at a significant scale is needed to meet our climate goals. In support of this goal, analysis is needed to determine whether today's EVs, despite their battery energy storage limits, meet the daily travel

Abbreviations: EPA, environmental protection agency; EV, electric vehicle; HEV, hybrid electric vehicle; L1, Level 1 charger; L2, Level 2 charger; NHTS, National household travel survey; PEV, plug-in electric vehicle; PHEV, plug-in hybrid electric vehicle; SOC, state of charge (of vehicle batteries); U.S., United States; V2G, Vehicle-to-grid.

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☆☆ EVs meet user needs, even when charged on 120 V outlets only.

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[1] The Williams et al. study [1], which focuses on the State of California's options for meeting GHG reductions targets for 2050, suggests that 70% of all vehicle miles travelled, including *almost all* light duty vehicle miles, must come from electrified transportation. The study [1] models a scenario for a transition to electrified transportation to meet 2050 GHG targets, and concludes that EV uptake is required soon and at significant scale, for instance 2.6 million plug-in vehicles by 2020 within California alone. Despite this need for substantial EV adoption, EV uptake has been slow thus far. In 2014 in the entire United States, battery electric vehicles constituted only 0.40% of vehicle sales. 63,416 battery electric vehicles were sold out of a total of nearly 16.4 million vehicles sold in 2014 in the U.S. [2].

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needs of U.S. drivers and provide sufficient buffer for unexpected trips. Prior analyses, reviewed below, lack detailed consideration of powertrain component efficiencies, battery energy storage limits, and knowledge of how drivers use their vehicles [3–9]. We address this gap by applying detailed physics-based models of EV powertrain systems, EV charging, and data on how U.S. drivers use their cars.

Electric vehicles (EVs) present a paradigm shift for both the personal transportation and electricity markets. For automotive manufacturers, EVs can meet all of the increasingly stringent regulations on vehicle efficiency and remove all tailpipe emissions. This supports national and international goals to advance energy security, lower greenhouse gas emissions, and presents benefits for public health by moving the source of emissions away from densely populated areas. For the electricity market, EVs can provide a distributed and growing source of rapidly ramping energy storage at low cost, with relatively low capital investment from grid agencies. Despite these benefits, EVs still face a number of hurdles to their widespread adoption, for instance:

1. Limited range compared with conventional vehicles, leading drivers to feel range anxiety.
2. A perceived limitation of available charging infrastructure.
3. Longer time to recharge an EV compared with the time for refilling the tank in a hydrocarbon or hydrogen-fueled vehicle.
4. Higher capital cost compared with conventional vehicles.

From a high level policy perspective, many governmental agencies have highlighted the benefits and their commitment to EVs for a clean transportation future. In the State of California, the California Public Utilities Commission released a whitepaper [10] that outlines the potential for EVs to enable clean transportation and vehicle-grid integration. The California Independent System Operator released a high level roadmap detailing the State's pathways toward enabling vehicle-grid integration [11] as part of the California Governor's targets for zero-emissions vehicle deployment [12]. Eight states across the United States established a cooperative agreement to deploy 3.3 million zero emissions vehicles, which include EVs, by 2025 [13]. At the Federal level in the United States, the Obama administration and the U.S. Department of Energy released the EV Everywhere Grand Challenge which targets to make 5-passenger EVs available by 2022 with a payback time of less than 5 years [14]. Similar targets and commitments have been expressed by governments in India [15], and China [16]. Considering the infrastructure and range related challenges that are hindering widespread adoption of electric vehicles to meet these policy goals, research to support better decision making for public and private investment in electric vehicles and their infrastructure is important to their success.

A small number of studies in the scientific literature examine the vehicle mobility impacts of different types of chargers in different locations. Axsen et al. [17] present consumer-informed estimates of residential access to charging infrastructure and conclude that about 50% of new car-buying U.S. households park in areas that are within 25 feet of an L1 electrical outlet, and that 20% of new car buyers are both willing and able to install L2 chargers at home. Similarly, the California Public Utilities Commission [10] and the National Household Travel Survey [18] show vehicles are used for mobility purposes for only a small fraction of time, leaving substantial time for adequacy of charging at lower power levels. Peterson et al. [19] and Zhang et al. [20] examine the cost effectiveness of larger batteries vs. the availability of non-home charging on PHEV gasoline consumption, while Dong et al. [21] study the impact on all electric range of PHEVs when public chargers are made available. Although these two studies are relevant to the questions addressed in the present study, the focus on PHEVs rather than pure EVs requires the consideration of different vehicle specifications and different constraints, leading to limited applicability of their findings to pure EVs. Meliopoulos et al. [22], in a study focused on distribution systems impacts of PHEV charging, suggest qualitatively that typical household circuit capacity (120 V/20 A) can recharge PHEVs in a sufficient and timely manner. Liu et al. [6] study optimal EV charging infrastructure locations for Beijing and suggest that 36% of mobility demands in Beijing can be met with home charging only while 45% are met when introducing public fast charging. Of importance in the Liu study is that significant constraints in the availability of parking near home locations are considered. A similar study by Dong et al. [3] on optimal EV charging station placement finds that 10–51% of a sample of 445 vehicles in Seattle can satisfy all their mobility requirements with only L1 home charging with little or no adjustment to their travel patterns. Ashtari et al. [4] apply simulations of EV energy consumption using a kWh/km approach to second-by-second GPS data collected for 76 vehicles over 1 year in the city of Winnipeg, Canada. As part of this study, results are presented that quantify the adequacy of different types of chargers in different locations for EV mobility. Zhang et al. [5] apply a method of using a kWh/mi vehicle energy modeling approach and consider L1 (1.44 kW) and L2 chargers (restricted to 3.3 kW) using the California samples in the 2009 National Household Travel Survey [18].

Although these prior studies are relevant for the research questions addressed in the present study, there are several limitations of the prior studies that justify the need and broad impact of the present study, including:

1. Considering a confined geographic area with only a small number of vehicles [3,4].
2. Considering a single type of charger deployed in all locations (i.e. L1 chargers everywhere, or L2 chargers everywhere) rather than considering different chargers in different locations [5].
3. Modeling EV energy use with constant kWh/km, regardless of trip characteristics (e.g. drive cycle), ancillary consumers of energy (e.g. cabin air conditioning), loss of battery capacity, or uphill driving, all of which impact EV range and the quantification of the adequacy of different types of chargers in different locations [3–9].
4. Failing to quantify the range remaining from unused charge during normal daily travel in EV batteries that can accommodate unexpected trips under different charging scenarios [3–9]. In this paper, we refer to this remaining range as the "buffer range" that remains for unplanned travel beyond the normal daily travel of each driver.

In the absence of considering these four important factors, prior studies do not present the analyses necessary to accomplish the central objectives of this study. The results of the present study show that EVs satisfy the daily mobility requirements for sizable fractions of drivers in the United States, that charging using widely available 120 V wall outlets is sufficient for most drivers, and that most drivers will have substantial levels of remaining range to accommodate unexpected trips. These findings can play an important role in alleviating the range anxiety concerns that drivers face when considering whether an EV will suit their requirements.

2. Specific objectives

This study quantifies the degree to which the perceived barriers for greater EV adoption listed in the introduction manifest in reality when using commercially available EVs. The study accounts for the higher energy efficiency of EVs enabled by their motor and batteries, the limited energy stored in their batteries, the daily

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