Lawrence Berkeley National Laboratory
LBL Publications

Title

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

Permalink

https://escholarship.org/uc/item/67z641qc

Authors

Saxena, Samveg
MacDonald, Jason
Moura, Scott

Publication Date

2015-11-01

DOI

10.1016/j.apenergy.2015.05.005

Peer reviewed

eScholarship.org Powered by the California Digital Library
University of California

Applied Energy 157 (2015) 720–728

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

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

Samveg Saxena [a,*], Jason MacDonald [a], Scott Moura [b]

[a] Lawrence Berkeley National Laboratory, United States
[b] University of California at Berkeley, United States

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.

ARTICLE INFO

Article history:
Received 20 August 2014
Received in revised form 26 April 2015
Accepted 2 May 2015
Available online 13 June 2015

Keywords:
Electric vehicles
Range anxiety
EV charging
EV range
Clean transportation

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.

© 2015 Elsevier Ltd. All rights reserved.

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.

[☆] This paper is included in the Special Issue of Clean Transport edited by Prof. Anthony Roskilly, Dr. Roberto Palacin and Prof. Yan.

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

[*] Corresponding author.

E-mail address: samveg@berkeley.edu (S. Saxena).

[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].

http://dx.doi.org/10.1016/j.apenergy.2015.05.005
0306-2619/© 2015 Elsevier Ltd. All rights reserved.

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 mobility needs of drivers in the U.S., and a variety of scenarios for the availability of vehicle chargers. Specifically, this study quantifies:

A. The fraction of daily travel by drivers in the United States that can be accommodated by EVs that charge predominantly using standard 120 V wall outlets (also called Level 1 chargers, which are limited to 1.4 kW charging rates) in different charging locations.
B. The increased fraction of daily travel patterns that can be accommodated by introducing additional charging locations and increasing the power level available at individual chargers.
C. The impact of vehicle usage parameters on the ability for each charger and charging location scenario to accommodate daily travel patterns with EVs.

3. Methodology

A simulation tool called the vehicle-to-grid simulator (V2G-Sim) [23–25] is created, validated and applied in this study to provide quantitative metrics to accomplish the above objectives. For this study, V2G-Sim is provided input data from the National Household Travel Survey (NHTS), which provides a survey of the 24-h vehicle usage profiles of a random sample of drivers across the United States, including trip start and end times, trip distances, and types of locations where vehicles are parked [18]. The NHTS provides 120,495 samples of weekday vehicle usage, 39,349 samples of weekend vehicle usage and appropriate weighting factors for each individual vehicle usage sample to construct a nationally representative description of when and where individual vehicles travel. Commercially available EVs, with specifications resembling a Nissan Leaf, are simulated in V2G-Sim to travel along the individual daily travel patterns specified by the NHTS data. While driving, each vehicle's energy consumption and battery state-of-charge (SOC) is predicted using vehicle powertrain sub-models [26] in V2G-Sim that are validated against measurement data [27]. These powertrain models determine the EV's energy consumption during a trip while accounting for the high energy conversion efficiency of chemical to electrical energy in the battery, and electrical to kinetic energy in the motor. When a vehicle parks at a location where it can plug into a certain type of charger (e.g. level 1 charger at 1.4 kW, level 2 charger at up to 7.2 kW, or fast charger), power transfer from the electricity grid to that vehicle is calculated using charging sub-models which are calibrated with measurement data [28].

3.1. Details of simulation methods and model validation

This section describes the methods and validation of V2G-Sim [23–25]. V2G-Sim models the driving and charging of many individual vehicles enabling predictions of vehicle energy usage and vehicle-grid energy interactions for large numbers of plug-in electric vehicles (PEVs), resolved on a second-by-second and spatially-resolved basis for each vehicle. As calculations are performed at the individual vehicle level, fine spatial resolution in vehicle-grid interactions (e.g. down to the distribution transformer level) can be obtained when providing V2G-Sim with the location of individual vehicles. For this study, V2G-Sim couples sub-models for: (a) vehicle usage by drivers, (b) vehicle powertrain models of energy usage while driving, and (c) vehicle charging. Each sub-model is described below, followed by a discussion of how V2G-Sim is applied for this study:

3.1.1. Vehicle usage by drivers

Inputs describing how drivers use their vehicles can be specified stochastically or deterministically. This study uses the deterministic approach by using travel survey data available in the National Household Travel Survey (NHTS) [18]. The NHTS database provides descriptions of how individual drivers in the United States use their vehicles, including trip start times, end times, distances travelled, and types of locations where vehicles park.

The simulation results from this study are properly weighted to enable nationally representative conclusions. Each vehicle sample in the NHTS database includes a household weighting factor that describes the number of households across the United States that would have driving patterns similar to the vehicle sample given in the NHTS database. For example, if a given NHTS vehicle sample X has a household weighting value of Y, then the V2G-Sim results of that vehicle sample X are taken to represent Y number of vehicles.

3.1.2. Vehicle powertrain models

For each trip taken by each vehicle, V2G-Sim can execute detailed or reduced vehicle powertrain models that calculate the performance parameters for a given vehicle on a given trip. The detailed models consider the dynamics of individual powertrain and vehicle components. V2G-Sim can leverage models available through the powertrain modeling software Autonomie [26] or built-in powertrain models. These powertrain models predict fuel consumption, energy consumption, and/or battery SOC during a given drive cycle for any vehicle type, e.g. pure EV, PHEV, HEV, or conventional vehicle. The present study focuses on charging infrastructure and mobility considerations for pure EVs, thus only the EV powertrain models are applied. Fig. 1 illustrates how the powertrain models interface with the overall V2G-Sim model architecture. The specific example of Fig. 1 shows an EV powertrain model created within Autonomie and called from V2G-Sim, however any other vehicle type can be considered. The component-level plant equations and powertrain control model equations are described in the user manual for Autonomie [26] and in prior publications by the authors [29–31].

The detailed powertrain model approach allows predictions of vehicle performance for any vehicle type, on any drive cycle, with any collection of vehicle components, or any powertrain control strategy. For the objectives of the present study, however, only EVs are considered on a finite number of drive cycles. As a result, reduced powertrain models which are calibrated against the detailed models are applied in this study. To enable accurate calibration of the reduced powertrain model, the detailed powertrain model is validated against experimental measurements [27], as shown in Fig. 2. Using the validated detailed powertrain model, the reduced powertrain model is initialized with Wh/km values for the different drive cycles with the required vehicle characteristics (see Table 1).

3.1.3. Vehicle charging models

For each charging event by each vehicle, a charger sub-model is executed which tracks a vehicle's battery SOC and power transfer to/from the electricity grid on a second-by-second basis. The charger sub-model considers vehicle restrictions such as maximum power transfer rate, requirements for reduced charging rates as a battery approaches a full SOC, etc. The charger sub-model also considers charger restrictions, including the charger's maximum power transfer rates, which are listed in Table 2 [32–35]. The charger sub-models are calibrated using experimental data for several different charger types collected by Idaho National Laboratory [28], with an example of the measurement data shown in Fig. 3.

3.2. Application of V2G-Sim for the present study

Simulations are run for different vehicle specifications under different scenarios of charger placement. Vehicle specifications

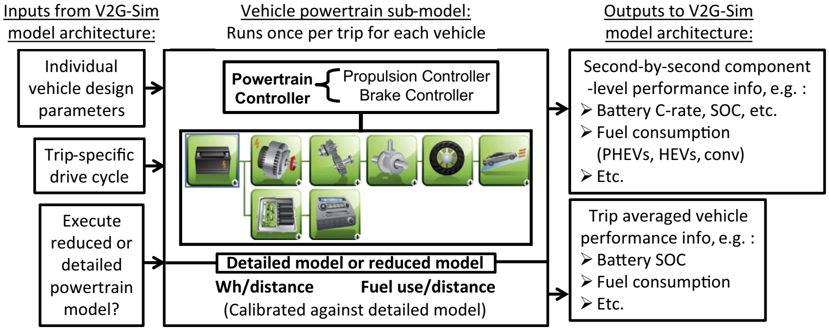

Fig. 1. Example of the reduced or detailed powertrain model architecture that is initialized, executed, and post-processed by V2G-Sim.

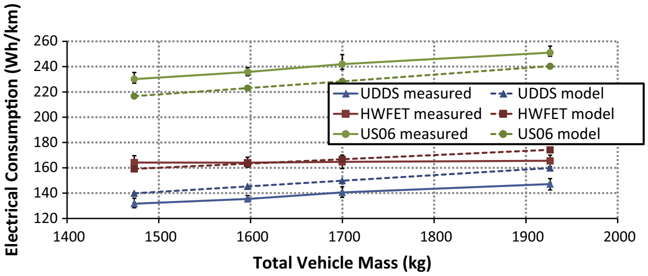

Fig. 2. Validation of detailed EV powertrain model against experimental measurements [27] collected for a Nissan Leaf on 3 different drive cycles applied in this study.

for each set of simulations are listed in Table 1. The results summarized in Figs. 4 and 5 apply the base case specifications listed in Table 1, while the sensitivity analysis results in Fig. 6 apply each of the other sets of specifications from Table 1.

By coupling the NHTS travel data, vehicle powertrain models, and vehicle charging models, the simulations predict second-by-second battery SOC profiles for each vehicle over a 24 h period in each of the 8 charging scenarios modeled. An example of the SOC profile results for two randomly chosen vehicles in each of the 8 charging scenarios is shown in Fig. 7. These battery SOC profiles are used to identify if and when a vehicle runs out of charge during its travel day under each of the 8 charging scenarios. In this manner the total fraction of vehicles that run out of charge by a certain time in the day can be identified, as shown in Fig. 8(A). The final timestep of the time-resolved results of Fig. 8(A) are used to plot the summary results of Fig. 8(B), which shows the fraction of drivers whose daily travel can be satisfied using an EV in each charger scenario. The results in Fig. 8(B) are the same as the weekday travel results shown in Fig. 4, and a similar procedure as depicted in Fig. 8 is followed to obtain all of the summary results that are plotted in Figs. 4 and 6.

Table 2
Specifications and power transfer rates of different types of EV chargers in the United States [32–35].

Charger type	Supported voltage	Maximum current	Maximum charging power
Standard wall outlet–level 1 (L1)	110–120 VAC	12–15 A	1.32–1.44 kW
Level 2 (L2)	240 VAC	17–80 A (often 30 A)	4.08–19.20 kW
DC fast/level 3 (L3)	208–600 VDC		50–100 kW

The SOC profiles for each vehicle in each charging scenario, as plotted in Fig. 7, are also used to determine the buffer range of each vehicle to accommodate unexpected trips. The minimum SOC value over a 24 h period is identified for each vehicle in each charging scenario, and this minimum SOC value is converted into range estimates that are plotted in Fig. 5. Conversion from the minimum SOC value to a remaining EV range is accomplished using the base case Wh/km values listed in Table 1, and assuming that unexpected trips will have a distribution of 55% city driving (UDDS cycle) and 45% highway driving (HWFET cycle) as per EPA guidelines [36] for driving in the United States. As the buffer range estimates are calculated using the minimum daily SOC value, the resulting range values are a worst case scenario. For example,

Table 1
Specifications of vehicles and powertrains simulated.

Parameter sweep		Base case	Ancillary loading	20% Battery capacity loss	3% Uphill grade	Worst case scenario
Relevant figures		4, 5	6	6	6	6
Vehicle & powertrain specifications	Vehicle mass (kg)	1550.0	Base	Base	Base	Base
	Traction motor	80 kW AC	Base	Base	Base	Base
	Total battery energy capacity (kWh)	23.83	Base	19.07	Base	19.07
	Usable SOC (%)	95–7.5%	Base	Base	Base	Base
	Useable battery capacity (kWh)	20.85	Base	16.68	Base	16.68
	Battery chemistry	Li-Ion	Base	Base	Base	Base
	Final drive ratio	7.9377	Base	Base	Base	Base
	Tire size	205/55R16	Base	Base	Base	Base
	Drag coefficient	0.285	Base	Base	Base	Base
	Frontal area (m^2)	2.6	Base	Base	Base	Base
	Ancillary load (kW)	1.00	4.82	Base	Base	4.82
	Road grade (%)	0%	0%	0%	3%	3%
Avg. electrical consumption while driving (Wh/km)	EPA City (UDDS)	143.25	271.70	143.25	291.21	420.37
	EPA Highway (HWFET)	161.75	214.17	161.75	315.21	368.43
	EPA High Speed (US06)	220.60	273.63	220.63	373.28	427.23

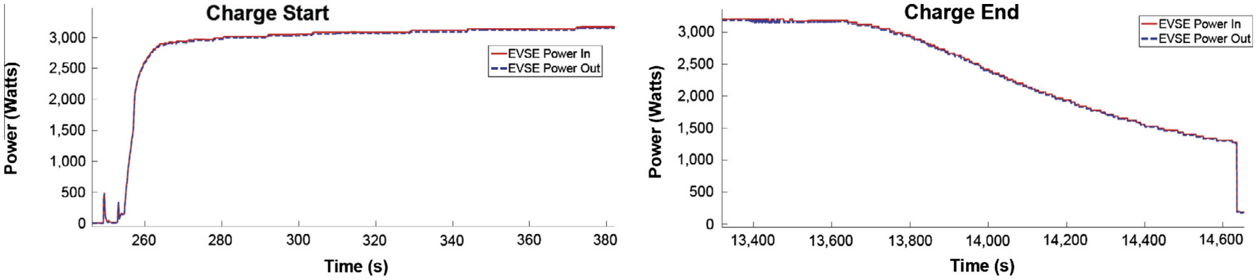

Fig. 3. Example of measurement data used to calibrate charging models within V2G-Sim of charging power vs. time for a Chargepoint CT503 Level 2 Charger [28].

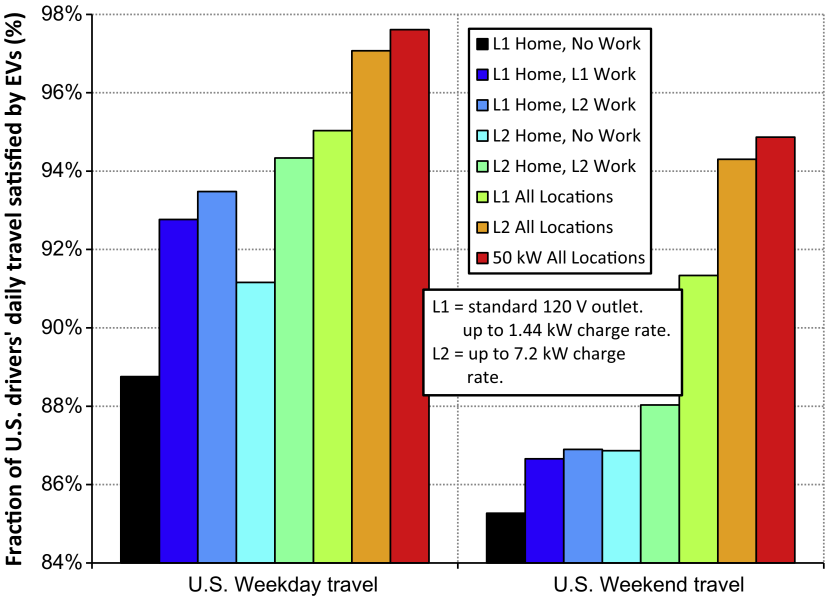

Fig. 4. Fraction of U.S. drivers whose normal daily travel needs can be satisfied by EVs considering several scenarios of charger availability.

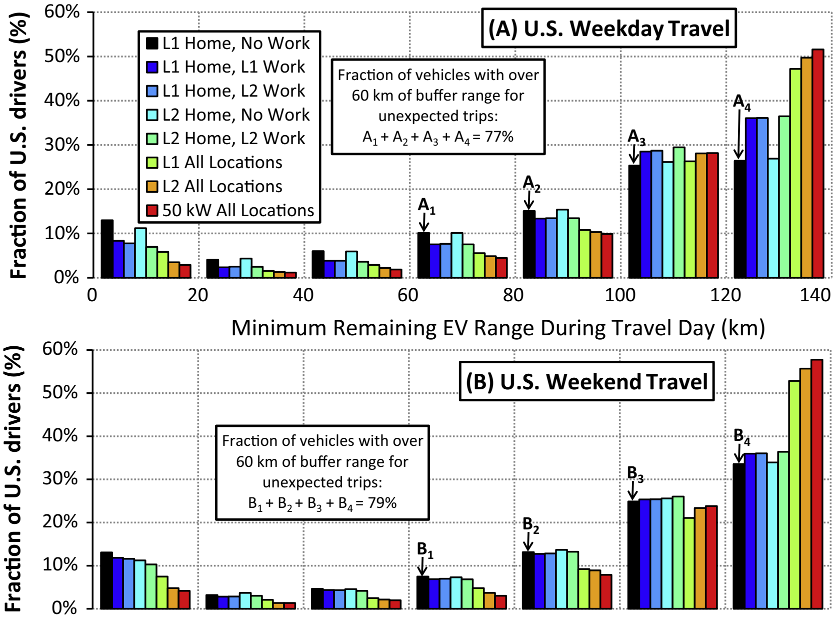

Fig. 5. Fraction of drivers with different levels of buffer EV range for unexpected trips beyond their normal daily travel.

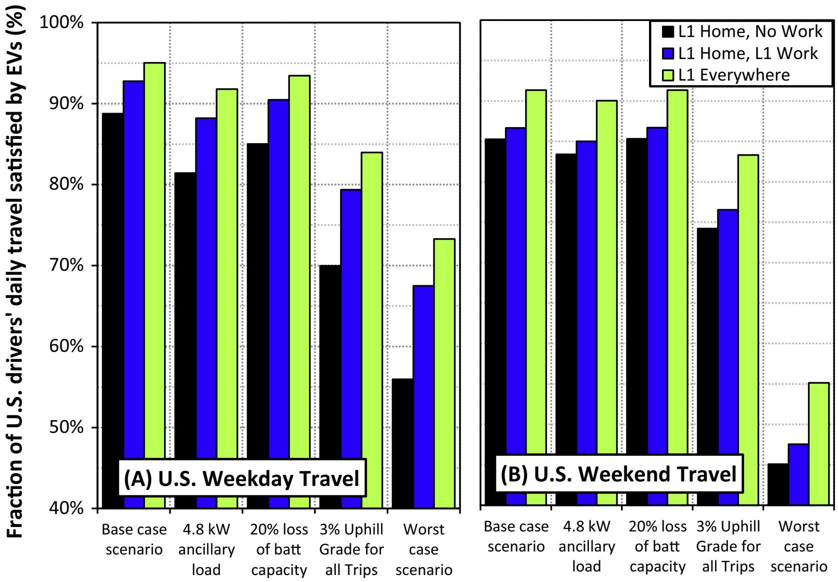

Fig. 6. Sensitivity analysis of the impact of vehicle usage characteristics on the fraction of U.S. drivers whose daily travel can be satisfied under the L1 charging scenarios.

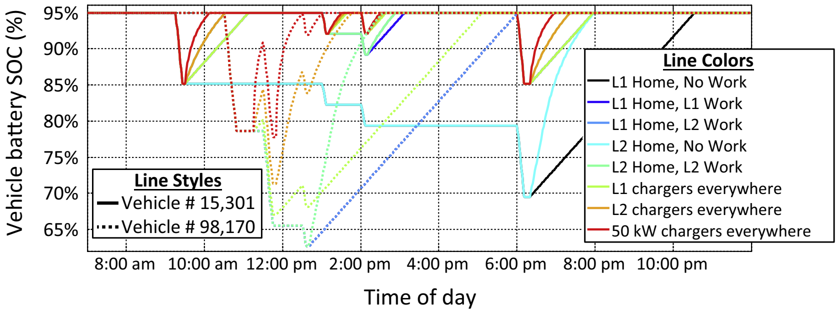

Fig. 7. Battery state-of-charge profile for two randomly selected vehicles over 24 h, each under 8 different scenarios of charger placement.

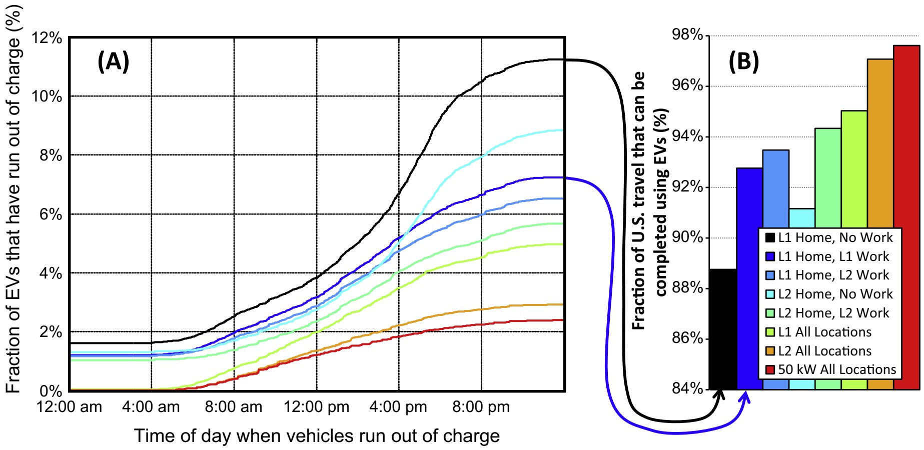

Fig. 8. (A) Time of day when vehicles run out of charge for U.S. weekday travel, and (B) summary result of total fraction of U.S. drivers' weekday travel satisfied considering charger availability.

vehicle number 98,170 plotted in Fig. 7 has a minimum SOC value of 63% at approximately 12:50 pm under several charging scenarios. Using this minimum SOC value, the buffer range that is reported for this vehicle in the Fig. 5 results would be 87 km. If however, the driver of this vehicle were to make an unexpected trip at any other time of day, their range availability for that unexpected trip would be higher. For instance, per the results for vehicle 98,170 in Fig. 7, if the unexpected trip occurred at 6 pm the driver would have a fully charged battery at the beginning of their unexpected trip.

4. Results

Fig. 4 summarizes the percentage of U.S. drivers whose daily travel needs can be satisfied by EVs, for various scenarios of the availability of charging infrastructure. Each EV has powertrain specifications resembling a Nissan Leaf[2] in terms of battery capacity, battery power, motor efficiency, battery efficiency, vehicle mass, aerodynamics, etc. The results in Fig. 4 present a base case in three respects. First, each vehicle is driving on flat terrain. Second, an average level of ancillary power demand is assumed (1 kW, i.e. from lights, cabin heating or air conditioning, audio, and other power consumers on the vehicle battery) [37]. Third, a fresh battery pack that provides the rated energy storage capacity is simulated. Simulations are run for weekday and weekend travel with each set having 8 scenarios of charger availability, including level 1 chargers, level 2 chargers, or fast chargers available in different locations. The simulation results show that the high efficiency of EVs enables 89% of U.S. drivers' normal weekday travel and 85% of U.S. drivers' normal weekend travel to be accommodated using commercially available EVs, despite the limited energy that is stored in these EV batteries. These results are for a case where EVs are charged only using standard 120 V wall outlets at home locations. When 120 V wall outlets are made available at work places as well, 93% of drivers' normal weekday travel and 87% of drivers' normal weekend travel is satisfied using these efficient EVs. Indeed, Fig. 4 demonstrates that the greatest amount of U.S. drivers' daily travel can be accommodated when fast chargers are available everywhere. However, there is greater marginal benefit from making standard 120 V wall outlets available in all locations than from deploying faster chargers (which are significantly more expensive) in a smaller number of locations.

Alleviating driver range anxiety requires more than simply showing that the daily travel needs of a high fraction of U.S. drivers can be accommodated for a given level of charger availability. Drivers must be confident that EVs can satisfy their mobility needs under several additional scenarios, including:

1. Unexpected trips beyond their normal daily driving.
2. High power drain [37] from heating, air conditioning, or other losses.
3. Capacity fade of EV battery packs due to degradation over time, or extreme climates [38].
4. The impact of terrain elevation on a given trip.
5. Simultaneous combinations of scenarios 2, 3, and 4.

The results in Fig. 5 address scenario 1 and the results in Fig. 6 address scenarios 2–5.

Fig. 5 shows the fraction of drivers whose vehicles will have different levels of buffer range to accommodate unexpected trips. The results in Fig. 5 are collected by identifying the minimum battery SOC that would be encountered for each vehicle's individual daily travel and charging activity (see Fig. 7) and calculating the remaining usable EV range at that minimum SOC value. The results show that after accounting for the limited energy storage capacity of each vehicle battery, the high energy efficiency of EVs, and the normal expected travel for each vehicle, a large fraction of vehicles have substantial buffer in remaining range to accommodate unexpected trips. For instance, when vehicles are charged using standard 120 V wall outlets at home only, 77% of drivers will have over 60 km of buffer range during weekday travel, and 79% of drivers have over 60 km of buffer range during weekend travel. When adding standard 120 V wall outlets at work locations, these values increase to 86% and 81% of drivers having over 60 km of buffer range for unexpected trips on weekdays and weekends respectively.

Fig. 6 quantifies the sensitivity of the results to different vehicle usage and battery parameters that decrease an EV's driving range. The "base case" values in Fig. 6 are the same as those shown in Fig. 4 and correspond to Nissan Leafs with a 1 kW ancillary power consumption [37], a fresh battery, and driving on flat terrain for all trips. Results presented in Fig. 6 quantify the impact of: (i) the highest levels of ancillary power consumption for a Nissan Leaf from using the cabin air conditioning/heating system, headlights, the audio system, etc.; (ii) a vehicle battery that has lost 20% of its usable energy storage capacity due to battery degradation[3] [24], and (iii) driving uphill on a 3% grade for all trips.[4] Of these three scenarios, uphill driving has the greatest impact on lowering the fraction of U.S. drivers whose daily travel will be accommodated by EVs because the increased energy required to scale terrain with a 3% uphill grade outweighs the increased energy from higher ancillary energy consumption, or from reduced battery storage capacity. For instance, from the base case to the 3% uphill case, the fraction of U.S. drivers whose daily travel will be satisfied by EVs charging on 120 V wall outlets at home decreases from 89% to 70% for weekday travel and from 85% to 74% for weekend travel. The uniform 3% uphill grade case may be considered unrealistically extreme, as real world driving includes some flat or downhill terrain. Nevertheless, this case provides bounds on the percentage of drivers whose daily travel needs that can be satisfied. The worst case scenarios plotted in Fig. 6 present an even more extreme bounding result, where all vehicles are always driving uphill, with high levels of ancillary power consumption and with a vehicle battery that has lost 20% of its original capacity. In these worst case scenarios when vehicles are charged using standard 120 V wall outlets at home only, 56% of U.S. drivers' normal weekday travel and 45% of drivers' normal weekend travel is satisfied.

5. Discussions

Fig. 4 through 6 summarize the findings that EVs meet the majority of daily travel needs of U.S. drivers, and the 'Simulation Methods and Validation' section explained the methodology to arrive at these results. As the findings in this study show that a surprisingly large fraction of daily driver mobility needs are satisfied by today's EVs despite the limited energy storage in EV batteries, this section is dedicated to explaining *why* this is the case.

Two underlying facts when considered together drive the study's findings:

1. Electric cars are more energy efficient than their conventional internal combustion (IC) engine counterparts. The energy conversion efficiency of batteries and motors taken together is significantly higher than that of IC engines.

---

[2] Although the simulated vehicle in this study has specifications resembling a Nissan Leaf, the study's results are applicable to most EVs on the market, particularly because most other vehicles have similar energy storage capacity and EPA-rated range to a Nissan Leaf. For instance, the Nissan Leaf has a 24 kWh battery and 84 mile EPA-rated range, Ford Focus EV has a 23 kWh battery and 76 mile EPA-rated range, and Fiat 500e has a 24 kWh battery and 87 mile EPA-rated range.

[3] 20% capacity loss was chosen because most prior literature on retirement and second life of EV batteries has assumed that EV batteries are retired from their vehicle life when they have 80% of their original energy storage capacity remaining. The results in Fig. 6 suggest that EV batteries will continue to meet the daily travel needs of drivers even once they have degraded to levels where it has been commonly assumed that the batteries must be replaced. Given the potentially surprising nature of these results, the authors published a separate study [25] recently that presents evidence to conclude that EV batteries will continue to meet driver needs even after substantial levels of battery degradation (from the perspective of both energy capacity fade and power fade).

[4] While going uphill on all trips for a driver's daily commute is not a realistic scenario, it does provide a useful bounding case when evaluating the impact of terrain on driving.

Table 3
Average total energy consumption and energy recovery from regenerative braking of an EV and a comparable conventional vehicle on various driving conditions.

Driving conditions	Average total energy consumption in various driving conditions (Wh/km)		Average energy recovered to batteries with regenerative braking (Wh/km)
	Comparable conventional vehicle	Electric vehicle (Table 2 base case)	Electric vehicle
EPA city (UDDS)	579	143	37
EPA highway (HWFET)	450	162	8
EPA high speed (US06)	674	221	39

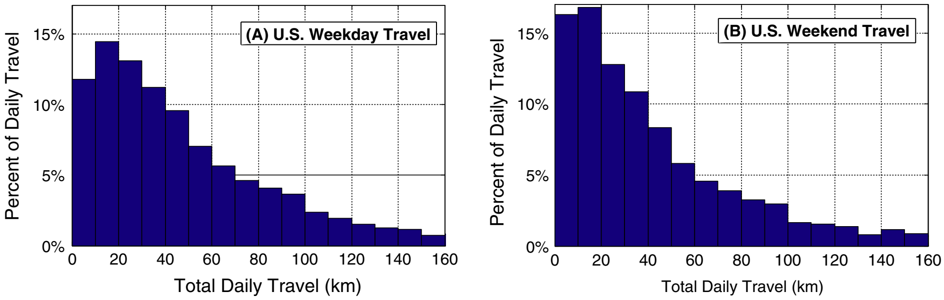

Fig. 9. Daily driving distances of drivers in the United States for (A) weekday travel, and (B) weekend travel. Over 85% of the daily travel needs of U.S. drivers require total daily travel of less than 100 km.

2. The way that people use their cars seldom requires driving range in excess of what an EV provides, and provides ample time for EVs to be charged.

The models applied in this study take into account the powertrain component-level details that lead to the higher efficiency, and the way that people use their cars. These facts are described in the following paragraphs.

A 13.2-gallon (50 L) tank of gasoline provides 445 kWh of stored energy [39], while a Nissan Leaf battery provides less than 24 kWh of stored energy. An IC engine, however, converts this stored chemical energy to kinetic energy at a relatively low conversion efficiency compared with the chemical to electrical conversion in batteries and electrical to mechanical conversion in motors, even when the battery and motor efficiency losses are taken together. Table 3 presents the average energy consumption per kilometer for an electric car having the base case powertrain specifications listed in Table 2, and the average energy consumption per kilometer for a comparable conventional vehicle. Both vehicles have the same maximum power output capabilities (i.e. acceleration), vehicle mass, ancillary power consumption, and aerodynamics, and are driven on identical driving conditions. The powertrain models take the operating efficiency of each powertrain component into account at each time step of the trip to predict overall vehicle energy consumption. Similar efficiency maps are considered for the motor and batteries in the EV to arrive at the average energy consumption results in Table 3, which show that the EV consumes 2.8–4.1 times less energy than the comparable conventional vehicle.

Beyond the higher conversion efficiency of the EV powertrain components, regenerative braking enables recovery of substantial amounts of kinetic energy to electrical to chemical energy to recharge EV batteries when the vehicle is braking. The higher component-level energy conversion efficiencies combined with regenerative braking allow an EV to travel farther on limited amounts of stored energy, effectively eliminating some of the need for excess energy storage. Using the vehicle powertrain models which consider the efficiency of a motor in regenerative braking and the efficiency to recharge the vehicle battery, the magnitude of energy recovered per kilometer from regenerative braking is quantified in Table 3. This regenerative braking energy is factored into the EV's average energy consumption values listed in Table 3.

Fig. 9 shows an analysis of the total daily travel distance of drivers across the United States using data in the National Household Travel Survey [18]. The data shows that the daily travel of over 85% of drivers involves less than 100 km of total travel. This data in combination with the results in Table 3 suggest that in order to meet the daily needs of U.S. drivers, conventional IC engine vehicles also do not need the substantial amounts of energy storage that their fuel tanks provide. It is inconvenient, however, for drivers to have to refuel at a gas station on a regular basis if their cars had smaller fuel tanks. For EVs, however, recharging can occur when a vehicle is parked and this study examines several scenarios of different types of chargers being available in the locations where vehicles park. NHTS data shows that vehicles spend only 4% of their time driving. The majority of time is spent parked at home or work locations, where they may have access to a 120 V electrical outlet or a faster charger. As a result of the ability to recharge EVs while they are parked on a daily basis, the limited energy storage in today's batteries does not hinder the ability of EVs to meet the daily travel needs of drivers in the U.S.

In summary, two major factors enable EVs to meet the daily travel needs of a majority of U.S. drivers. First, the higher efficiency of EV powertrain components coupled with regenerative braking enable trips in an EV to consume 2.8–4.1 times less energy than a comparable conventional vehicle. Second, U.S. drivers seldom travel long distances and leave their vehicles parked a significant majority of the time allowing plenty of time to recharge a vehicle. These two factors outweigh the limited energy storage capability of EV batteries, enabling EVs to satisfy the daily travel needs 85–89% of U.S. drivers when charging only using a standard 120 V wall outlet at home.

6. Conclusions

Comparison and interpretation of the results from EV charging and vehicle usage scenarios presented in Fig. 4 through 6, leads to the following broadly applicable findings:

1. 89% of U.S. drivers on a typical weekday and 85% of U.S. drivers on a typical weekend can be accommodated using EVs that are charged on standard 120 V wall outlets at home only.

2. Increasing the number of locations in which vehicle owners have access to charging infrastructure has a larger impact than increasing the charging rate available at charging stations. This is unsurprising given the large amount of time that electric vehicles are parked.
3. After accounting for normal weekday and weekend travel, many drivers will have significant remaining battery charge to accommodate unexpected trips. For instance, 77% and 79% of drivers in weekday and weekend travel respectively will have over 60 km of buffer range for unexpected trips when charging only using standard 120 V wall outlets at home locations.
4. Higher ancillary power consumption, 20% reduced battery capacity, and driving continuously uphill decrease the fraction of U.S. daily weekday and weekend travel that is satisfied by EVs. Of these three scenarios considered separately, uphill driving on a 3% grade has the greatest impact and yet still leads to 70% and 74% of U.S. drivers' weekday and weekend travel being satisfied when charging EVs using 120 V wall outlets at home only.

Greater deployment of EVs that are already commercially available will lead to national and international benefits in terms of energy security, air quality, public health, and reducing greenhouse gas emissions. High energy conversion efficiencies of chemical to electrical energy in EV batteries, and electrical to kinetic energy in an EV motor overcomes much of the limitations from the lower amount of energy stored in vehicle batteries. This higher efficiency combined with the fact that the daily mobility needs of U.S. drivers seldom include long trips enables today's EVs to satisfy the typical daily travel of a substantial majority of U.S. drivers. The results show that this is true even when charging EVs only using widely available 120 V wall outlets which are already the standard across the U.S. Overall the findings in this study suggest that EVs can play a large part in satisfying the mobility needs of U.S. drivers, even despite the energy storage limitations of today's EV batteries.

Acknowledgment

This work was supported with funding through the Laboratory Directed Research & Development program at Lawrence Berkeley National Laboratory, by the Director, Office of Science, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

The vehicle-to-grid simulator (V2G-Sim), which was developed and applied in this study, is available for use by all stakeholders. V2G-Sim provides a valuable research, development, and deployment platform for users to understand how different vehicles will perform for different drivers, and how different vehicles will interact with the electricity grid. Stakeholders benefiting from V2G-Sim include engineers, scientists, researchers, policy makers, analysts, and investors across the automotive industry, electricity grid industry, policy and regulatory sectors, and end users. More information is available at http://v2gsim.lbl.gov.

References

[1] Williams JH, DeBenedictis A, Ghanadan R, Mahone A, Moore J, Morrow WR, et al. The technology path to deep greenhouse gas emissions cuts by 2050: the pivotal role of electricity. Science 2012;335:53–9.

[2] Electric Drive Sales; 2014 <http://electricdrive.org/index.php?ht=d/sp/i/20952/pid/20952: Electric Drive Transportation Association>.

[3] Dong J, Liu C, Lin Z. Charging infrastructure planning for promoting battery electric vehicles: an activity-based approach using multiday travel data. Transport Res Part C: Emerg Technol 2014;38:44–55.

[4] Ashtari A, Bibeau E, Shahidinejad S, Molinski T. PEV charging profile prediction and analysis based on vehicle usage data. Smart Grid, IEEE Trans 2012;3:341–50.

[5] Zhang L, Brown T, Samuelsen S. Evaluation of charging infrastructure requirements and operating costs for plug-in electric vehicles. J Power Sources 2013;240:515–24.

[6] Liu J. Electric vehicle charging infrastructure assignment and power grid impacts assessment in Beijing. Energy Policy 2012;51:544–57.

[7] Hartmann N, Özdemir ED. Impact of different utilization scenarios of electric vehicles on the German grid in 2030. J Power Sources. 2011;196:2311–8.

[8] Kelly JC, MacDonald JS, Keoleian GA. Time-dependent plug-in hybrid electric vehicle charging based on national driving patterns and demographics. Appl Energy 2012;94:395–405.

[9] Weiller C. Plug-in hybrid electric vehicle impacts on hourly electricity demand in the United States. Energy Policy 2011;39:3766–78.

[10] Langton A, Crisostomo N. Vehicle-Grid Integration: A Vision for Zero-Emission Transportation Interconnected throughout California's Electricity System. <http://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M080/K775/80775679.pdf>: California Public Utilities Commission; 2013.

[11] California Vehicle-Grid Integration (VGI) Roadmap: Enabling vehicle-based grid services. <http://www.caiso.com/Documents/Vehicle-GridIntegrationRoadmap.pdf>: California Independent System Operator; 2014.

[12] 2013 ZEV Action Plan: A roadmap toward 1.5 million zero-emission vehicles on California roadways by 2025. Office of Governor Edmund G. Brown Jr., Governor of the State of California; 2013.

[13] State Zero-Emission Vehicle Programs Memorandum of Understanding. <http://arb.ca.gov/newsrel/2013/8s_zev_mou.pdf2013>.

[14] President Obama Launches EV-Everywhere Challenge as Part of Energy Department's Clean Energy Grand Challenges. http://energy.gov/articles/president-obama-launches-ev-everywhere-challenge-part-energy-department-s-clean-energy>: U.S. Department of Energy; 2012.

[15] National Electric Mobility Mission Plan Launched Today. Ministry of Heavy Industries & Public Enterprises; 2013.

[16] Energy-saving and new energy automotive industry development plan. The Central People's Government of the People's Republic of China; 2012.

[17] Axsen J, Kurani KS. Who can recharge a plug-in electric vehicle at home? Transport Res Part D: Transport Environ 2012;17:349–53.

[18] National Household Travel Survey. <http://nhts.ornl.gov/>: U.S. Department of Transportation, Federal Highway Administration; 2009.

[19] Peterson SB, Michalek JJ. Cost-effectiveness of plug-in hybrid electric vehicle battery capacity and charging infrastructure investment for reducing US gasoline consumption. Energy Policy 2013;52:429–38.

[20] Zhang L, Brown T, Samuelsen GS. Fuel reduction and electricity consumption impact of different charging scenarios for plug-in hybrid electric vehicles. J Power Sources 2011;196:6559–66.

[21] Dong J, Lin Z. Within-day recharge of plug-in hybrid electric vehicles: Energy impact of public charging infrastructure. Transport Res Part D: Transport Environ 2012;17:405–12.

[22] Meliopoulos S, Meisel J, Cokkinides G, Overbye T. Power system level impacts of plug-in hybrid vehicles. 2009.

[23] V2G-Sim. <http://v2gsim.lbl.gov>: Lawrence Berkeley National Laboratory; 2014.

[24] Saxena S, Le Floch C, MacDonald J, Moura S. Quantifying EV battery end-of-life through analysis of travel needs with vehicle powertrain models. J Power Sources 2015;282:265–76.

[25] Saxena S, MacDonald J, Black D, Kiliccote S. Quantifying the Flexibility for Electric Vehicles to Offer Demand Response to Reduce Grid Impacts without Compromising Individual Driver Mobility Needs. SAE Technical Paper 2015-01-0304; 2015.

[26] Autonomie. <http://www.autonomie.net/>: Argonne National Laboratory; 2014.

[27] Carlson R, Lohse-Busch H, Diez J, Gibbs J. The measured impact of vehicle mass on road load forces and energy consumption for a BEV, HEV, and ICE vehicle. SAE Int J Alternative Powertrains 2013;2:105–14.

[28] Electric Vehicle Supply Equipment (EVSE) Testing. Idaho National Laboratory.

[29] Saxena S, Gopal A, Phadke A. Understanding fuel savings mechanisms from hybrid vehicles to inform optimal battery sizing for India. Int. J. Powertrains 2014;3:259–78.

[30] Saxena S, Gopal A, Phadke A. Electrical consumption of two-, three- and four-wheel light-duty electric vehicles in India. Appl Energy 2014;115:582–90.

[31] Saxena S, Phadke A, Gopal A. Understanding the fuel savings potential from deploying hybrid cars in China. Appl Energy 2014;113:1127–33.

[32] Yilmaz M, Krein PT. Review of battery charger topologies, charging power levels, and infrastructure for plug-in electric and hybrid vehicles. Power Electron, IEEE Trans 2013;28:2151–69.

[33] Foley AM, Winning IJ, Gallachoir BPO. State-of-the-art in electric vehicle charging infrastructure. Vehicle Power and Propulsion Conference (VPPC); 2010 IEEE2010. p. 1–6.

[34] Botsford C, Szczepanek A. Fast charging vs. slow charging: Pros and cons for the new age of electric vehicles. EVS24. Stavanger, Norway; 2009.

[35] Transitions to Alternative Vehicles and Fuels: The National Academies Press; 2013.

[36] Final Technical Support Document: Fuel Economy Labeling of Motor Vehicle Revisions to Improve Calculation of Fuel Economy Estimates. United States Environmental Protection Agency; 2006. p. 29.

[37] Allen M. Real-world range ramifications: heating and air conditioning. <http://www.fleetcarma.com/electric-vehicle-heating-chevrolet-volt-nissan-leaf/>: Fleetcarma; 2014.

[38] Moura SJ, Stein JL, Fathy HK. Battery-health conscious power management in plug-in hybrid electric vehicles via electrochemical modeling and stochastic control. Contr Syst Technol, IEEE Trans 2013;21:679–94.

[39] Alternate Fuels Data Center – Fuel Properties Comparison. <http://www.afdc.energy.gov/fuels/fuel_comparison_chart.pdf>: U.S. Department of Energy; 2013.