Estimating the HVAC energy consumption of plug-in electric vehicles

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HIGHLIGHTS

- Dynamic electric vehicle thermal comfort model based on control volume approach.
- Light duty single and fleet level HVAC electrical energy (including heater) requirements.
- Impact of HVAC loads on electric vehicle range.
- State-wise sensitivity of range for 24 kWh electric vehicle.

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ABSTRACT

Plug in electric vehicles are vehicles that use energy from the electric grid to provide tractive and accessory power to the vehicle. Due to the limited specific energy of energy storage systems, the energy requirements of heating, ventilation, and air conditioning (HVAC) systems for cabin conditioning can significantly reduce their range between charges. Factors such as local ambient temperature, local solar radiation, local humidity, length of the trip and thermal soak have been identified as primary drivers of cabin conditioning loads and therefore of vehicle range. The objective of this paper is to develop a detailed systems-level approach to connect HVAC technologies and usage conditions to consumer-centric metrics of vehicle performance including energy consumption and range. This includes consideration of stochastic and transient inputs to the HVAC energy consumption model including local weather, solar loads, driving behavior, charging behavior, and regional passenger fleet population. The resulting engineering toolset is used to determine the summation of and geographical distribution of energy consumption by HVAC systems in electric vehicles, and to identify regions of US where the distributions of electric vehicle range are particularly sensitive to climate.

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1. Introduction

Plug-in Electric Vehicles (PEVs) are an increasingly important component of the US light-duty passenger fleet [1]. PEVs generally enable lifecycle cost savings [3], reduced lifecycle energy consumption [2], and lower environmental impacts [4], but these benefits most often come at an incremental purchase cost.

In PEVs, the energy storage system must generally provide all of the energy to power the full function of the vehicle including traction loads, accessory loads, and cabin thermal comfort conditioning loads. Cabin thermal comfort conditioning loads especially have been the focus of continuing technological and system development to reduce their energy consumption, but the benefits of these systems are difficult to assess. Because of differences in driving behavior and climate conditions, the effect of cabin thermal comfort conditioning loads on PEVs varies regionally and temporally. Despite its importance in understanding the performance, robustness, and consumer acceptability of PEVs, the role of thermal comfort conditioning loads has been relatively under-researched. A few studies have modeled the device-level function and energy consumption of vehicle heating, ventilation, and air conditioning (HVAC) systems [6–9], but none have attempted to translate these device-level performance metrics into geographically- or temporally-realized, transportation-system-level energy consumption metrics for PEVs.

The most relevant recent work was performed by researchers at the National Renewable Energy Laboratory (NREL). These researchers have found that the energy required to provide cabin cooling for thermal comfort can reduce the range of PEVs from 35% to 50% depending on outside weather conditions [6]. These NREL models did not consider the role of cabin heating on PEV energy consumption, [6,8,9] and used a temporally- and

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seasonally-averaged model of temperature and climate. This model of HVAC actuation disregards the dynamic thermal comfort conditioning requirements that result from changing environmental conditions (i.e. hourly changes in irradiation and ambient temperature). In this previous work, the definition of thermal comfort was based on Fanger’s description of person’s thermal sensation vote [10], wherein the person’s thermal sensation is related to the heat balance on the body as a whole. The metric of ‘predicted percent dissatisfaction’ (PPD) was defined as a function of deviation in person’s heat balance from a thermally neutral sensation. A PPD > 0 was used to be representative of a person likely to feel too hot. Under these assumptions, PPD was treated as a statistical representation of the fraction of time the air conditioning (AC) is turned on [8,9,11,12], whereas in real-world PEVs heating loads (due to the lack of engine waste heat) and transient HVAC loading may be important contributors to overall energy consumption [13].

In order to understand the detailed role of climate and driving patterns on the energy consumption of PEVs, this paper presents a study of the regional differences in PEV cabin thermal comfort conditioning loads across the US. This study synthesizes dynamic models of thermal comfort, driver behavior, HVAC system function, and hourly weather data to model the geographical distribution of cabin thermal comfort conditioning loads for US PEVs. Discussion focuses on the implications of including heater loads on PEV environmental performance, on comparison of PEVs to conventional vehicles, and on the effect of HVAC energy consumption on vehicle range.

2. Methods

In this paper, we seek to understand the effects of thermal comfort conditioning (cabin heating and cabin cooling) on PEV performance based on a bottom-up control volume approach inclusive of the dynamics of climate, driving behavior, cabin temperature, and HVAC system control and load [14]. The relationship among these models is represented in Fig. 1 and described in the following sections.

2.1. Climate and solar irradiation modeling

The first database input to the model characterizes the environmental conditions under which the vehicle will be simulated. In this model, the cabin space is subjected to hourly changes in environmental conditions \(T_{\text{ambient}}\), relative humidity, \(Q_{\text{solar}}\) and the cabin temperature \(T_{\text{cabin}}\) and HVAC loading varies accordingly. The input environmental conditions are derived from the National Solar Resource Database (NSRDB), which contains hourly environmental data for 365 days of the year across 1019 locations within US. The input to the model is based on the NSRDB typical meteorological year (TMY) 3 dataset.

2.2. Vehicle trip modeling

During an automobile trip, HVAC systems may or may not be used based on factors such as the timing of previous trips in the vehicle, and the ambient conditions as a function of time of day. To capture these interactions, the HVAC energy consumption model must be informed by a model of driver behavior including trip start and stop times, trip type, type of vehicle used, and type of driving encountered. These data are extracted from a subset of the 2009 National Household Transportation Survey (NHTS). The NHTS is a periodic, federally-funded survey of the U.S. population whose purpose is to gather information on daily and long distance travel. For the 2009 NHTS, 150,147 households completed the survey. Individuals are surveyed regarding their household makeup, personal demographics, vehicle characteristics and travel during an assigned travel day. The NHTS survey data are normalized using appropriate weights to represent the US population as a whole.

For this study, the NHTS subset made up of light-duty vehicles that were 5 years old or younger was chosen to reduce the probability of including inoperable vehicles in the sample. Each driver is assumed to have the same distribution of driving behavior as does the NHTS, independent of geography, demography or any potential vehicle range limitations. Each light-duty vehicle trip is performed in a vehicle with an active energy consumption of 300 DC Wh mile\(^{-1}\) (186 DC Wh km\(^{-1}\)). Each vehicle is assumed to charge before each trip from home.

2.3. Geographical light-duty passenger fleet modeling

In order to establish the geographical and therefore climatic distribution of PEVs across the US, this model extracts the state-wise vehicle population distribution from the US Census Bureau, 2009 and allocates EV energy consumption to the geographic regions of the US. A synthesis of this dataset is shown in Fig. 2, California has approximately 14% of the 241.8 million registered light-duty vehicles in US. For this study, EVs are assumed to be distributed among the state of the US in proportion to their conventional light-duty vehicles population.

2.4. Vehicle thermal comfort model

The transient inputs from the NSRDB and NHTS databases are fed into the dynamic vehicle thermal comfort model which is built using the Matlab/Simulink simulation platform. The vehicle characteristics such as size of the vehicle, window configurations, and material properties are used to evaluate losses by conduction, convection, and radiation. This control volume based approach dynamically evaluates the power required by the AC and the heater to maintain the passenger’s thermal comfort for every hour in which the driver is driving.

Previously thermal comfort predictions were based on experiments conducted in a climate-controlled chamber. The physical (air temperature, mean radiant temperature, relative humidity and air velocity) and physiological variables (metabolic rates and clothing) were measured experimentally. However, numerous studies [16,17] have shown large measurement errors in predicting actual thermal comfort, resulting from difficulty in controlling all 6 variables accurately. As opposed to the approach proposed in Fanger and the previous NREL studies, in this study, cabin thermal comfort is assumed to be achieved if the cabin is maintained...
between 23°C and 27°C with <50% relative humidity (RH). The thermal set points were set based on ASHRAE map of thermal comfort [18]. Some of the vehicle thermal comfort model parameters are presented in Table 1 (see Appendix for a full listing of modeling parameters).

2.5. Summary

These models are synthesized to construct a temporally-, geographically- and climatically-realized cabin comfort conditioning thermal simulation. The outputs from these simulations are used to synthesize A) the energy consumed by PEVs both at vehicle-level and fleet-level, B) the geographical variations in net HVAC energy consumption across US, C) the performance of EVs across US using all electric range as a metric, and D) the net gasoline displaced as a result of EVs replacing conventional light-duty vehicle fleet.

3. Results

3.1. Single vehicle thermal comfort modeling

This section provides results on the function of the dynamic thermal comfort model for a single light-duty vehicle. The transient inputs into the cabin comfort conditioning thermal model are those shown in Fig. 1. The cabin space temperature is regulated automatically by operating the cabin heater and AC system such that the temperature inside the cabin is controlled to be between 23°C and 27°C with <50% relative humidity. For an example of the function of dynamic thermal comfort model, two scenarios are simulated on January 1st (0 h – 24 h) at 29 Palms, California. Fig. 3a presents the result of a “no trip scenario” (representative of vehicle staying at home all day) and of a sample trip occurring between 11:00 and 13:00. The resulting cabin temperatures and the hourly trace of local ambient temperatures are presented as a function of time of day (TOD). During the sample trip, the cabin temperature \( T_{\text{cabin}} \) is pulled down from the soak temperature \( T_{\text{cabin: No Trip}} \) at 11 h (≈ 35°C) to the thermal comfort condition (27°C) by operating the AC. The HVAC electrical output power \( (Q_{\text{AC}}^r) \) and \( Q_{\text{heater}}^r \), local solar irradiation \( Q_{\text{solar}} \) (inclusive of direct and diffuse components), and thermal losses \( Q_{\text{losses}} \) (inclusive of convective and conductive losses to the environment) as a function of TOD are represented in Fig. 3b. The AC cooling output consists of 7800 W of peak transient cooling power and ~1200 W of steady-state output. The total HVAC electrical energy (0.52 kWh: transient, 1.91 kWh: steady-state, inclusive of system COP) for the sample trip is computed by integrating the HVAC loads during the length of the trip.

3.2. State-averaged fleet PEV HVAC energy consumption

Operating the HVAC system to achieve thermal comfort consumes on-board energy and shortens the driving range of the PEV, but this range penalty associated with HVAC operation is a strong function of geographical location and local weather conditions. For example, the geographical distribution of the annual energy consumed by the HVAC system for a single PEV is represented in Fig. 4a for each of the US states and for 12,000 mi (19,312 km) of annual driving distance. The HVAC energy consumption is divided into electrical energy expended for heating and for cooling the PEV cabin space. The ratio of AC load to heater load is highest in Arizona and lowest in Alaska (1.58). Fig. 4b shows that for similar driving conditions, a PEV in Arizona requires approximately 1000 kWh (~30 gallons gasoline equivalent) more electrical energy per year for passenger comfort conditioning compared to a PEV in West Virginia. This translates into the need for a PEV user in Arizona to charge ~54 times more per year than a PEV user in West Virginia.

3.3. US light-duty vehicle fleet HVAC energy consumption

To estimate the total annual HVAC energy required by a hypothetical 100% PEV US light-duty vehicle fleet the HVAC energy consumed by a single PEV across different states (Fig. 4a) can be combined with the vehicle fleet distribution (Fig. 2), as represented in Fig. 5. For this hypothetical 100% PEV fleet, we estimate that 565 billion kWh of energy would be required annually for thermal...
comfort, as shown in Table 2. AC energy requirements are modeled to exceed heating energy requirements by $2.75$ times. This is equivalent to 17 billion gallons of gasoline consumption ($13.7\%$ of 2011 US annual oil imports [1]).

Of course, a 100% PEV light-duty fleet is not representative of any near-term feasible scenario, but the presentation of results in this format allows for the simple calculation of the HVAC energy consumption of near-term light-duty fleets through multiplication of either national or state-level energy consumption by the PEV fleet penetration fraction. For example, at present, there are 59,952 PEV in the US light duty vehicle fleet, which represents 0.03% of the 2009 census value of 242 million vehicles. At present, the energy allocated to heating and cooling PEVs in the US is approximately 0.14 billion kWh DC.

The scale of the energy involved in thermal comfort conditioning of PEVs justifies the treatment of PEV HVAC systems design...
as means for achieving significant transportation-system energy consumption reductions.

4. Implications of HVAC energy consumption on PEV energy consumption and range

The results of the cabin comfort conditioning thermal model demonstrate that HVAC energy consumption in PEVs is a strong function of climate and therefore varies considerably among the regions of the US.

The results above are presented in terms of the energy consumption of the HVAC system have implications on the PEV as a vehicle. In this section, we discuss the implications of HVAC energy consumption of the PEV in terms of its range. This discussion has relevance for PEV engineers, analysts and consumers.

4.1. PEV energy consumption analysis

The energy consumption of PEVs is an important input into studies of PEV performance, economics, and environmental impacts [19].
A wide variety of studies \cite{3-7,9} of electrified vehicles have made comparisons between PEVs and CVs on the basis of their EPA 5-cycle measured fuel economy, but the EPA 5-cycle fuel economy test does not measure the effect of heating loads on the fuel economy of either EVs or CVs. Other aspects of vehicle performance that are not measured on the EPA 5-cycle test have relatively equivalent effects on both EVs and CVs (e.g. daytime running light energy consumption), but as demonstrated by the results of this study, the use of the heater in EVs does increase EV energy consumption, whereas the use of the heater in CVs has no effect on fuel consumption. By using the EPA 5-cycle fuel economy results to compare the performance of EVs to the performance of CVs, the literature ignores the sensitivity of PEV energy consumption to heater use. Using the results of this study, we can make a comparison of the energy consumption of PEVs and CVs that does consider their real-world fuel consumption due to HVAC loads.

Table 2
Total annual energy required for operating a hypothetical 100% PEV US light-duty fleet.

<table>
<thead>
<tr>
<th>Air conditioning energy</th>
<th>Heating energy</th>
<th>Traction energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>415 billion kWh\text{DC}</td>
<td>151 billion kWh\text{DC}</td>
<td>1012 billion kWh\text{DC}</td>
</tr>
</tbody>
</table>

Fig. 5. (a) Annual total HVAC energy consumption by the light duty vehicle fleet in individual states of USA. (b) States with minimum and maximum Total HVAC energy consumption per year.
To construct this comparison, we can consider CV with a measured 5-cycle energy consumption of 27.5 mi gal\(^{-1}\) (8.55 L (100 km)\(^{-1}\)), and a EV with a measured 5-cycle energy consumption of 300 WhDC mi\(^{-1}\) (186 WhDC km\(^{-1}\)).

Table 3 shows the results of this comparison. The left column of results shows the comparison between the example CV and EV using the EPA 5 cycle results. The right column of results compares the CV and EV energy consumption inclusive of the US national average AC energy consumptions (for the CV and EV) and the US national average heater energy consumption of 744.1 kWh per year (for the EV). This comparison shows that inclusive of the energy consumption of PEV HVAC systems, the PEVs exhibit a 74% annual energy savings. Using EPA 5-cycle test methods\(^{[3,9]}\) overestimates the energy savings due to PEVs by 28%, resulting in inaccurate estimations of the PEV range, cost, energy consumption, and lifecycle emissions.

### 4.2. Implications of HVAC energy consumption on PEV range

One of the primary consumer concerns with mass-market PEVs is their relatively low range and the large observed fluctuation in that range that comes with geography and climate\(^{[15]}\). The results of this study can be used to quantify these effects for our model PEV.

For this discussion, we can compare the HVAC-inclusive energy consumption, and PEV range across various locations in the US. The simulations were performed across all 1019 NSRDB locations. For example, Fig. 6 shows the distribution of PEV range available for each of the 365 days of the year for Los Angeles, CA and Detroit, MI. The distribution clearly indicates that the range available from this model PEV will vary due to different environmental conditions at these two locations. Los Angeles has more days where the HVAC energy consumption reduces the available PEV range, whereas Detroit has a bimodal distribution wherein milder times of year require less HVAC energy consumption and therefore have less range impact. Fig. 7 compares the geographical distribution of expected range across the US, aggregated by state. The variation in PEV range within a state is due to the variation in climate within that state.

### 5. Conclusions

This study provides a detailed analysis of the system-level impacts of thermal comfort on the performance of PEVs. The results of this study are a novel contribution toward understanding the challenges and benefits associated with passenger fleet electrification. The modeled connections between the low-level performance of these vehicles’ accessory systems and their system-level energy consumption and range performance will allow vehicle designers, policy makers, and consumers to understand the interactions between vehicle technologies, their conditions of use, climate, the characteristics of the US vehicle fleet, and its energy use. As examples, consider that regional electric utilities must plan for both the tractive and HVAC loads of EVs to be included in their load growth scenarios, consumers will have to understand that the performance of their vehicle will be sensitive to climate, and vehicle designers should understand that improvements in HVAC system energy consumption will improve the effectiveness with which EVs can meet energy consumption and sustainability objectives.

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Table 3

Comparing the annual energy consumed by conventional and electric vehicles (12,000 mi/yr, mid-sized car).

<table>
<thead>
<tr>
<th></th>
<th>Estimated energy consumption using 5-cycle EPA test methods (^{[39]})</th>
<th>Estimated energy consumption using 5-cycle EPA test methods including real-world heater energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional vehicle</td>
<td>14.6 MWh(_{LHV})</td>
<td>14.6 MWh(_{LHV})</td>
</tr>
<tr>
<td>Electric vehicle</td>
<td>3.6 MWh(_{DC})</td>
<td>4.3 MWh(_{DC})</td>
</tr>
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Fig. 6. Performance variation of PEV at Los Angeles, CA and Detroit, MI.

Fig. 7. Geographical PEV range distribution across US states.
Acknowledgments

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jpowsour.2014.02.033.

References


