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Article

Electrification of Vehicle Miles Traveled and Fuel Consumption within the Household Context: A Case Study from California, U.S.A.

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Abstract: Plug-in electric vehicles (PEVs), consisting of battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), combined with the decarbonization of the electricity sector, can significantly help reduce greenhouse gas emissions in the transport sector. This study used empirical data from 287 households with at least one plug-in electric vehicle in California between 2016 and 2020. We estimated electric vehicle miles traveled (eVMT), fuel consumption and utility factor at the household level, i.e., taking into consideration all vehicles. We also studied the effect of household-specific factors—such as frequency of overlaps between vehicles, frequency of charging and frequency of long-distance trips—on eVMT, utility factor and fuel consumption within two-car households. Our results indicate that PHEVs with a range of at least 35 miles have the potential to electrify a similar share of total household miles as some short range BEVs, or can reach up to 70% as much electrification as some long range BEVs and, thus, can play an important role in decarbonizing the transport sector.

Keywords: plug-in electric vehicles (PEVs); eVMT; utility factor; charging behavior

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1. Introduction

1.1. Motivation and Background

The use of plug-in electric vehicles (PEVs), split into two main categories, battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), combined with the decarbonization of the electricity sector, can help reduce greenhouse gas emissions in the transport sector [1–8]. BEVs use an electric drive train for propulsion and their only source of energy is their rechargeable battery packs. PHEVs, on the other hand, combine an electric drive train with a conventional one, which leads to a more complex analysis of fuel economy compared with BEVs and internal combustion engine vehicles (ICEVs) [9]. In order to assess the potential to reduce greenhouse gas emissions from these vehicles, it is important to understand the share and number of miles that can be electrified. Traditionally, this has been performed on a per vehicle basis, however the household context is also important to consider. For example, trips can be shifted between vehicles, increasing or decreasing the electrified miles. However, this has not been previously studied enough, partly due to the difficulty of collecting good empirical data at the household level. Our contribution to the literature and the aim of this paper is to fill this gap by analyzing measures related to electric vehicle miles traveled in the household context. We based our analysis on a case study of 287 households in California.

Utility factor (UF) of a PHEV—defined as the share of electrified vehicle miles traveled (eVMT) within total vehicle miles traveled (VMT)—is the most common metric in analyzing the performance of PHEVs in order to understand the degree to which they provide emission-free travel. Previous literature on the utility factor focuses either solely on the PEV or ignores the other conventional vehicles in the household. The literature on multi-car households with PEVs is also limited due to the difficulty of collecting (and, therefore, lack of) empirical data on multi-car households. See [10–16]. To our knowledge, there has not been any assessment of the UF at the household level—as the share of eVMT within total household miles traveled—that takes into account all vehicles in a household and captures the overall household electrification of miles. The goal of this paper is to fill this gap and assess the UF within the household context, and investigate how household factors impact electrification of vehicle miles traveled and fuel consumption, using an empirical data set. We used data from 650 vehicles which had onboard loggers that recorded driving and charging data for a year, distributed among 287 households where each household had a PEV. Our dataset included BEVs along with PHEVs, and the UF of the BEVs is one by default since all of their traveled miles are electrified. On the household level, UF can be calculated for BEV-households—since each household owns only one PEV, they can be classified as either a BEV or PHEV household—and this enabled us uniquely to compare the UFs of BEV-households and PHEV-households.

The UF of a PHEV encapsulates the eVMT and VMT of that PHEV; similarly, the UF of a household encapsulates the eVMT of the PEV of that household and the VMT of that household. Therefore, in this paper, we use the following metrics regarding electrification of vehicle miles traveled: eVMT of the PEV, VMT of the PEV, VMT of the household, UF of the PHEV, and UF of the household. We define the household context using three categories: (1) PEV technology in the household, (2) household vehicle usage, and (3) ICEVs in the household. For each of these categories, we identify relevant factors and the corresponding variables in our data set. Then, we use descriptive statistics to explain how the most salient factors impact our metrics. This is followed by a regression analysis for each of our metrics where we investigate the statistical significance of the identified factors. In addition, we also analyze the household fuel consumption and perform a regression analysis on how these factors impact fuel consumption in: (1) all households, (2) PHEV households, and (3) BEV households. For our analysis, we focus mostly on two-car households—which is most common in our dataset, with 64% of households being two-car households, and also the largest group of vehicle owners in California—for a more standard comparison between different PEV-type households.

The outline of the paper is as follows: An overview of previous literature regarding the utility factor is presented in Section 1.2. In Section 2, the data and methods are described, followed by the results in Section 3. We close with a discussion and conclusions in Section 4.

1.2. Previous Literature

There are two main approaches to assessing UF in the literature. The first approach is to run simulations based on test-cycles or transportation surveys. In this approach, the UF is calculated under certain assumptions regarding the charging frequency, vehicle characteristics and driver characteristics. It is also common practice to follow the standardized methods from the Society of Automotive Engineers, SAE J2841 and SAE J1711, to calculate the UF [17,18]. Elgowainy et al. [19] used the U.S. National Household Transportation Survey (NHTS) to report on the UFs of PHEVs with an all-electric-range (AER) of 10, 20, 30, 40 and 60 miles. Axsen et al. [20] used survey data from 877 Californian new vehicle buyers and estimated the UF of PHEVs with an AER of 20 and 40 miles under different emission scenarios. Tal et al. [21] used a self-reported web map survey with a sample size of 800 Prius plug-ins and 600 Chevrolet Volts to study charging behavior. Moawad et al. [22] used a test cycle—measured by the U.S. Environmental Protection Agency (EPA), in which they collected driving statistics from 100 drivers in Kansas City for the duration of a day—to estimate the decrease in the consumed fuel of PHEVs with a battery capacity of 4, 8, 12 and 16 kWh, compared with ICEVs. Björnsson et al. [23] used GPS data logged for a representative sample of individual conventional vehicles in private use, to analyze how the utility factor is influenced by the choice of objective function when determining optimal battery sizes for PHEVs. Standardized methods that rely heavily on assumptions were criticized for not accounting for complex scenarios. SAE J2841, for instance, is based on the assumptions that each vehicle starts the day fully charged, does not charge until after the last trip of the day and only charges once a day; it also assumes that PHEVs are driven in the same patterns as national average vehicles [24,25]. Bradley and Quinn [24] investigated how different assumptions in these standards would result in different UF calculations, and they found that UF calculations were very sensitive to assumptions regarding charging behavior, vehicle age and vehicle annual distance driven.

The second approach is to use empirical, real-world data to estimate the UF, which provides an insight into actual travel behavior patterns. Plötz et al. [26] and Plötz et al. [27] used publicly available real-world driving data from two online sources, voltstats.net and spritmonitor.de, to estimate the UFs for several PHEVs in the U.S., Canada and Germany. Ligterink et al. [28] analyzed the fueling and charging data of plug-in vehicles, collected from lease companies in the Netherlands, and estimated the UF for the Dutch plug-in fleet. Davies and Kurani [29] analyzed the data from 25 converted Toyota Prius which had onboard loggers to record driving and charging data; they compared the observed UF with the simulated UF of a scenario that accounted for additional workplace charging, and concluded that additional workplace charging can result in a relatively higher UF. Idaho National Laboratory, in their EV project, analyzed the driving and charging data of 21,600 vehicles in the U.S., obtained from several OEMs, and reported their estimated eVMT and VMT [30]. Nicholas et al. [31] used a subset of the dataset we used in this paper—which contained logger data placed on vehicles for a year—and reported on the UF of Toyota Prius, Ford Energi and Chevrolet Volt. Hao et al. [32] studied the actual UF of seven Chinese cities using PHEV driving big data, concluding that PHEVs with an all-electric-range of over 50 miles would lead to better energy saving and emission reduction potential. Srinivasa Raghavan and Tal [33] and Raghavan and Tal [34] used multi-year longitudinal data from PHEVs in California and studied charging and driving patterns. Plötz et al. [35] analyzed the real world utility factor of over 1000 PHEVs in Germany. Tal et al. [36] analyzed vehicle usage and refueling behavior in California using logger data, surveys and interviews.

In summary, existing studies on the utility factor lack the household context, often ignoring multi-car households and focus solely on the PEV. Here, we fill this gap with an analysis of the UF within the household context, and investigate how household factors impact electrification of vehicle miles traveled and fuel consumption, using empirical data from 287 households with 650 vehicles in total.

2. Data and Methods

The data we used was from the Advanced Plug-in Electric Vehicle Travel and Charging Behavior Project which aims to provide an insight into how plug-in electric vehicles are used on a day to day basis within the household travel context, by placing data loggers in participant households for one year [31]. The project was initiated by the Electric Vehicle Research Center at the University of California. Data was collected from summer 2015 to summer 2020, in California, U.S.A., from 287 households, by placing a monitor in all household vehicles driven more than 1000 miles per year. Participating households were selected, in consultation with the California Air Resource Board, to fit an appropriate sampling of the population. Odometer readings were taken from cars that were driven less than 1000 miles per year. Each household owned only one PEV. Among the 287 households, 20 had a Toyota Plug-in Prius, 45 had a Ford C-Max/Fusion Energi, 25 had a Toyota Prius Prime, 23 had a Chrysler Pacifica, 71 had a Chevrolet Volt, 43 had a Nissan Leaf, 23 had a Chevrolet Bolt, and 37 had a Tesla Model S. Including the conventional vehicles in the households, the dataset has 650 vehicles in total. Nissan Leaf, Chevrolet Bolt and Tesla Model S were the BEVs in the data set, and the rest were PHEVs. The model years for the PEVs in the dataset ranged from 2012 to 2019. The dataset also included an extensive survey with the PEV owners prior to the placement of the monitors.

2.1. Provided Datasets

The raw data collected from the loggers and through the survey was cleaned by the Electric Vehicle Research Center. We used two main sets of data in our analysis: trip data and charging data.

2.1.1. Trip Data

Trip data consisted of each single trip by the logged vehicle. The separating factor between trips was that the car remained at the same position idly with a speed of zero for at least 5 min. The dataset provided information regarding the start time and duration of the trip, the total distance traveled, and fuel consumption during the trip. It also included the electric vehicle miles traveled (eVMT) and gasoline vehicle miles traveled (gVMT) for each single trip. The calculation of eVMT and gVMT were performed by the Electric Vehicle Research Center. eVMT calculation methods do not differ much from each other, as other studies show, e.g., eVMT calculation based on label fuel economy versus vehicle average charge sustaining fuel consumption differed less than 2.5% in a study by the Idaho National Laboratory [30].

Logger information was also available in the dataset with the following variables: logger installation date, logger uninstall date, initial odometer reading and final odometer reading. The dataset also included the following variables related to household identification: household id no., list of PEVs in the household, list of ICEVs in the household, number of drivers in the household, size of the household, number of vehicles in the household and vehicle–driver ratio.

2.1.2. Charging Data

Charging data consisted of each single charging event performed by the logged vehicle. It provided information regarding the start and end times of the charging event, charge levels (either level 1 or level 2), and start and end state of charge (SOC). In addition, the charging dataset also contained information regarding vehicle and household identification and logger information, as in the trip data set. All driving and charging data were annualized prior to analysis.

2.1.3. Other Sources of Information

The range of the PEVs that we used in our analysis was based on the information provided by the U.S. Environmental Protection Agency; which was: 11 miles for Toyota Prius, 19 miles for Ford Energi, 25 miles for Toyota Prius Prime, 33 miles for Chrysler Pacifica, 35–38 miles for Chevrolet Volt, 73–84 miles for Nissan Leaf, 238 miles for Chevrolet Bolt, and 249 miles for Tesla Model S.

2.2. Compiled Dataset for Analysis

From the datasets provided by the Electric Vehicle Research Center, we selected and computed the following variables that we labeled as factors corresponding to the three categories of the household context.

For the category of PEV technology in the household, we selected the variable range and computed the variable frequency of charging. Range was defined as the all-electric range of the plug-in electric vehicle of that household. Frequency of charging was defined as the average number of charging events per day for the PEV of the given household.

Regarding household vehicle usage, we computed the variables frequency of overlaps, frequency of long-distance trips and standard deviation (SD) of daily household VMT. Frequency of overlaps was defined as the percentage of PEV trips that overlapped with any of the ICEV trips in the household. Frequency of long-distance trips was defined as the percentage of single trips (not daily) above 50 miles undertaken by the PEVs. We also computed the frequency of long-distance trips with a threshold of 20, 30 and 40 miles, respectively, in order to see how the definition of a long-distance trip would impact our results.

For the category regarding the ICEVs in the household, we defined the variable MPG (miles per gallon) of the ICEV in the household as the real-life MPG based on actual driving distance and fuel consumption.

We computed the following dependent variables for our analysis: eVMT, VMT of the PEV, VMT of the household, utility factor of the PHEV, utility factor of the household and household fuel consumption in gallons per 100 miles. eVMT was defined as the annualized electric vehicle miles traveled by the PEV in the household. VMT of the PEV was defined as the sum of annualized eVMT and gVMT for the PEV in the household. VMT of the household was the sum of all annualized vehicle miles traveled of all the vehicles in the household. Utility factor of the PHEV was defined as the share of eVMT within the VMT of the PHEV. Utility factor of the household was defined as the share of eVMT within the VMT of the household. In our annualization, we used the first and last recorded trip for that vehicle. Finally, household fuel consumption was defined as the combined fuel consumption of all vehicles in the household in gallons per 100 miles.

All variables that we selected or computed are summarized in Table 1 below.

Table 1. Variables in our compiled dataset.

Dependent Variables	eVMT, VMT of the PEV, VMT of the household, utility factor of the PHEV, utility factor of the household, household fuel consumption.
Independent Variables	Range, frequency of charging, frequency of long distance trips, frequency of overlaps, standard deviation of daily household VMT, MPG of ICEV.

2.3. Methods

We used descriptive and inductive statistical methods, and regression analysis, on our compiled dataset to assess the electrification of vehicle miles traveled and fuel consumption within the household context. We used descriptive statistics to study the household level in more detail, and regression analysis to provide a high-level view and explain overall trends. For the regression analysis, we focused only on two-car households.

Below is our generic regression model, where we used the same independent variables for all:

$$\begin{aligned} Y_i = \beta_0 + \quad & \beta_1 Range + \beta_2 FreqCharging \\ & + \beta_3 FreqLongdistance + \beta_4 FreqOverlaps \\ & + \beta_5 SD\_dailyHHVMT + \beta_6 ICEVMpg + \varepsilon \end{aligned}$$

$i = \{1, \ldots, 8\}$ *where* $Y_1 = eVMT$, $Y_2 = VMT\ of\ the\ PEV$, $Y_3 = VMT\ of\ the\ household$, $Y_4 = Utility\ factor\ of\ the\ PHEV$, $Y_5 = Utility\ factor\ of\ the\ households$, $Y_6 = Fuel\ consumption\ of\ households$, $Y_7 = Fuel\ consumption\ of\ PHEV\ households$, $Y_8 = Fuel\ consumption\ of\ BEV\ households$

We performed multiple linear regression analysis on *eVMT*, *VMT* of the *PEV* and *VMT* of the household, and logistic regression on the UF of the PHEV, and the UF of the household, since the utility factor was always between 0 and 1. Similarly, we performed a logistic regression on the fuel consumption of all households, because we observed a logarithmic relationship between fuel consumption and all-electric range when all PEVs were included (this can be seen in Figure 3 in Section 3.2). When we observed the relationship between fuel consumption and all-electric-range for PHEV households and BEV households separately, this logarithmic relationship disappeared. Therefore, to investigate further, we performed multiple linear regression analyses on the fuel consumption of PHEV and BEV households, separately.

3. Results

The results section is divided into three parts: first we provide descriptive statistics summarizing the dataset and explain how the most salient factors corresponding to household context categories impact our main metrics. Second, we present the results of the regression analysis for each of our main metrics to estimate the statistical significance of the identified factors. Third, we present the sensitivity analysis for our results.

3.1. Descriptive Statistics

Summary statistics for all two-car households are provided in Table 2 (all households combined) and also in Table A1 (households grouped by PEV-type) in the Appendix A. Frequency of charging was, on average, higher for PHEVs compared with BEVs, ranging from 0.67 per day for Chevrolet Bolts, to 1.1 per day for Ford C-Max/Fusion. The frequency of long-distance trips, in general, was low for all PEVs, except Tesla Model S which went on long-distance trips, on average, almost three to six times more often than the other PHEVs in our dataset.

Table 2. Summary statistics for two-car households.

	Min.	0.25-Quantile	Median	Mean	0.75-Quantile	Max.
All households combined (N = 183)						
Annual household VMT (mi)	7341	16,535	21,200	22,426	27,485	56,521
Daily household VMT (mi)	20.11	45.30	58.08	61.44	75.30	154.85
Household utility factor (%)	0.59%	27.41%	42.99%	41.77%	54.70%	98.35%
PHEV utility factor (%) *	1.27%	31.35%	51.54%	50.15%	69.32%	98.95%
Household fuel consumption (gal/100 mi)	0.04	1.54	2.15	2.12	2.61	5.01
Household tailpipe emissions (gCO_2/km)	2.25	83.72	116.84	115.27	141.55	271.99
ICEV fuel economy (MPG)	11.17	19.52	23.93	26.26	30.85	52.83
PHEV fuel economy (MPG) *	36.64	57.78	86.25	156.80	133.75	4065.52
Frequency of charging (events per day)	0.01	0.61	0.80	0.87	1.13	2.73
Frequency of long-distance trips with PEV (%)	0.00%	0.24%	0.88%	2.53%	2.45%	37.97%
Frequency of overlaps (%)	0.00%	6.22%	10.68%	12.00%	16.61%	51.09%

Note: * Excluding BEV (Leaf, Bolt, Model S) households.

The utility factor of the household allows a comparison between households with different number of cars, and between PHEV and BEV households. As seen in Figure 1, the utility factor of the households had a downward trend when the number of cars increased. In other words, households with more cars electrified a lower share of their total travel, which was expected since these households also drive more in total, as seen in Figure 2. Overall, we observed that there was a general increase in eVMT and UF with all-electric range.

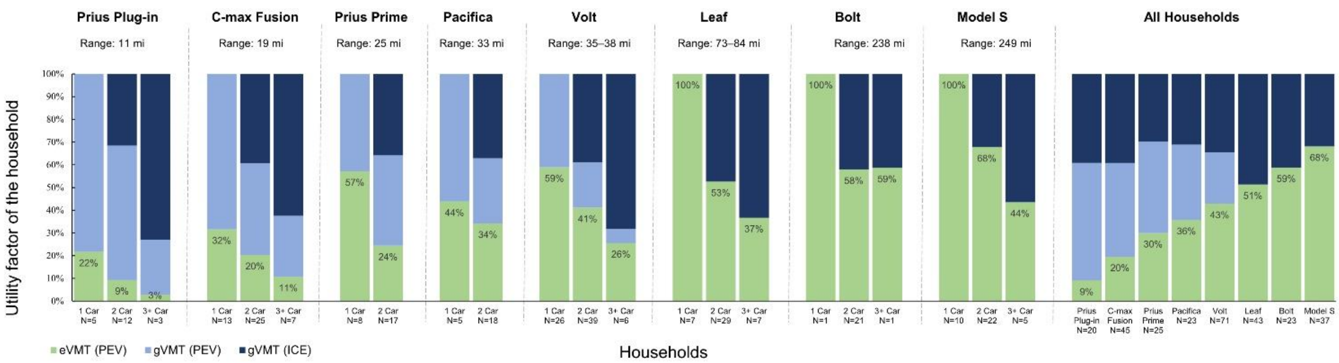

Figure 1. Utility factor of households, categorized by PEV-type and total number of cars in the household.

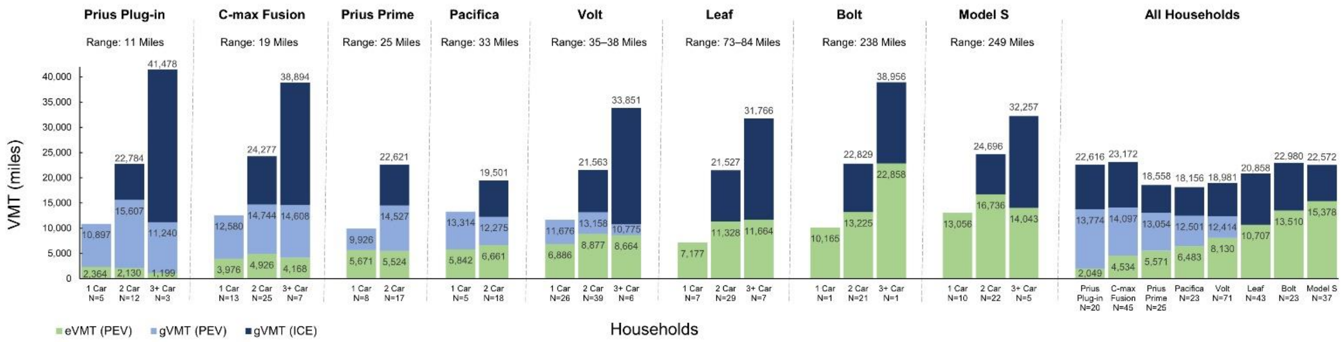

Figure 2. VMT of households, categorized by PEV-type and total number of cars in the household.

Combining same-PEV households and observing their utility factor provided quite interesting results. When we scrutinized the UF of households (Figure 1), we observed that Chevrolet Volt, a PHEV with a range of 35–38 miles, electrified 43% of the total household miles; whereas Nissan Leaf, a BEV with a range of 73–84 miles, was at 51%; Chevrolet Bolt, a BEV with a range of 238 miles, was at 59%; and Tesla Model S, a BEV with a range of 249 miles, was at 68%. This finding shows that, in the context of the whole household, a PHEV such as the Chevrolet Volt, can electrify a similar share of household miles as a low range BEV (Leaf), and can electrify around 70% as many household miles as long range BEVs (Bolt and Model S).

Total annual household VMT among the households were similar, as seen in Figure 2, ranging from 18,156 miles for Pacifica households, to 23,172 miles for C-max Fusion households.

3.2. Regression Analysis

The results of the regression analysis for eVMT, VMT of the PEV, VMT of the household, UF of the PHEV, and UF of the household, are given in Table 3. The results of the regression analysis on household fuel consumption is given in Table 4. Note that both regression analyses were performed only on two-car households.

Table 3. Regression results for how household factors impact vehicle miles and electrification in two-car households.

Dependent	eVMT (mi)		VMT of the PEV (mi)		VMT of the Household (mi)		UF of the PHEV (%)		UF of the Household (%)	
Intercept	−3061.20 (1440.65)	*	2125.20 (1476.15)		3518.39 (2002.98)	.	−3.87 (8.28)		24.88 (4.77)	***
Range (mi)	43.58 (3.77)	***	3.18 (3.87)		1.92 (5.25)		1.82 (0.15)	***	0.17 (0.01)	***
Frequency of charging (events per day)	6023.18 (756.55)	***	5763.80 (775.19)	***	4964.41 (1051.85)	***	17.37 (3.13)	***	15.55 (2.51)	***
Frequency of long-distance trips (%)	307.55 (71.18)	***	519.61 (72.93)	***	274.30 (98.96)	**	−1.31 (0.46)	**	0.16 (0.24)	
Frequency of overlaps (%)	28.24 (39.75)		117.28 (40.73)	**	329.89 (55.27)	***	−0.13 (0.19)		−0.43 (0.13)	**
Standard deviation of daily household VMT (mi)	25.26 (17.71)		79.63 (18.14)	***	197.93 (24.62)	***	−0.26 (0.09)	**	−0.20 (0.06)	***
ICEV fuel economy (MPG)	36.82 (32.56)		−8.90 (33.36)		6.31 (45.27)		0.13 (0.16)		0.11 (0.11)	
N	183		183		183		111 [x]		183	
Multiple R-squared	0.5919		0.5638		0.5517		-		-	
Adjusted R-squared	0.5779		0.5487		0.5362		-		-	
F-statistic	42.07		37.48		35.69		-		-	

Confidence levels *** 99.9%, ** 99%, * 95%, . 90%. Values represent estimates, standard error is given in parentheses.
[x] Excluding BEV (Leaf, Bolt, Model S) households.

Table 4. Regression results for how household factors impact fuel consumption in two-car households.

Dependent	Household Fuel Consumption (gal/100 mi)					
	All Households		*PHEV Households*		*BEV Households*	
Intercept	3.704 (0.174)	***	3.889 (0.238)	***	3.745 (0.339)	***
Range (mi)	−0.004 (0.0004)	***	−0.018 (0.004)	***	−0.003 (0.001)	
Frequency of charging (events per day)	−0.509 (0.091)	***	−0.451 (0.090)	***	−0.753 (0.236)	
Frequency of long-distance trips (%)	−0.023 (0.009)	**	−0.020 (0.013)		−0.023 (0.012)	
Frequency of overlaps (%)	0.021 (0.005)	***	0.020 (0.005)	***	0.019 (0.009)	
Standard deviation of daily household VMT (mi)	0.009 (0.002)	***	0.011 (0.002)	***	0.007 (0.004)	
ICEV fuel economy (MPG)	−0.054 (0.0034)	***	−0.050 (0.005)	***	−0.054 (0.007)	***
N	183		111		72	
Multiple R-squared	-		0.6435		0.6153	
Adjusted R-squared	-		0.6229		0.5787	
F-statistic	-		31.28		16.8	

Confidence levels *** 99.9%, ** 99%, * 95%, . 90%. Values represent estimates, standard error is given in parentheses.

Our results in Table 3 show that range was statistically very significant in electrification of miles, and higher ranges resulted in higher eVMT, UF of the PHEV, and UF of the household. This result confirmed the initial trend observed in the descriptive statistics section, and was also in line with the findings of previous studies [9,24,25].

As seen in Table 3, frequency of charging was also statistically significant, showing up in all main metrics. This suggests that more frequent charging results in higher eVMT, UF of the PHEV and UF of the household. However, it should be noted that the frequency of charging was based on the number of charging events and not the length of these charging events; also, the charging level was not taken into account.

The frequency of long-distance trips was statistically significant for eVMT, VMT of the PEV, VMT of the household, and UF of the PHEV. The results show that more frequent long-distance trips increased eVMT and VMT of PEV as expected, but decreased the UF of the PHEV. This suggests that the decrease in the UF of the PHEV can be explained by the increase in gVMT of the PHEV, meaning a lower fuel economy as long-distance trips become more frequent. Plötz, Funke and Jochem [9] and Mandev et al. [37] also reached the same conclusion in their papers on the impact of daily and annual driving on fuel economy, where they concluded that the tendency for long-distance trips decreased the UF of a PHEV, and PHEV fuel economy.

As seen in Table 3, the frequency of overlaps was statistically significant for the VMT of the household and the UF of the household. As expected, more overlaps between PEVs and ICEVs resulted in higher ICEV usage which increased the gVMT and VMT of the household and, thus, lowered the UF of the household.

In Table 4, we observe that the range and frequency of charging was significant in reducing household fuel consumption in PHEV households, but not in BEV households. Table 4 also shows that for every 10-mile increase in range for PHEV households, household fuel consumption and household tailpipe emissions were reduced by 0.2 gal/100 mi and 17.5 gCO_2/mi (10.9 gCO_2/km), respectively. Conversion of fuel consumption to tailpipe emission was performed by using U.S. Environmental Protection Agency values [38].

In Figure 3, we show the household fuel consumption vs range for two-car households categorized by PEV-type, with a logistic regression curve (marked as B in the figure) and also box plots with the distribution of household fuel consumption. We observed only a small difference between long range BEV households and short range BEV households. The decrease in fuel consumption was smaller in long range BEV households than what was intuitively expected, compared with short range BEV and long range PHEV households. In two-car households with one PEV, BEVs did not reduce household fuel consumption as significantly, compared with long range PHEVs; and consequently, some long range PHEVs reduced household fuel consumption to a similar degree as BEVs.

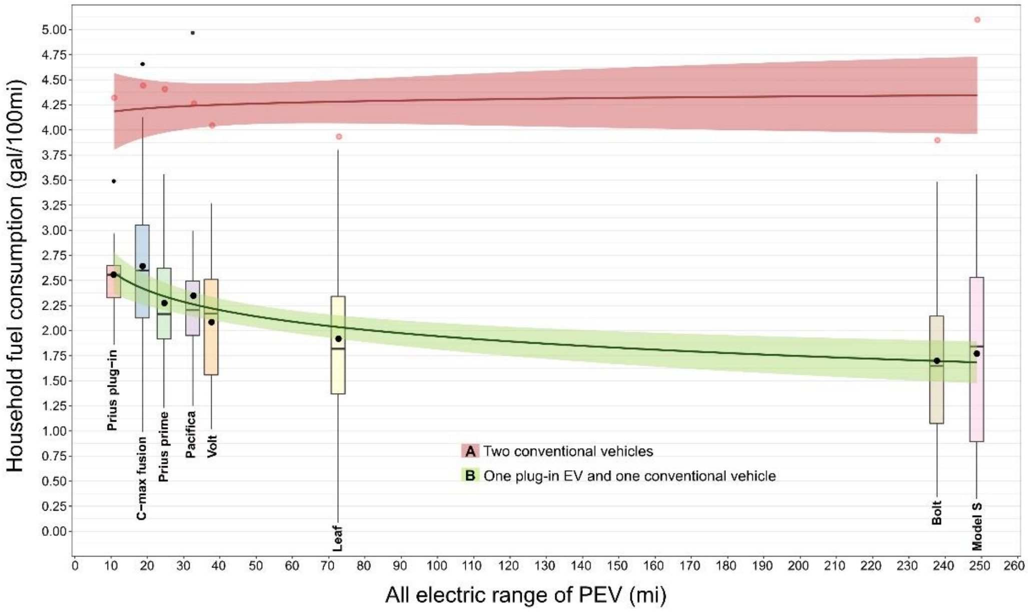

Figure 3. Household fuel consumption vs. range of PEV in two-car households.

Tesla model S households had the lowest ICEV MPG, as given in Table A1 in the Appendix A. This behavior of owning low MPG cars increased the overall household fuel consumption, as seen in Figure 3. This was not observed for Bolt, even though these two cars have a similar range.

Figure 3 also shows a logistic regression curve (marked as A in the figure) for the household fuel consumption if the households had two of the same ICEV instead of one PEV and one ICEV. (We assumed a hypothetical scenario that the second ICEV would be the same as the one already owned, where in reality it could have a higher or lower MPG.) The difference between curve A and B visualizes how much fuel consumption is hypothetically saved through owning a PEV instead of an ICEV. We do not expect the difference in fuel consumption between households with a PHEV or a BEV to change much in the future because long range PHEVs such as Volt can have a higher fuel economy than a new ICEV. Volt production has ended, but similar long range PHEVs could have the potential to further lower household fuel consumption. The new EPA target of 1.9 ga/100 mi (166 gCO_2/mi) [39] for 2023 and EU target of 1.75 ga/100 mi (153 gCO_2/mi) [40] during 2020-24 for newly sold passenger cars, means that buying two new conventional passenger cars would end up consuming the same amount of fuel by the household as having a long range BEV and an older conventional car with lower MPG. To really achieve a decrease in fuel consumption, households will need to shift to two PEVs and no ICEV.

3.3. Sensitivity Analysis

In our results, we presented fewer variables than identified in the data and methods section to label factors corresponding to the categories of the household context. Some of the variables we considered included the number of drivers, commute distance, size of ICEVs in the household, size of the household, whether a charger was present at work, and the age of the PEV users. We first ran our regression models with those variables included, we estimated variance inflation factors to check for multicollinearity, and ran likelihood ratio tests to see if our models were better off without those variables. Removing those variables made our model more robust, so we decided to omit them. The regression models presented in this paper had variance inflation factors lower than 2 for all variables.

For the frequency of long-distance trips, we tested several different variations to make our model more robust. We considered trips over 50 miles in our models, but we also set the threshold at 20, 30 and 40 miles. A higher threshold increased the statistical significance of the variable; thus, we decided to use 50 miles as the threshold for long-distance trips.

4. Discussion and Conclusions

As for all datasets, our dataset has its limitations. First, the sample size of our data was limited to 287 households, of which 183 were two-car households. This had implications both for the regression analysis and the representativeness of our data. From a regression point of view, a larger dataset might have allowed us to include more variables. On the other hand, the strengths of the dataset were that it was collected for the length of a year, which control for the learning phase of a new car, seasonality and other external effects; it also contained several variables and included all vehicles in the households, which is quite unique. There is often a trade-off in empirical data sets between level of detail, length of measurement and number of entities (households, individuals, or vehicles) that are measured.

Our study was regionally bound to California, and the households included could be considered early adopters, with higher education levels and income. Of the households in our dataset, 76% had an annual income of over USD 100,000 compared with the USD 78,672 median income in California in 2020 [41]. Based on the household survey, 86% of the adults had at least a college degree or higher. We recognize that this might have created a bias towards more conscious driving and charging behavior. Our results might have differed slightly if a larger and geographically more diverse population sample had been used. However, California is one of the leading EV markets, and at the time of the data collection for this study, California was in the early adopter phase regarding EV adoption [42]; therefore, we considered these limitations inevitable.

In 2020, 30% of households in California owned one vehicle, 37% owned two vehicles, 26% owned three or more vehicles, and 7% owned no vehicles [43]. This shows that two-car households are the dominant group in the population sample, with every two out of five households being two-car households. This was in line with our dataset, where the majority were also two-car households. Therefore, investigating how two-car households behave is vital to understanding the trends in the general population, and this further strengthened our focus on two-car households in this paper.

Analysis of PHEVs, regarding their electrification potential if conducted without taking into account the household context, lacks the tools to assess how they are used (1) in combination with ICEVs and (2) in comparison to households that have BEVs instead of PHEVs. For instance, Chevrolet Volt as a stand-alone PHEV can electrify, on average, 70% of its miles driven; a two-car household with a Chevrolet Volt and a conventional vehicle can electrify, on average, 43% of the total household miles; this amounts to 63% of the electrification potential of a two-car household with a Tesla Model S, and 73% of the electrification potential of a two-car household with a Chevrolet Bolt.

In this paper, we aimed to analyze how factors within the household context impact electrification of miles and fuel consumption. The results indicated that a PHEV with a higher all-electric-range resulted in more electrification and, thus, a higher UF for both the PHEV and the household. Furthermore, our results showed that—considering the UF of the household—a PHEV such as the Chevrolet Volt, with half the range of a BEV such as the Nissan Leaf, can electrify a similar share of miles, and can electrify around 70% as much household miles as long-range BEVs (Bolt and Model S) within the household context. Our results also indicated that more frequent charging resulted in higher electrification of miles and a higher UF for both the PHEV and the household. However, it should be noted that we did not take charging duration into account.

The results showed that, for two-car households, every 10-mile increase in range for PHEV households reduced the household fuel consumption and household tailpipe emissions by 0.2 gal/100 mi and 17.5 gCO_2/mi (10.9 gCO_2/km), respectively. In addition, our results indicated that in two-car households with one PEV, BEVs did not reduce household fuel consumption as expected (compared with long range PHEVs) and some long range PHEVs reduced household fuel consumption to a similar degree. Aside from the impact of all-electric-range in reducing fuel consumption, our results also showed how significantly having a PHEV or BEV, instead of an ICEV, can reduce household fuel consumption and related tailpipe emissions. This aspect of replacing an ICEV with a PEV is especially important to understand, especially for future households with multiple PEVs. For instance, in a two-car household with one BEV and one ICEV, replacing the ICEV with a PHEV could significantly increase electrification of vehicle miles and reduce fuel consumption. Two-car households with long range BEVs such as the Chevrolet Bolt and Tesla Model S in our dataset had a household utility factor of 58% to 68%, on average. If the ICEVs in those households were replaced by efficient long-range PHEVs such as the Chevrolet Volt (with a mean utility factor of 70%, see Table A1), their total household electrification could increase by a further 20% to 30%, and reach almost 90%. On the other hand, in future households with two BEVs, the challenge lies with how to tackle long-distance trips. We observed in our dataset that Chevrolet Bolt and Tesla Model S have very different frequencies of long-distance trips. Bolt averaged 0.73% for the frequency of long-distance trips (over 50 miles) which was significantly lower than the PHEVs in our dataset (which ranged from 1.35% to 3.17%, on average); Tesla Model S, however, had an average frequency of long-distance trips of 8.75%, which was three to six times higher than PHEVs (see Table A1). This difference between the two long range BEVs is likely due to the difference in the availability of fast charging opportunities, with Tesla supercharger stations being quite prevalent in California. Contrary to the general assumption that BEVs would have lower frequencies of long-distance trips than PHEVs, Tesla Model S users in our dataset showed that, with the right charging infrastructure, long-distance trips can stop being an obstacle. This finding strengthens the transition to future households with multiple BEVs, which can make the goal of reaching 100% electrification in the household a reality. Our analysis in this paper, therefore, provides a basis for understanding future households with multiple PEVs.

In this paper, we found that PHEVs with more than a 35 mile all-electric-range when used by private households in the U.S., can be an effective tool to decarbonize the transport sector. However, further research is needed to see how much this electrification potential changes from country to country, e.g., how much this is impacted by electricity and gasoline prices. To reach 100% electrification in the household, a switch to households with multiple BEVs is necessary. Understanding how households with multiple BEVs drive and charge is an important topic of future research, to be able to understand the overall environmental benefits of these vehicles. Further research is needed to see how multiple BEVs in a household can be integrated into the grid, utilizing their batteries as storage units and using vehicle-to-grid technologies, e.g., to address peak demand and irregularity of renewable energy sources [44,45]. One potential drawback to using electric vehicle batteries to store energy is the loss of energy and reduced efficiency arising from double conversion (grid-to-vehicle and vehicle-to-grid). This suggests the feasibility of vehicle-to-grid technologies as an area of future research, and future developments in battery technology can help address this issue in coming years. Future developments in charging infrastructure, such as e-road technologies, are also an important area of future research [46–48]. Households with multiple BEVs utilizing e-road technologies has the potential to remove long-distance trips from being an obstacle to reaching 100% electrification in the transport sector.

In conclusion, our results provide an insight into the electrification of vehicle miles traveled within the household context, which is rarely taken into consideration. The implication for policy makers is that PHEVs with a range of at least 35 miles have the potential to electrify a similar share of total household miles as some short range BEVs, or can reach up to 70% as much electrification as some long range BEVs and, thus, can play an important role in decarbonizing the transport sector.

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Appendix A

Table A1. Summary statistics of two-car households categorized by PEV-type.

	Min.	**0.25-Quantile**	**Median**	**Mean**	**0.75-Quantile**	**Max.**
Prius plug-in households (N = 12) [PHEV]						
Annual household VMT (mi)	7984	12,708	23,923	22,784	28,628	43,070
Daily household VMT (mi)	21.87	34.82	65.54	62.42	78.43	118.00
Household utility factor (%)	2.26%	7.10%	10.39%	10.97%	11.21%	31.62%
PHEV utility factor (%)	3.19%	9.98%	14.17%	16.57%	18.57%	49.10%
Household fuel consumption (gal/100 mi)	1.84	2.32	2.55	2.55	2.65	3.50
Household tailpipe emissions (gCO_2/km)	100.10	126.00	138.80	138.80	143.80	190.30
ICEV fuel economy (MPG)	16.00	18.05	23.60	25.64	27.13	50.23
PHEV fuel economy (MPG)	45.66	53.63	56.57	59.53	59.44	102.14
Frequency of charging (per day)	0.13	0.74	0.97	0.92	1.24	1.64
Frequency of long-distance trips with PEV (%)	0.11%	0.20%	0.67%	3.17%	2.94%	16.70%
Frequency of overlaps (%)	0.11%	4.74%	9.29%	9.63%	13.79%	20.08%
C-max fusion households (N = 25) [PHEV]						
Annual household VMT (mi)	9280	17,081	24,515	24,277	31,197	50,807
Daily household VMT (mi)	25.43	46.80	67.16	66.51	85.47	139.20
Household utility factor (%)	0.59%	10.45%	22.90%	23.52%	31.48%	62.95%
PHEV utility factor (%)	1.27%	20.12%	37.09%	38.07%	50.83%	98.95%
Household fuel consumption (gal/100 mi)	0.96	2.11	2.60	2.64	3.06	4.69
Household tailpipe emissions (gCO_2/km)	52.29	114.91	141.11	143.43	166.17	254.81
ICEV fuel economy (MPG)	13.54	18.67	22.54	25.31	30.25	49.94
PHEV fuel economy (MPG)	36.64	48.06	61.55	234.64	89.35	4065.52
Frequency of charging (per day)	0.01	0.67	0.99	1.10	1.42	2.73
Frequency of long-distance trips with PEV (%)	0.00%	0.30%	1.31%	2.31%	3.10%	8.38%
Frequency of overlaps (%)	0.00%	8.97%	12.20%	13.79%	19.33%	51.09%
Prius prime households (N = 17) [PHEV]						
Annual household VMT (mi)	8220	18,624	23,165	22,621	27,805	40,374
Daily household VMT (mi)	22.52	51.03	63.47	61.97	76.18	110.61
Household utility factor (%)	4.06%	20.01%	27.61%	26.63%	34.66%	43.44%
PHEV utility factor (%)	5.73%	34.68%	42.27%	40.91%	52.67%	65.91%
Household fuel consumption (gal/100 mi)	1.21	1.90	2.16	2.27	2.62	3.57
Household tailpipe emissions (gCO_2/km)	65.49	103.41	117.10	123.12	142.45	194.21
ICEV fuel economy (MPG)	13.94	20.40	21.41	24.97	24.88	48.44
PHEV fuel economy (MPG)	51.77	86.25	95.57	105.72	103.98	222.10
Frequency of charging (per day)	0.14	0.61	0.88	0.82	0.96	1.41
Frequency of long-distance trips with PEV (%)	0.00%	0.42%	0.73%	1.35%	2.18%	4.67%
Frequency of overlaps (%)	2.83%	7.62%	10.40%	11.77%	14.08%	28.62%

Table A1. *Cont.*

	Min.	0.25-Quantile	Median	Mean	0.75-Quantile	Max.
Pacifica households (N = 18) [PHEV]						
Annual household VMT (mi)	7341	14,426	20,720	19,501	22,718	30,299
Daily household VMT (mi)	20.11	39.52	56.77	53.43	62.24	83.01
Household utility factor (%)	16.88%	23.42%	32.40%	34.49%	43.37%	55.94%
PHEV utility factor (%)	26.48%	44.04%	55.15%	55.13%	65.12%	86.21%
Household fuel consumption (gal/100 mi)	1.22	1.94	2.20	2.34	2.49	5.01
Household tailpipe emissions (gCO_2/km)	66.53	105.26	119.28	127.19	135.23	271.99
ICEV fuel economy (MPG)	11.17	20.44	23.26	26.70	31.00	50.40
PHEV fuel economy (MPG)	40.26	56.50	65.33	89.24	118.06	227.14
Frequency of charging (per day)	0.36	0.69	0.95	1.04	1.39	1.78
Frequency of long-distance trips with PEV (%)	0.00%	0.45%	1.38%	1.59%	2.23%	5.63%
Frequency of overlaps (%)	0.89%	5.17%	9.57%	10.28%	13.95%	24.65%
Volt households (N = 39) [PHEV]						
Annual household VMT (mi)	7406	16,455	19,825	21,563	26,757	37,197
Daily household VMT (mi)	20.29	45.08	54.31	59.08	73.31	101.91
Household utility factor (%)	8.25%	35.26%	42.99%	43.00%	53.15%	66.66%
PHEV utility factor (%)	18.74%	58.99%	71.81%	69.96%	85.12%	96.29%
Household fuel consumption (gal/100 mi)	0.99	1.54	2.16	2.07	2.51	3.28
Household tailpipe emissions (gCO_2/km)	53.68	83.55	117.48	112.60	136.12	178.17
ICEV fuel economy (MPG)	14.60	20.00	25.10	26.61	30.38	43.29
PHEV fuel economy (MPG)	41.95	88.53	134.72	190.29	241.98	916.66
Frequency of charging (per day)	0.14	0.63	0.83	0.89	1.11	1.77
Frequency of long-distance trips with PEV (%)	0.00%	0.51%	1.23%	2.39%	2.34%	26.48%
Frequency of overlaps (%)	1.51%	6.27%	11.40%	11.65%	14.12%	33.99%
Leaf households (N = 29) [BEV]						
Annual household VMT (mi)	8947	16,602	21,657	21,527	26,137	34,203
Daily household VMT (mi)	24.51	45.48	59.33	58.98	71.61	93.71
Household utility factor (%)	19.82%	44.23%	49.65%	51.88%	54.94%	98.35%
Household fuel consumption (gal/100 mi)	0.04	1.34	1.80	1.90	2.34	3.82
Household tailpipe emissions (gCO_2/km)	2.25	73.07	97.95	103.46	126.89	207.52
ICEV fuel economy (MPG)	13.62	21.20	27.00	28.79	34.25	52.83
Frequency of charging (per day)	0.23	0.67	0.70	0.79	0.87	1.53
Frequency of long-distance trips with PEV (%)	0.00%	0.00%	0.10%	0.62%	0.44%	6.46%
Frequency of overlaps (%)	0.00%	7.43%	9.84%	10.75%	13.27%	23.92%
Bolt households (N = 21) [BEV]						
Annual household VMT (mi)	7930	17,020	19,953	22,829	28,929	38,190
Daily household VMT (mi)	21.73	46.63	54.67	62.55	79.26	104.63
Household utility factor (%)	37.36%	50.94%	54.54%	58.06%	67.84%	88.14%
Household fuel consumption (gal/100 mi)	0.30	1.05	1.63	1.68	2.13	3.50
Household tailpipe emissions (gCO_2/km)	16.48	56.78	88.47	91.34	115.92	189.96
ICEV fuel economy (MPG)	13.94	19.84	26.42	28.32	35.00	44.00
Frequency of charging (per day)	0.17	0.38	0.60	0.67	0.93	1.68
Frequency of long-distance trips with PEV (%)	0.00%	0.15%	0.36%	0.73%	0.79%	4.38%
Frequency of overlaps (%)	0.00%	3.88%	12.26%	11.41%	18.99%	22.73%
Model S households (N = 22) [BEV]						
Annual household VMT (mi)	12,149	17,043	20,793	24,696	29,811	56,521
Daily household VMT (mi)	33.29	46.69	56.97	67.66	81.67	154.85
Household utility factor (%)	46.22%	56.35%	63.29%	65.88%	74.27%	89.42%
Household fuel consumption (gal/100 mi)	0.28	0.86	1.83	1.80	2.53	3.58
Household tailpipe emissions (gCO_2/km)	15.15	46.82	99.31	97.76	137.20	194.26
ICEV fuel economy (MPG)	13.10	16.00	18.14	22.38	24.96	49.11
Frequency of charging (per day)	0.22	0.54	0.69	0.72	0.85	1.39
Frequency of long-distance trips with PEV (%)	0.81%	2.01%	3.85%	8.75%	8.19%	37.97%
Frequency of overlaps (%)	3.23%	8.14%	14.14%	15.80%	19.16%	37.54%

Note: Please note that the household utility factors here show the distribution among households and is not aggregated as in Figures 1 and 2 and, thus, are slightly different.

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