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Identifying Patterns of Real-World Charging Frequency for a Sample of Plug-in Hybrid Electric Vehicles in North America

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Abstract

Plug-in Hybrid Electric vehicles (PHEVs) have the capability to effectively utilize electricity from the grid as an energy source for powering an appreciable portion of the total vehicle miles travelled (VMT), thereby reducing greenhouse gas (GHG) emissions, since the Carbon Intensity (CI) of electricity is often less than that of liquid fuels in many parts of the world. Several real-world usage factors can affect the fraction of VMT electrified, with the frequency of charging being one of the most influential factors. Studies in recent years have attempted to characterize the real-world performance of PHEVs based on long-term average fuel consumption and/or other data flags in the readout from vehicle On-Board Diagnostics (OBD), but such approaches are unable to infer accurate estimates for the occurrence of charging events. This paper adopts an approach that relies on analysis of highly granular (trip by trip) information obtained from vehicles equipped with a data communication module (DCM) to infer the occurrence of charging events from change in the battery state of charge (SoC) between trips. Analysis of data obtained from a large sample of PHEVs (one full calendar year for hundreds of vehicles) in the US and Canada reveals three distinct patterns: i) vehicles that are consistently charged, ii) vehicles that are consistently not charged, and iii) vehicles with temporally varying frequency of charging. Unlike some other studies about PHEVs in other parts of the world, results of our sample for PHEVs in North America show that the majority are consistently charged, but with various frequency levels that are regionally dependent.

Introduction

Electric Drive Vehicles (EDVs) [1] or vehicles with electrified powertrains [2] refer to a broad category of powertrain configurations that include one or more electric motors as well as a traction battery, which combined, can supply an appreciable portion (or all) of the required instantaneous propulsion power for the vehicle. Aside from Hydrogen Fuel cell vehicles, which are also EDVs, but are still in very early stages in market share of light-duty vehicles, one may consider the spectrum of EDVs as stretching between (non-plug-in) Hybrid Electric Vehicles (HEVs) at one end, and Battery-only Electric Vehicles (BEVs) at the other end. While all EDVs bring forth beneficial reductions in Greenhouse Gas (GHG) emissions or consumption of liquid fuels compared to Conventional Internal Combustion Engine vehicles (CICEs), HEVs are reliant on liquid fuels as their sole energy source, while BEVs rely on electricity from the grid as their sole energy source. With electricity often having lower Carbon Intensity (CI) per unit of energy than liquid fuels in many parts of the world, BEVs are often viewed as the solution that has largest capability for GHG emissions reduction in light-duty vehicles. However, unlike HEVs, which only face little challenges towards mass market adoption (primarily due to technology familiarity and a minor premium on the purchase price), BEVs have more challenges to overcome [3-7], including shorter driving range compared to CICEs, relatively longer charging time, availability of charging infrastructure and oftentimes higher purchase price. Plug-in Hybrid Electric vehicles (PHEVs) may be thought of as somewhere between HEVs and BEVs on the spectrum of EDVs. PHEVs have the capability to charge their batteries from the electric grid and yet retain all the attractive qualities of HEVs, aside from higher purchase price than a comparable HEV. However, depending on several factors, the GHG emissions from a PHEV could be anywhere from close to a comparable HEV, close to a comparable BEV and everything in-between.

One approach for estimating how close the operation of a PHEV is to a comparable BEV (as opposed to a comparable HEV), is to consider what is known as the “Utility Factor” (UF). UF is defined per the SAE J2841 [8] standard as the ratio of distance travelled while in Charge Depletion (CD) mode, where energy from the traction battery is the main (or only) source of propulsion power, to the total distance travelled by the PHEV. Regulation of GHG emissions in most parts of the world often relies on standardized UF curves to estimate a UF for PHEVs, typically as function only of its electric driving range. Though standard UF curves are empirical estimates that rely on standard condition assumptions about the PHEV charging, energy consumption and driving patterns, there have been studies that attempted to estimate a “Real-World UF” [9-14]. In several of those studies, the prevailing message was that PHEVs are not measuring up to their theoretical GHG emission reductions, often hinting at PHEVs not being charged (thus, operating like HEVs) being the root cause.

The charging of PHEVs may indeed be an issue for company cars in Europe, as evidenced in [10, 11], where it is understood that several companies provide employees with a vehicle as part of the compensation package, along with paid gasoline (but not paid electricity). However, with having a company car as part of the compensation not prevalent in the US, it was shown in [12, 13] that the estimated performance of PHEVs in the US is close to the reference standard. Nonetheless, the study in [14] argued that the results in [12, 13] ought to be dismissed as “early adopters’ behavior” and instead considered two new sources of data for PHEVs in the US, namely, Fuelly [15] and BAR [16]. While the results based on Fuelly data in [14] were reassessed in [17] and shown to be within the typical expected variation margin from the standard reference, the observed PHEVs performance in BAR data remains an open question. Collection of BAR data comes from smog checks in the state of California, where model-year 2019 and later vehicles (compatible with the 2017 revision of SAE J1979 standard [18]) have their On-Board Diagnostics (OBD) data downloaded to an external device at a smog testing station, and the downloaded OBD data is also copied/reported to the BAR database. Though some refer to BAR data as “publicly available”, there is no mechanism for the public to obtain such data except under the Public Records Act (PRA) [19] or through limited releases, the latest of which, to the best of the authors’ knowledge, was in the wake of a workshop organized by California Air Resources Board (CARB) in June 2024 [20].

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BAR data has several limitations, including being only limited to California vehicles, as well as the occurrence of errors during the data communication, with some of such errors being clearly identifiable in a large fraction of the some of the released data records [17]. In addition, the nature of the conditions that dictate a smog check for PHEVs in California pose serious concerns about bias in the sample towards vehicles that had relocated from out of state [17] or were very short term/incomplete leased vehicles. While short-term lease returns are not mandated to do a smog check, dealers often do the smog check anyway, according to CARB. Even setting all such concerns aside and considering BAR records that have no obvious errors, charging behavior is but one factor among others that affect the real-world performance of PHEVs [21-22]. As such, the OBD data fields for vehicle lifetime fuel, electric energy consumption, as well as the distance travelled in different driving modes, cannot reliably infer the charging behavior of the vehicles. Despite such drawbacks in BAR data, it has fueled negative claims in the media that "PHEVs are hardly ever charged" [23], as well as basis for reduction of the GHG compliance value of PHEVs [24]. Such conceptions about charging may stand in stark difference from stated behavior in some survey data such as Martiz [25] New Vehicle Consumer Survey (NVCS), as shown in Fig. 1, which shows significant charging utilization, though stated behavior may often be considered less reliable than directly obtained data from vehicles.

This paper aims to re-examine the charging frequency question about PHEVs in the US and Canada via leveraging large-scale data of hundreds of small SUV PHEVs throughout the full calendar year 2024. Small SUVs are one of the vehicle categories and body style that have become very popular in the US and Canada in the recent years and was therefore chosen as a focus for this study. The data sample also covers both regular and luxury segments. Beyond establishing motivation for the research, the next section provides data description, followed by details of the analysis approach, which in turn, leads to results, discussion, and conclusion of the paper.

Data Sample Description

The data is collected from vehicles of one particular make-model regular segment small SUV PHEV (model-year 2021-2024) and one particular make-model luxury segment small SUV PHEV (model-year 2023-2024). The data collection process starts automatically upon consent of the vehicle owners while initiating connectivity features of the vehicle. The data collection and transmission over wireless network where it is anonymized and securely maintained remains in effect until the owner chooses to disable it. For purposes of the study in this paper, a random sample of vehicles among the larger pool is queried for the duration of the calendar year 2024. Summary of the queried sample size of vehicles is shown in Table 1.

Table 1: Number of Vehicle Samples in the Data Query.

	USA	Canada
Luxury Segment Vehicles	603	100
Regular Segment Vehicles	3,960	1,658

The data transmitted includes various fields and at different frequencies depending on type of the data field. As part of the data preprocessing and filtering, all the received data is remapped to one-second intervals in local time where the vehicle is driving. Data fields that are sampled at higher frequency than once per second are averaged for the duration of the one second periods, while data fields that are sampled at a frequency lower than once per second are held constant at their last reported value until a new value is reported. Data fields relevant to the current study include: vehicle speed, odometer reading and an eight-level indicator of the state of charge (SOC) for the traction battery (similar levels to what is shown on the vehicle dashboard). One limitation about the data is that it is only reported while the vehicle is in "key-on". In other words, for the most part, no data collection occurs during charging events. However, it is reasonable to infer the occurrence of a charging event when an increase by one level step (or more) in the SOC indicator happens between two different trips (with a "trip" being key-on to key-off). In general, working with real-world data often encounters data errors that could be due to issues with communication module(s), wireless signal drop-out, network transmission, coding and decoding or other unknown reasons. Thus, towards ensuring good data quality for the analysis in this paper, data filtering rules are applied as follows:

- A driving day is only considered "valid" if the difference between total distance travelled as estimated from odometer signal to the total distance travelled as estimated from integration of the speed signal is within 5%, and the total distance travelled throughout the day must be at least 1 mile. This excludes driving days with too short driving distance or ones that have significant drop-outs in the data.
- Only valid driving days are considered for the count of driving days and occurrences of charging events, and a vehicle sample must have at least 50% of its days that show occurrence of driving, as valid driving days. Otherwise, the whole vehicle sample is excluded.
- Every month within the study period must have at least 5 valid driving days. This excludes vehicles that are not in active use, experienced faults in their data connectivity or opted out from the data collection during the calendar year of the study.

The number of vehicle samples passing the criteria of the data quality filters is shown in Table 2 the luxury segment and Table 3 for the regular segment vehicles. Table 2 and Table 3 also provide some broadline statistics (total driving days analyzes, total trips and miles), as well as a distinction between the number of vehicles that pass all the data quality filters except "year-long continuity". This in turn helps distinguish (by comparing count of vehicles) the fraction of samples removed due to data transmission errors versus those that may have had a fault in the data communication module or opted out during the year. Further, the number of vehicle samples that fully passed the criteria of the data quality filters in sub-regions of interest in the US are shown in Table 4. The three sub-regions are: i) the state of California, ii) Washington state, and iii) Northeastern US, which collectively includes Pennsylvania, Maryland, Washington DC, New Jersey, New York, Connecticut, Massachusetts, Rhode Island, Vermont, New Hampshire and Maine.

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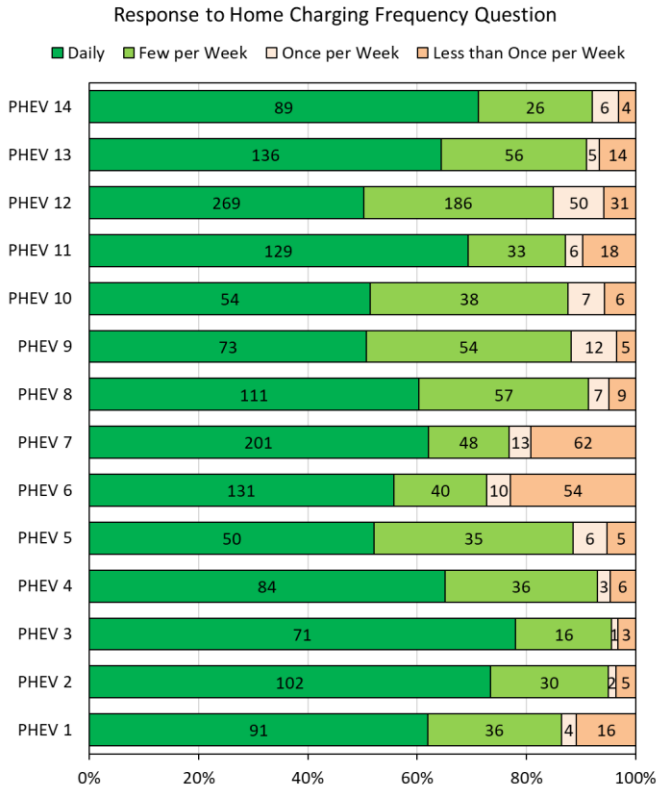


Figure 1. Summary of responses about charging frequency in Oct 2023 – Sep 2024 Martiz NVCS for 14 PHEV Make Models that had 40 or more samples. Raw sample count shown inside each response category of each PHEV.

Table 2: Summary Statistics for Luxury Segment Vehicle Samples that passed the data quality filters.

	USA	Canada
Num. Vehicles Passing Quality Filter	590	100
Num. Vehicles Passing w/ Full Year	432	86
Total Number of Valid Drive Days	87,960	24,272
Total Number of Trips	346,897	102,621
Total Distance Travelled [miles]	3,167,979	865,112

Table 3: Summary Statistics for Regular Segment Vehicle Samples that passed the data quality filters.

	USA	Canada
Num. Vehicles Passing Quality Filter	2,912	1,648
Num. Vehicles Passing w/ Full Year	2,835	1,272
Total Number of Valid Drive Days	767,043	352,309
Total Number of Trips	3,171,424	1,476,153
Total Distance Travelled [miles]	34,217,580	13,283,410

Table 4: Number of Vehicle Samples that passed the data quality filters for three sub-regions in the US.

	California	Washington State	North-East US
Luxury Segment Vehicles	222	--	76
Regular Segment Vehicles	748	63	1,186

Analysis Approach

The primary metric of performance considered is the charging frequency, which we refer to via the symbol (μ) and has units of [Charging-Event/Driving-Day], written in shorter form as [Chg/Day]. For each vehicle sample $i \in \Phi$, with Φ being the set of vehicle samples for a country or sub-region of study, let (d_{ij}) be the vehicle sample's count of driving days in month $j \in \{1 \text{ to } P\}$, with P being the period of study (12 months). Further, let (c_{ij}) be the vehicle sample's count of detected charging events in the month j. The average charging per driving day for a given month of a vehicle sample is calculated as:

$$\mu_{ij} = \frac{c_{ij}}{d_{ij}} \tag{1}$$

We then define a "low charging frequency" threshold (ε), set at a value of 0.1 in this work, as a means of assessment of the charging behavior of the vehicle samples throughout the study period. We then identify different categories of charging behavior. The first of which being Φ^{I}, which are vehicles whose charging frequency never falls below the threshold in any month during the study period. In other words:

$$i \in \Phi^{I} \Leftrightarrow \mu_{ij} \geq \varepsilon \ \ \forall \ j \tag{2}$$

At the other end of the spectrum, we define Φ^{III_b}, which are vehicles whose charging frequency is always less than the threshold in every month of the study period.

$$i \in \Phi^{III_b} \Leftrightarrow \mu_{ij} < \varepsilon \ \ \forall \ j \tag{3}$$

Furthermore, one may calculate the overall average charging frequency of a vehicle sample throughout the whole study period as:

$$\mu_i = \frac{\sum_{j=1}^{P} c_{ij}}{\sum_{j=1}^{P} d_{ij}} \tag{4}$$

We define another class of charging behavior (Φ^{III}) as the vehicles whose study period average charging frequency is less than the threshold as:

$$i \in \Phi^{III} \Leftrightarrow \mu_i < \varepsilon \tag{5}$$

It follows that by construction, Φ^{III_b} must be a subset of Φ^{III}, and that Φ^{I} and Φ^{III} do not intersect (i.e. no vehicle samples can belong to both sets Φ^{I} and Φ^{III}). We then define a category Φ^{II} for all the remaining vehicle samples that do not belong to either Φ^{I} or Φ^{III}, as:

$$\Phi^{II} = \Phi - \left(\Phi^{I} \cup \Phi^{III}\right) \tag{6}$$

From an interpretation perspective, the set Φ^{III_b} represents vehicles that are consistently charged very little or not charged at all. For the main analysis in this paper, we adopt the value of $\varepsilon = 0.1$ (Less than 1 charging event per 10 driving days being the threshold indicator of a choice not-to-charge by a vehicle owner). We also conduct a brief sensitivity analysis and further discussion about choice of the

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threshold in the next section of the paper. While noting that the set Φ^{III} includes Φ^{III_b} but may also include vehicles that have done some charging ($\mu_{ij} \geq 0.1$) during one or more months of the year, for simplicity, we collectively refer to Φ^{III} as the set of "Non-charging Vehicles".

On the other hand, the set Φ^{I} includes vehicles that are charged at least once per 10 driving days in every month of the study period. Though the set Φ^{I} can (and often does) include vehicles that barely clear the threshold to vehicles that charge more than once per day, never falling below the threshold in any month is arguably indicative that those are PHEVs being used as PHEVs, or as we refer to this set of vehicles as "Consistently Charged". As a note about the set Φ^{I}, "Consistently Charged" does not necessarily imply the same charging frequency as the standard assumption in SAE J2841 [8], which assumes that PHEVs would be charged overnight before every driving day, but not charged at all during the day. The set Φ^{I} can (and does) include vehicles that charge less frequently than once per day, or more than once per day. As long as no month-long period within the overall observation period (one full year) falls below the threshold, a vehicle is considered part of the set Φ^{I}.

Lastly, the set Φ^{II} represents vehicles whose charging frequency notably changes throughout the year, referred as "Transitional vehicles". Φ^{II} is formally defined as vehicles whose average charging frequency throughout the study period is more than the threshold but have had a month (or more) less than the threshold. Examples of month-by-month charging for individual Φ^{II} vehicle samples in the data are shown in Fig. 2. This can include charging improvement, decline, or having one/some unusual month(s).

The overall average charging for a set/category of charging behavior is calculated and reported as a separate metric as:

$$\mu^{k} = \frac{1}{|\Phi^{k}|} \sum_{i \in \Phi^{k}} \mu_i \tag{7}$$

Another metric of consideration is the overall average charging frequency for all vehicles (including all categories of observed charging behavior) in a country or sub-region Φ, calculated as:

$$\mu = \frac{1}{|\Phi|} \sum_{i=1}^{|\Phi|} \mu_i \tag{8}$$

Results and Discussion

A brief sensitivity analysis is conducted for choice of the threshold value (ε) for the largest sample available in the data (all USA regular segment). Fig. 3 shows pie chart plots for the fraction of the vehicle samples that would be categorized into either Φ^{I}, Φ^{II} or Φ^{III}, for values of ε that corresponds to one charging event per 5, 8, 10 or 20 driving days. Understandably, for higher threshold values, the fraction of vehicle samples that would be classified as "Non-Charging" would be larger, while the fraction of vehicle samples classified as "Consistent Charging" would be smaller, while the reverse is observed when setting lower threshold values. As the primary goal of this study is to identify intentional non-charging behaviors (i.e. vehicle owners who for one or more reasons are making a choice to not charge), we believe a threshold set at 0.2 is inappropriate since a PHEV with approx. 40 miles of range could do most of its driving in electric mode for 5 driving days if the average distance per day is about 8 miles. We also note from Fig. 3 that the fraction of consistent charging vehicles does not appear to significantly change whether the threshold is set at one charging event per 8, 10 or 20 driving days. We also note from Fig. 3 that the fraction of non-charging vehicles does not appear to change much between a threshold of one charging event per 8 or 10 driving days.

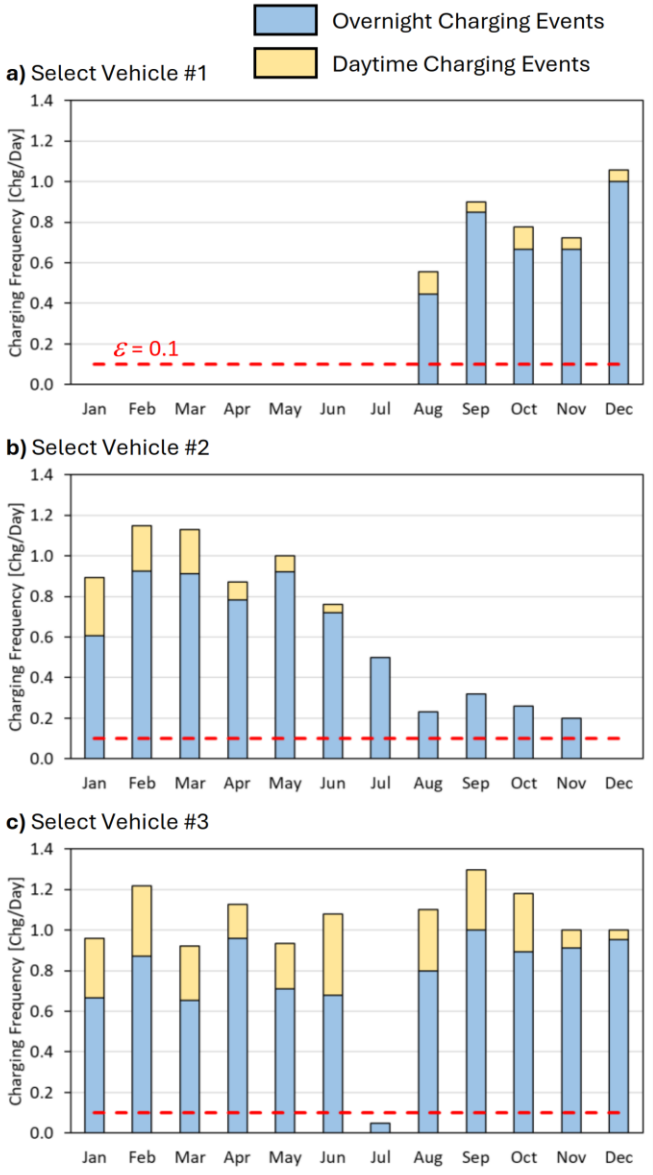


Figure 2. Month-by-month charging frequency for three select sample vehicles categorized as "Transional Vehicles" with patterns resembling a) Going from non-charging to consistent charging, b) Going from consistent charging to non-charging, c) One unusual month during the year.

For the main study in this paper, we settled at $\varepsilon = 0.1$ (one charging event per 10 driving days) since it is more likely to correspond to a "decision" by the vehicle owners rather than simply not charging due to not needing to charge (for low daily mileage).

Vehicle categorization results are shown in Fig. 4 as pie charts representing the fraction of the vehicle samples that were observed as

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belonging to the sets Φ^{I}, Φ^{II} and Φ^{III} for both the luxury and regular segments in the US (Fig. 4.a) and Canada (Fig. 4.b). Further break-down of US vehicles in three sub-regions of interest are also provided in Fig. 4.c to Fig. 4.e for the state of California, Washington state and Northeastern US, respectively. The overall year average charging frequency for all the vehicles in each region (per Eqn. 8) and for the set of consistently charged vehicles in each region (μ^{I} per Eqn. 7) are provided in Table 5 and Table 6, respectively. As a note, no results were generated for the luxury segment in Washington state due to insufficient number of vehicle samples.

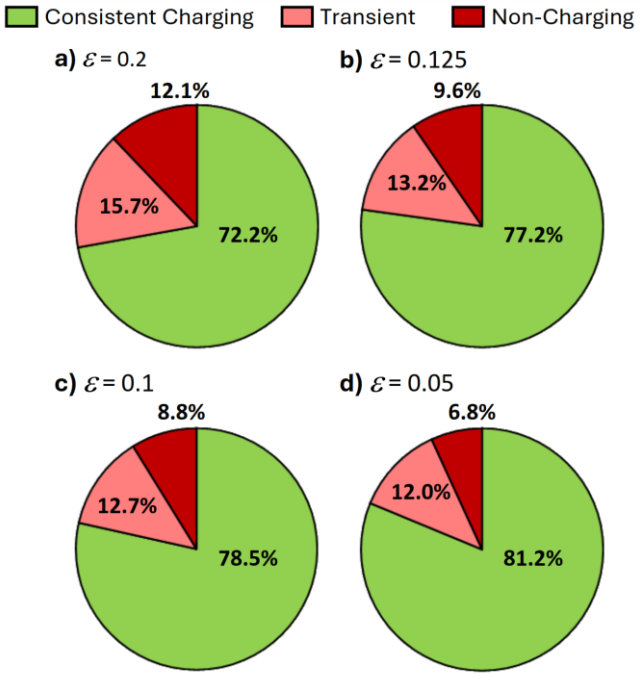


Figure 3. Sensitivity of the fraction of vehicle samples in different charging categories to the threshold (ε) for regular segment vehicles in all USA.

Table 5: Yearly average charging frequency for all vehicles in each region.

	Luxury Segment Vehicles	Regular Segment Vehicles
All USA	0.84	0.71
All Canada	0.96	0.95
California	0.82	0.72
Washington State	--	0.95
Northeastern US	0.91	0.64

Table 6: Yearly average charging frequency for Φ^{I} vehicles in each region.

	Luxury Segment Vehicles	Regular Segment Vehicles
All USA	0.92	0.84
All Canada	0.99	0.98
California	0.93	0.84
Washington State	--	1.02
Northeastern US	0.98	0.84

One key observation from Fig. 4 is that the large majority of the PHEV samples across both luxury and regular segments in all considered regions are consistently being charged (i.e. belonging to the category Φ^{I}), with the regular segment vehicles in Northeaster US sub-region having the smallest fraction of Φ^{I}, at 75% of the total vehicles in the sub-region. For the overall US sample, the fraction of consistently charged PHEVs is approx. 79% for the regular segment and approx. 86% for the luxury segment. The largest fraction of non-charging vehicles (i.e. belonging to the category Φ^{III}) was also observed for the regular segment vehicles in Northeastern US, at approx. 12%. The fraction of consistently charged PHEVs in the US for the analyzed data (as shown in Fig. 4.a), at approx. 79% and 86% for the regular and luxury segments respectively, appears to be somewhat less than the stated behavior about charging in surveys such as Fig. 1 (where most of the make-model have more than 90% of respondents indicating they charge at least once per week at home). Nonetheless, the results from Fig. 4.a stand in strong contrast to some of the claims (without evidence) that have been made in the media (such as [24]) that PHEVs are almost never charged.

When comparing charging frequency categories between Canada (Fig. 4.b) and the US (Fig. 4.a), as well as the overall average charging frequencies (Table 5), one may readily observe that the Canadian vehicles have higher charging frequency. Though we regard this as a topic for further detailed investigation, one well-known factor that could be contributing to this observation is the gasoline prices generally being more expensive in Canada than in the US, while electricity prices are generally more expensive in the US than in Canada. As such, the "economic incentive to drive electric" is most likely much better in Canada than in the US. On a similar note, when considering the three sub-regions in the US, sources such as FRED [26] indicate the prices of both gasoline and electricity to be high in California, while both gasoline and electricity prices are more moderate in the Northeast US, with the contrasting sub-region of Washington state having higher gasoline prices, along with low electricity prices. Unsurprisingly, the fraction of consistently charged PHEVs in Washington state (Fig. 4.d) and average charging frequency (Table 5) appear noticeably better for Washington state compared to the other sub-regions in the US. Further, when observing the overall average charging frequency for category Φ^{I} in Table 6, which we may view as representative of the PHEVs being used as PHEVs, one could tell that upon addressing economic and other issues that cause a minority of vehicles to not be charged, the overall charging behavior could eventually approach the standard assumption of once per driving day.

Another observation from Fig. 4, is that the luxury segment vehicles tend to be more likely to have larger fraction of consistently charged vehicles (category Φ^{I}) and smaller fraction of non-charging vehicles (category Φ^{III}). Though such observation requires further investigation to validate, it may lend support to a hypothesis that consistent and frequent charging behavior requires not only a sufficient economic incentive to charge, but also convenient charging access, with the typical mode of convenient access is a dedicated parking spot (or personal garage) with electricity access. Luxury segment vehicles, being more likely to be operated by higher-income persons, are also likely to be housed in a place that meets those conditions. Further investigation of this hypothesis will be conducted in future work.

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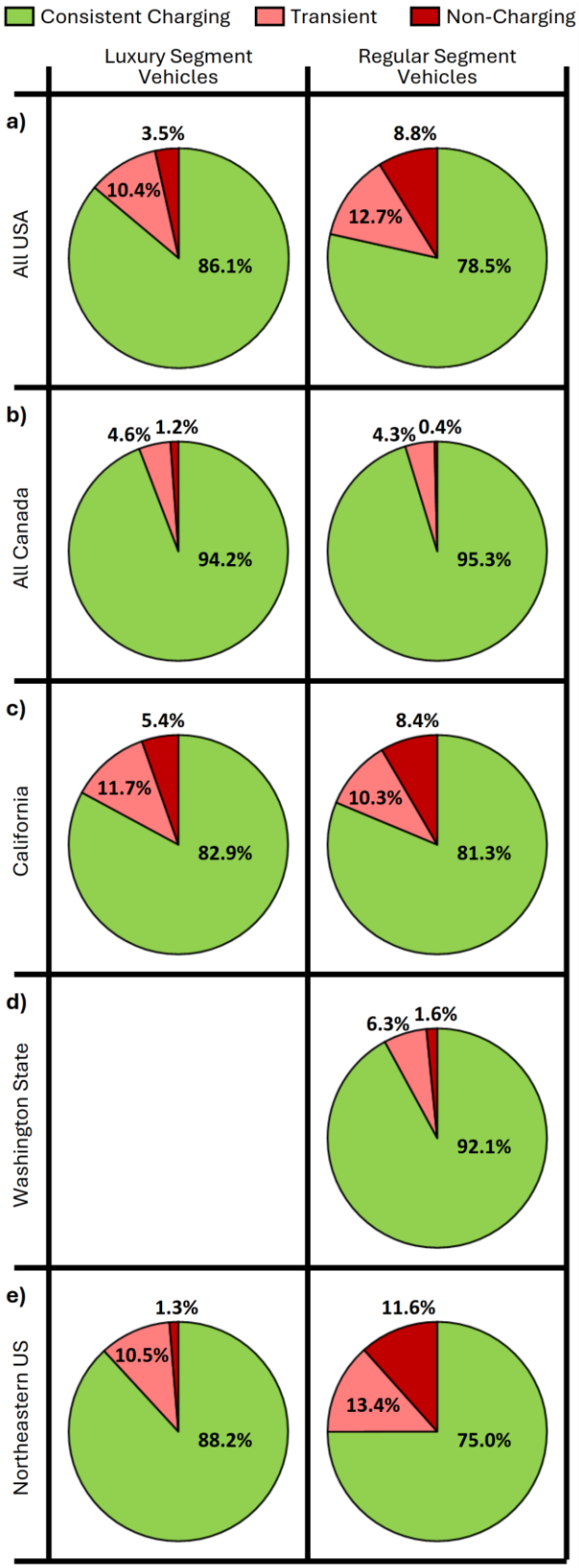


Figure 4. Fraction of vehicle samples in different categories of charging behavior.

Conclusion

This paper presented a preliminary summary of findings about the observed charging frequency in a large sample of "small SUV" size category PHEVs in the US and Canada for both luxury and regular segments. A key result from this work is showing that although the charging frequency is not always perfectly aligned with the standard assumption of once per day, the large majority of PHEVs in the US (75% or more), and even larger majority in Canada (94% or more), are being consistently charged. The observed average charging frequency may be slightly less than self-reported values among surveys of new vehicle buyers, but the overall result stands in strong contrast to some of the media articles claiming (without evidence) that PHEVs are hardly ever charged. Additional observations that are yet to be further investigated, including charging frequency being better in luxury segment vehicles and plausible causal relationship with the costs of gasoline and electricity, align with a hypothesis that consistent and more frequent charging require both convenient access to charging, as well as sufficient economic incentive. This hypothesis will be examined in future work.

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