THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

The Role of Plug-in Hybrid Electric Vehicles in Electrifying Personal Transport

Analysis of empirical data from North America

AHMET MANDEV

Division Physical Resource Theory

Department of Space, Earth and Environment

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2020

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AHMET MANDEV

Department of Space, Earth and Environment

Chalmers University of Technology

SE-412 96 Gothenburg

Sweden

Telephone + 46 (0)31-772 1000

Author email: mandev@chalmers.se

Printed by Chalmers Reproservice

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Abstract

Plug-in hybrid electric vehicles (PHEV) can help reduce the greenhouse gas emissions in the transport sector, combined with the decarbonization of the electricity sector, and play an important role in electrifying personal transport. This thesis uses empirical data from North America to investigate the role of PHEVs in electrifying personal transport, with a focus on the household context and charging behavior. There is a lack of assessment of electrification at the household level in the literature and Paper I fills this gap by analyzing how household factors impact the share of electrification of vehicle miles travelled (eVMT) considering all vehicles in the household. There is also a lack of empirical studies in the literature analyzing the charging behavior for large samples of PHEV users. Paper II fills this gap with an analysis of a large sample and long observation period for Chevrolet Volt (a long-range PHEV) in North America. To the authors' best knowledge, it is the first study to map out the range of charging behavior with additional daytime charging and no overnight charging frequencies. Previous studies in the literature have analyzed well-to-wheel greenhouse gas emissions of PHEVs but neglect the effect of charging behavior on tail-pipe emissions. Paper III fills this gap by quantifying the environmental effects of PHEV charging behavior with a focus on tail-pipe emissions of a long-range PHEV such as the Chevrolet Volt.

Our results indicate that PHEVs with a range of at least 35 US miles (56 km) have an important role to play, especially in the electrification of vehicle miles travelled within the household context where they can achieve as much electrification as some battery electric vehicles; regular overnight charging can have a noteworthy reduction on tail pipe emissions of PHEVs and substantially increase share of electrification of miles; and policy for PHEVs should prioritize easy access to overnight charging above public and workplace infrastructure to achieve high shares of electrification.

Keywords: PHEV (Plug-in hybrid electric vehicle), eVMT, eVKT, utility factor, charging behavior, fuel consumption, greenhouse gas (GHG) emissions

List of appended papers

I **Mandev** A., Sprei F., Tal G. (2020). Electrification of vehicle miles travelled within the household context: a case study from California, USA. Paper to be submitted.

FS and GT initiated the work. AM, FS and GT developed the idea. AM analyzed the data. AM wrote the paper with contributions from FS and GT.

II **Mandev** A., Plötz P., Sprei F. (2020). Empirical charging behavior of plug-in hybrid electric vehicles. Paper to be submitted.

AM, PP and FS developed the idea. AM analyzed the data with contributions from PP. AM wrote the paper with contributions from PP and FS.

III **Mandev** A., Plötz P., Sprei F. (2020). The environmental benefits of plug-in hybrid electric vehicle charging. Working paper.

AM, PP and FS developed the idea. AM analyzed the data with contributions from PP. All authors wrote the manuscript.

Related publications not included in this thesis

I **Mandev** A., Plötz P., Sprei F. (2020). Empirical recharging behavior of plug-in hybrid vehicles. In *33rd Electric Vehicle Symposium (EVS33)*, Portland.

II **Mandev** A., Sprei F., Tal G. (2020). Electrification of vehicle miles travelled within the household context. In *Transportation Research Board 99th Annual Meeting*, Washington DC.

III **Mandev** A., Sprei F., Tal G. (2019). Electrification of vehicle miles travelled within the household context. In *32nd Electric Vehicle Symposium (EVS32)*, Lyon.

IV **Mandev** A., Sprei F., Tal G. (2018). What impacts the electrified miles travelled (eVMT) of Plug-in Electric Vehicles (PEVs) within the household context? In *Swedish Transportation Research Conference*, Gothenburg.

Acknowledgements

Thanks to my supervisor Frances for her guidance that made this thesis possible. Your approach to both work and life has inspired me a lot and I've learned a lot from you. There were some bumps along the road, like the recent self-isolation we had to endure due to coronavirus, but we came over those in the best way possible thanks to you. You are an excellent mentor and I feel lucky to have you as my supervisor. I would also like to thank my co-authors Gil Tal and Patrick Plötz for their contributions and constructive comments.

Thanks to my examiner Sonia, my manager Martin and other colleagues at FRT for providing a great working environment. Special thanks to friends at work, Çağlar, Niko, Yuan, Ella, Xiaoming and Jinxi for making days of hard work go easier.

Thanks to my family for their unconditional support.

I also would like to acknowledge the funding of Swedish Electromobility Centre that enabled the work presented in this thesis.

Göteborg, October 2020

Ahmet Mandev

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List of Commonly Used Abbreviations

AER:	All-electric-range
BEV:	Battery electric vehicle
EV:	Electric vehicle
eVKT:	Electric vehicle kilometers travelled
eVMT:	Electric vehicle miles travelled
FCEV:	Fuel cell electric vehicle
gVKT:	Gasoline vehicle kilometers travelled
gVMT:	Gasoline vehicle miles travelled
HEV:	Hybrid electric vehicle
ICEV:	Internal combustion engine vehicle
MPG:	Miles per gallon
PEV:	Plug-in electric vehicle
PHEV:	Plug-in hybrid electric vehicle
UF:	Utility factor
VKT:	Vehicle kilometers travelled
VMT:	Vehicle miles travelled

1 Introduction

As stated in the Paris Agreement, to combat climate change and build a sustainable low carbon future, greenhouse gas mitigation is strongly needed in the transport sector. Electrifying personal transport can help reach that goal through reduction of emissions by abandonment of fossil fuels and increasing the use of renewable energy sources. Plug-in hybrid electric vehicles (PHEV) can help reduce the greenhouse gas emissions in the transport sector, combined with the decarbonization of the electricity sector and play an important role in electrifying personal transport (EPRI, 2007, Kromer et al., 2009, Stephan and Sullivan, 2008, Yang et al., 2009, Poullikkas, 2015).

Electric vehicles (EVs) in general are split into three categories: plug-in electric vehicles (PEV), hybrid electric vehicles (HEV) and fuel cell electric vehicles (FCEV). FCEVs use fuel cells to generate electricity using compressed hydrogen. HEVs are hybrid vehicles with an electric engine and a conventional engine, but the battery packs cannot be charged by plugging in. PEVs, on the other hand, are split into two categories: battery electric vehicles (BEVs) and PHEVs. BEVs utilize only an electric engine for propulsion and their only source of energy is their rechargeable battery packs; whereas PHEVs combine an electric engine with a conventional one, so they have rechargeable battery packs as well as fuel tanks. Unique position of PHEVs as a vehicle that can utilize two different energy sources make the analysis of their fuel economy and environmental impact more complex (Plötz et al., 2018).

The position of PHEVs in the process of electrification of the transport sector has always been debated, especially in comparison to BEVs. PHEVs have a few advantages compared to BEVs. First, they don't have a strict range limitation as BEVs and don't depend entirely on the charging infrastructure, so they can appeal to more people. Second, they can be manufactured at a lower cost if the battery prices are high and the range expectations continue to increase. In a scenario with high battery prices and increasing range expectations, even though PHEVs include an extra engine, this extra cost might not offset the battery cost difference between PHEVs and BEVs. Although it should be noted that if a high-range PHEV is compared to a low-range BEV, this difference can be minimized. However, in terms of environmental impact, in a single case comparison, a BEV would perform better than a PHEV due to not using fuel given that the electricity to charge their batteries come from low carbon sources, however larger battery sizes —as in BEVs— also imply a larger impact on energy production and material resources (Emilsson and Dahllöf, 2019). In addition to that, battery pack prices have been in a long trend to fall, from 1,160 $/kwh in 2010 to 156 $/kwh in 2019 on average (Goldie-Scot, 2019, Henze, 2019). As battery costs decline, BEVs can be manufactured at lower costs, even close to conventional vehicles, and higher ranged BEVs are making their way into the market, thus making the range limitation less of an issue for more people.

1.1 Scope and contributions

In this licentiate thesis, with the three papers appended, the role of PHEVs in electrifying personal transport is investigated. The process of electrification in the transport sector has a wide scope and ranges from the electricity mix that goes into the battery of the vehicles to the manufacturing of the vehicle and batteries, the driving and charging behavior, shifting transport modes, car-sharing and infrastructure developments (installment of charging points). Therefore, it is important to define the scope within which the role of plug-in hybrid electric vehicles is investigated in this licentiate thesis. All the datasets used for analysis in the appended papers come from mostly private users, hence the focus in this licentiate is on personal transport; furthermore, the role of PHEVs in electrifying personal transport are investigated in the following contexts:

- **Household context:** Paper I analyzes measures related to electric vehicle miles travelled in the household context. The household context is defined using four categories: (1) plug-in electric vehicle technology in the household (range of the vehicle and the frequency of charging associated with it), (2) household vehicle usage, (3) internal combustion engine vehicles (ICEVs) in the household and (4) driver identity.
- **Charging behavior:** Paper II maps out the range of charging behavior with additional daytime charging and no overnight charging frequencies and analyzes this behavior with respect to characterization of frequent chargers and charging days. Paper III analyzes the direct effect of PHEV charging on tail pipe emissions.

In order to assess the potential of PHEVs to reduce greenhouse gas emissions, several aspects of their usage are important to understand. First, it is important to understand the share and number of miles that can be electrified within the household context. Traditionally, the analysis on the share of electrification of miles has been done on a per vehicle basis, however the household context is of increasing importance due to e.g. shifting trips between vehicles in multi-car households. **There is a gap in the literature such that PHEVs have not been previously studied within the household context due to the difficulty of collecting good empirical data at the household level; Paper I fills this gap.** Second, it is important to understand the charging behavior. Understanding the charging behavior is important for several reasons; (1) charging behavior provides insights on how future charging infrastructure policies should be developed (Gnann et al., 2018, Morrissey et al., 2016), (2) it adds to the understanding of the relationship between more public charging infrastructure and users' charging behavior (Jochem et al., 2016, Rahman et al., 2016, Xi et al., 2013), (3) it clarifies the relation between battery size and charging behavior and whether people choose the vehicle they purchased based on their driving needs (Jenn et al., 2020, Tal et al., 2014a, Tal et al., 2014b, Zhou et al., 2020) and (4) it adds to the understanding of the environmental performance of PHEVs by giving an insight into how much of the driving is done on gasoline and how much on electricity (Plötz et al., 2017a, Plötz et al., 2018, Ligterink et al., 2013, Davies and Kurani, 2013, Nicholas et al., 2017, Plötz et al., 2017b). **There is a lack of empirical studies in the literature that analyze charging and driving behavior for large samples of PHEV users and Paper II fills this gap.** Finally, it is important to understand the effect of charging behavior on tail pipe emissions. Previous studies in the literature have analyzed well-to-wheel greenhouse gas emissions (Nordelöf et al., 2014, Kamiya et al., 2019), but **the direct effect of PHEV charging on tail pipe emissions has not been analyzed in detail, Paper III fills this gap.**

All three papers appended in this licentiate thesis use empirical, real-world, data — of which there is a lack of in the literature— from North America (California for Paper I and, US & Canada for Paper II & III) for analysis to assess the role of PHEVs in electrifying personal transport more accurately. There are different views on the role of PHEVs in the decarbonization of the transport sector and thereof what policies should be applied, for instance they are subsidized due to their electrification potential but can be driven on fossil fuels. This thesis provides empirical analysis on how PHEVs are used, and how much they can electrify vehicle miles travelled and provide environmental benefits, thus all three papers presented here are policy relevant.

1.2 Disposition of this thesis

The thesis consists of seven chapters that provide information on the research that has been carried out, followed by three appended papers. Chapter 2 provides background on how share of electrification of vehicle miles, charging behavior and environmental impact of PHEVs have been approached in the literature. Chapter 3 gives a summary of the range of demand side policy instruments related to PHEVs. Chapter 4 describes the methods that have been used in the appended papers. Chapter 5 gives a brief summary of appended papers. Results and discussion are given Chapter 6. Key contributions are given in Chapter 7.

2 Background

This chapters gives a brief overview on how the share of electrification of vehicle miles, charging behavior and environmental impact of PHEVs have been approached in the literature, and how these are related to each appended paper.

2.1 Utility factor

Utility factor (UF), defined as the share of electrified vehicle miles travelled (eVMT) within total vehicle miles travelled (VMT), is the most common metric to analyze the performance of PHEVs regarding their ability to provide emission-free travel. There are two main approaches to assess the UF in the literature. The first is to run simulations based on test-cycles, logged data on conventional vehicles or transportation surveys. It is common practice to follow standardized methods such as SAE J2841 and SAE J1711 from the Society of Automotive Engineers to calculate the UF, under assumptions regarding the charging frequency, vehicle characteristics and driver characteristics (SAE International, 2010a, SAE International, 2010b). Many studies in the literature fall under this first approach:(Elgowainy et al., 2009, Moawad et al., 2009, Axsen et al., 2011, Tal et al., 2014a, Björnsson et al., 2018). However this approach is criticized for not accounting for complex scenarios, and UF calculations are found to be very sensitive to assumptions regarding charging behavior, vehicle age and vehicle annual distance driven (Bradley and Quinn, 2010, Paffumi et al., 2018).

The second approach is to use empirical, real-world, data to estimate the UF. The use of empirical data provides an insight into actual travel behavior patterns without the shortcomings of assumptions made in the first approach. The studies in the literature are limited due to the availability of empirical data: (Davies and Kurani, 2013, Ligterink et al., 2013, Carlson, 2015, Plötz et al., 2017a, Plötz et al., 2017b, Nicholas et al., 2017). Apart from the report of Nicholas et al. (2017), which serves as a predecessor to Paper I, the studies focus solely on the PHEV and the household context is neglected.

Paper I, for the first time in the literature, makes an assessment of the UF at the household level, as the share of VMT within total household vehicle miles travelled, that includes all vehicles in the household and captures the overall household electrification of miles.

2.2 PHEV charging behavior

In the literature, there are two main approaches to assessing the charging behavior of PHEVs. The first is to use a range of methods and data, but no actual PHEV charging or driving data. Some of the data and methods used include household travel surveys, simulation and optimization models, online questionnaires, stated preference surveys or data from internal combustion engine vehicles applied to PHEVs. Some studies focus on the impact of charging behavior on charging infrastructure (Dong and Lin, 2012, Xi et al., 2013, Bi et al., 2017, Pagani et al., 2019), and some focus on charging patterns, environmental impacts, share of electric driving and battery requirements (Axsen et al., 2011, Tal et al., 2014a, Tal et al., 2014b, Björnsson and Karlsson, 2015, Philipsen et al., 2018, Ashkrof et al., 2020, Zhou et al., 2020).

The second approach is to use empirical PHEV or PEV charging or driving data. Some of these studies use data from charging stations (Morrissey et al., 2016, Gnann et al., 2018), and some use data directly collected from the vehicles (Ligterink et al., 2013, Davies and Kurani, 2013, Nicholas et al., 2017, Chakraborty et al., 2019, Srinivasa Raghavan and Tal, 2020). Data directly collected from vehicles often lack in the size of the sample or the observation period; for instance Davies and Kurani (2013) use data from 25 converted Toyota Prius, Nicholas et al. (2017) analyze charging behavior of 72 PEV households, Chakraborty et al. (2019) analyze the 30-day charging behavior of 5,418 PHEV users in California, Srinivasa Raghavan and Tal (2020) use data from 153 PHEVs in California.

Existing studies on PHEV charging behavior are often based on conventional vehicles or have a limited PHEV sample with a short observation period. Paper II and III fill this gap with a large sample and long observation period for one PHEV model in North America.

2.3 Environmental Impact of PHEVs

Well-to-wheel greenhouse gas emissions of PHEVs have been previously analyzed in the literature. There are some studies focusing on greenhouse gas emission reduction solely based on fuel use and excluding any emissions arising from vehicle manufacturing and disposal. Axsen et al. (2011), for instance, simulate greenhouse gas emissions with one million new PHEVs on the road with data from new vehicle buyers in California.

There are also studies that do a partial or full life-cycle analysis (LCA) by taking into account greenhouse gas emissions arising from vehicle manufacturing, battery production and disposal (Shiau et al., 2009, Michalek et al., 2011, Plötz et al., 2017a, Kamiya et al., 2019). Michalek et al. (2011), for instance, finds that battery and electricity production emissions are substantial mostly due to greenhouse gas emissions from coal-fired power plants, and PHEVs with smaller battery packs can be favored over long-ranged PHEVs because they can reduce externality damages at a lower additional cost over their life time. On the other hand, Kamiya et al. (2019) models short and long term well-to-wheel effects of PHEVs and finds that PHEVs substantially contribute to reducing greenhouse gas emissions in all contexts. There is a lack of a clearly stated goal in most LCA studies and general conclusions are drawn without a discussion of the complexities of the outcomes (Nordelöf et al., 2014).

There is a lack of analysis on the effect of PHEV charging on real-world tail-pipe emissions. Existing studies in the literature focus on well-to-wheel greenhouse gas emission reductions, but the effect of charging behavior on tail-pipe emissions is neglected. Paper III fills this gap by analyzing the effect of charging behavior on tail pipe emissions using real-world consumption data with a long observation period.

3 Demand Side PHEV Policies

This chapter provides a brief summary of the range of demand side policy instruments related to PHEVs with comparison to BEVs in Europe and US (California) since all appended papers in this thesis are policy relevant due to different views on the role of PHEVs in the decarbonization of the transport sector and thereof on what policies should be applied.

Policy instruments in general aim to address specific market barriers. There are three principal market barriers in the case of PEVs: lack of market supply, higher upfront costs and systemic failures (Whitehead et al., 2020). Lack of market supply refers to the changes required in manufacturing, especially within the supply chain. Higher upfront costs refer the increased manufacturing costs of PEVs (both PHEVs and BEVs) compared to conventional vehicles, which make PEVs cost more to purchase —in the absence of policy instruments— and thus leading to reduced demand. Systemic failures refer to a wide range of existing gaps that are required for a system-wide change, e.g. charging infrastructure, consumers' awareness of the technology.

Whitehead et al. (2020) categorize PEV policy instruments based on their primary purpose and primary type. Primary purpose shows which market barrier the policy instrument is aiming to address. According to Whitehead et al. (2020), there are three primary purposes: technology push, market/demand pull and systemic. Technology push addresses the market barrier of lack of market supply and aims to ease the change in manufacturing technology, stimulate the development of PEVs and its market formation. Policy instruments such as CO_2 emission standards, research and development grants, PEV quotas fall under the purpose of technology push. Market/demand pull addresses the barrier of higher upfront costs and the reduced demand caused by those costs. It aims to create or stimulate demand for PEVs. Policy instruments such as purchase subsidies, tax exemptions and fuel taxes fall under the purpose of market/demand pull. Systemic policies address the barrier of systemic failures. Policy instruments such as technology standardization, charging infrastructure subsidies, emission zones fall under the systemic purpose.

There are three primary types of PEV policy instruments: economic (market-based), regulatory and information. Economic instruments directly influence the total cost of ownership of the PEV; regulatory instruments improve market conditions in favor of PEVs through technical specifications; and information policies improve awareness of the technology in society (Whitehead et al., 2020).

The overview of existing policies here focuses on the demand side PHEV policies with the primary purpose of market/demand pull. I briefly look into the policies regarding the purchase and operation costs of the vehicle and the long-term strategy of that country where the distinction between PHEVs and BEVs is likely to appear. Information policies such as labelling of vehicles, and awareness campaigns or systemic policies such as public infrastructure development are left out, because they usually cater to both PHEVs and BEVs and it is difficult to distinguish between the two. Selected for comparison are the state of California in the US and countries of Sweden, France, Germany, Netherlands, Norway and the UK in Europe. These selected countries/states are at the forefront of the electrification process in the transport sector. In addition to that, PHEV policies in California are relevant to this thesis research due to the datasets used in the appended papers; and in Sweden due to where this thesis research has been carried out and funded, and future work has been planned.

EV Policies in California

There is a variety of national policies and information campaigns for PEVs in the United States that apply to California. Zero Emission Vehicle (ZEV) program regulates manufacturers in certain states including California to sell a certain number of electric vehicles with a credit system. Certain portions of the requirement must be BEVs or FCEVs. There is a federal tax credit for all new electric vehicles up to $7,500 per vehicle. The amount is based on the range of the vehicle, therefore providing BEVs with a higher credit compared to PHEVs due to their higher range. There is also a rebate under the Clean Vehicle Rebate Project, up to $1,000 for PHEVs and $2,000 for BEVs (CSE, 2020). There is no state-wide or federal ban on the sale of gasoline or diesel vehicles, but the city of Los Angeles plans to ban the new sale of gasoline and diesel vehicles from 2030 onwards (Burch and Gilchrist, 2020).

EV Policies in Sweden

Sweden uses a bonus-malus system which rewards vehicles that emit up to 60 gCO_2/km, with a maximum bonus of 60,000 SEK and burdens vehicles that emit relatively higher amounts of CO_2 with a higher vehicle tax for the first three years (Transport Styrelsen, 2020). BEVs receive the highest bonus and PHEVs receive relatively smaller bonuses based on their battery size. Prior to 2018, there was a five-year exemption from annual circulation taxes and an upfront subsidy of 40,000 SEK for super-environmental cars ("supermiljöbilspremien") that emit no more than 50 gCO_2/km, but both have been replaced by the bonus-malus system. The government of Sweden is investigating a plan to ban the sale of new petrol and diesel cars by 2030 (Kristensson, 2019).

EV Policies in France

In France, there is a registration tax for cars emitting more than 119 gCO_2/km. Therefore, the registration tax applies to PHEVs, but not to BEVs (Wappelhorst et al., 2018). There is a one-time subsidy of maximum 6,000 euros including VAT for vehicles emitting less than 20 gCO_2/km. Most PHEVs on the road are designed to achieve below 50 gCO_2/km, but actual emissions are higher and there is a high discrepancy between different models (e.g. for Chevrolet Volt emit on average 29 gCO_2/km, whereas Toyota Prius emits 91 gCO_2/km) (Plötz et al., 2017a). This results in a situation where the one-time subsidy only applies effectively to BEVs. Vehicles emitting less than 190 gCO_2/km are exempt from the ownership tax, therefore applying to both PHEVs and BEVs. In its long-term strategic planning, the French government seeks to ban the new sale of conventional vehicles emitting greenhouse gases by 2040 (BBC, 2017).

EV Policies in Germany

In Germany, there is no registration tax upon purchase, however there is an annual tax on ownership based on CO_2 emissions of the vehicle and the cylinder capacity. Cars emitting 95 gCO_2/km or less are exempt from the emission component of the annual tax on ownership. BEVs on other hand are exempt from both components and pay no annual tax on ownership. Most PHEVs on the road emit less than 95 gCO_2/km, so effectively PHEVs only pay an annual tax on ownership based on their cylinder capacity. There is a one-time subsidy upon purchase of BEVs and PHEVs, limited to a maximum 4,380 euros for BEVs and 3,285 euros for PHEVs including VAT (Wappelhorst et al., 2018). Germany has not yet announced a timeline for the phasing out of fossil fuel vehicles.

EV Policies in the Netherlands

In the Netherlands, BEVs are exempt from both the registration tax and the annual motor vehicle tax. PHEVs on the other hand are subject to both taxes (although at a much lower rate compared to conventional vehicles) based on their CO_2 emissions (Wappelhorst et al., 2018). In June 2020, The Dutch government introduced a new subsidy scheme for electric vehicles. According to the new scheme, there is a subsidy of 4,000 euros for purchasing or leasing a new BEV and a subsidy of 2,000 euros for purchasing or leasing a used BEV (RVO, 2020). The subsidy applies to BEVs with a value of 12,000 to 45,000 euros and a minimum range of 120 km. Previously PHEVs used to enjoy a wider range of incentives, however the Netherlands has completely changed its policies about PHEVs and removed incentives in 2016 after an analysis of fuel-card data showed that users were not charging the vehicles and using them instead as conventional vehicles (Gibbs, 2019). This was due to PHEVs being used as company cars where fuel got paid by the company but not the electricity; thus leaving no incentive for the user to charge. The Dutch government plans to ban the sales of new petrol and diesel vehicles by 2030 (Dugdale, 2018).

EV Policies in Norway

In Norway, a 25% VAT is paid on the vehicle's base price, however zero-emission vehicles are exempt from paying this, therefore 25% VAT applies to PHEVs but not to BEVs. Norway has a high vehicle registration tax due to the CO_2 intensity element in the tax calculation, but it also has a long history of incentives, with the first BEV incentive in the form of exemption from vehicle registration tax being introduced temporarily in 1990 (Figenbaum, 2017). Currently, for vehicles emitting less than 71 gCO_2/km, there is no registration tax, thus most PHEVs and BEVs are both exempt from this tax (Wappelhorst et al., 2018). BEVs pay maximum 50% of the total amount on toll roads, whereas PHEVs pay the regular amount. In Norway, the annual motor vehicle tax (ownership tax) was replaced by traffic insurance fee in 2018, from which BEVs are exempt. Norway plans to ban the sale of new petrol and diesel vehicles by 2025 (Norsk Elbilforening, 2020).

EV Policies in the UK

In the UK, BEVs are exempt from annual ownership tax if their list price is less than 45,500 euros whereas PHEVs are subject to this tax although at a lower rate than conventional vehicles (Wappelhorst et al., 2018). All vehicles above a list price of 45,500 euros are subject to an annual ownership tax rate. BEVs are also exempt from the registration tax whereas PHEVs are only exempt if they emit less than 50 gCO_2/km. Government provides subsidies for BEVs to a maximum of 5,100 euros including VAT and to a maximum of 2,800 euros including VAT if they emit less than 75 gCO_2/km. UK plans to ban the new sale of petrol, diesel and hybrid vehicles (including PHEVs) by 2035 (Johnston, 2020).

Discussion of Policies

Within the existing policies regarding PEVs, a difference between PHEVs and BEVs appear in the following policy instruments: exemption from registration tax, exemption from annual ownership tax, exemption from road tolls, purchase subsidies, tax credits, exemption from the VAT and ban of certain types of vehicle sales. All of these instruments have the primary purpose of market/demand pull and except for the ban of certain vehicles which is a regulatory instrument, all are economic instruments. A summary of these policy instruments for the analyzed countries/states are given in Table 1.

Table 1: Different policy instruments applying to PHEVs and BEVs in different countries

	California	**Sweden**	**France**	**Germany**	**Netherlands**	**Norway**	**UK**
Exemption from registration tax	-	-	BEV	-	BEV	PHEV, BEV	PHEV, BEV
Exemption from annual ownership tax	-	-	PHEV, BEV	BEV	BEV	BEV	BEV
Exemption from road tolls	-	-	-	-	-	BEV	-
Purchase subsidy	PHEV, BEV (more for BEV)	PHEV, BEV (more for BEV)	BEV	PHEV, BEV (more for BEV)	BEV	-	PHEV, BEV (more for BEV)
Tax Credit	PHEV, BEV (more for BEV)	-	-	-	-	-	-
Exemption from VAT	-	-	-	-	-	BEV	-
Ban on certain types of vehicles' sales	2030 (petrol, diesel) Applies to the city of Los Angeles	2030 (petrol, diesel)	2040 (petrol, diesel)	-	2030 (petrol, diesel)	2025 (petrol, diesel)	2035 (petrol, diesel and PHEV)

Norway utilizes the highest number of economic policy instruments which is in line with their ambitious goal of banning the new sale of petrol and diesel vehicles by 2025. The only applicable policy instrument for PHEVs in Norway is the exemption from registration tax, all other policies are targeted towards BEVs. Netherlands, on the other hand, does not have any policy instruments —among those listed in Table 1— applicable to PHEVs, all of their policy instruments are targeted towards BEVs. Among the seven countries/states, Norway, Sweden and the Netherlands have the most ambitious timeline with phasing out of fossil fuel vehicles, and their policy instruments favor BEVs over PHEVs, although Sweden uses a relatively lower number of policy instruments. France has a timeline for banning petrol and diesel vehicles that is further away compared to Norway, Sweden and the Netherlands, but similarly their policy instruments are also targeted towards BEVs, the most important being that the purchase subsidy only applies to BEVs.

Existing policies in Norway, Sweden, Netherlands and France indicate that they see PHEVs as second to BEVs, perhaps as a gateway vehicle to shift the market towards BEVs. However new sales of PHEVs will still be allowed after the phase-out of petrol and diesel vehicles, which shows that PHEVs will still stay as viable option for some consumers even in the long-term in those countries.

California, apart from the city-wide ban planned in Los Angeles, along with Germany are the only states analyzed here without a timeline for banning petrol and diesel vehicles. In Germany, purchase subsidy still applies to PHEVs along with BEVs. This indicates that Germany, as home to leading car manufacturers in the world, and California are not as keen to abandon PHEVs as other European nations of Norway, Sweden, Netherlands and France, and still see it as a viable long-term option for some consumers.

UK, on the other hand, has significant subsidies for PHEVs, both a purchase subsidy and exemption from registration tax. However, the UK stands out as being the only country banning PHEVs as part of its plan to phase out fossil fuel vehicles. From this standpoint, the UK's position on PHEVs is more radical compared to other countries. This indicates that UK sees PHEVs as a short-term option, however the current policies do not exactly reflect this view. Therefore, one can expect policies in the UK to favor BEVs more in the near future and for instance remove purchase subsidies for PHEVs.

In conclusion, existing PEV policies in the seven countries/states briefly summarized here indicate that there are different views on the role of PHEVs in the process of electrification of the transport sector. Norway, Sweden, Netherlands and France favor BEVs in their policy making over PHEVs, but still share the view that PHEVs can be a long-term viable option for some consumers. Germany and California are the only countries/states without a commitment to ban fossil fuel vehicles. UK is the only country banning the new sale of PHEVs together with petrol and diesel vehicles, therefore the only country seeing PHEVs as a short-term option, however their current policies do not fully reflect this standpoint.

4 Methods

All appended papers use descriptive and inductive statistical methods. The methods used and the relevant datasets that have been analyzed are briefly summarized in this chapter. For more details on the data, variables and the methods, please refer to the relevant appended paper.

For Paper I, we use a compiled dataset from the available raw data (trip data, charging data, survey data and other sources) for 71 households in California with at least one PEV (PHEV or BEV). Table 2 below shows the variables in this compiled dataset. Data was collected from summer 2015 to summer 2016. We run regression analysis on the compiled dataset in order to assess the electrification of vehicle miles travelled within the household context. We use descriptive statistics to see the household level in more detail and the regression analysis to provide a helicopter view and explain overall trends.

Table 2: Variables in the compiled dataset of Paper I and how they relate to provided raw datasets

	Trip data	Charging data	Survey data	Other sources
Dependent variables	eVMT, VMT of the PEV, VMT of the household, Utility factor of the PEV, Utility factor of the household	-	-	-
Independent variables	Frequency of overlaps, Frequency of long-distance trips, MPG of ICEVs in the household	Frequency of charging	Number of drivers, Commute distance, Size of ICEVs in the household, MPG of ICEVs in the household, Share of PEV usage of the main driver	Range (from U.S. EPA)

Note: MPG stands for miles per gallon. MPG of ICEVs in the household is derived both from the trip dataset and the survey, and so appears under both.

Generic regression model used for Paper I is given below; we use the same independent variables for all.

$$Y_i = \beta_0 + \beta_1 \cdot Range + \beta_2 \cdot Number\ of\ drivers + \beta_3 \cdot Commute\ distance + \beta_4 \cdot PEV\ Share + \beta_5 \cdot Frequency\ of\ charging + \beta_6 \cdot Frequency\ of\ long\text{-}distance\ trips + \beta_7 \cdot Frequency\ of\ overlaps + \beta_8 \cdot ICEV\ Size + \beta_9 \cdot ICEV\ MPG + \varepsilon$$

$i = \{1, \ldots, 5\}$ where $Y_1 = eVMT$, $Y_2 = VMT\ of\ the\ PEV$, $Y_3 = VMT\ of\ the\ household$, $Y_4 = Utility\ factor\ of\ the\ PEV$, $Y_5 = Utility\ factor\ of\ the\ household$

Multivariate regression analysis was performed on eVMT, VMT of the PEV and VMT of the household, and logistic regression was performed on UF of the PEV and UF of the household.

The dataset for Paper II and III contains user specific performance data of Chevrolet Volt (a PHEV) users from 2011 to 2020 with 4.3 million driving days and 10,488 users from US and Canada. Based on the available raw data, the following parameters were calculated per day and user: electric vehicle kilometers travelled (eVKT), gasoline vehicle kilometers travelled (gVKT) and total vehicle kilometers travelled (VKT). We developed our own method to identify charging events based on available driving data. First, we define calculated UF and observed UF for each day and user, as given in Equation 1 and 2 respectively (AER stands for all electric range of the vehicle).

$$\mathrm{UF_{cal}} = \begin{cases} {}^{AER}/_{daily\ VKT}, & \text{if } daily\ VKT > AER \\ 1, & \text{otherwise} \end{cases} \tag{1}$$

$$\mathrm{UF_{obs}} = {}^{daily\ eVKT}/_{daily\ VKT} \tag{2}$$

The calculation assumes a full charge overnight implicitly. If the observed UF is much higher than the calculated UF, there must have been at least one additional charge during the day for that user. We use the assumptions given in Equation 3 and 4 for the occurrence of additional daytime charging or no overnight charging, for a user, for a given day.

$$\text{additional daytime charging} = \begin{cases} \text{true}, & \text{if } \frac{UF_{obs}}{UF_{cal}} > 1.5 \\ \text{false}, & \text{otherwise} \end{cases} \tag{3}$$

$$\text{No overnight charging} = \begin{cases} \text{true}, & \text{if } \frac{UF_{obs}}{UF_{cal}} < 0.5 \\ \text{false}, & \text{otherwise} \end{cases} \tag{4}$$

Thereafter, we calculate the frequency of additional daytime charging and the frequency of no overnight charging for each user. The frequency of additional daytime charging is the share of days where additional daytime charging occurs within all driving days during the entire observation period. Similarly, the frequency of no overnight charging is the share of days where no overnight charging occurs within all driving days.

In Paper II we use additional daytime and no overnight charging frequencies and analyze charging behavior with respect to characterization of frequent chargers and charging days. In Paper III, we plot additional daytime and no overnight charging frequencies against mean fuel consumption and utility factor; and analyze the impact of charging behavior on fuel consumption, tail pipe emissions and share of electrification of vehicle miles.

All appended papers utilize empirical, real-world, data to provide insights into actual travel behavior patterns.

5 Summary of Appended Papers

This chapter summarizes the work that has been carried out in each appended paper. Summary of results and discussion of the papers are given in Chapter 6.

Paper I: Electrification of vehicle miles travelled within the household context: a case study from California, USA

The study aims to investigate PHEVs within the household context and analyze how household factors impact electric vehicle miles travelled (eVMT), vehicle miles travelled (VMT) of the PHEV, VMT of the household including all household vehicles, utility factor (UF) of the PHEV and the UF of the entire household including all household vehicles. There is a lack of assessment of electrification at the household level in the literature and Paper I fills this gap. Our dataset consists of 71 households in California with detailed logger data on all actively used cars from summer 2015 to summer 2016. Each household in the dataset owned one PEV, in addition to conventional vehicles. 53 households had a PHEV model (either a Toyota Plug-in Prius, Ford C-Max/Fusion Energi or Chevrolet Volt) and 18 households had a BEV (Nissan Leaf). This composition of the households enables us uniquely to compare the contribution of electrification on the household level between PHEVs and BEVs.

The household factors were identified under four categories: (1) for the category of plug-in electric vehicle (PEV) technology in the household, we use range and the frequency of charging; (2) for the category of household vehicle usage, we use number of drivers, commute distance, frequency of overlaps between PEV and conventional vehicles and frequency of long-distance trips; (3) for the category regarding other conventional vehicles in the household, we use size of internal combustion engine vehicles (ICEVs) in the household and miles per gallon (MPG) of ICEVs in the household; (4) for the category regarding driver identity, we use share of PEV usage of the main driver. We perform a regression analysis to investigate how these factors impact electrification.

Paper II: Empirical charging behavior of plug-in hybrid electric vehicles.

The study aims to investigate the empirical charging behavior of plug-in hybrid electric vehicles. We analyze over 10,000 users with a total of 4.3 million driving days from 2011 to 2020, for one PHEV model (Chevrolet Volt) in the US and Canada. There is a lack of empirical studies in the literature analyzing the charging behavior for large samples of PHEV users. Paper II fills this gap, and to the authors' best knowledge, is the first study to map out the range of charging behavior with additional daytime charging and no overnight charging frequencies and analyze this behavior with respect to characterization of frequent chargers and charging days. We also study the utility factor and the distribution of driving distances to understand its relation to charging behavior.

Paper III: The environmental benefits of plug-in hybrid electric vehicle charging

In this paper, we analyze the change in utility factor —share of kilometers driven on electricity within total vehicle kilometers travelled— and fuel consumption with respect to charging behavior. We quantify the environmental effects of PHEV charging behavior with a focus on tail pipe emissions by looking at the frequencies of not charging a PHEV overnight and charging a PHEV twice or more frequently per day for Chevrolet Volt, a long-range PHEV. We analyze daily driving data from 7,491 Chevrolet Volt users in the US and Canada, with a total of 3.4 million driving days. Previous studies in the literature have analyzed well-to-wheel greenhouse gas emissions but neglect the effect of charging behavior on tail pipe emissions. Paper III fills this gap in the literature with an analysis on the effect of charging on tail pipe emissions.

6 Results & Discussion

This chapter provides first a summary of results from each appended paper, followed by a discussion of all papers together.

Paper I: Electrification of vehicle miles travelled within the household context: a case study from California, USA

In our analysis of the frequency of charging, which we define as the average number of charging events per day by plugging the PEV into the grid, we observe that it is on average similar for all three models of PHEVs in our dataset (Toyota Prius, Ford C-max/Fusion Energi and Chevrolet Volt) ranging from 1.00 to 1.05/day. For households with a Nissan Leaf, the only BEV in our dataset, the frequency of charging on average is 0.86. Therefore, the BEV in our dataset is charged slightly less frequently than the PHEVs per day. However, it should be noted that Nissan Leaf has a higher all-electric-range (73 to 84 US miles) compared to the PHEVs in our dataset (11 US miles for Toyota Prius, 20 US miles for Ford C-max/Fusion Energi and 35 to 38 US miles for Chevrolet Volt). We also observe that the frequency of long-distance trips (single trips made by the PEV that are above 50 US miles) is on average lower for the Nissan Leaf at 1% compared to other PHEVs, as expected due to BEV's range limitation.

Figure 1 shows the utility factor (UF) of households (share of electrified vehicle miles travelled within total household travelled miles considering all vehicles) and Figure 2 shows the vehicle miles travelled (VMT) of households, both categorized by PEV-type and total number of cars in the household. We observe that households with more cars electrify a lower share of their total travelling from Figure 1; this is expected due to households with more cars driving more in total as seen in Figure 2. From Figure 1, we observe that households that have PHEVs with higher ranges end up electrifying a larger share of their total miles. Looking at the utility factor at the household level uniquely allows us to compare PHEV and BEV households, and we observe that households with Chevrolet Volt have a similar utility factor of 46% at the household level compared to households with Nissan Leaf at 45%. This shows that, in the context of the entire household, a PHEV like Chevrolet Volt with half the range of a BEV like Nissan Leaf, can electrify a similar share of total household miles. Looking at the share of electrified VMT just for the PHEVs, thus looking at the UF just for the PHEV and not at the household level, we find that, on average, Toyota Prius has a UF of 15%, Ford C-max/Fusion Energi has a UF of 57% and Chevrolet Volt has a UF of 76%, which are similar to the findings of Carlson (2015) for the same set of vehicles.

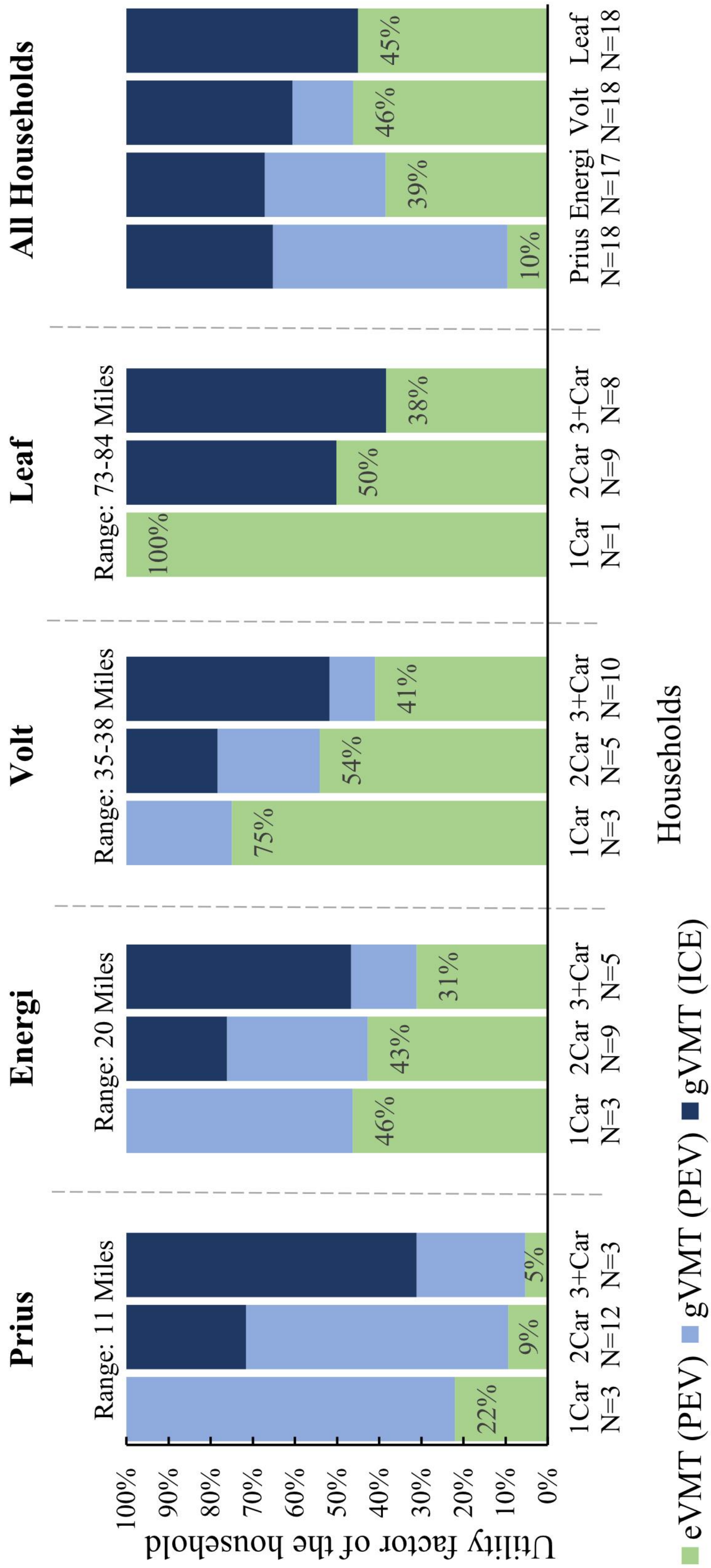

Figure 1: Utility factor of households categorized by PEV-type and total number of cars in the household (Paper I)

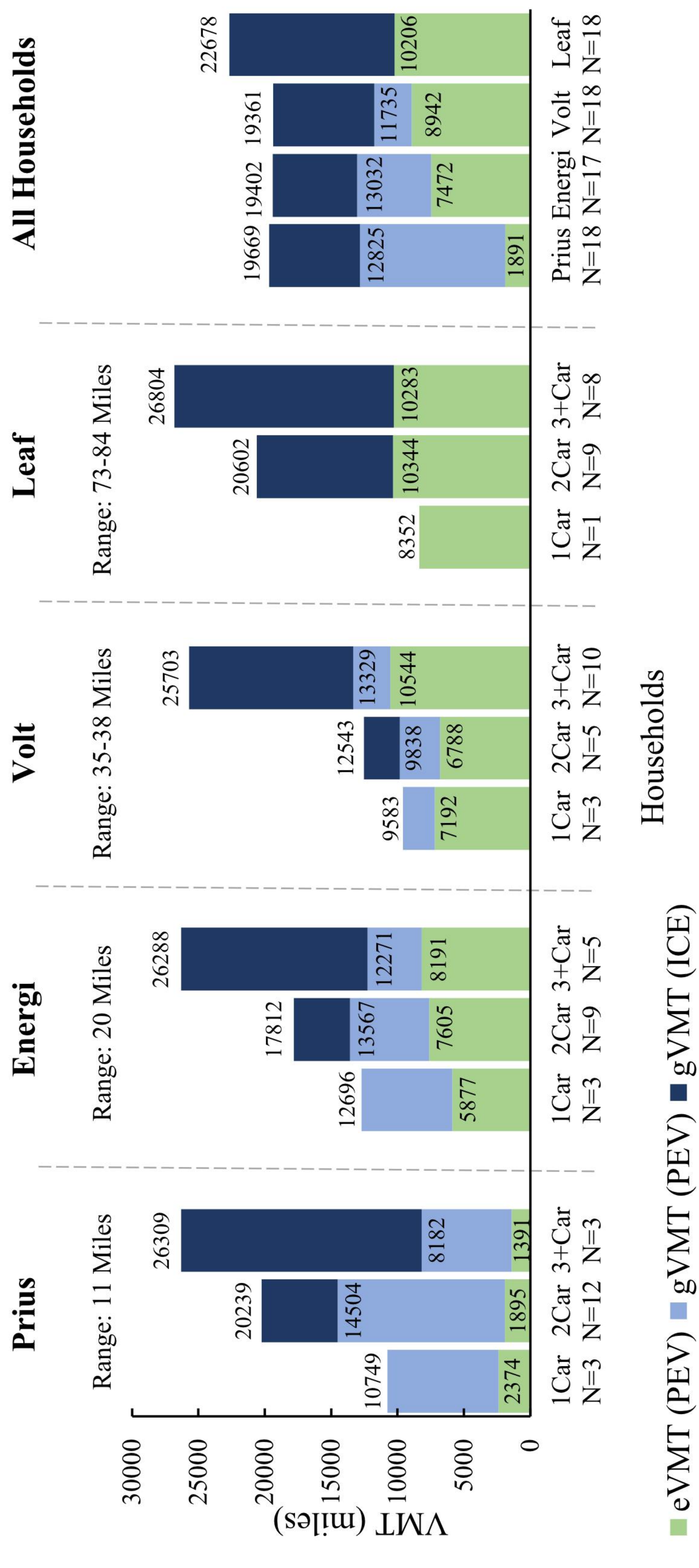

Figure 2: VMT of households, categorized by PEV-type and total number of cars in the household. (Paper I)

We observe that annual household VMT is similar among PHEV households as seen in Figure 2, ranging from 19,361 US miles to 19,669 US miles; BEV households on the other hand have a slightly higher annual total VMT at 22,678 US miles.

We performed a regression analysis to investigate the impact of household factors on eVMT, VMT of the PEV, VMT of the household, UF of the PEV and UF of the household. Regression results are given below in Table 3.

Table 3: Regression results for eVMT, VMT of the PEV, VMT of the household, UF of the PEV and UF of the household

Dependent	eVMT		VMT of the PEV		VMT of the household		UF of the PEV		UF of the household	
Intercept	-1988.15 (3351.14)		7897.02 (4360.13)	.	3215.47 (6283.84)		-0.312 (0.212)		0.289 (0.180)	
Range	103.09 (14.98)	***	-28.72 (19.49)		-0.89 (28.08)		0.021 (0.002)	***	0.005 (0.001)	***
Number of drivers	363.64 (567.20)		96.38 (737.97)		3995.29 (1063.57)	***	0.068 (0.040)		-0.048 (0.031)	
Commute distance	31.83 (23.45)		85.97 (30.51)	**	101.44 (43.97)	*	0.001 (0.001)		-0.001 (0.001)	
Share of PEV usage of the main driver	593.58 (2782.06)		-805.96 (3619.71)		-61.76 (5216.74)		0.113 (0.181)		0.049 (0.150)	
Frequency of charging	3237.85 (959.58)	**	2207.12 (1248.49)	.	622.12 (1799.33)		0.140 (0.056)	*	0.157 (0.052)	**
Frequency of long-distance trips	8618.78 (12335.02)		54434.77 (16048.95)	**	40128.76 (23129.79)	.	-2.029 (0.728)	**	-0.019 (0.663)	
Frequency of overlaps	9289.84 (11063.43)		14331.23 (14394.51)		148452.86 (20745.40)	***	-1.124 (0.673)		-1.446 (0.595)	*
Size of ICEVs in the household	-368.87 (763.94)		104.06 (993.95)		-396.65 (1432.49)		0.021 (0.048)		-0.043 (0.041)	
MPG of ICEVs in the household	-0.21 (31.04)		23.42 (40.39)		37.25 (58.21)		0.001 (0.002)		-0.004 (0.002)	*
N	71		71		71		53		71	
Multiple R-squared	0.542		0.504		0.731		-		-	
Adjusted R-squared	0.475		0.431		0.692		-		-	
F-statistic	8.024		6.881		18.44		-		-	
Confidence levels	*** %99.9, **%99, *%95, .%90									
Values represent estimates, standard error is given in parentheses.										

Regression results show that range is statistically significant in the electrification of miles; and a higher all-electric range is associated with higher eVMT, higher UF for the PEV and a higher UF within the household context. This is in line with the findings of previous studies (Bradley and Quinn, 2010, Paffumi et al., 2018, Plötz et al., 2018). Frequency of charging is also statistically significant in the electrification of miles, similarly a higher frequency of charging is associated with a higher eVMT, higher UF for the PEV and a higher UF for the household. A higher frequency of long-distance trips is associated with a higher VMT for the PEV, but also a lower UF for the PEV, which suggests that the decrease in UF can be explained by an increase in gasoline VMT of the vehicle, meaning a lower fuel economy with more frequent long-distance trips. This is in line with the findings of Plötz et al. (2018) on the tendency for long-distance trips decreasing PHEV fuel economy and UF. We also find that a higher MPG for ICEVs in the household is associated with a lower UF for the household, however MPG of ICEVs in the household does not have a statistically significant relationship with neither the VMT of the household nor the eVMT of the PEV. Therefore, an explanation for this reduction in UF of the household is that ICEVs with higher MPGs are likely to replace trips from PEVs in the household.

Paper II: Empirical charging behavior of plug-in hybrid electric vehicles.

In this paper, we use a dataset of over 10,000 PHEVs (Chevrolet Volt) with a total of 4.3 million driving days. We estimate the frequencies of additional daytime charging and the frequencies of no overnight charging for each user. We compare observed and calculated utility factors in our estimation for the occurrence of an additional daytime or no overnight charging on a given day; and our calculation implicitly assumes a full charge overnight. We observe that average share of days with additional charging during daytime is typically 3 – 8 % of the days as seen in Figure 3 with a mean of 7.9%, and that typical share of days without overnight charging is 3 – 7 % as seen in Figure 4 with a mean of 6.6 %, meaning users avoid high share of nights without charging and PHEVs in our sample are, on average, almost daily charged. A further analysis on charging on different days of the week finds that additional daytime charging is more common on working days and not charging overnight is more common on weekends.

Figure 5 shows the distribution of observed utility factor (UF), daily vehicle kilometers travelled (VKT), frequency of additional daytime charging and frequency of no overnight charging in different user groups. The different user groups are top 10% and bottom 90% of most frequent additional daytime chargers and no overnight chargers, and intense vehicle users who have more 30,000 annual vehicle kilometers travelled and non-intense vehicle users. We find that not charging overnight has more effect on the UF of the PHEV than more frequent additional daytime charging. The change in UF from not charging overnight is typically larger than charging additionally during daytime. We also find that intense vehicle users have a higher frequency of additional daytime charging, but this increased frequency falls short of matching their high annual VKT and results in a lower UF for the vehicle. Intense vehicle users also have a higher daily VKT as expected, and even though their UF is lower, they end up electrifying more kilometers in sheer numbers, meaning they are an important group to target when it comes to charging availability and behavior. We observe that top 10% most frequent no overnight chargers have on average a higher daily VKT compared to the rest, meaning that they have a higher potential to electrify but choose not to do so.

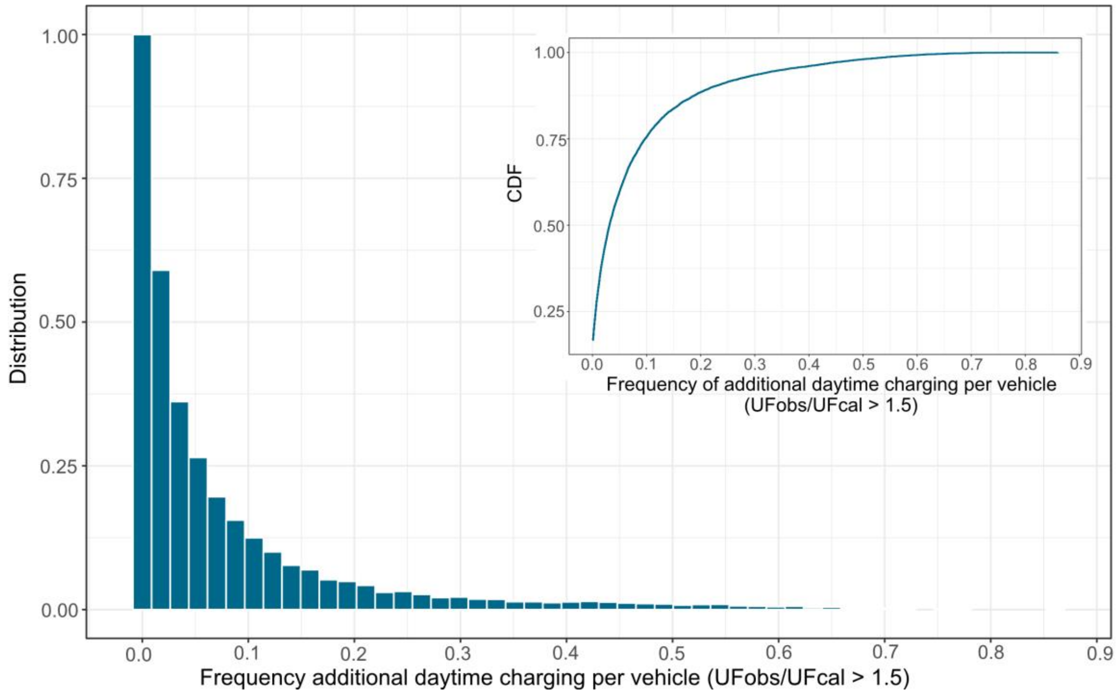

Figure 3: Distribution of additional daytime charging frequency, normalized so maximum is 1. CDF given inset. (Paper II)

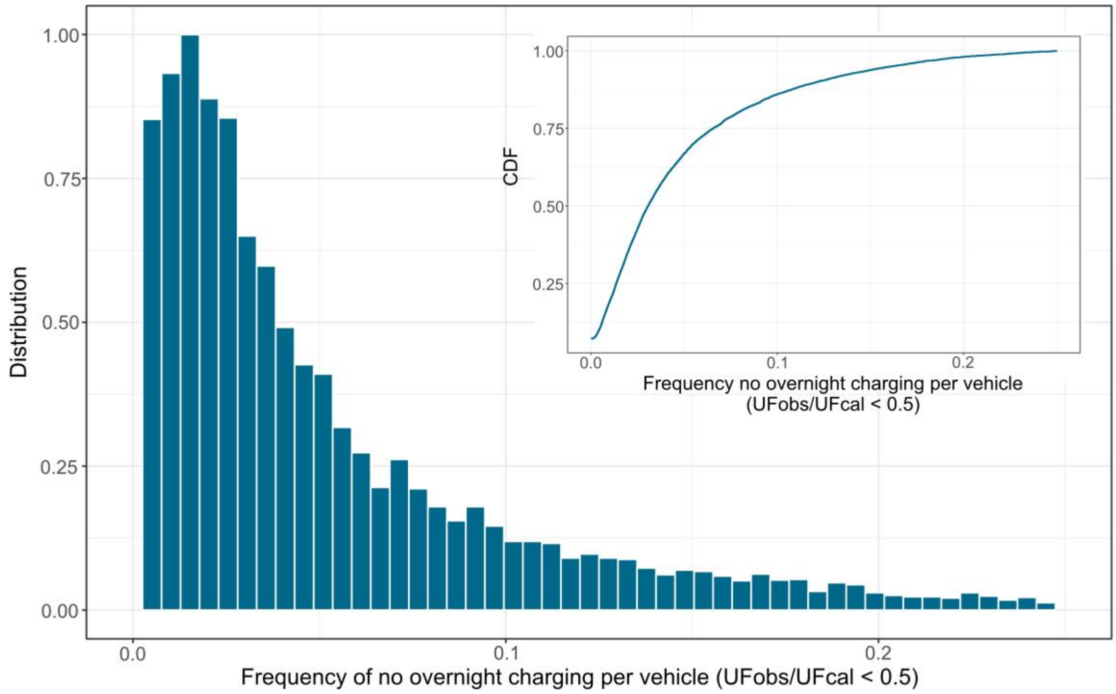

Figure 4: Distribution of frequency of no overnight charging, normalized so maximum is 1. CDF given inset. (Paper II)

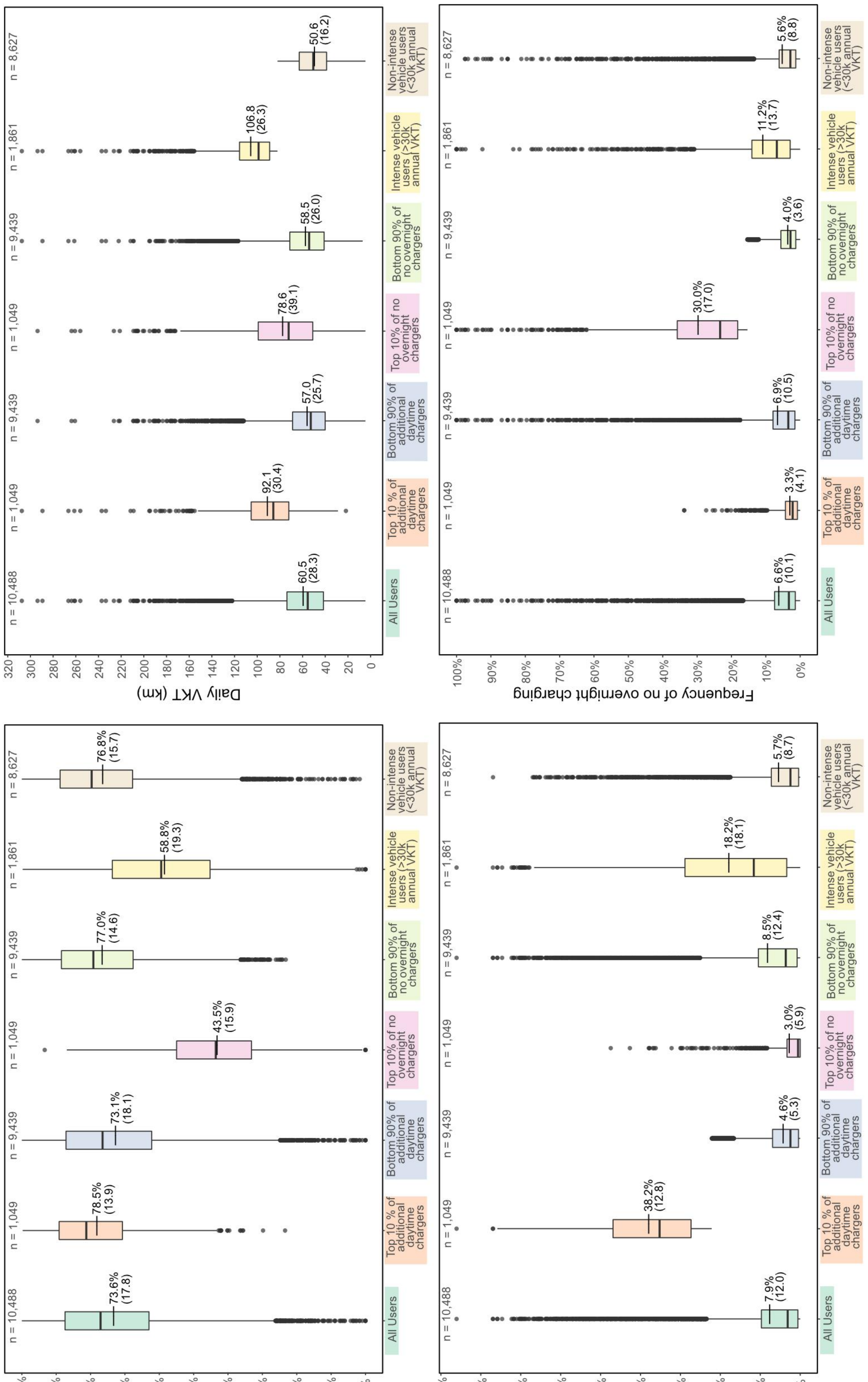

Figure 5: Distribution of observed utility factor (UF), daily VKT, frequency of additional daytime charging and frequency of no overnight charging in different user groups. Means are indicated and the standard deviation is given in parentheses. (Paper II)

Further analysis on long distance driving reveals that daily VKT larger than 100 km happens on 19.7% of the driving days for all users but account for 41.3% of the annual VKT, meaning that it has a noteworthy impact and can be a limiting factor for the effect of additional daytime charging on electrification.

Paper III: The environmental benefits of plug-in hybrid electric vehicle charging

In our analysis on the effect of charging behavior on fuel consumption, we find that regularly charging overnight —low frequencies of no overnight charging— can reduce mean fuel consumption to below 1 liter per 100 km, as seen in Figure 6. We observe that irregular overnight charging, where overnight charging does not happen for instance above 60% of the nights, can push up the mean fuel consumption above 5 liters per 100 km. This shows that regularly charging overnight has a substantial effect on mean fuel consumption. We find that from 0% to 10% driving days without overnight charging, fuel consumption and tail pipe emissions increase by 1 ¾ liters of gasoline or 4.0 kg tail pipe CO_2 per 100 km. From 10% to 20% driving days without overnight charging, fuel consumption and tail pipe emissions increase by ¾ liters of gasoline or 1.73 kg tail pipe CO_2 per 100 km. Above 20% of driving days without overnight charging, fuel consumption and tail pipe emissions increase by approximately 0.4 liters of gasoline or 0.92 kg tail pipe CO_2 per 100 km every 10% of driving days without overnight charging.

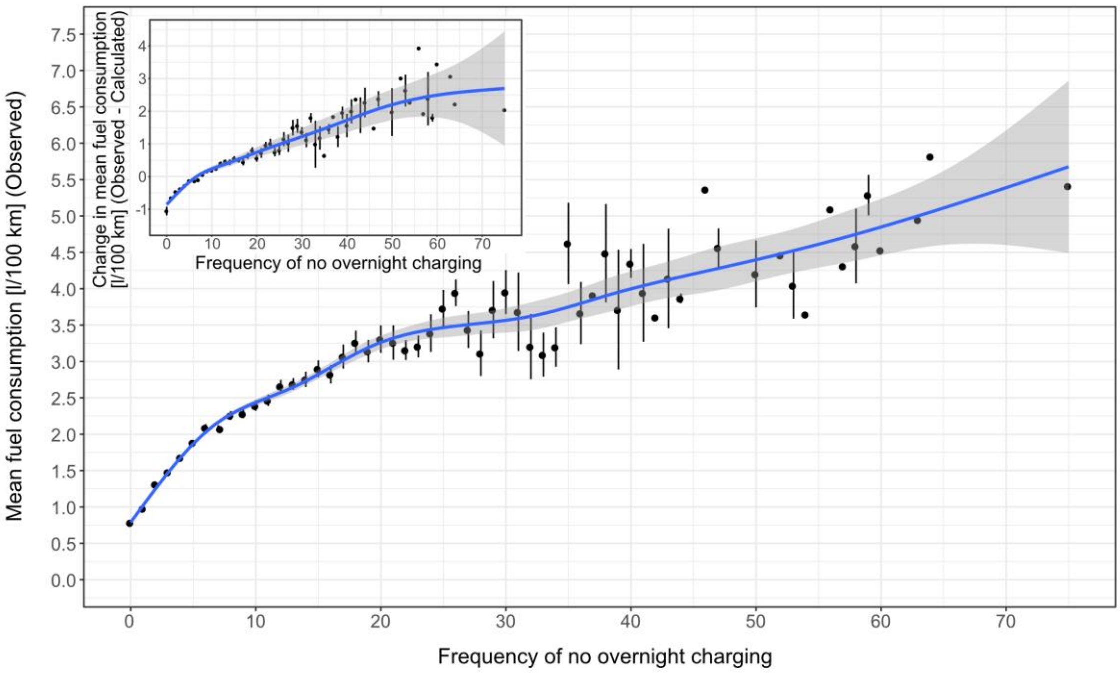

Figure 6: Mean fuel consumption vs frequency of no overnight charging, change in mean fuel consumption (observed-calculated) vs frequency of no overnight charging given inset. (Paper III)

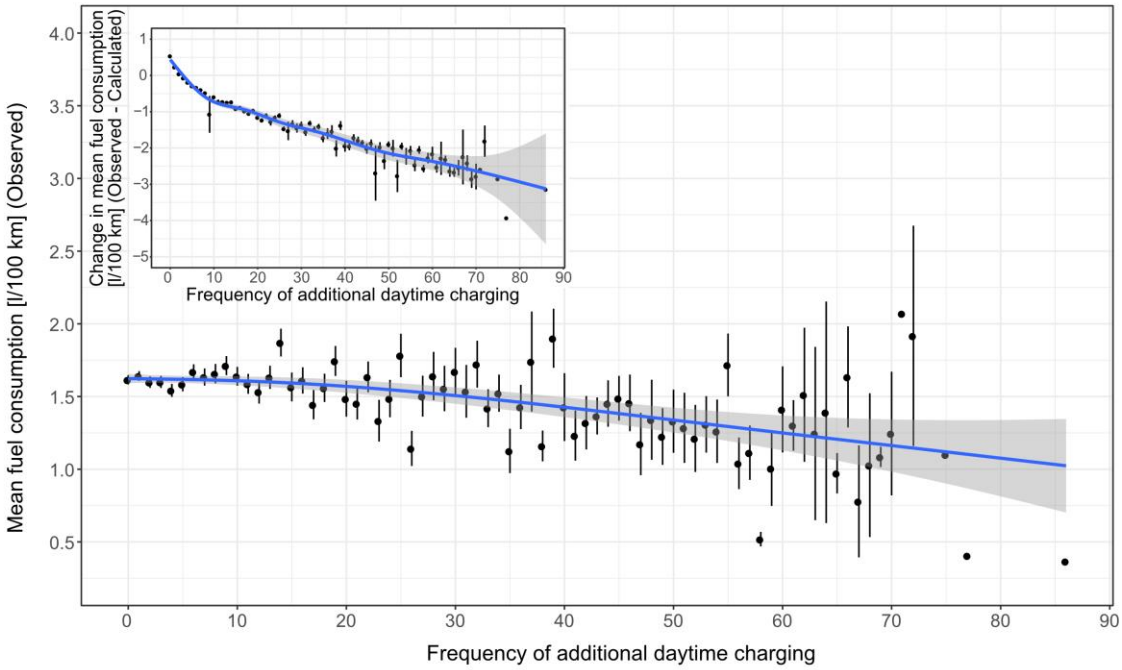

Figure 7: Mean fuel consumption (observed) vs frequency of additional daytime recharging, change in mean fuel consumption (observed-calculated) vs frequency of additional daytime charging given inset. (Paper III)

As shown in Figure 7, we also find that the effect of additional daytime charging (charging more than once per day) is less substantial compared to overnight charging, yet still higher shares of additional daytime charging lowers the mean fuel consumption. We observe that above 20% of driving days with additional daytime charging, mean fuel consumption and tail pipe emissions decrease approximately by 0.1 liters or 0.23 kg tail pipe CO_2 per 100 km every 10% of driving days with additional daytime charging.

We also look at the effect of charging behavior on UF and find that high shares of nights without overnight charging have a substantial effect on UF, e.g. not charging overnight 60% of the days can reduce observed UF as much as 50 percentage points compared to the calculated UF which presumes charging every night. Additional daytime charging, on the other hand, has a smaller effect on observed UF compared to no overnight charging.

Discussion of appended papers

It was previously reported in the literature that a longer all-electric-range is associated with a higher utility factor for the PHEV (Bradley and Quinn, 2010, Paffumi et al., 2018, Plötz et al., 2018). Paper I finds this also holds true for the share of electrification within the household context, considering all vehicles. Furthermore, our results show that, within the household context, a PHEV like the Chevrolet Volt with half the range of a BEV like the Nissan Leaf can electrify a similar share of miles. It is not clear if this result would hold for longer range PEVs and different models, still our results indicate that a longer-range PHEV has the potential to electrify a high share of miles within the household context. The main implication for policymakers is that PHEVs with a range of at least 35 US miles have the potential to electrify a similar share of total household miles as low range BEVs and thus can play an important role in decarbonizing the transport sector.

Paper I also finds that more frequent charging is associated with a higher share of electrification of miles for both the vehicle and the household. Both Paper I and Paper II conclude that PHEVs are charged during most nights or once per day. Paper II and III find that overnight charging has a bigger effect on the share of electrification of miles than charging additionally during the day. Based on our findings on frequency of charging from all papers, developing the charging infrastructure to facilitate an increase in charging frequency can have beneficial effects on electrification, and in that process easy access to overnight charging should be prioritized above public and workplace charging infrastructure.

In Paper I, we find that more frequent long-distance trips are associated with lower UF for the PHEV and result in a lower PHEV fuel economy, as previously reported in the literature (Plötz et al., 2018). Similarly, in Paper II, we find that long-distance driving has a noteworthy impact on annual mileage. The impact of long-distance driving can be a limiting factor for the effect of additional daytime charging as we see in Paper II, even frequent chargers with long-ranged PHEV can hardly achieve more than 90% electric driving.

Paper I contributes to the literature with the finding that ICEVs with higher MPGs have a higher likelihood to replace trips from the PEV and consequently lower the UF within the household context.

Both Paper I and Paper II conclude that UF, on its own, should not be used as the only measure of environmental performance. For instance, in the case of ICEVs replacing trips from PEVs within the household, the amount of direct reduction in electrification offset by the increased MPG of ICEV miles should also be taken into account. Similarly, users with a low share of electrification can drive above average miles on electricity per year and thus electrify more in terms of sheer number of miles, meaning that UF on its own would not provide a full picture on environmental performance and the wider context should also be taken into account.

We look at the direct effect of charging behavior on fuel consumption and tail pipe emissions in Paper III and provide a better understanding of the environmental performance of PHEVs. We find that regular overnight charging can substantially reduce tail pipe CO_2 emissions. The main policy implications of our results in Paper

III is that adequate access and incentives for users to plug-in every night is necessary to make sure PHEVs can contribute to a reduction of CO_2 emissions.

There are however some limitations to the datasets used in the appended papers. For Paper I, for example, the sample size is limited to 71 households. A larger dataset would allow us to include more variables, however the strong suit of our dataset is that it was collected for the length of a year and includes all vehicles in the household, which is unique. For Paper II and III, the data is rich when it comes to number of users and observation time, but sparse in additional information about the users; also, it only covers one PHEV model. Other factors can impact charging behavior such as access to workplace charging, dwelling type and commute distance (Lee et al., 2020).

The dataset in Paper I is regionally bound to California and the dataset in Paper II and III to Canada and US, which means all datasets used come from North America with a high availability of home charging in garages (Funke et al., 2019); therefore our results are not directly transferrable to other parts of the world with less home charging like China or Japan. The users in all datasets are almost all private users, therefore our results are also not directly transferrable to company cars or fleet vehicles. The users in the datasets of all appended papers can be considered as early adopters and it is not certain that early majority users will have the same behavior.

In conclusion, results from appended papers point out that PHEVs with a range of at least 35 US miles (56 km) have an important role to play in electrifying personal transport, especially in the electrification of vehicle miles travelled within the household context where they can achieve as much electrification as some BEVs (Paper I); regular overnight charging can have a noteworthy reduction on tail pipe emissions of PHEVs and substantially increase share of electrification of miles (Paper II and III); and policy for PHEVs should prioritize easy access to overnight charging above public and workplace infrastructure to achieve high shares of electrification (Paper II and III).

7 Key Contributions

Key contributions of this licentiate thesis are summarized below.

1. Analysis on the share of electrification of miles within the household context is of increasing importance due to e.g. shifting trips between vehicles in multi-car households. Our analysis of PHEVs within the household context shows that PHEVs with a range of at least 35 miles (56 km) can achieve as much electrification as some BEVs and can play an important role in electrifying personal transport.

2. Additional charging during daytime is typically in the range of 3 – 8% of the driving days; and the typical shares of days without overnight charging is in the range of 3 – 7% of driving days, indicating users avoid high shares of nights without charging.

3. Effect of additional daytime charging is limited due to long-distance driving having a noteworthy impact on annual mileage. This is observed especially for users with high annual mileage (above 18,600 miles or 30,000 km) who have higher frequencies of additional daytime charging but end up with lower shares of electrification on average. Yet, users with high annual mileage electrify more kms in sheer number of miles than the average user and are an important group to target when it comes to charging availability and behavior.

4. Regular charging overnight has a noteworthy reduction on tail pipe emissions of PHEVs and substantially increase share of electrification of miles. Therefore it is important to ensure adequate access and incentives for users to plug-in every night to make sure PHEVs can contribute to a reduction of CO_2 emissions; and policies for PHEVs should prioritize easy access to overnight charging above public and workplace infrastructure to achieve high shares of electrification.

In the continuation of my doctoral studies, given the availability of data, I plan to extend the research on charging behavior of especially PHEVs to look at country specific differences that affect charging behavior and how that reflects itself in the policy making.

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