THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Car movement patterns and the PHEV

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Göteborg, Sweden 2017

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ISBN: 978-91-7597-550-4

Doktorsavhandlingar vid Chalmers tekniska högskola
Ny serie nr 4231
ISSN0346-718X

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Printed by Chalmers Reproservice

Göteborg, Sweden 2017

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ABSTRACT

Roughly 30% of Sweden's total greenhouse gas emissions originate from transport and a majority of them from cars. The plug-in hybrid electric vehicle (PHEV) avoids the range limitation of the fully electric vehicle while still allowing for a major share of the fuel to be replaced by electricity from the grid and can thereby reduce greenhouse gas emissions, local pollutants and energy security concerns. The expected share of electric driving for a given battery size is however dependent on the individual car's movement. In this thesis, the potential to reduce fuel use in Swedish passenger car transport through an introduction of PHEVs is assessed by utilizing a comprehensive data set on Swedish car movements logged by GPS.

In paper I, we analyze how individuality in movement patterns may affect optimal battery design, economic viability and potential for fuel substitution. Both optimal battery sizes and savings are found to vary substantially between drivers. Commuters are found to be among the first to reach viability for PHEVs.

In paper II we analyze how different objectives can affect optimal battery range, viability, savings and share of electric driving. Our results suggest that different objectives among stakeholders could result in different optimal battery sizes and that a high share of PHEVs in a vehicle fleet is not enough to ensure a high share of electric driving.

In paper III we evaluate the relative benefit of a PHEV in comparison to a BEV in a two-car household. The results suggest that the BEV in general is economically favored over the PHEV in two-car households if the vehicle usage is optimized within the household. The difference in potential share of electric driving between a PHEV and a BEV is in general small. In paper IV we analyze the potential for brake energy regeneration in Swedish driving conditions. We find that city drivers have the highest potential to regenerate energy per km of driving, but long distance drivers have the largest potential to regenerate energy on a yearly basis. Also, extra energy gains from higher regeneration power capacity were found to fall off quickly.

Keywords: PHEV, BEV, battery size, GPS logging, car movement pattern, PHEV viability, PHEV potential, Sweden, electrification, brake energy regeneration.

List of Publications

I. Lars-Henrik Björnsson and Sten Karlsson, "Plug-in hybrid electric vehicles: How individual movement patterns affect battery requirements, the potential to replace conventional fuels, and economic viability", *Applied Energy*, Volume 143, 1 April 2015, Pages 336-347.

SK conceived the idea; LHB performed the data preparation and modelling; LHB and SK analyzed the results; LHB wrote the paper together with SK.

II. Lars-Henrik Björnsson, Sten Karlsson, Frances Sprei "Objective functions for PHEV battery range optimization and possible effects on the vehicle fleet", *Submitted to Transportation Research Part C.*

LHB conceived the idea; LHB performed the modelling; LHB analyzed the results with contributions from SK and FS; LHB wrote the paper with contributions from SK and FS.

III. Lars-Henrik Björnsson and Sten Karlsson, "Electrification of the two-car household, PHEV or BEV?", *Working paper, to be submitted to Transportation Research Part C.*

SK conceived the idea and contributed with input data from earlier work; LHB developed the modelling for the PHEV in GAMS; LHB wrote the economic model in Matlab; LHB analyzed the results with contributions from SK; LHB wrote the paper.

IV. Lars-Henrik Björnsson and Sten Karlsson, "The potential for brake energy regeneration under Swedish conditions", *Applied Energy*, Volume 168, 15 April 2015, Pages 75-84.

LHB conceived the idea; LHB performed the modelling; LHB analyzed the results with contributions from SK; LHB wrote the paper with contributions from SK.

ACKNOWLEDGEMENTS

Sten, you have been straightforward and tough in your judgement, picky with details, quick to scrap anything but the essentials in any text I've ever sent you[1], and I love it. You are truly a fantastic supervisor and I want to thank you for everything. Your importance for my time as a PhD student cannot be overstated. Frances, when I thought my texts were finished for print (since only the essentials remained), you taught me the importance of a text being understandable.[2] Thank you for that, and for many other things. Niklas, you have been part of all my years at Chalmers and I want to thank you for all good times spent together. It is not without fear that I realize that I soon will have to stop consider myself as a student, but it is then comforting to know that you will take good care of the rest of the noodles in our office.

I would like to thank all my friends and colleagues at Physical Resource Theory for making this a great workplace. I really can't describe how much I enjoy sitting at the lunch table, just listening to the discussions about farmland inspections in Brazil, probabilities of extra-terrestrial life, battlefield strategies of Gustav II Adolf or pretty much anything in between.

I would also like to thank family and friends for all the support and patience you are showing your absent-minded family member/friend, who greatly appreciate your company.

Thank you, Kristofer Björnson, for always being available for debugging or consultation, no matter the hour. Thank you, Anders Olsson, for good comments on texts and much more.

Finally, no one has shown more patience and endured more hardships due to my PhD studies than you Christine. I can't thank you enough. You know I wouldn't be anything without you. Jag älskar dig! och Tage din lille skrutt, dig älskar jag också!

[1] Not all texts had essentials.

[2] Not all texts were understandable.

CONTENTS

1 INTRODUCTION

The passenger car plays a significant role in the Swedish transport system. For example, 77% of the Swedish households have access to at least one car [1] and 77% of all passenger kilometers travelled in 2015 were done by car [2]. Car travel does however contribute to a number of problems like congestion, local air pollution, reduced energy security and not the least greenhouse gas emissions. Roughly 30% of Sweden's total greenhouse gas emissions originate from transport of which passenger cars are responsible for about 60% [3]. In addition, passenger car transport is projected to increase by about 1.5% per year until 2030 [4]. The Swedish parliament has adopted a vision to reach a carbon neutral society in 2050 [5], and as a step towards this goal the vehicle fleet should be independent of fossil fuels by 2030 [6]. This requires a combination of measures, both structural, in order to reduce the need for transport and to shift to more energy efficient transport modes, as well as technology specific measures to increase the use of fossil free energy and to increase the energy efficiency of vehicles [5]. Increased electrification of passenger cars has, through the associated fuel reduction, the potential to not only reduce greenhouse gas emissions but also local pollutants, and energy security concerns.

Although often suggested as a technology for the future, the electric car is as old as the automobile itself. It was together with steam and gasoline cars one of the main automobile technologies around 1900.[3] The gasoline car later became the dominating technology and the electric cars almost vanished from the scene around 1930 [8], but the electric car has now and then been discussed as a possible alternative. For example, it was suggested as an energy security measure in connection to the oil crises in the 1970's,[4] but also as an option to increase air quality and public health in cities in the 1990's.[5] These advantages are still well recognized and together with the potential to reduce greenhouse gas emissions they make electrification an interesting alternative to current conventional cars.

Despite the advantages described above, the fully electric car or the *battery electric vehicle* (BEV henceforth) has not yet managed to reach any larger market shares. Two of the main barriers for the BEV has over the years been the high cost and low performance of batteries.

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[3] The American census in year 1900 concluded that during this year 109 manufacturers produced 4192 vehicles of which 1681 steam cars, 1574 electric cars and 936 gasoline cars [7].

[4] In 1976 the U.S. Congress enacted public Law 94-413, the Electric and Hybrid Vehicle Research, Development, and Demonstration Act. The law was meant to incentivise improvements of batteries, motors and other hybrid and electric components [9]

[5] For example, by the introduction of the Zero-Emission Vehicle mandate adopted 1990 by the California Air resource board further discussed in [10].

The resent years' development has however resulted in a dramatic improvement of Li-Ion batteries where for example the energy density has increased from below 100 Wh/kg in 1990 to about 250 Wh/kg in 2010. At the same time the costs has been lowered from about $3000/kWh down to about $500/kWh in 2010 [11]. Since then battery costs have fallen further and there are now reports of costs of about $300/kWh [12]. Although the current trend indeed seems promising the price is still regarded as too high to reach a general commercialization of the BEV (commonly considered to need a battery cost of about $150/kWh [12]). This makes one of the most well recognized drawbacks of the BEV, the limited range, to linger on. In combination with long recharging times this has since long been seen as a major obstacle for the technology. Different types of hybrid cars, which combine some benefits of the electric drivetrain with a long range provided by an internal combustion engine have therefore been discussed for almost as long as the electric car has been around.[6] The *hybrid electric vehicle* (HEV), uses the engine as its primary source of energy and cannot be recharged from the grid since it is equipped with a rather small battery. Still by temporarily storing energy in the battery, the HEV can recover braking energy and let the whole drivetrain function more efficiently. While the HEV mainly leads to a more efficient fuel use the *plug-in hybrid electric vehicle* (PHEV) has the possibility to substitute a large share of the fuel by electricity from the grid. The internal combustion engine (ICE) is working as a range extender, when the battery is emptied, and possibly also in parallel to the motor for power delivery. It can basically be an HEV with a larger energy battery that can be charged from the electricity grid (e.g. Toyota Prius PHEV) but it can also be designed with a more powerful electric powertrain (e.g. Chevrolet Volt). Because the PHEV, unlike the BEV, does not suffer from range limitation it can be fitted with a smaller battery well suited for the user's specific driving needs, which increases the possibilities to reach a high utilization rate of the battery and a low total cost of ownership (TCO). The extra powertrain investment cost for carrying two drivetrains can however be substantial.

The PHEV (as well as the BEV) requires a greening of the electricity system to result in any larger amounts of greenhouse gas reductions [14-16]. However, in the EU the electricity system's emissions are capped by the EU emissions trading system (EU ETS). Increased use of electricity in transport should thus not lead to increased CO_2 emissions as long as the cap of the trading system is kept. Even without a trading scheme, decarbonizing the electricity

[6] Ferdinand Porsche built the first hybrid car around 1900. It had hub-mounted electric motors and could be powered by a battery and a gasoline engine generator [13].

production is seen as a simpler task than a decarbonization of the road transport. Switching to electric energy in transport should therefore facilitate an easier transition [17]. It is however still difficult to assess the PHEVs potential for greenhouse gas reduction simply because this depends on its resulting share of electric driving.

The PHEVs potential for fuel replacement

The 'fuel economy' of the PHEV is complicated compared to other vehicle technologies since the power to propel the vehicle can be either a chemical fuel (e.g. gasoline, diesel) or electricity. To estimate how large share of the driving that will be electric in a PHEV is thus important to better understand suitable battery sizing and the resulting consumer viability [18-20]. It is also important on a societal level to understand the future market penetration of the PHEV and its potential societal benefits in terms of reduced fossil fuel use, greenhouse gas emissions, local pollution and energy security concerns. For a given battery size, the share of electric driving depends on driving style (aggressive/defensive) but even more so on general car movement patterns such as length of trips, duration of parking, and access to charging [18].[7] This suggests that good information on individual car movement patterns in terms of trip distances and time, duration and location of car parking would considerably enhance the assessment of the PHEV's potential for fuel replacement.

1.1 Aim

The main aim of this thesis is to assess the potential to reduce fuel use in Swedish passenger car transport through an introduction of plug-in hybrid electric vehicles (PHEVs) (paper I, II and III). This has been achieved by taking departure in the following general questions:

-What do the characteristics of individual Swedish car movement patterns imply for the possibilities to reduce fuel use through an introduction of PHEVs?

-How large share of the driving can be expected to be electric?

-How viable is the PHEV?

-What is an optimal battery size for the PHEV?

The thesis also includes an assessment of the potential for brake energy regeneration in Swedish driving (paper IV).

[7] Comprehensive datasets on car movements are also needed for simulation and optimization of powertrains and software development [21, 22].

Paper I, II and III investigate, to various extent, how large share of the driving that potentially can be electric. For example, for an individual driver (paper I), for an individual two-car household (paper III) and for the fleet of studied vehicles (paper I, II and III). The economic viability compared to an HEV is assessed in paper I and II while in paper III we investigate the economic viability compared to the BEV. An individually optimal battery range to minimize total cost of ownership (TCO) is studied in paper I while in paper II we study the fleet optimized battery ranges to maximize the number of drivers reaching viability with a PHEV; to minimize the total cost of ownership; and to maximize the electric driving. TCO-optimal battery ranges are investigated for a two-car household under three different usage strategies in paper III. The analyzes are all done by utilizing two comprehensive data sets of GPS-measured Swedish car movements further described in Chapter 3.

1.2 Outline of this thesis

Chapter 1 The first Chapter provides a general background to why the plug-in electric vehicle (PHEV) is considered as a potential solution to some of the problems related to passenger car transport. The main aim of the thesis is also described.

Chapter 2 This chapter includes a summarized overview of earlier studies relating to the questions studied in this thesis.

Chapter 3 The third chapter presents the two GPS-measured car movement data sets that have been utilized in the analysis and describes how the measured data have been corrected.

Chapter 4 This chapter provides an overview and discussion of the methodology that constitute the basis for the analyses in paper I, II and III and concerns how we describe the PHEV investment cost and how we model the costs and benefits of marginal battery range.

Chapter 5 The fifth chapter gives a short summary of the aim and main findings of each of the thesis' four articles.

Chapter 6 The last chapter presents some final remarks.

2 RELATED WORK

This chapter provides an introduction to how earlier studies have represented car movements, estimated share of electric driving, suggested optimal battery sizing and discussed economic viability of the PHEV. In addition, the chapter also contains a review of studies related to brake energy regeneration which is included for paper IV.

2.1 AVAILABLE CAR MOVEMENT DATA

A large variety of data has been collected to be able to analyze different aspects of road traffic. Measurements of total traffic flows on roads have been conducted to for example increase knowledge about road capacity limitations. More detailed data on shorter drive cycles have been used to create car emission models and to analyze driving behavior. Earlier studies assessing the PHEV's environmental benefits and/or user economics through reduced fuel use, have often used simplified statistics based on travel surveys or similar data to describe the car movement pattern [23-46]. National and/or regional travel surveys are gathered on a regular basis in many countries but they are focused on the travel behavior of persons rather than the movement pattern of cars. These often self-reported surveys have also been recognized to underestimate the travelling, due to a certain share of non-reported trips [47, 48]. In addition, the measurement period is usually only one day (as in Sweden) or sometimes up to a week [49]. Travel surveys can be of great importance to estimate average travel behavior of people in a certain country or region but are less useful to understand day-to-day variation in the usage of an individual car. The latter is problematic since individual car movements have been shown to vary considerably from day to day [50-52] and it is therefore important to use data from longer measurement periods when assessing the potential share of electric driving for the individual car [18, 20, 29], and by extension, the total cost of ownership and range limitation problems an individual driver may experience.

A more detailed picture of individual car's movement is possible to achieve by measurement of time, speed and position with GPS (Global Positioning System) equipment. There are a limited number of GPS-measured data sets gathered and publicly available but most have been collected during a short time period, for specific purposes or have been focused on a smaller area. In North America, earlier measurements include for example a one-day measurement of 227 vehicles in St Louis, used to assess the PHEVs real world energy use [19]. Puget Sound Regional Council's 2007 traffic choices study [53] was originally conducted to analyze changes in travel behavior as a response to (hypothetical) road tolling in the Seattle metropolitan area. This data set includes loggings of about 450 cars and has for instance been used to estimate total cost of ownership for BEVs and PHEVs [54-57]. The commute Atlanta study [58], a Georgia Tech project measuring commuters active within Atlanta metropolitan area, has been used to estimate the range requirement for BEVs and to analyze the importance of access to charging [59, 60]. The first phase of this project included up to one year of logging of 445 cars from 273 households. In Canada, Department of Geography at University of Winnipeg, has been logging 76 cars in Winnipeg to be able to, for instance, assess the prerequisites for electrification with PHEVs [61-64]. European data sets include an Italian set where part of the data gathered from at least 650,000 cars for insurance purposes (by a private company) was used to analyze various aspects of electrification in and around the Firenze and Modena regions [65-67]. In Denmark, a total of 360 cars were tracked with GPS for 14 to 100 days in 2001-2003. The data only regards cars belonging to families with one car and living in Greater Copenhagen, and only to families attached to the labor market [68]. There is also a Chinese data set from Beijing where 112 vehicles were measured with GPS from June 2012 until March 2013 as part of Beijing passenger car travel survey, and this car movement data has for example been used to assess the energy demand and battery sizing for PHEVs in Beijing [69-71]. Data over multiday driving behavior has also been collected with GPS in Australia (Sydney). The original purpose was to assess behavioral change to a financial intervention but the data has also been utilized to assess the feasibility of battery electric vehicles for day-to-day driving [72].

Many of the electric vehicles sold so far have also been subjected to various measurements. Part of the EV-project includes collecting travel and recharging data from privately driven Chevrolet Volt [73]. In California, drivers of PHEVs and BEVs have been asked about charging practices, showing that the Toyota Prius PHEV owners charge less often than the Chevrolet Volt owners [74]. Real world usage of PHEVs was also studied in [75] where the Volt owners were found reaching an average share of electric driving of 78% but with large differences between individual drivers. Although it is highly important to understand the actual usage of PHEVs, these very early adopters of the technology are not expected to be representative for the average car owner.

There are also some GPS data available from Sweden. For example, a small set of cars from Västerås were logged for about two weeks with the purpose of verifying modelling of driving behavior and emissions [76]. In this project the measurement equipment was installed in 5 specifically prepared vehicles, which then were placed in 29 families, where they substituted for a car of similar size. Another project was carried out within and in the proximity of Lund with the purpose to analyze the impact and acceptability of Intelligent Speed Adaptation (ISA) equipment [77]. Here about 200 cars were logged for about 100 days. Although valuable, both these datasets are covering limited geographic regions and are today about 15 years old.

Thus, until now there has not been any public data set available, that has been gathered with the purpose of getting a representative data set for car movement patterns in any country or larger region over a longer time period. This thesis utilizes GPS-measurements of Swedish car movement patterns collected with the specific purpose to assess the possibilities of electrification of passenger cars. The two data sets are further described in Chapter 3.

2.2 SHARE OF ELECTRIC DRIVING

As mentioned in the introduction, it is of importance to estimate how large share of the driving that will be electric in a PHEV to understand suitable battery sizing and the possibilities for the individual driver to reach economic viability [18-20]. It is also essential to understand the PHEVs potential societal benefits in terms of reduced fossil fuel use, greenhouse gas emissions and local pollution. Earlier studies have commonly used the term utility factor (UF) to describe a PHEVs share of electric driving. The UF can be described as the share of driving conducted in charge depleting (CD) mode compared to charge sustaining mode (CS) [57, 78]. Although still frequently used in the literature we have in this work chosen to instead use the term share of electric driving or electric drive fraction (EDF) defined as the share of the driving [km] propelled with electricity from the grid, or otherwise externally supplied.[8] In the following review we do however consider studies who used UF, share of electric driving or simply fuel reduction.

The typical study evaluating the share of electric driving with a PHEV do so by investigating one or a few number of different battery sizes used by an average driver or when used by every driver in a vehicle fleet [30-34, 55, 57, 70, 71]. Both travel surveys [30-34] and GPS-measured car movement patterns [55-57, 70, 71] have been used to estimate the share of a PHEVs driving that can be expected to be electric. There are however also some studies evaluating the actual share of electric driving among PHEVs that are on the road today [73-75].

[8] The reason for doing so is simply that *share of electric driving* and *electric drive fraction* are terms that are more self-explanatory than the term *utility factor*.

Survey based studies

Based on American travel survey data Zhang et al. 2014 show that a PHEV of 16 and 40 miles reach about 45% and 70% fuel reduction, respectively, compared to a HEV [30], while Kelly et al. 2012 report that a PHEV of 42 miles would in their base scenario reach a UF of about 67% [31]. Duigou et al. 2014 report based on French travel survey data that a driver averaging 15,000 km of driving per year could reach up to 40% electric driving with a PHEV of 20 km range [32]. Based on data from Mobilität in Deutschland 2004, Özdemir et al. 2012 find that 25 and 50 km range would result in about 50 and close to 80% electric driving respectively [33]. Based on Mobilität in Deutschland 2008, Redelbach et al. 2014 report results for an average driver (15,000 km/year) and find that a PHEV of 20, 40 and 60 km of range would result in 40, 60 and 75% of electric driving, respectively [34].

Studies based on GPS-measured car movement data

Based on the car movement data from Seattle, Wu et al. 2013 describe the expected reduction in fuel use to be consistent with the findings of Zhang et al. 2014 described above [54, 30]. Wu et al. 2014 investigate how earlier travel-survey-based estimates of the utility factor (UF) on a fleet level compare to similar estimates based on GPS-measured data from Seattle [57]. They find the fleet UF based on Seattle data is larger than the corresponding UF based on travel survey data and that workplace charging could largely improve the UF for short ranged batteries. Based on the same Seattle data set, Neubaur et al. 2012 find for a home-charging-only scenario the share of electric driving for PHEV of 15 and 45 miles to be about 48 and 80%, respectively [55]. Zhang et al. 2014 have derived UFs from GPS-measured vehicles from Beijing passenger car travel survey, and find a PHEV of 20 and 50 km results in a UF of 42 and 74%, respectively, when only charging at night, rising to 59 and 83%, respectively, when also assuming possibility to charge at public parkings (workplace, school, etc.) [70]. The same dataset is also used to compare the UF from Beijing with the UF based on American travel survey data which results in 23% lower share of electric driving in Beijing for a 50 km range-PHEV [71].

Studies evaluating actual PHEV users

Smart et al. 2013 use data collected from 1400 privately owned Chevrolet Volt and conclude that the share of electric driving (73%) achieved by these early adopters is higher than estimates (66.5%) based on the national travel survey (NHTS) [73]. Plötz et al. 2015 analyze data from 1800 Chevrolet Volt driven in the US and Canada, and from 150 other PHEVs (Toyota Prius PHEV, Mitsubishi Outlander, Opel Ampera, Volvo V60) driven in Germany

[75]. The observed share of electric driving for the Volt was 79% while that for Prius PHEV was 39% (only 88 observations though). The variance of empirical PHEV fuel economy was found to be considerably higher than for conventional vehicles. By using an online survey concerning charging habits among 600 Volt and 800 Prius PHEV owners in California, Tal et al. 2013 estimate the share of electric driving in a Volt and a Prius PHEV to about 80 and 26%, respectively. The Prius PHEV scores low because of the shorter battery range but also because of an in general lower charging frequency [74].

The above studies have primarily focused on assessment of the share of electric driving on a fleet level or for an average driver. Although the expected share of electric driving for an average driver or for the fleet in general could be enough for many research question, it is insufficient to use in assessments of battery sizing for the individual driver. The latter is, as earlier mentioned, interesting for the understanding of the general viability of the PHEV and is especially important when trying to understand what type of drivers that could be seen as potential early adopters.

2.3 How viable is the PHEV?

The possibilities of the PHEV to affect the passenger car fleet's overall fuel use, greenhouse gas emissions and contribution to local pollution will depend on the level of market penetration. To understand the implications and possibilities for a large-scale introduction of PHEVs, it is therefore necessary to study the viability of the PHEV. Car buyers that are environmentally conscious and/or interested in new technology could be prepared to pay extra for a PHEV compared to a conventional vehicle, but it is likely that the PHEV needs to be economically preferable to the alternatives to be able to reach a higher market share. The PHEV has, compared to a conventional vehicle, a high investment cost but holds also an opportunity to offset this extra investment cost through lower running costs.

Market diffusion

The actual car purchase decision is influenced by a large number of factors beyond the total cost of ownership, such as: household income, buyer's car brand preference, available models, access to information, environmental consciousness, interest in new technology etc. To actually predict how well the PHEVs will perform on the market is therefore difficult based on comparison of the TCO only, and is therefore outside the scope of this thesis. See for example Al-Alawi et al. 2013 for a review over HEV, PHEV and BEV market modelling in the US where the most commonly used methods were found to be agent based models, consumer choice models and diffusion rate and time series models [79].

Viable compared to what?

What today should count as a "conventional" vehicle (CV) is somewhat ambiguous. Driven to a large extent by the increasingly stricter regulations on fuel use and CO_2 emissions, the on-going trend towards more fuel-efficient cars has led to various degrees of hybridization of the powertrain. A wide variety of models up to and including full hybrids are successfully marketed and sold, and most cars will soon have at least a stop/start system. Earlier studies concerning the economic performance of the PHEV have for example compared the PHEV to a CV [56], an HEV [35], both a CV and an HEV [37-39], while some also compared to a BEV [40-42].

Powertrain design of the PHEV

Also PHEV technology varies. Many manufacturers have introduced PHEV models that differ with respect to battery range, power of the electric powertrain, and departure from the manufacturer's non-PHEV models. For example, the Toyota Prius PHEV builds on its original gasoline HEV-only Prius. The body design and fully integrated series/parallel hybrid powertrain are at large the same in the PHEV as in the HEV. The first version of the PHEV had, compared to other PHEVs, a relatively small battery with a moderate electricity-only range of 20 km while the rest of the powertrain is kept intact with moderate electric power. It could only go all electric up to 100 km/h and demanded therefore blended mode (using both electricity and fuel) for highway driving. The new version from late 2016 is offered with an all-electric range of approximately 35 km and can go all electric up to 130 km/h. On the other hand, General Motors' Chevrolet Volt/Opel Ampera is a PHEV with greater electric range, about 85 km (first version about 60 km), with a reasonably small fuel engine as a range extender. The electrical components are therefore necessarily designed for electric drive and for meeting all the power requirements of the vehicle. The vehicle only exists as a PHEV with its own design, which differs from those of all other (hybrid and non-hybrid) vehicles in the GM family.

Thus, depending on the market perception of both how a PHEV should be designed and the requirement on its electric powertrain, as well as of what the alternative conventional/hybrid car looks like, it is possible that the transition from the fuel-efficient conventional/hybrid car to the PHEV may involve a small or a large change of the electric powertrain and its performance. This implies, besides the extra costs for a smaller or larger PHEV battery, a smaller or a larger powertrain cost corresponding to the level of technical change. Some studies evaluating the PHEVs viability only consider one PHEV powertrain type [35, 37-40]. Lin et al. 2012 even assume that the battery cost is the only difference in investment cost between an HEV and a PHEV [35]. There are however a number of studies that consider different PHEV powertrains [41, 42, 56]. Bishop et al. 2014 compared cost effectiveness of alternative powertrains for reducing energy use and CO_2 emissions in passenger cars. They simulate series and parallel PHEVs and found that in both cases the HEV is more cost effective [41]. Khan et al. 2012 performed a cost comparison between Chevrolet Volt and Chevrolet Cruse and found that vehicles that travels more than 30 miles per day on average will need a little more than ten years to pay back the extra initial investment through running cost savings. The Toyota Prius PHEV needed about 12 years to pay back the extra investment cost compared to a Toyota Corolla [56]. Hutchinsson et al. 2014 on the other hand concluded that a hybrid synergy drive (HSD) PHEV (i.e. Toyota Prius PHEV) could be a competitive option compared to mild hybrids, full hybrids and conventional vehicles depending on the share of city driving and on energy cost savings. The series PHEV (Chevrolet Volt) was on the other hand not found to be competitive due to high investment costs and slow payback from running cost savings [42].

Cost of battery capacity

Batteries are still relatively expensive, making the economic viability of the PHEV dependent on the degree to which the available energy capacity is utilized. Earlier studies have commonly focused on total battery cost without discussing the marginal cost and its effect on cost-effective battery sizing. Lin et al. 2012 have however studied the marginal gains and costs for individual drivers of PHEVs from an incremental increase of the battery range and showed that the PHEV can be ready to compete with the HEV at a battery cost of $450/kWh and a fuel price of roughly $1/liter (4$/gallon) [35]. Some studies have also considered marginal battery costs implicitly by analyzing the total cost of ownership for a number of ex ante given battery sizes [30, 39, 40, 43, 44, 54, 55]. Neubauer et al. 2012 found the battery range to have a small impact on the TCO for a PHEV [55], while Peterson et al. 2012 reached the conclusion that short-range PHEVs would reduce gasoline consumption more per dollar spent than large range PHEVs [43]. Michalek et al. 2011 and Wu et al. 2014 discussed the difficulty for large batteries to offset the marginal battery cost with corresponding marginal cost savings [44, 54].

Running cost savings

To investigate if the relatively high investment cost of the PHEV can be offset by a lower running cost over time it is common to assess the total cost of ownership over the car's lifetime [35, 37, 38, 41, 42, 56]. As discussed in section 2.2 the car movement pattern will determine the possibilities for electric driving. This will in turn together with the cost for gasoline and electricity determines the possibilities for running cost savings, while typically omitting other potential cost differences, such as maintenance costs [35, 37, 38, 41, 42, 56].

There does not seem to be any clear consensus in how the economic viability of the PHEV should be evaluated. The results above suggest that the PHEVs *investment cost* is dependent on battery size and powertrain design (of both the PHEV and the vehicle of comparison) while the *running cost savings* depends on battery size in combination with the individual driver's car movement pattern and faced energy costs. An evaluation of the PHEV's economic viability that take the above-mentioned factors into account under Swedish conditions has not previously been conducted.

2.4 What is an optimal battery size for the PHEV?

As discussed above, the PHEVs battery range has a strong influence on the share of electric driving and the economic viability. There is therefore of importance to study what an optimal battery range would be. A number of studies have analyzed optimal driving ranges for PHEVs [33-38, 45, 46, 63, 69]. There are however many possible objectives to which a PHEV battery could be optimized for. Some have investigated optimality through minimizing the total cost of ownership (TCO) [34, 35, 63, 69]. Others have compared the tradeoffs between minimizing TCO versus minimizing GHG emissions or fuel use [33, 36-38]. Meinrenken et al. 2014 have, without considering the resulting economic viability, optimized battery range to minimize greenhouse gas emissions over the cars life time [45]. Kontou et al. 2015 instead translated the costs of GHG emissions into monetary terms to find an optimal battery range that minimizes total societal cost during the car's lifetime [46]. The battery range can be argued to indirectly have been optimized in Peterson et al. 2012, who analyzed cost effectiveness of subsidizing PHEVs for reducing gasoline consumption, and in Michalek et al. 2011, who assessed the potential for reducing oil consumption and air emissions by introducing HEVs, PHEVs, or BEVs [43], [44].

The studies above give a somewhat diverging view on what an optimal battery range for the PHEV should be. Shiau et al. 2009, Michalek et al. 2011, and Kontou et al. 2015 found that low-range PHEVs minimize the TCO, the cost of fuel reduction, and the total societal cost, respectively [37, 44, 46]. Redelbach et al. 2014 optimize battery sizes for series and parallel PHEVs and show that there are significant differences in optimal battery size between different powertrain designs due to assumed need for blended mode driving in the parallel drivetrain [34]. Lin et al. 2012 suggest that the optimal battery range for an individual driver is about two thirds of the daily driving distance at a battery cost of $450/kWh delivered price and a gasoline price of $4/gallon ($1.06/liter) [35]. Meinrenken et al. 2014 found a battery range of 35 and 140 km to be optimal for the PHEV under current US electricity grid-mix and in a scenario where electricity was produced with solar and wind, respectively [45]. Shiau et al. 2010 and Shiau et al. 2011 point out that for the purpose of GHG reduction, the optimal battery range would increase as the use of fossil fuels decrease in power generation [37, 38].

What should be considered as an optimal battery range seems to be dependent on the chosen objective function for the optimization. There are several stakeholders that in different ways possibly could influence the battery range of the PHEV, for example, manufacturers through design choices, drivers through purchase decisions and society through policies and regulation. It is therefore difficult to say what a likely or desirable development of the PHEVs battery design looks like and to what extent it will fulfil different objectives that possibly reflect different stakeholder's interests.

2.5 Regenerative braking

A common feature for all but the simplest systems for electrification of vehicle drivetrains is the ability to regenerate energy when braking. The amount of energy that can be regenerated is of interest to understand the viability of regeneration technology and its possibilities to reduce greenhouse gas emissions, local pollutants, energy insecurity and driver's running costs. The expected energy savings depends on how the car is driven, but also on the regeneration power capacity, general drivetrain design and on the control strategy. Many studies have therefore been focused on evaluating drivetrain design and/or control strategies of different hybrids by testing the new designs and/or control strategies on standardized drive cycles (see for example [80-88]), which enables an easy comparison with earlier studies. In addition, the test cycles are what matters for the car producers when the fuel use regulations of the car need to be fulfilled.

The test cycles' ability to represent real world driving has however been questioned. For example, the new European drive cycle (NEDC), used for emission certification and fuel use labelling in Europe, is not very representative of real-world driving [89, 90]. It does not, for instance, include the vertical driving profile, although a number of studies have shown the importance of road grade for fuel consumption and emissions [91-93] also in the analysis of hybrid and electric vehicles [94, 95].

The drive cycle of the upcoming Worldwide harmonized Light vehicle Test Procedure (WLTP) includes more realistic accelerations and more dynamic speed variations to reach more accurate fuel and emission estimates [89]. Although improved, this drive cycle still includes somewhat low levels of accelerations compared to how many drivers actually drive, since the cycle has to be drivable by all cars [89], and data on road gradient are still not included.

Although there are strong indications both that the standardized test cycles are not very representative for real world driving and although the type of driving is of importance for the potential brake energy regeneration, the number of studies assessing the potential for brake energy regeneration in real world driving are few and the data used in these studies have so far been not been representative of any larger group of drivers and commonly collected from one or a small number of predefined routes (see for example [95, 96]). Another problem with standardized test cycles is that the diversity in between individual drivers in the car fleet is missed, which would be of importance for example when analyzing which drivers could be expected to reach highest benefits from hybridization.

How large energy savings that can be expected from brake energy technology in real world driving and how the results differs between individual drivers have not been studied to any larger extent. It would therefore be possible to increase the knowledge on the potential for brake energy regeneration by utilizing data from Swedish real world driving.

3 CAR MOVEMENT DATA

This chapter presents the two GPS-measured car movement data sets that have been utilized in the analyses and describes how the measured data have been corrected and used.

3.1 MEASUREMENT PROJECT I: THE SWEDISH CAR MOVEMENT DATA PROJECT

The aim of the Swedish car movement data project was to gather and analyze a larger amount of data on the characteristics and distribution of individual movements for privately driven cars in Sweden by measurement with GPS equipment. This was done specifically to enable a more well-informed assessment of PHEVs and other electrified vehicles. Therefore, there was an active choice to focus on relatively new cars (≈100 months or younger) since their movement patterns are more likely to be relevant in a purchase of a new car.[9] For an inquiry about participation in the project, cars were randomly selected from the Swedish vehicle register, which includes both privately owned cars and company cars. Company cars were identified by addressing the inquiry letter to the driver of the specified car and asking if it was a company car and if it was used for private driving. If so it was of interest for the project. About 7% percent of the requests got a positive answer. The extracted cars were registered in the county of Västra Götaland or in Kungsbacka municipality. This region has a population of about 1.6 million inhabitants and 0.7 million cars, which corresponds to about 1/6 of Swedish total population and car fleet, respectively. The cars are reasonably representative for Sweden in terms of fleet composition, car ownership, household size, and distribution on larger (for example it includes Gothenburg, the second-largest town in Sweden) and smaller towns and rural areas, and therefore probably also concerning the movement patterns. A questionnaire was sent to all participants to gather some complementary data on the logged cars, their drivers and households, such as age of the drivers and number of cars in the household.

The loggings were done in campaigns during all seasons from June 2010 to September 2012. The cars were logged with a relatively high frequency of 2.5 Hz to also make it possible to use the data for more detailed analysis of the driving, which is also fully utilized in paper IV. The logged data includes, for example, time, position (latitude and longitude), altitude and velocity (speed and direction). The raw data were stored in an SQL database, then a processing of the raw data was performed to provide the material in a more accessible format. The result was stored in yet another SQL database, called the "analysis database". The

[9] Many people who buy a new car will however, not keep it for as long as 100 months, which means that in the data set there are also loggings from cars, which were bought second hand.

analysis database holds data on three levels. *The first level* contains second by second data similar to the raw data but now smaller apparent anomalies are corrected and the data is organized into trips. Absence of loggings for more than 10 seconds denotes the start of a new trip, while shorter gaps of data in between loggings are interpreted as a data loss and was interpolated. *The second level* provides statistical data for each trip such as times and locations for trip start/stop, travelled distance, averages of speed, of speed squared, and of speed cubed, trip duration, number of interpolated data gaps and values. *The third level* holds statistical data for each device/vehicle such as total distance travelled during the measurement period, points of time for first/last measurement, average speed for all driving, total number of trips etc.

Altogether around 770 households have had GPS equipment sent to them for measurement of their car's movements. Some of these have not installed the equipment or the equipment has not registered any data. 529 of the vehicles that have registered data have had their movements logged for 30 days or more, that is, the difference between first and last gathered data is at least 30 days. The data has later been further filtered and/or repaired depending on the specific need in each project (see section 3.3). For a more extensive description of the measurement project see [97] or the final report [98].

3.2 MEASUREMENT PROJECT II: THE TWO-CAR HOUSEHOLD

The overall objective behind this measurement project was to enable an assessment of the potential for a BEV to replace one of the conventional cars in Swedish commuting two-car households. The car movement data was derived by simultaneous GPS logging of the movement patterns of both (conventional) cars in two-car households for about two to three months. Households were randomly drawn from the Swedish vehicle register and restricted to households:

-within 13 Swedish municipalities around and including Gothenburg

-which possess exactly, and only, two private cars,

-with both cars of model year 2002 or younger,

-with both cars ≤ 200 kW of engine maximum power,

-with car owner(s) < 65 years old.

Of the around 331 000 private cars in the targeted region 48% belong to many-car households and 33% are in 2-car households. With the further restrictions mentioned above the number is reduced to about 37 000 or 11% of the private cars in the region.

Through the participation request the households were further restricted to households
-with ≥ 2 actively used driving licenses,
-with commuting with at least one car ≥ 10 km one way.
These restrictions were made to as much as possible target two-car households with a reasonable amount of frequent and possibly simultaneous driving of cars, and with cars that could be replaced with a similar, but electric car.

When a positive answer to participation was obtained (around 5% of the distributed requests) two GPS logging equipment were sent by mail to be mounted by the owner(s) themselves. The participating households were also asked to fill in a smaller questionnaire concerning household composition, car use, commuting, towing, and home charging options. The loggings were performed with 2.5 or 1 Hz and the raw data was, similar to measurement project I, stored in an SQL data base and later processed into a more accessible format in the "analysis database".

3.3 Data Correction

Data is sometimes missing for various reasons (e.g. because of loose contact in power supply, lost satellite connection). As mentioned above, interruptions in trips shorter than 10 seconds are interpreted as a data loss and are interpolated. The GPS-equipment also needs some time (often about 30 seconds) in the beginning of each trip to find satellites before it starts logging. Thus, the first start-up phase for each trip is consequently missed. The problems are handled differently depending on the intended use of the data set and following sections will describe the repairing method used for the four papers

Paper I and II, measurement project I

The data demanded for the analyses of paper I and II is individual car movement patterns in the form of drivers' distances travelled together with the time of standstill in between the trips over at least a 30 days' measurement period. The data missing in the beginning of each trip was estimated as the distance (as the crow flies) between the start position of logging and the stop location of the previous trip. Of all the trips, about 70% and 90% had a distance between start and previous stop shorter than 100 m and 500m, respectively. A long distance between stop location of a trip and start location of the next trip, may however not only arise from delayed logging but might be caused by losses in data (because loss of data longer than 10 seconds gives two trips in the analysis data base). As mentioned, a simple way to adjust for the missed distance is to just add it as the crow flies to the trip's distance it is however difficult to know when and for how long time the car had been driving in between the recorded trips. A maximum of 5% of damaged trips was allowed per car movement pattern. This reduced the number of usable car movement patterns from the 529 with 30 days' measurement or more down to 378 car movement patterns that also had at maximum 5% damaged trips. Some data losses could be repaired by utilizing a trip advisor tool to estimate distance and travel time between the points where data was missing. When the time suggested for travel a certain distance roughly corresponded to the time period of the missing data, it was assumed that the time was used to travel the missing distance. The number of car movement patterns with acceptable data increased to 432 when accepting mended trips as undamaged and keeping the tolerance level at maximum 5%.

Paper III, measurement project II

Around 130 households received logging equipment under the second measurement project, but in paper III the investigation is restricted to 64 households with good data quality for both cars simultaneously for an analysis period of 1.5 to 2.5 months. Good data quality means here that we have the needed data, or have been able with reasonable certainty to reconstruct it, for all home-to-home trips in the analysis period in the form of distances driven, as well as departure and arrival positions and points of time. This means that, days with uncertainty in at least one of the cars driving data have been excluded. Adjustment in distances have been made for GPS registration of ferry trips and of garage parking, during which, due to bad signal conditions, the GPS has falsely detected ongoing car movements. Trip distances for shorter losses (for instance, at starts of trips) have been adjusted (as the crow flies) to the arrival points of the previous trip. Occasionally, when needed for longer losses of registration, the adjustment has been made with an estimated loss of distance depending on assumed driving along the road network.

Paper IV, measurement project I

Paper IV utilizes the speed and altitude profile of individual car movement pattern that were measured for more than 30 days. Mending data with the help of a trip advisor tool is for this paper of little use since neither the speed or the altitude profile can be recovered. The data sample used in paper IV is therefore limited to the 378 vehicles, which only showed signs of missing data for less than 5% of the trips.

Some quality aspects of the measured position data with a focus on the altitude have been assessed by comparing the logged altitude from two countryside road sections frequently driven in both directions to reference road altitude data from the Swedish Transport Administration [99]. The main errors in the logged altitude, originating from differences in atmospheric conditions, were found to vary only slowly in time and space. Changes in satellite constellation of the measurement introduced insignificant errors; the standard deviation for adjacent points in time was 127 mm compared to 123 mm for non-changing constellation. Rapid error changes can also be a result of signal reflections in nearby structures such as building in cities, but these have not been evaluated.

During longer parking hours the conditions in terms of atmospheric conditions can change so that the difference in altitude measurement in between trips can be relatively large. This makes it difficult to in a reliable way compensate for the loss of altitude data in the beginning of each trip. It is however possible to roughly compensate for the missed speed data in the beginning of each trip by including an estimated speed with moderate acceleration up to the first logged speed value. This was done to prevent a systematic underestimate of the total energy use.

In addition, the data have been filtered to reduce and remove the above described errors from differences in atmospheric conditions, signal reflections and other possible noise in the measurement that could lead to an overestimation of the available braking energy. First, data collected under bad signal conditions are removed. Then, speed and altitude data are filtered through a low pass filter to exclude noise resulting from the limitations in measurement accuracy and logging frequency. Acceleration/deceleration and road gradient at time t were derived from the filtered speed and altitude data at $t \pm 1$ and finally unrealistic values at this stage were also filtered.[10] We have found that the above described errors occasionally could add power levels of around 1 kW to the drive cycle while more typically adding power of around 0.1 kW and they should not affect our main results to any larger extent since the studied braking power varies from 0 to 50 kW.

[10] Maximum allowed acceleration/deceleration is here limited to ± 10 m/s^2, and maximum road grade is limited to 15%.

4 A PHEV MODEL

This chapter provides an overview of the PHEV model that constitute the methodological base of paper I, II and III.

To facilitate a focus on the effects of individual car movement patterns, identical (except for battery size) PHEVs were assumed, characterized by the specific energy uses e_e (electricity) and e_f (fuel) [kWh/km] in the charge-depleting (CD) and charge-sustaining (CS) mode, respectively. The PHEV all-electric range *AER* [km] is the maximum possible distance driven in the CD mode and the battery was assumed to maintain its properties throughout the car's economic lifetime.[11] The extra weight from enlarging the battery was ignored since the weight increase will make a rather small difference to the vehicles energy demand.[12] Although the energy use in reality varies with battery size/weight, driving conditions, and properties such as speed, driving aggressiveness, terrain, load, weather and road conditions, and the use of auxiliary power (e.g., air conditioning), the specific energy uses are assumed constant, and the total energy thus only depends on the distance driven in CS and CD mode, respectively. There are two main reasons behind this choice: firstly, to be able to easily isolate the effects of individuality in car movement patterns, and secondly, because the results are only to a smaller extent affected by the above-mentioned factors, which is also further discussed in section 4.6.

4.1 ECONOMIC VIABILITY

As described earlier it is useful to study the economic viability of the PHEV to better understand the possibilities for and implications of a large-scale introduction of PHEVs. For the economic assessment of the PHEV we focused on the differences in total cost of ownership (TCO) for a PHEV relative to an HEV. The HEV can in this case be seen as an energy efficient future version of the CV and was assumed to have the same specific fuel use as the PHEV in CS mode, e_f. The difference in the TCO included any extra investment costs and the annual running cost savings. All other costs, such as maintenance costs, were assumed equal and thus could be omitted as has been done in several earlier studies [35, 37, 38, 40-42,

[11] It is not likely that a battery replacement would be economically feasible. It is thus assumed that the PHEV battery must be built to satisfy requirements over the cars lifetime.

[12] According to [37] the extra weight for battery range will make the energy demand for a PHEV of 96 km range about 10% higher than for a PHEV of 11 km range (including extra structural weight to support a heavier battery). Also, we do not know the weight of future batteries. Lower specific battery cost will give larger optimal batteries. This cost decrease will probably mainly come as result of higher specific capacity (higher kWh/kg) leading to less increase over time in the weight of the optimal battery, if any.

56]. The extra annual cost C [\$/yr] for the PHEV comprised the annuity α [yr^{-1}] for the initial investment costs I_B and I_P [\$] for the battery capacity and the powertrain, respectively.

$$C = \alpha(I_B + I_P) \quad (1)$$

I_P includes any battery-capacity-independent investment cost for turning the HEV into a PHEV, such as an on-board charger, increased maximum power of the electric drivetrain, and also the cost for battery power. I_B includes only the cost for the battery's energy capacity. We thus divided the total battery cost into a cost for power and a cost for energy capacity [100]. To take care of different possible PHEV designs we have aimed at using powertrain cost levels which roughly correspond to the cost of "Prius-like" and "Volt-like" powertrain designs. Argonne national laboratory (ANL) recently estimated future vehicle costs for power-split PHEVs (i.e. Toyota Prius PHEV) and series PHEVs (i.e. Chevrolet Volt) at large production volumes. From these estimates, we can deduce an estimated extra powertrain cost compared to an HEV for 2020 of $270 and $1,600 for a power-split and series PHEV respectively. With a markup cost of 50%[13] the extra powertrain cost faced by the buyer of the vehicle would be about $400 and $2,400 for a power-split and series PHEV, respectively [101].[14]

We further assumed that the specific energy uses e_e and e_f are indifferent to powertrain cost and we do not consider a blended CD mode in which both fuel and electricity are used for propulsion. It should therefore be made clear that our examples of extra powertrain cost said to resemble a "Prius-like" and a "Volt-like" case cannot be used to assess these two specific models.[15] In reality it is likely that the powertrain configuration does affect the specific energy use to some extent. The difference will however primarily be found between a model that demands blended mode driving and a model designed for pure CD mode driving. The first version of the Toyota Prius PHEV could only go all electric under limited power. It thus demanded blended mode driving in for example steep ascents and in all speeds above 100 km/h. Such a PHEV could then in practice result in considerably lower share of electric driving than a comparable PHEV designed for electric driving in all power needs [34]. The new Prius PHEV version, Prius Prime, can however handle somewhat higher power outtakes

[13] A markup cost of 50% is for example used in [102].
[14] This is somewhat lower than the values we used ($500 and $3,500 respectively) to exemplify extra powertrain costs in paper I and II. The ANL figures could therefore suggest that more drivers would reach economic viability in paper I and II and that the differences between studied objective functions in the "Volt-like" case of paper II would be somewhat larger.
[15] In addition, the two models are much different in both vehicle size and overall performance so even with accurate numbers on energy use for these specific models it would not be a fair comparison of the economic viability of the powertrain designs.

(it can for example manage to go all electric up to 130 km/h). The focus of our analysis was however not to perform a complete assessment of the differences between a “Prius-like” and a “Volt-like” powertrain design but to assess if and how the extra powertrain cost affect the individual driver’s possibilities to reach economic viability with a PHEV.

4.1.1 Battery utilization and the Marginal Electric Distance

How individual drivers can utilize the PHEV battery is key to understand the possibility of offsetting the relatively high investment cost of the PHEV with lower fuel costs. We analyzed this by investigating the marginal benefit of marginal battery range in terms of extra km of electric driving for each individual driver in the data set. It was assumed that the battery is recharged only and fully in every parking period of at least size T h. In reality the charging frequency may depend on the drivers’ charging habits [73, 74], but our results serve to show the potential battery utilization. Recharging during all stops of 10 h or more efficiently picks out night-time charging for most drivers. Charging during parking periods as short as 4 h can emulate the opportunity to charge at work. The battery charging will in reality be dependent on the available charging power and losses. For instance, 1*16A/230V can deliver a charging rate of around 3 kW at the battery when the grid-to-battery losses are around 18%. This is in par with the losses measured for charging of a BEV (Peugeot Ion) in Belgium [103]. It would then be possible to charge the battery with electricity corresponding to 150 km and 60 km range in 10 and 4 hours, respectively (assuming e_e = 0.2 kWh/km). In paper I and II we allow battery ranges up to 200 km and we can therefore not be certain that they always will be fully charged after each parking of length T. These larger batteries could therefore in reality result in somewhat lower share of electric driving. It should however be noted that many parking stops can be longer than T hours and the battery will not always be completely empty (especially when the battery is large). In the same way, most people stay about 8 hours at work which increases the possibilities to charge an amount corresponding to 120 km of driving instead of 60 km.[16]

It is also implicitly assumed that the drivers have access to charging at home and at work which is not necessarily the case. Many people in cities rely on public parking and most workplaces are not adapted to provide charging power. However as described earlier our results are to be seen as describing the potential of an eventual introduction of PHEVs rather than predicting the outcome from it.

[16] In addition, most people do not travel as much as 120 km one way to work.

With the above mentioned assumptions, for vehicle k, the annual electric mileage, $D_{e,k}(AER,T)$ [km/yr], is derived by summing the distances up to the all-electric range AER of all trips between recharging periods of length T [20, 104]. The annual distance driven on fuel is denoted $D_{f,k}$ (AER,T) [km/yr]. The marginal electric distance MED_k $[\frac{km_e /yr}{km_r}]$[17] is defined as the derivative of $D_{e,k}$ with respect to the range AER:

$$MED_k(AER,T) \equiv D'_{e,k}(AER,T) \tag{2}$$

So that:

$$D_{e,k}(AER,T) = \int_0^{AER} MED_k\,(AER,T)dAER \tag{3}$$

Figure 1 shows an MED curve for an illustrative movement pattern where the driver has travelled 20 km or longer 270 times in a year (roughly 5 times per week on average). A marginal battery range increase from 19 to 20 km would thus result in an extra 270 km of electric distance travelled per year. Figure 2 shows the large individuality in between car movement patterns, and the large variance compared to the average MED (black line). Some cars will be used for distances over 100 km over 250 times a year while others travel 25 km or longer less than 50 times a year.

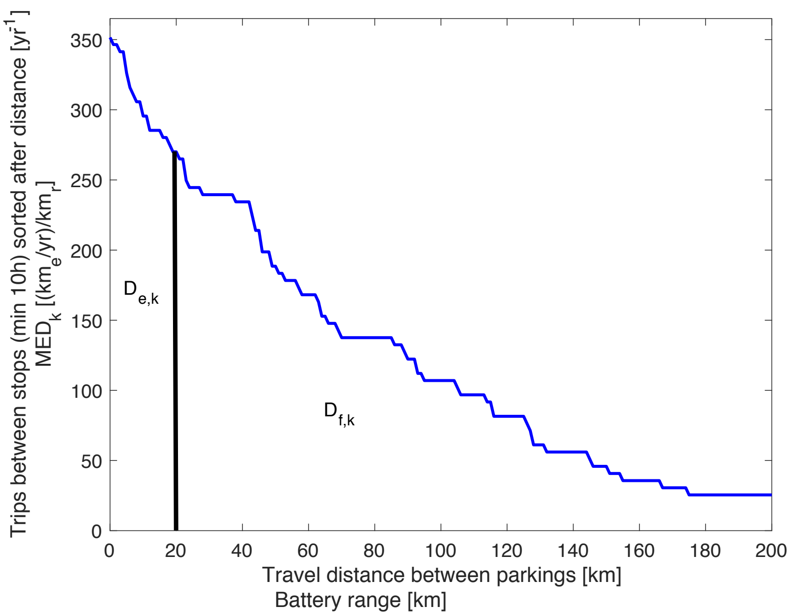

Figure 1: The curve (blue) gives the number of times per year an example vehicle k has driven a specific distance or longer between stops of duration 10 h or more. It can also be seen as the resulting MED for a PHEV with all electric range AER fulfilling vehicle k's movement pattern and the battery is assumed fully charged in every stop of duration 10 h or more. The areas $D_{e,k}$ and $D_{f,k}$ are then the PHEV's resulting yearly distance travelled on electricity and fuel, respectively.

[17] In economics, the marginal cost is defined as the derivate of the total cost with respect to the number of goods. The marginal electric distance, *MED*, is defined analogously. In earlier work, we have used an equivalent variable, the recharging frequency of the marginal battery capacity.

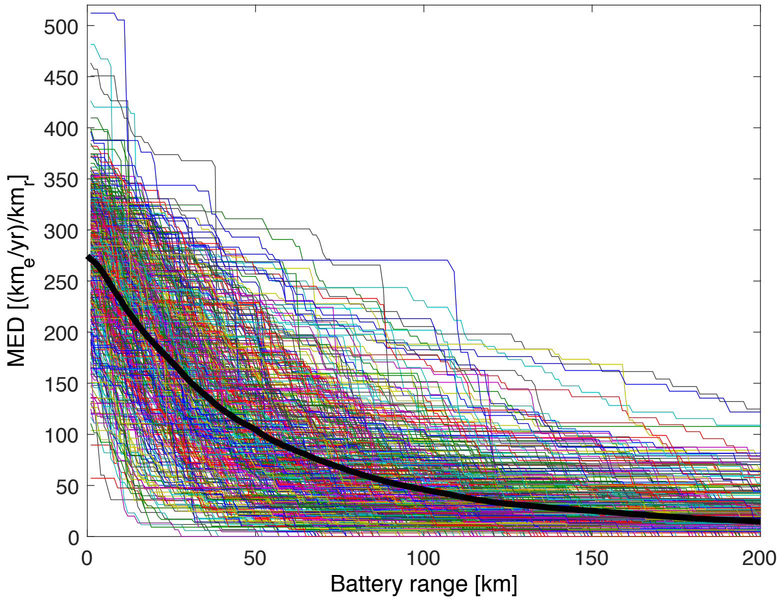

Figure 2: The resulting marginal electric distance *(MED)* for 432 individual car movement patterns when assuming the battery to be fully charged in every parking period of 10h or more.[18] Depicted is also the average *MED* for the vehicle fleet (black line).

4.1.2 Optimal battery sizing

As earlier mentioned we ignore possible differences in maintenance costs, insurance costs, etc., and focus on the running cost savings from replacing fuel with electricity. The annual operational cost reduction R_k [$/yr] is found as the total electric distance multiplied by the specific operational cost savings r [$/km] of using electricity instead of fuel. With the specific energy uses e_e (electricity) and e_f (fuel) [kWh/km] in the CD and CS modes, respectively, and prices p_e and p_f [$/kWh] for electricity and fuel, we have

$$r = (p_f e_f - p_e e_e) \quad (4)$$

$$R_k = D_{e,k} * r \quad (5)$$

The annual per range marginal operational cost reduction R_k' [$/km/yr] is found as

$$R_k'(AER, T) = MED_k(AER, T) * r \quad (6)$$

Assuming the specific battery capacity cost a constant i_B [$/kWh (nominal)] independent of battery range, the per range marginal battery cost I_B' [$/km/yr], is

$$I_B' = \alpha\beta^{-1} i_B e_e \quad (7)$$

where β [kWh (utilized)/kWh (nominal)] is the battery depth of discharge[19].

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[18] Since the battery is assumed fully charged after 10h of parking it is possible to fit more than one charge per day, explaining why the maximum MED is not 365.

[19] *Utilized capacity* refers to the capacity corresponding to the maximum grid electricity stored. Outside this range in state-of-charge, part of the nominal capacity can be used for hybrid energy management.

We define MED_{COST} as the MED for which, on the margin, the operational cost savings equal the battery investment cost.[20] This is also the MED that minimizes the total cost of ownership for the individual driver. Combining Eqs. (4), (6), and (7) we get

$$MED_{COST} = \frac{I_B'}{r} = \frac{\alpha\beta^{-1} i_B}{p_f \frac{e_f}{e_e} - p_e} \tag{8}$$

The owner of a PHEV can offset a higher investment cost C with reduced running costs R_k. The (annual) net TCO savings S_k [\$/yr] for PHEV k are given as:

$$S_k = R_k - C \tag{9}$$

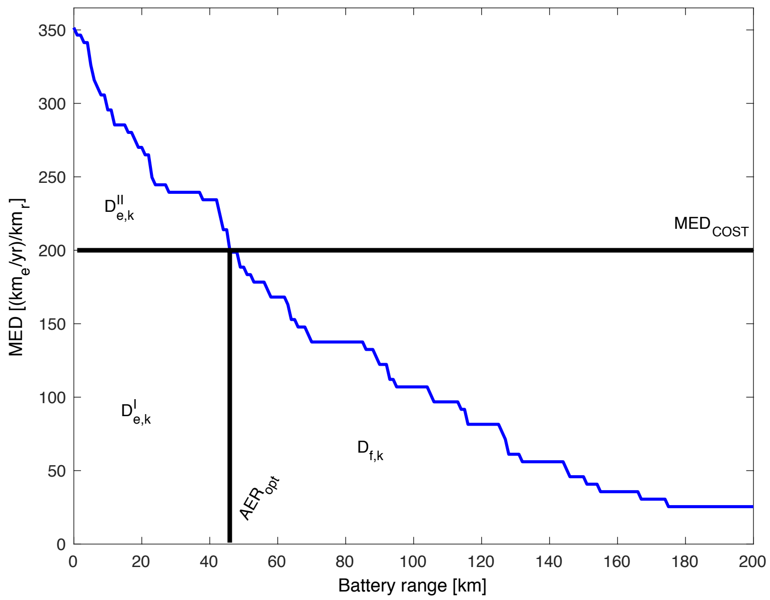

Figure 3: The curve (blue) gives the number of times per year an example vehicle k has driven a specific distance or longer between stops of duration 10 h or more. This MED curve in combination with an MED_{COST} of 200 $[\frac{km_e/yr}{km_r}]$ (horizontal black line) results in an optimal battery size AER_{opt}. $D^I_{e,k}$ together with $D^{II}_{e,k}$ equals the total distance driven on electricity ($D_{e,k}$) and $D_{f,k}$ is the distance traveled on fuel for vehicle k.

For the case of an optimal battery $AER_{k,opt}(T)$, we can further define $D^I_{e,k}$ [km/yr] as the annual electric distance, for which operational cost savings offset the cost for the battery capacity investment, see Fig. 2, and get:

$$D^I_{e,k} = MED_{COST} * AER_{k,opt}(T) \tag{10}$$

That is, the annuitized cost for battery-capacity-investment is

$$\alpha I_{B,k} = r * D^I_{e,k} \tag{11}$$

[20] MED_{COST} is in paper I called MED_{OPT}.

In the continuation, we call the cost reduction made available through the remaining electric distance $D_{e,k}^{II}$ [km/yr][21], see Fig 3, the annual battery savings $S_{B,k}$ [\$/yr]. It is useful to our analysis since it can be used to help offset the extra powertrain cost, I_P. $S_{B,k}$ is thus the remaining savings after a deduction of the annual costs for battery range. We have:

$$S_{B,k} \equiv r * D_{e,k}^{II} = R_k - I_{B,k} \tag{12}$$

Figure 4 depicts the resulting battery savings, $S_{B,k}$ and optimal battery range for 432 individual drivers at an MED_{COST} of 200 [$\frac{km_e/yr}{km_r}$]. The horizontal dotted lines illustrate the battery savings needed to offset an extra powertrain cost level of \$500 and \$3,500, respectively. The battery savings, $S_{B,k}$, are proportional to the distance represented by area $D_{e,k}^{II}$ illustrated for an example driver in Fig. 3. It can be noted that although the powertrain cost does not affect the optimal battery range for the individual car movement pattern, it will be difficult for short ranged PHEVs to reach high enough savings to offset a high powertrain cost.

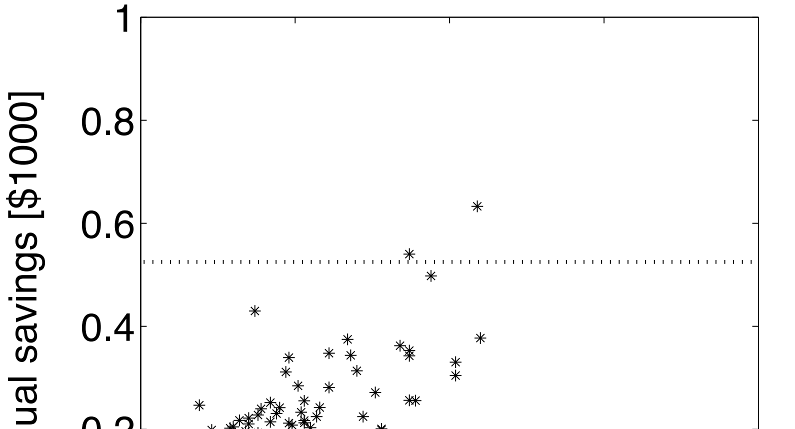

Figure 4: Optimal battery sizes for 432 individual movement patterns and their corresponding annual battery savings ($S_{B,k}$). Each point represents an individual car movement pattern. Results are shown for MED_{COST} = 200 [$\frac{km_e/yr}{km_r}$] and charging requirement T = 10. The two horizontal dotted lines indicate the savings needed to offset an extra powertrain cost, I_P, of \$500 and \$3,500 respectively.

[21] $D_{e,k}^{II} = D_{e,k}$-$D_{e,k}^{I}$

4.2 HANDLING TECHNO-ECONOMIC CONDITIONS

In earlier studies concerning the PHEVs economic viability it is in general more common to vary battery cost, gasoline price, annuity, etc., separately. The parameter MED_{COST} makes it possible to evaluate a continuum of scenarios without defining an exact level of the specific battery capacity cost, battery depth of discharge, annuity, etc., which have been utilized in paper I and II. The nominal cost for battery capacity, i_b is a difficult parameter to precisely determine and has been changing considerably during the later years. Nykvist et al. 2015 reported battery costs of about $410 for 2014 and argued that the price could go down to $200/kWh 'in a near future' [12]. These estimated battery costs are given as total cost divided by the (nominal) energy capacity [$/kWh]. But the specific cost of current PHEV batteries depends on the capacity for both power and energy. For a given power, the additional cost for energy capacity, i_B, can be considerably lower than the specific cost for the whole battery. On the other hand, stated costs are often production costs and do not include mark up costs.

We can illustrate the MED_{COST} with an example: Assuming Swedish and American running cost savings, r, to be roughly $0.08/km and $0.04/km, respectively and assuming other techno-economic parameters in accordance to Table 1 (with a somewhat cautious battery cost met by the buyer of $466/kWh) the Swedish driver would meet an MED_{COST} of about 200 [$\frac{km_e\ /yr}{km_r}$], while an American driver would meet an MED_{COST} of about 400 [$\frac{km_e\ /yr}{km_r}$].[22] The assumed annuity of 15% could for example correspond to a payback time for the extra PHEV battery and equipment of 8 years at a 5% discount rate. Or it could correspond to a situation where the car is sold after 3 years for a resale value of 55% of the original purchase price.

Table 1. Examples of possible techno-economic parameters resulting in an MED_{COST} of 200 or 400 [$\frac{km_e\ /yr}{km_r}$].

Annuity, α [-]	0.15
Electricity use, e_e [kWh/km]	0.2
Fuel use, e_f [kWh/km]	0.6
Grid electricity SOC window, β [-]	0.7
PHEV running cost savings per km, $r_{Swe} = p_f e_f - p_e e_e$ [$/km]	0.08
PHEV running cost savings per km, $r_{USA} = p_f e_f - p_e e_e$ [$/km]	0.04
Battery nominal capacity cost, i_B [$/kWh]	466

[22]Assuming that running cost savings are twice as high in Sweden compared to the USA can be considered a cautious estimate based on the average fuel and electricity prices between 2010 and 2015 for Sweden and USA reported in [105-109]. Combining the average energy costs, ($p_{f,Swe}$ = 0.23, $p_{e,Swe}$ = 0.23, $p_{f,USA}$ = 0.10, $p_{e,USA}$ = 0.12) with the energy assumptions from above(e_f = 0.6, e_e = 0.2) would result in running cost savings r_{Swe} = $0.092/km, r_{USA} = $0.036/km. The actual difference economic viability between Sweden and the USA would in reality be somewhat smaller due to 10-15% lower taxation on new car sales in the USA but this effect is small compared to the difference in running cost savings.

4.3 DISCUSSION

In real world driving, differences in driving behavior, ambient conditions and use of auxiliaries would result in individual parameter values e_e and e_f. Despite this, the cars in our model were assumed to all have the same specific energy use corresponding to some average conditions. In the beginning of this chapter we claimed that a reason for making such an assumption is that the results only to a smaller extent are affected by the above-mentioned factors. In this section, we will elaborate on how this assumption may affect our results.

In general

As a first approximation, we can assume that these varying conditions result in an equally large relative increase or decrease in energy demand per km in both CD and CS mode corresponding to an equally large relative increase (decrease) in e_e as in e_f. This would lead to an equally large increase (decrease) of the expected savings per km (r) and of the marginal battery cost (I_B') (see Eqs. (4) and (7)). The *MED* will not change since these two effects cancel out (see Eq. (8). The annual battery savings $S_{B,k}$ will however increase (decrease) since the savings per km have increased (decreased) (see Eq. (12)). Individual use of most auxiliary system, differences in road conditions (road gradient, wet tarmac, gravel etc.) and weather conditions etc. will therefore to a first order approximation not affect the MED_{COST} in our model. The effect of the increase or decrease of the annual battery savings $S_{B,k}$ simply tells us, as is often the case, that more energy-consuming users have more money to save from energy efficient technologies.

Heating of the passenger compartment

Heating the passenger compartment is different though. In CS mode, free waste heat from the engine can reasonably be used. However, in CD mode, for instance, according to a study on BEVs [110], a battery-supplied electric heater of 4.5 kW in constant use would lead to a higher energy use per km (especially at lower speeds). From the results from [110] we can estimate that on a yearly basis heating of the passenger compartment can result in about 7% higher and 6% lower MED_{COST} for urban and highway driving, respectively.[23] If using an

[23] A battery-supplied electric heater of 4.5 kW in constant use would lead to a 16%, 35% and 64% higher energy use if following the Artemis highway, rural and urban cycle respectively, or 38% in the weighted common Artemis drive cycle (CADC) [110]. This electric heating therefore results in 16% lower and 19% higher energy use per km in Artemis exclusively highway and urban driving, respectively, compared to the CADC, or about 4% lower and 5% higher, respectively, in yearly average specific energy use when assuming the heater is used only a quarter of the year. This would in turn lead to 7% higher and 6% lower MED_{COST} for Artemis urban and highway driving, respectively.

electric heat pump for compartment heating, a halving of the needed electric heating power could be expected.

City or highway driving

The specific energy use will also be dependent on the type of driving. To estimate what level of variation that can be expected we exemplify by e_e and e_f in the 2014 EPA fuel economy labeling for the two most sold electric car[24] and hybrid models, the Nissan Leaf and Toyota Prius HEV, respectively [111]. The difference between EPA's combined cycle and their data on city and highway driving is shown in Table 2. In the rather extreme cases of entirely city or highway driving the change in e_e and e_f results in an 8% decrease and a 12% increase in MED_{COST}, respectively.[25] [26] It should also be noted that these type-of-driving effects work in the opposite direction to the effects of passenger compartment heating, which increases with slower driving.

We can conclude that taking into account differences in driving behavior, ambient conditions and use of auxiliaries resulting in individual parameter values e_e and e_f, only to a small extent affect the MED_{COST} level faced by the individual driver.

Table 2, Example of variations in e_e and e_f due to difference in drive cycles (EPA's city and highway cycles) and the corresponding changes in other relevant parameters normalized to EPA Combined cycle. Data from EPA's labeling of Nissan Leaf (2014) and Toyota Prius v (2014).

Parameter in our model	EPA Combined	EPA City	EPA Highway
e_e	1	0.90	1.13
e_f	1	0.95	1.05
I_B'	1	0.90	1.13
MED_{COST}	1	0.92	1.12

[24] We here use electric cars as proxy for the PHEV in CD mode since EPA does not label city and highway driving separately for PHEVs.

[25] Similar results are achieved when for example substituting the Leaf with a Mitsubishi iMiev (2014) or substituting the Prius HEV with a Ford Fusion Hybrid (2014). Even smaller effect on the MED_{COST} is achieved if substituting the Leaf with a Ford Focus Electric.

[26] 95% of the measured vehicles have average velocities higher than the average velocity of the EPA city cycle and lower than the EPA highway cycle. 74% of the vehicles have an average speed which is more close to the average speed of combined EPA cycle than to the average speed of either the EPA city or highway cycle.

5 SUMMARY OF PAPERS

This chapter presents a short summary of the aim, method and main findings of each of the thesis' four articles.

Paper I: Plug-In Hybrid Electric Vehicles: How Individual Movement Patterns Affect Battery Requirements, the Potential to Replace Conventional Fuels, and Economic Viability

Aim: To analyze optimal battery design, economic viability and potential for PHEV electrification considering real car movement patterns in Sweden.

Method: An optimization method was developed relying on marginal costs and gains from an incremental battery capacity enlargement on individual car movement patterns for a vehicle model capturing the important features of a PHEV with CD/CS modes (Chapter 4). The analysis utilized a data set including 432 GPS-measured individual car movement patterns (Section 3.1 and 3.3) and assessed the PHEV's economic viability in Sweden for a wide range of techno-economic conditions and different charging options.

MAIN FINDINGS

- The possibilities for electric driving in a PHEV were found to vary substantially between individual drivers depending on their car movement pattern. This in turn results in considerable variation in the individual driver's possibility to reach economic viability.
- Better charging options leads to a higher battery utilization and a higher share of electric driving. Therefore, it also enables more cars to reach economic viability as PHEVs and higher savings, Fig 5. For commuters, charging at the workplace can be as important as halving the battery cost.
- Due to good possibilities for recharging, regularity in movement pattern and in general higher yearly mileage commuters are on average reaching higher share of electric driving and higher savings. They are also in majority among the drivers in the data set that first reach viability as PHEVs when the economic prerequisites improve. Therefore, commuters are likely to be the first drivers for whom the PHEV will be cost-effective.

- The potential share of electric driving on a fleet level is dependent on the individual cars possibilities to reach economic viability, Fig 6.
- The marginal electric distance needed to deliver enough running cost savings to offset a marginal increase in battery range is important for the individual car's economic viability and its optimal battery range.
- The PHEV viability is also dependent on the extra powertrain cost I_P[27], and a higher cost can delay and slow down the introduction of PHEVs to the market, Fig 6.

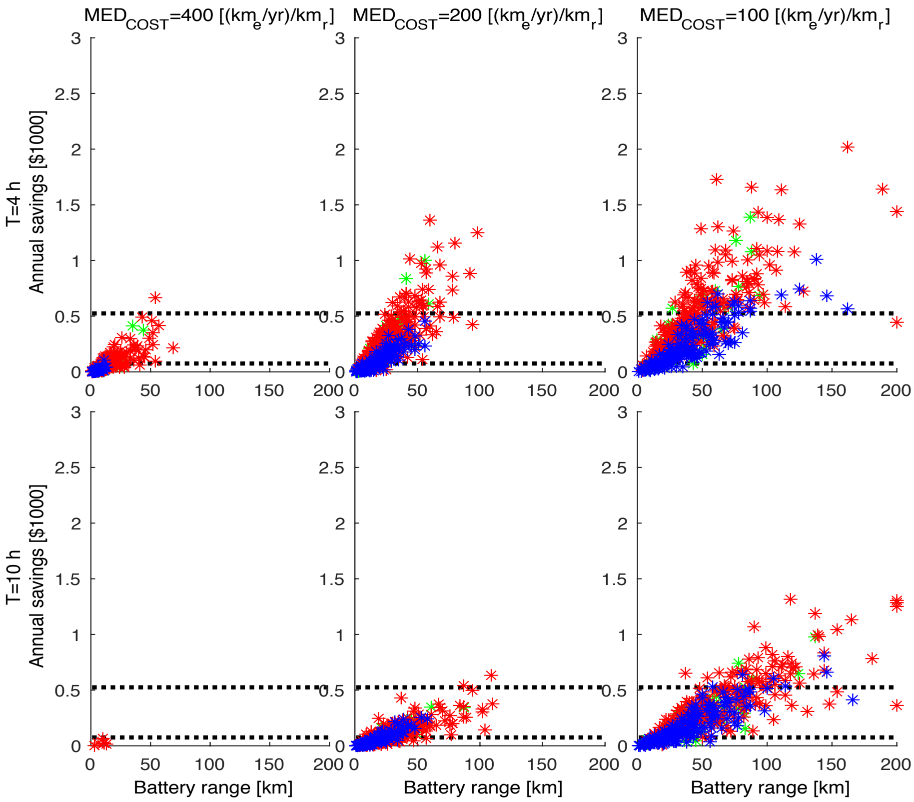

Figure 5: Battery optimization of individual movement patterns and their corresponding yearly savings from the battery investment. Each point represents an individual movement pattern; the color of the marker indicates if the car commutes (red) or not (blue) or if commuting status is unknown (green). Results are shown for minimum marginal electric distance MED_{COST} = 400, 200 and 100 $[\frac{km_e /yr}{km_r}]$ and minimum parking period T = 10 and 4 hours. The two horizontal dotted lines indicate the savings needed to offset an I_P of \$500 and \$3,500, respectively.

[27] In our first paper, we called this cost the battery-capacity-independent cost, I_F, though.

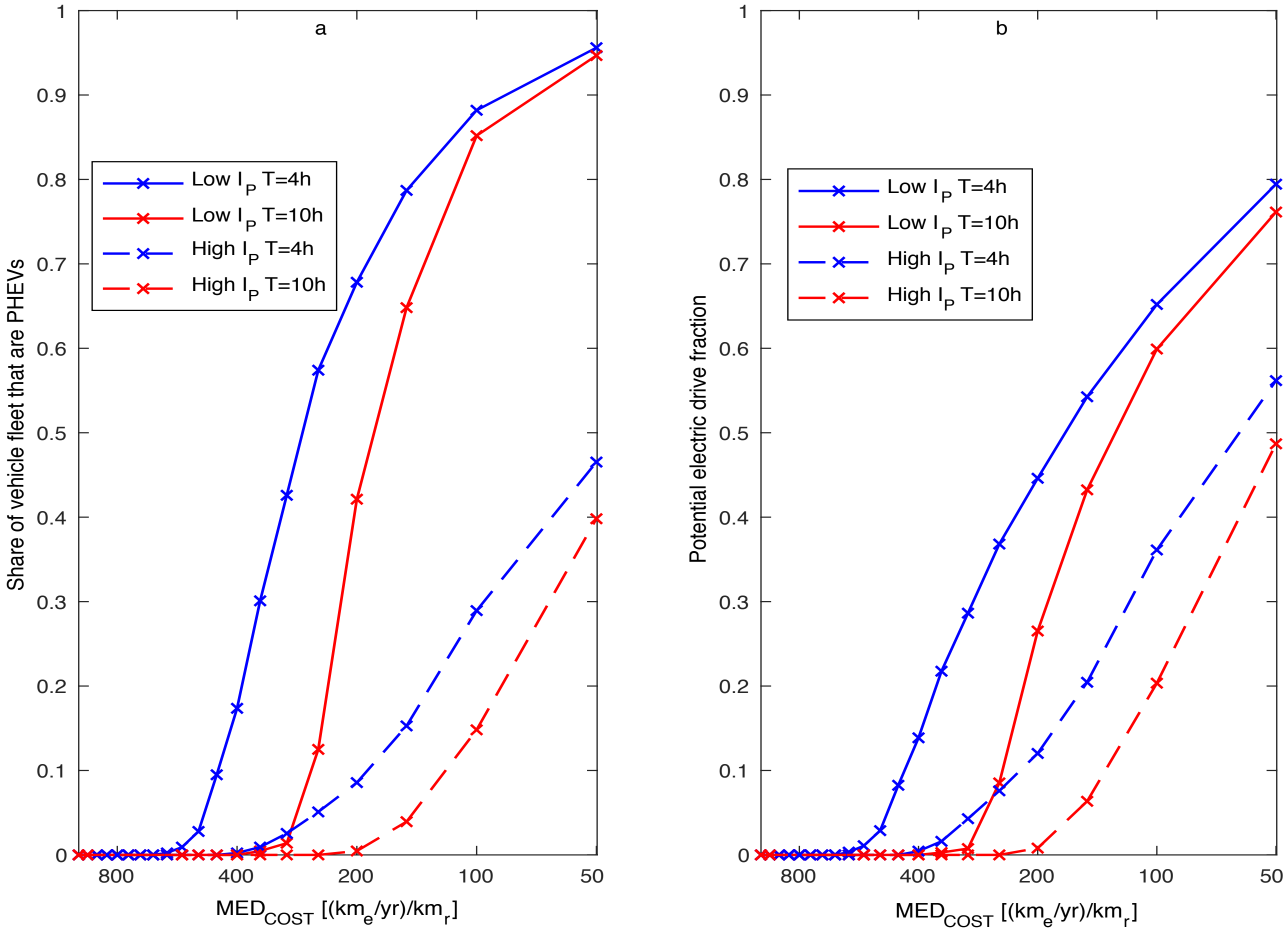

Figure 6: For the investigated car fleet, a) PHEV share; b) potential electric drive fraction, for different charging options and battery independent investment cost (Low I_P = \$500 and High I_P = \$3,500), as a function of the viability parameter MED_{COST}.

Paper II: Objective functions for PHEV battery range optimization and possible effects on the vehicle fleet

Aim: To analyze how the choice of objective function, which potentially represents stakeholders' interests, influences the resulting vehicle fleet in terms of the optimal battery range for the PHEVs, share of PHEVs, TCO savings, and electric drive fraction.

Method: A data set including 432 GPS-measured individual car movement patterns was used together with the battery utilization model developed in paper I to assess fleet optimal battery sizes for three studied objective functions. The studied objectives were: to maximize the total number of PHEVs in the vehicle fleet; to maximize the total cost of ownership savings; and finally, to maximize the total electric driving in the vehicle fleet.

MAIN FINDINGS

- Possible diverse objectives among stakeholder could result in very different optimal battery sizes, Fig. 7.
- Optimizing the battery range to maximize the number of PHEVs sold resulted in a short battery range and low share of electric driving, while optimizing the battery range to maximize the overall fleet's share of electric driving resulted in relatively few PHEVs with larger batteries, Fig. 7.
- High share of PHEVs in a vehicle fleet does not automatically imply a high share of electric driving, Fig. 7.
- In the base case, optimizing the battery to maximize drivers' TCO-savings resulted in only somewhat lower levels of share electric driving compared to when the battery is optimized to maximize the overall fleet's share of electric driving, Fig. 7d.
- The PHEV viability is dependent on the extra powertrain cost and a higher cost can in general delay and slow down the introduction of PHEVs to the market, Fig 7-8.
- Policies to promote PHEVs can alleviate or magnify the difference in optimal battery range between the objective functions.
- The results point to countries and regions with high running cost savings as possible forerunners for the technology and also suggest that the level of running cost savings should be considered in the choice and design of PHEV policies.
- A low investment cost for PHEVs (either through a low I_P and/or low MED_{COST}; or through a subsidy) means that a relatively short electric distance is needed to reach viability. This enables a large variation in electric distance driven among the viable PHEVs and a large difference in optimal battery range between the studied objective functions. This should therefore be considered when formulating policy.

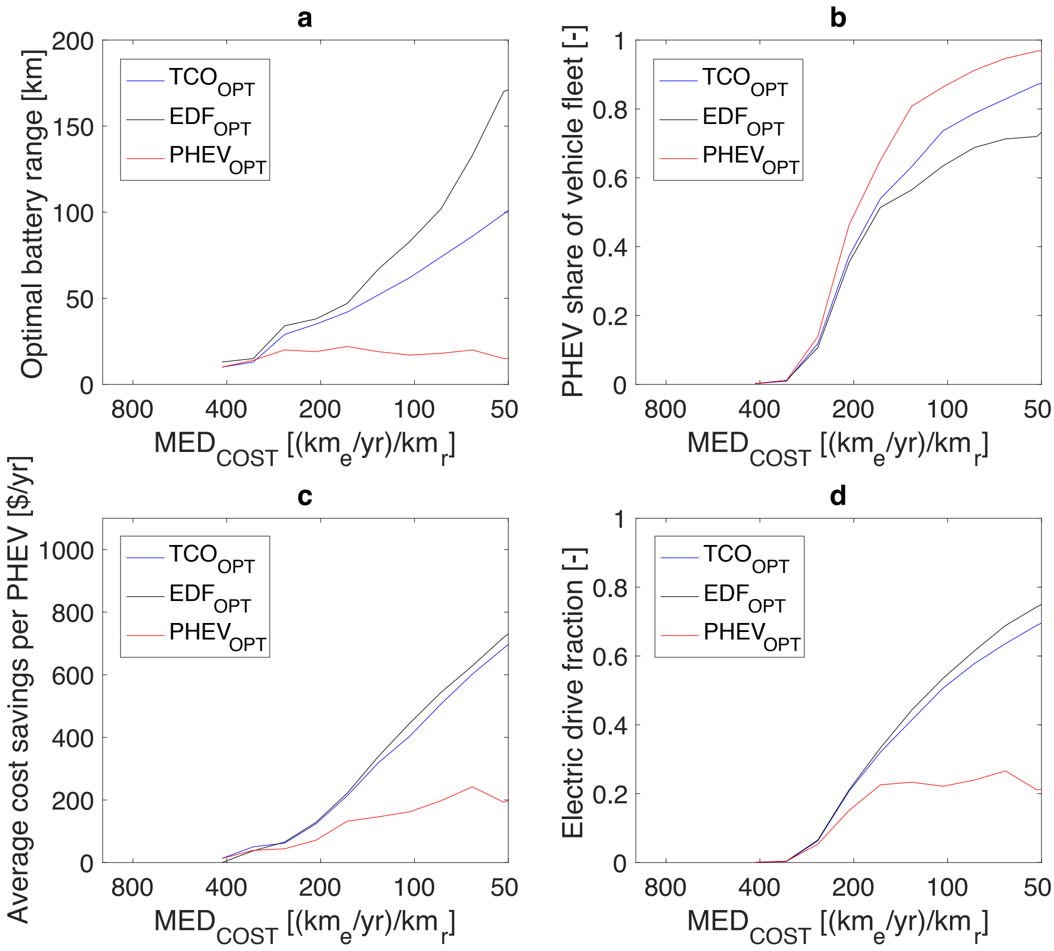

Figure 7: For the studied car fleet under three different objective functions, a) the optimal battery range; b) the PHEV share of fleet; c) the cost savings per PHEV; and d) the share of electric driving, all as a function of MED_{COST}, for Low-I_P ($500) and with night-time charging only (T = 10 h). The objective functions respectively maximize the number of PHEVs in the car fleet, $PHEV_{OPT}$; the TCO savings in the car fleet, TCO_{OPT}; and distance of electric driving of the car fleet, EDF_{OPT}.

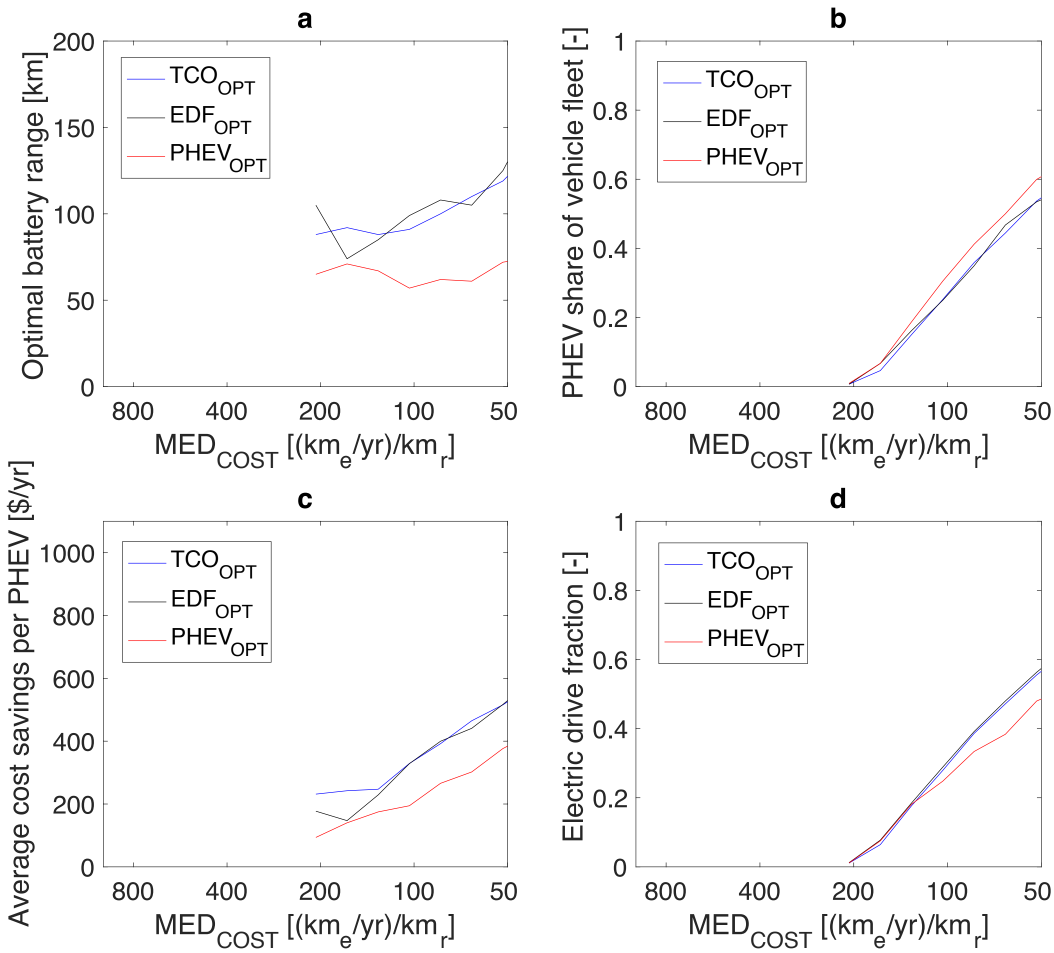

Figure 8: For the studied car fleet under three different objective functions, a) the optimal battery range; b) the PHEV share of fleet; c) the cost savings per PHEV; and d) the share of electric driving, all as a function of MED_{COST}, for High-I_P ($3,500) and with night-time charging only (T = 10 h). The objective functions respectively maximize the number of PHEVs in the car fleet, $PHEV_{OPT}$; the TCO savings in the car fleet, TCO_{OPT}; and distance of electric driving of the car fleet, EDF_{OPT}.

Paper III: Electrification of the two-car household, PHEV or BEV?

Aim: To: 1) estimate the potential benefit from an optimized use of the PHEV in a two-car household; 2) assess for what levels of powertrain cost the PHEV can be an economically better choice for the two-car household compared to the BEV; and finally, 3) analyze how the resulting electric drive fraction (EDF) depend on whether the households drive a PHEV or a BEV.

Method: A GPS-measured data set of both car's movement patterns in 64 Swedish two-car households is utilized with an optimization model to estimate the potential electric driving for a PHEV/BEV in a two-car household. This is done for different battery sizes and three car substitution strategies. Car 1: the PHEV/BEV is used to fulfil the 1st car's driving and none of 2nd car.[28] Car 2: the PHEV/BEV is correspondingly used to fulfil only the 2nd car's driving. Both: the PHEV/BEV is used interchangeably between 1st and 2nd car's driving to minimize the use of fuel and so also maximize the distance driven on electricity. The resulting electric mileage is used to assign to each household a PHEV/BEV with a cost optimal battery under each vehicle usage strategy. Finally, the resulting TCO economics and electric driving are compared between the PHEV and the BEV. The study is a continuation of the work in Karlsson 2016 [112].

MAIN FINDINGS

- The potential benefit, in terms of increased share of electric driving and lowered running costs, from an optimized use (denoted 'Both' in Fig. 9) of the PHEV in a two-car household was estimated to be less than half the benefit from an optimized use of the BEV. Thus, the flexibility made available in two-car households thus does not generally benefit PHEVs in comparison to BEVs.
- When taking into account the difference in powertrain cost investment between the PHEV and the BEV, the results suggest that an optimized use of the BEV in general will result in a lower total cost of ownership compared to using a PHEV, Fig. 9.
- There are some indications that the PHEV could be a tougher opponent than what the TCO results suggest at first, including: the household maybe can't or doesn't want to optimize the use of the vehicle; people could be prepared to pay extra for a car without range limitation or do not accept a too 'short-ranged' BEV.
- Even if PHEVs would take the BEVs place in the two-car household this would not hamper the share of electric driving in the vehicle fleet to any larger extent, Fig 10. Instead the usage strategy was found more important than the choice of vehicle. From a fuel replacement perspective, it is for example, often better to exchange the first car with a PHEV than to replace the second car with a BEV.

[28] We define the 1st car as the car with the longest total driving distance during the analysis period and the 2nd car consequently is defined as the car with shortest total driving distance.

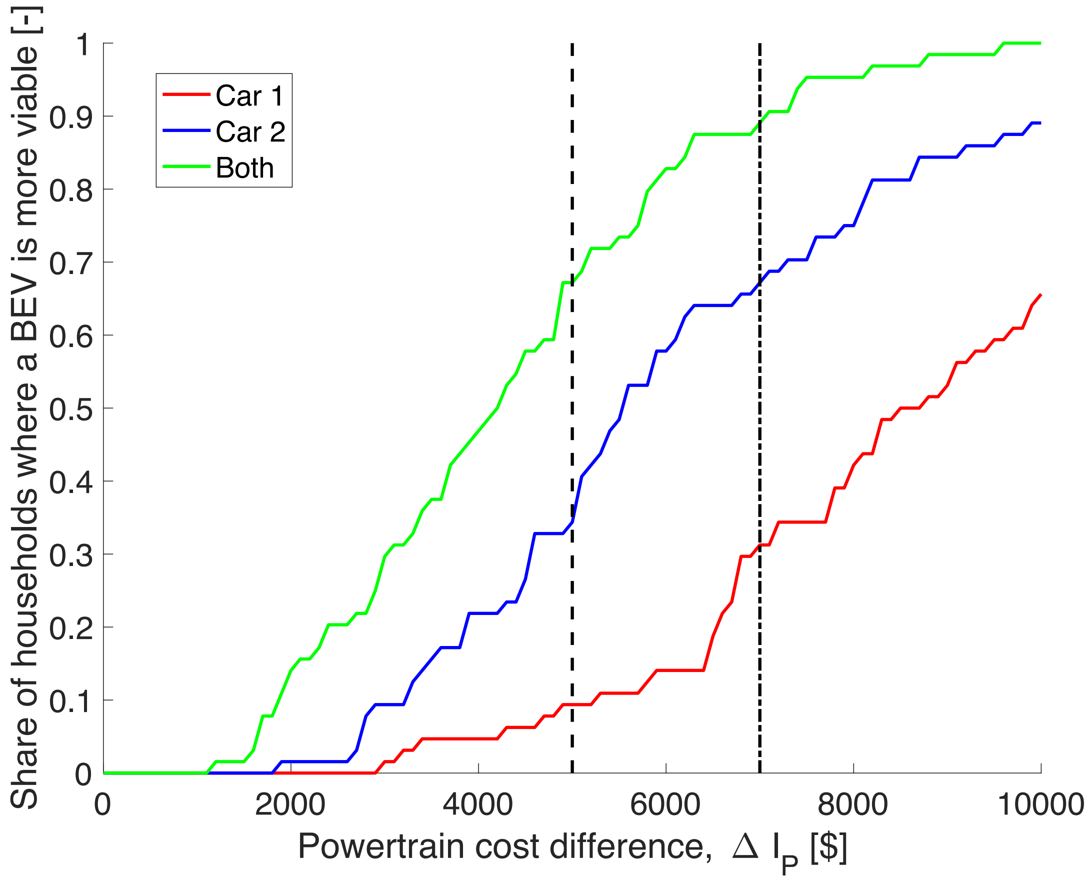

Figure 9: For three vehicle usage strategies (Car 1, Car 2 and Both) the share of households where driving a BEV results in lower TCO compared to driving a PHEV, per powertrain investment cost difference, ΔI_P, for the PHEV compared to the BEV. Estimates of the difference in powertrain cost between the PHEV and the BEV for a "Prius-like", \$5000 and a "Volt-like" PHEV powertrain are included for reference, (dashed vertical lines).

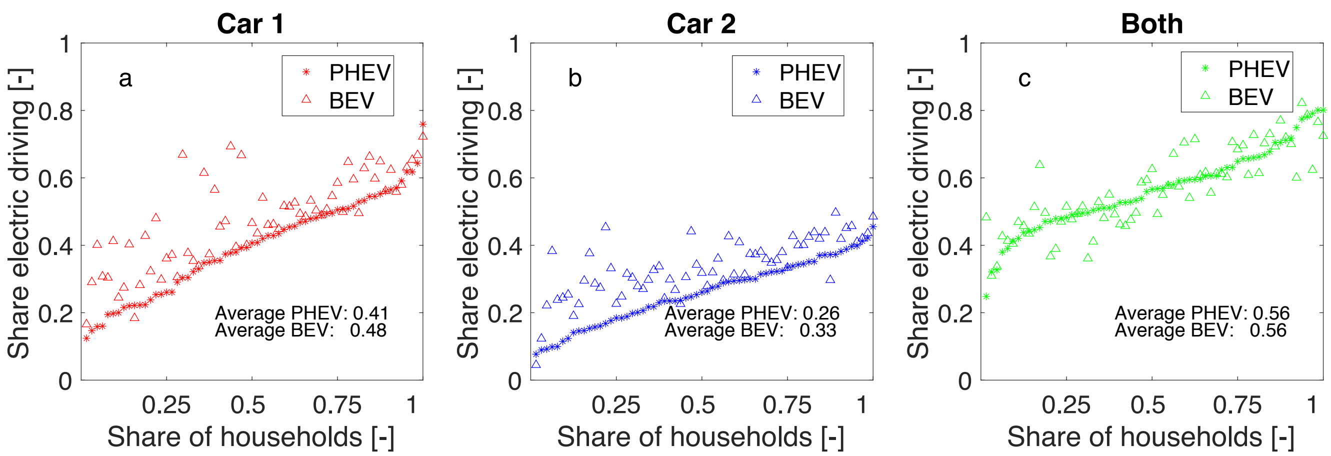

Figure 10: For three vehicle usage strategies (Car 1, Car 2 and Both) and for each individual household the resulting EDF (of the total household distance) for the cost optimal battery range for the PHEV and BEV, respectively. The households are sorted after the PHEV's result for each strategy.

Paper IV: The potential for brake energy regeneration under Swedish conditions

Aim: To analyze the potential for brake energy regeneration in Swedish driving conditions.

Method: To analyze individual driver's potential for brake energy regeneration a model of the power and energy fluxes at the wheels for a normalized car was developed and applied to GPS-derived distance, speed and altitude data from 378 privately driven cars in Sweden. The speed profiles of the NEDC and WLTP test cycles were used for comparison. A rough estimate of what levels of energy and cost savings that can be achievable in practice by investigating two drivetrains, a ''battery electric vehicle" (BEV) and a ''mild hybrid" (mHEV) was also conducted.

MAIN FINDINGS

- Braking energy varies considerably between individual movement pattern, up to a factor of six, Fig. 11.
- City drivers have highest potential to regenerate energy per km of driving.
- Long distance drivers have highest potential to regenerate energy on a yearly basis.
- It is of importance to include road grade in analyses of the regeneration potential in real-world driving.
- The braking loss per km for the standard test cycles are not far off from those of the measured real-world driving despite the former not including road grades. The relatively high braking loss (and thus regeneration potential) for the test cycles can be explained by the lower air drag loss due to a lower average speed compared to in the real-world driving data.
- The expected extra efficiency gains from higher regeneration power capacity fall off quickly, and a 10kW mild hybrid is enough to capture on average almost three quarters of the energy available for regeneration for the assumed standard car, Fig. 12.
- The findings indicate that regeneration of braking energy under current Swedish driving conditions could increase energy efficiency, with average energy savings at the wheels of about 15% for a battery EV and up to 10% for a "mild" hybrid.
- An economic estimate indicates that under current Swedish conditions, the economic savings from using less fuel due to regeneration will for most drivers not be sufficient on their own to offset the estimated investment cost of hybrid technology.

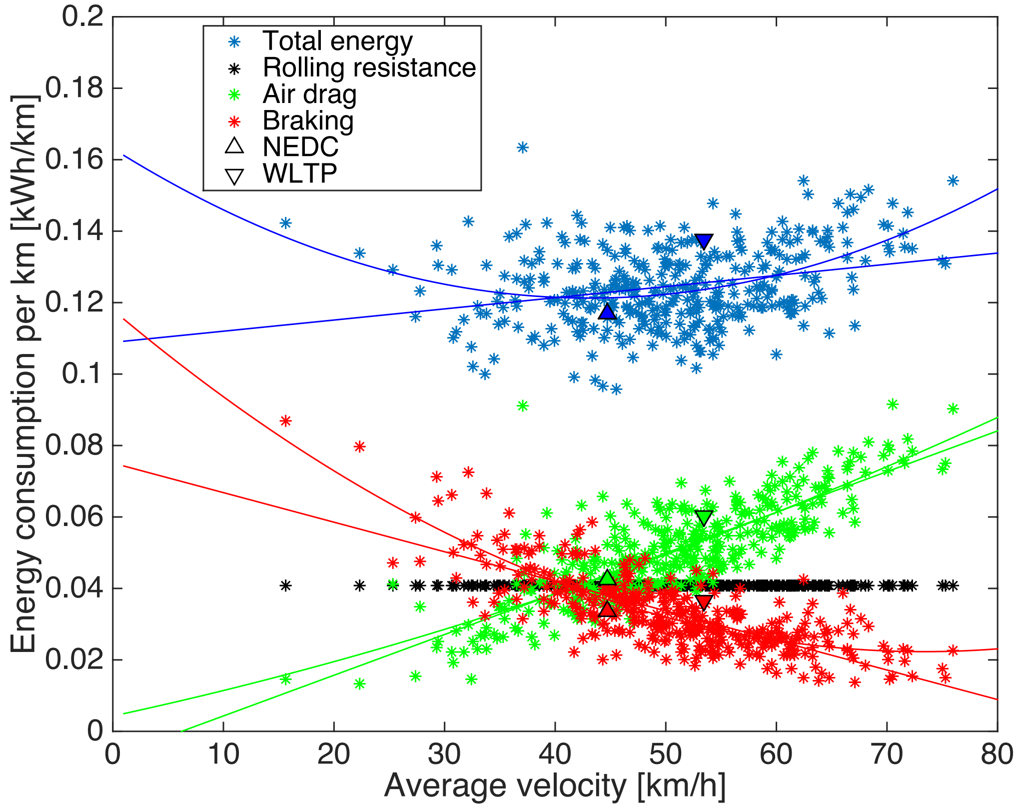

Figure 11: For the assumed midsize car (m = 1500 kg, C_D*A = 0.7 m^2), for each movement pattern (asterisks: individual vehicles in our data; triangles: test cycle values, see legend), the average energy at the wheels (components: rolling resistance, air drag, and braking) lost per km of driving and its components, as a function of the average velocity. Solid lines correspond to linear and quadratic regressions. Rolling resistance coefficient $c_r = 0.01$.

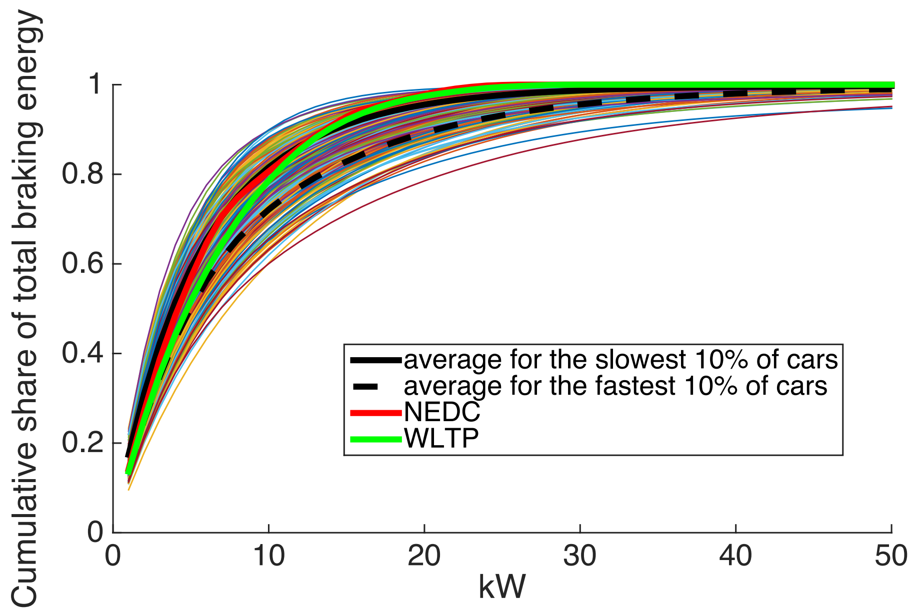

Figure 12: For the assumed midsize car (m = 1500 kg, C_D*A = 0.7 m^2) and for each movement pattern, the cumulative likelihood that the braking power is less than a given power level. Rolling resistance coefficient $c_r = 0.01$.

6 FINAL REMARKS

When the work of this thesis started in 2011 there were hardly any PHEVs found on the Swedish roads.[29] GM had just recently launched the Chevrolet Volt (December 2010) and Toyota Prius PHEV was not yet on the market (launched in Japan early 2012). Battery cost estimates as high as $1000/kWh and above were discussed. Since then we have seen a quite remarkable development, where now battery costs as low as $200/kWh are seen as possible in the near future [12]. Assessing technology under such development could be expected to come with some challenges. As described in the introduction the main aim of this thesis has been to assess the potential to reduce fuel use in Swedish passenger car transport through an introduction of PHEVs. This has been achieved by investigating four general questions:

-What does the characteristics of individual Swedish car movement patterns imply for the possibilities to reduce fuel use through an introduction of PHEVs?

-How large share of the driving can be expected to be electric?

-How viable is the PHEV?

-What would be an optimal battery size for the PHEV?

We have however not stated very precise answers to any of these questions! Instead our answers have been in the form of possible development over a span of techno-economic conditions. This has proven quite useful given the technology's rapid development. The availability of the highly detailed data sets over Swedish car movement patterns have enabled us, unlike most earlier studies, to focus on the individual driver's car movement pattern and study his/her marginal benefits from battery range enlargement. Through the methodological framework developed around the marginal electric distance (*MED*) we have been able to improve the understanding of how characteristics of individual driver's car movement patterns affect the potential share of electric driving, cost optimal battery sizing, and the resulting total cost of ownership and economic viability for Swedish drivers in general (paper I, II), and for two–car households in particular (paper III). Dividing the additional investment cost for a PHEV, compared to an HEV, in two parts, one for powertrain and one for battery range capacity, has been useful to point out the importance of the former when it comes to

[29] There was one PHEV registered in Sweden during 2011 (a Chevrolet Volt) [113].

individual drivers total cost of ownership and their possibility to reach economic viability when compared to an HEV (paper I, II), but also when compared to the BEV (paper III).

Also, more and more PHEVs are sold in Sweden (about 10,000 in 2016 up from about 5,700 the year before [114]). Many car brands are now offering PHEVs and/or BEVs. Although the PHEVs still only constitute a small fraction of the total car sales, the total number of PHEVs in traffic have increased manifold since 2011 and at the end of 2016 the total number of PHEVs in the Swedish vehicle fleet reached almost 20,000 cars [114]. This makes it possible to answer many new types of questions as well as old ones, but now based on real and revealed behavior rather than assumptions, models and stated preferences. For instance, how do people choose battery range and on what grounds, how can potential customers be informed on how to choose range. Who are the buyers of PHEVs and why do they choose a PHEV instead of a conventional vehicle or a BEV. Are the policies put in place to speed up the introduction of PHEVs effective? Our results show that PHEVs *can* result in a substantial fuel reduction but they do not *have to* be charged. It is therefore of great importance to continue to study the actual share of electric driving by PHEVs and the charging behavior among users, started out by Smart et al. 2014 Tal et al. 2013 and Plötz et al. 2015 [73-75]. If the drivers don’t charge it would be important to assess how one could make them to do so through improved access to infrastructure, improved economic benefits from driving on electricity or maybe by introducing inductive charging.

7 REFERENCES

[1] Trafikanalys, Peak car i sikte? Statistik och analys över Sveriges personbilsflotta och dess användning, PM 2015:14, Trafikanalys Stockholm. Available at: http://www.trafa.se/globalassets/pm/pm-2015_14-peak-car-i-sikte-statistik-och-analys-over-sveriges-personbilsflotta-och-dess-anvandning.pdf, (in Swedish).

[2] Trafikanalys, Uppföljning av de transportpolitiska målen, Rapport 2014:4, Stockholm Trafikanalys, Available at: http://www.trafa.se/globalassets/rapporter/rapport_2013_4_uppfoeljning_av_de_transportpolitiska_maalen.pdf, (in Swedish).

[3] Trafikverket, Transportsektorns utsläpp, Trafikverket.se, 2016, accessed 2016-12-18, available at: http://www.trafikverket.se/om-oss/var-verksamhet/sa-har-jobbar-vi-med/miljo-och-halsa/klimat/transportsektorns-utslapp/, (in Swedish).

[4] Trafikverket, Prognoser för arbetet med nationell transportplan 2014–2025 – persontransporters utveckling fram till 2030, Rapport 2013:055, Trafikverket Borlänge. Available at: https://trafikverket.ineko.se/Files/sv-SE/10796/RelatedFiles/2013_055_prognoser_for_arbetet_med_nationell_transportplan_2014_2025_persontransporters_utveckling_fram_till_2030.pdf, (in Swedish).

[5] Regeringen, En sammanhållen klimat - och energipolitik – Klimat, Regeringens prop. 2008/09:162, (in Swedish).

[6] Regeringen, Fossiloberoende fordonsflotta - ett steg på vägen mot nettonollutsläpp av växthusgaser. Regeringens Dir. 2012:78. Available at: http://www.regeringen.se/rattsdokument/kommittedirektiv/2012/07/dir.-201278/, (in Swedish).

[7] Mom G, The Electric Vehicle: Technology and Expectations in the Automobile Age. Johns Hopkins University Press, 2004.

[8] Chan C. C, The State of the Art of Electric, Hybrid, and Fuel Cell Vehicles, Proceedings of the IEEE, vol. 95, Issue: 4, 2007.

[9] United State Congress, Electric and Hybrid Vehicles Research, development and demonstration Act of 1976 15 USC 2501, Law 94-413.

[10] Fogelberg H, Electrifying vision, the technopolitics of electric cars in California and Sweden during the 1990's. PhD dissertation, Section for Science and Technology Studies, University of Gothenburg, 2000.

[11] Crabtree G, Kócs E and Trahey L, The energy-storage frontier: Lithium-ion batteries and beyond, MRS Bulletin, vol. 40, Issue 12, pp. 1067-1078, 2015.

[12] Nykvist B and Nilsson M, Rapidly falling costs of battery packs for electric vehicles, Nature Climate Change, vol. 5, no. 4, pp. 329–332, 2015.

[13] Wikipedia, Lohner-Porsche, article available online at: http://en.wikipedia.org/wiki/Lohner-Porsche accessed 2016-12-18.

[14] Samaras C and Meisterling K, Life cycle assessment of greenhouse gas emissions from plug-in hybrid vehicles: implications for policy. Environmental science and technology. Vol. 42, pp. 3170-3176, 2008.

[15] Argonne National Laboratory, Well-to-wheels analysis of energy use and greenhouse gas emissions of plug-in hybrid electric vehicles, ANL/ESD/10-1, U.S. Department of energy, Oak Ridge, 2010.

[16] Onat N C, Kucukvar M and Tatari O, Conventional, hybrid, plug-in hybrid or electric vehicles? State-based comparative carbon and energy footprint analysis in the United States, Applied Energy vol. 150, pp. 36-49, 2015

[17] Azar C, Lindgren K and Andersson B A, Global energy scenarios meeting stringent CO_2 constraints – cost-effective fuel choices in the transportation sector, Energy Policy, vol. 31, issue 10, pp. 961-976, 2003

[18] Gonder, J and A Simpson, Measuring and Reporting Fuel Economy of Plug-In Hybrid Electric Vehicles. NREL/CP-540-40377, National Energy Renewable Laboratory, USA, 2006.

[19] Gonder J, Markel T, Simpson A and Thornton M, Using global positioning system travel data to assess real-world energy use of plug-in hybrid electric vehicles. Transportation Research Record 2007, 26–32.

[20] Karlsson S and Jonson E, The importance of car movement data for determining design, viability and potential of PHEVs. In Proceedings of International Mobility Advanced Forum (IAMF) Geneva March 8-9, 2011.

[21] Larsson, V, Route Optimized Energy Management of Plug-in Hybrid Electric Vehicles, ISBN 978-91-7597-002-8, PhD. Thesis, Chalmers University of Technology, Gothenburg, SE-41296 Sweden, 2014

[22] Pourabdollah M, Optimization of Plug-in Hybrid Electric Vehicles, ISBN 978-91-7597-149-0, PhD. Thesis, Chalmers University of Technology, Gothenburg, SE-41296 Sweden, 2015

[23] Electric Power Research Institute, Comparing the benefits and impacts of hybrid electric vehicle options. Palo Alto [CA]: Electric Power Research Institute; 2001.

[24] Electric Power Research Institute, Comparing the benefits and impacts of hybrid electric vehicle options for compact sedan and sport utility vehicles. Palo Alto [CA]: Electric Power Research Institute; 2002.

[25] Electric Power Research Institute, Advanced batteries for electric drive vehicles a technology and cost-effectiveness assessment for battery electric vehicles, power assist hybrid electric vehicles and plug-in hybrid electric vehicles. Palo Alto [CA]: Electric Power Research Institute; 2004.

[26] Simpson A. Cost-benefit analysis of plug-in hybrid electric vehicle technology. In: Proceedings to 22nd International battery, hybrid and fuel cell electric vehicle symposium and exposition (EVS-22). Yokohama (Japan): National Renewable Energy Lab; 2006.

[27] United States Department of Energy (DOE), Annual energy outlook 2009 with projection to 2030. Washington [DC]: U.S. Energy Information Administration; 2009.

[28] Kihm A and Trommer S, The new car market for electric vehicles and the potential for fuel substitution. Energy Policy, vol. 73, pp.147-157, 2014.

[29] Lin Z and Greene D, Assessing energy impact of plug-in hybrid electric vehicles: significance of daily distance variation over time and among drivers. Transportation Research Record, 2011.

[30] Zhang, L, Brown, T and Samuelsen G S, Fuel reduction and electricity consumption impact of different charging scenarios for plug-in hybrid electric vehicles, Journal of Power Sources, vol. 196, pp. 6559-6566, 2011.

[31] Kelly J, MacDonald J and Keoleian G, Time-dependent plug-in hybrid electric vehicle charging based on national driving patterns and demographics. Applied Energy vol. 94, pp. 395-405, 2012.

[32] Le Duigou A, Guan Y and Amalric Y, On the competitiveness of electric driving in France. Impact of driving patterns. Renewable Sustainable Energy Review, vol. 37, pp. 348-359, 2014.

[33] Özdemir E D and Hartmann N, Impact of electric range and fossil fuel price level on the economics of plug-in hybrid vehicles and greenhouse gas abatement costs, Energy Policy, vol. 46, pp. 185–192, 2012.

[34] Redelbach M, Özdemir ED and Friedrich HE, Optimizing battery sizes of plug-in hybrid and extended range electric vehicles for different user types. Energy policy vol. 73, pp. 158-168, 2014.

[35] Lin Z, Optimizing and Diversifying the Electric Range of Plug-in Hybrid Electric Vehicles for U.S. Drivers, SAE International, Warrendale, PA, SAE Technical Paper 2012-01-0817, Apr. 2012.

[36] Shiau C-S and Michalek J, Global optimization of plug-in hybrid vehicle design and allocation to minimize life cycle greenhouse gas emissions, Journal of. Mechanical Design, vol. 133, 2011.

[37] Shiau C-S, Samaras C, Hauffe R and Michalek J, Impact of battery weight and charging patterns on the economic and environmental benefits of plug-in hybrid vehicles, Energy Policy, vol. 37, no. 7, pp. 2653–2663, 2009.

[38] Shiau C-S, Kaushal N, Hendrickson C T, Peterson S B, Whitacre J F, Michalek J, and others, Optimal plug-in hybrid electric vehicle design and allocation for minimum life cycle cost, petroleum consumption, and greenhouse gas emissions, Journal of. Mechanical Design, vol. 132, 2010.

[39] Al-Alawi B and Bradley T, Total cost of ownership, payback, and consumer preference modeling of plug-in hybrid electric vehicles. Applied Energy vol. 103, pp.488–506, 2013

[40] Karabasoglu O and Michalek J, Influence of driving patterns on lifecycle cost and emissions of hybrid and plug-in electric vehicle powertrains. Energy policy, vol. 60, pp. 445-461, 2013.

[41] Bishop J, Martin N and Boies A. Cost-effectiveness of alternative powertrains for reduced energy use and CO_2 emissions in passenger vehicles. Applied Energy, vol. 124, pp. 44-61, 2014.

[42] Hutchinson T, Burgess S and Herrmann G, Current hybrid-electric powertrain architectures: applying empirical design data to life cycle assessment and whole-life cost analysis, Applied energy vol. 119, pp. 314-329, 2014.

[43] Peterson S and Michalek J, Cost-effectiveness of plug-in hybrid electric vehicle battery capacity and charging infrastructure investment for reducing US gasoline consumption. Energy policy, vol. 52, pp 429-438,

[44] Michalek J, Chester M, Jaramillo P, Samaras C, Shiau C-S and Lave L, Valuation of plug-in vehicle life cycle air emissions and oil displacement benefits. PNAS, vol. 180, no. 40, pp. 16554–16558, 2011.

[45] Meinrenken C J and Lackner K S, Fleet view of electrified transportation reveals smaller potential to reduce GHG emissions, Applied Energy, vol. 138, pp. 393–403, 2015.

[46] Kontou E, Yin Y and Lin Z, Socially optimal electric driving range of plug-in hybrid electric vehicles, Transportation Research Part D, vol. 39, pp. 114–125, 2015.

[47] Wolf J, Loechl M, Thompson M, and Arce C, Trip rate analysis in GPS-enhanced personal travel surveys. In Stopher. P. Johns. P. (Eds.). Transport Survey Quality and Innovation. Pergamon Press. pp. 483-498. (2003).

[48] Stopher P, FitzGerald C and Xu M, Assessing the accuracy of the Sydney Household Travel Survey with GPS. Transportation Vol 34. 2005 pp: 723-741.

[49] Karlsson S and Wiedemann T, G4V: impact and possibilities of a mass introduction of electrified vehicles on the electricity networks in Europe. In: Proceedings of EVS25, Shenzhen, China; November 5–9, 2010.

[50] Elango V, Guensler R and Ogle J. Day-to-day travel variability in the commute Atlanta study. Transportation Research Records, 2014:39–49.

[51] Pas E and Sundar S, Intrapersonal variability in daily urban travel behavior: some additional evidence. Transportation (Netherlands) vol. 22, pp. 135-150, 1995.

[52] Pendyala R and Pas E, Multi-day and multi-period data for travel demand analysis and modeling. In: TRB transportation research circular EC008: Transportation; 2000.

[53] Puget Sound Regional Council, Traffic choices study. Technical report, 2008 <hhttp://www.psrc.org/assets/37/summaryreport.pdf>; [accessed 01.07.14].

[54] Wu X, Dong J, and Lin Z, Cost analysis of plug-in hybrid electric vehicles using GPS- based longitudinal travel data. Energy Policy vol. 68, pp. 206-217, 2014.

[55] Neubauer J, Brooker A and Wood E, Sensitivity of plug-in hybrid electric vehicle economics to drive patterns, electric range, energy management, and charge strategies. Journal of Power Sources vol. 236, pp. 357-364, 2012.

[56] Khan M and Kockelman K, Predicting the market potential of plug-in electric vehicles using multiday GPS data. Energy Policy vol. 46, pp. 225-233, 2012.

[57] Wu X, Aviquzzman Md and Lin Z., Analysis of plug-in hybrid electric vehicles' utility factors using GPS-based longitudinal travel data, Transportation Research Part C, vol. 57, pp. 1-12, 2015.

[58] Schoenfelder S, Li H, Guensler R, Ogle J and Axhausen K, Analysis of commute Atlanta instrumented vehicles GPS data: destination choice behavior and activity spaces. Arbeitsberichte Verkehrsund Raumplanung, 303, IVT, ETH, Zürich; 2005.

[59] Pearre N, Kempton W, Guensler R and Elango V, Electric vehicles: how much range is required for a day's driving? Transportation Research Part C, vol. 19, pp. 1171-1184, 2011.

[60] Santini D, Zhou Y, Elango V, Xu Y and Guensler R, Daytime charging-what is the hierarchy of opportunities and customer needs? – A case study based on Atlanta commute data. In: TRB 93rd annual meeting compendium of papers; 2014.

[61] University of Winnipeg, Monitoring driving behaviour for Plug-In Hybrid Electric Vehicle (PHEV) research, 2011, http://auto21.uwinnipeg.ca/index.html, Accessed 2017-02-16.

[62] Ashtari A, Bibeau E and Shahidinejad S, Using large driving record samples and a stochastic approach for real-world driving cycle construction: Winnipeg driving cycle. Transportation Science, vol. 48, pp. 170-183, 2014.

[63] Smith R, Shahidinejad S, Blair D and Bibeau E, Characterization of urban commuter driving profiles to optimize battery size in light-duty plug-in electric vehicles. Transportation Research Part D, vol. 16, pp. 218-224, 2011.

[64] Smith R, Morison M, Capelle D, Christie C and Blair D, GPS-based optimization of plug-in hybrid electric vehicles' power demands in a cold weather city. Transportation Research Part D, vol. 16, pp. 614-618, 2011.

[65] Paffumi E, De Gennaro M, Scholz H and Martini G, Assessment of the potentiality of electric vehicles and charging strategies to meet urban mobility requirements. Transportation Research Part A, vol. 11, pp. 22-60, 2014.

[66] De Gennaro M, Paffumi E, Scholz H and Martini G, GIS-driven analysis of e- mobility in urban areas: an assessment of the impact on the electric energy distribution grid. Applied Energy, vol. 124, pp. 94-116, 2014.

[67] De Gennaro M, Paffumi E, Scholz H and Martini G, Analysis and assessment of the electrification of urban road transportation based on real-life mobility data. In: 27th Electric vehicles symposium, Barcelona (Spain); 2013.

[68] Christensen L, Kveiborg O and Mabit, S L, The market for electric vehicles – What do potential users want. In: Conference paper at 12th WCTR, July 11– 15, Lisbon, Portugal, 2010.

[69] Hou C, Wang H and Ouyang M, Battery Sizing for Plug-in Hybrid Electric Vehicles in Beijing: A TCO Model Based Analysis, Energies, vol. 7, no. 8, pp. 5374–5399, 2014.

[70] Zhang X and Wang H, Utility factors derived from Beijing passenger car travel survey. State Key Laboratory of Automotive Safety and Energy, China Automotive Energy Research Center, Tsinghua University, Beijing, China, 2014, report number F2014-AHF-060.

[71] Wang H, Zhang X and Ouyang M, Energy consumption of electric vehicles based on real-world driving patterns: a case study of Beijing, Applied Energy vol. 157, pp. 710-719, 2015

[72] Greaves S, Backman H and Ellison A, An empirical assessment of the feasibility of battery electric vehicles for day-to-day driving Transportation Research Part A, Vol. 66, pp. 226–237, 2014

[73] Smart J, Bradley T and Salisbury S, Actual versus estimated utility factor of a large set of privately owned Chevrolet volts. SAE world congress 2014.

[74] Tal, G, Nicholas M, Davies J and Woodjack J, Charging behavior impacts on electric VMT: Evidence from a 2013 California drivers survey, TRB 2014 annual meeting

[75] Plötz P, Funke S and Jochem P, Real-world fuel economy and CO_2 emissions of plug-in hybrid electric vehicles, working paper sustainability and innovation No. S 1/2015

[76] Johansson H et al., Körsätt 98, inledande studie av körmönster och avgasutsläpp i tätort samt utveckling av metod för att mäta förändringar av acceleration och hastighet kring korsningar. Vägverket Publikation 1999:137, 1999. (in Swedish)

[77] Vägvärket, LundaISA, Sammanfattning av ISA-projektet I Lund. Vägvärket Publication 2002:94, Borlänge, Sweden, 2002 (in Swedish)

[78] Society of Automotive Engineers (SAE). Recommended practice for measuring the exhaust emissions and fuel economy of hybrid-electric vehicles. Hybrid Committee, March 1999, SAE-J1711.

[79] Al-Alawi B M and Bradley T H, Review of hybrid, plug-in hybrid, and electric vehicle market modeling studies, Renewable and Sustainable Energy Reviews, vol. 21, pp. 190-203, 2013.

[80] Ott T, Zurbriggen F, Onder C and Guzzella L, Cycle-averaged efficiency of hybrid electric vehicles, Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, vol. 227, no. 1, pp. 78–86, 2013.

[81] Saxena S, Phadke A, Gopal A and Srinivasan V, Understanding fuel savings mechanisms from hybrid vehicles to guide optimal battery sizing for India, International Journal of Powertrains, vol. 3, no 3, 2014.

[82] Gao Y, Chen L and Ehsani M, Investigation of the Effectiveness of Regenerative Braking for EV and HEV, Technical Paper 1999-01-2910, 1999

[83] Christidis P, Hernandez H, Georgakaki A and Peteves S D, Hybrids for road transport, Status and prospects of hybrid t echnology and the regeneration of energy in road vehicles, European Commission, Technical Report EUR 21743 EN, 2005.

[84] Sovran G and Blaser D, Quantifying the Potential Impacts of Regenerative Braking on a Vehicle's Tractive-Fuel Consumption for the U.S., European, and Japanese Driving Schedules, SAE Technical Paper 2006-01-0664, 2006.

[85] Martins L, Brito J, Rocha A and Martins J, Regenerative braking potential and energy simulations for a Plug-in hybrid electric vehicle under real driving conditions, Proceedings of IMECE09: 2009 ASME International Mechanical Engineering Congress and Exposition November 13-19, 2009, Lake Buena Vista, Florida, USA.

[86] Wang B, Xu M and Yang L, Study on the economic and environmental benefits of different EV powertrain topologies, Energy Conversion and Management, vol. 86, pp. 916–926, 2014.

[87] Saxena S, Phadke A and Gopal A, Understanding the fuel savings potential from deploying hybrid cars in China, Applied Energy, vol. 113, pp. 1127–1133, 2014.

[88] Lv C, Zhang J, Li Y and Yuan Y, Mechanism analysis and evaluation methodology of regenerative braking contribution to energy efficiency improvement of electrified vehicles, Energy Conversion and Management, vol. 92, pp. 469–482, 2015.

[89] Mock P, German J, Bandivadekar A, Riemersma I, Ligterink N and Lambrecht U, From laboratory to road - A comparison of official and 'real-world' fuel consumption and CO_2 values for cars in Europe and the United States, White paper ICCT, 2013.

[90] Smokers R, Vermeulen R, Mieghem R, Gense R, Skinner J, Fergusson M, Mackay E, Brink P, Fontaras G and Samaras Z, Review and analysis of the reduction potential and costs of technological and other measures to reduce CO2-emissions from passenger cars, Report to the European Commission, 2006.

[91] Boriboonsomsin K and Barth M, Impacts of Road Grade on Fuel Consumption and Carbon Dioxide Emissions Evidenced by Use of Advanced Navigation Systems, Transportation Research Record: Journal of the Transportation Research Board, vol. 2139, pp. 21–30, 2009.

[92] Frey H C, Zhang K and Rouphail N M, Fuel Use and Emissions Comparisons for Alternative Routes, Time of Day, Road Grade, and Vehicles Based on In-Use Measurements, Environmental Science and Technology, vol. 42, no. 7, pp. 2483–2489, 2008.

[93] Park S and Rakha H, Energy and Environmental Impacts of Roadway Grades, Transportation Research Record: Journal of the Transportation Research Board, vol. 1987, pp. 148–160, 2006.

[94] Wood E, Burton E, Duran A and Gonder J, Contribution of Road Grade to the Energy Use of Modern Automobiles Across Large Datasets of Real-World Drive Cycles, SAE International, Warrendale, PA, SAE Technical Paper 2014-01-1789, 2014.

[95] Travesset-Baro O, Rosas-Casals M and Jover E, Transport energy consumption in mountainous roads. A comparative case study for internal combustion engines and electric vehicles in Andorra, Transportation Research Part D, vol. 34, pp. 16–26, 2015.

[96] Lorf C, Martínez-Botas R F, Howey D A, Lytton L and Cussons B, Comparative analysis of the energy consumption and CO2 emissions of 40 electric, plug-in hybrid electric, hybrid electric and internal combustion engine vehicles, Transportation Research Part D, vol. 23, pp. 12–19, 2013.

[97] Karlsson S. The Swedish car movement data project: final report. PRT report 2013:1, Chalmers University of Technology, Gothenburg. <http://publications. lib.chalmers. se/records/fulltext/187380 /local_187380.pdf>; 2013.

[98] Karlsson S, Kullingsjö L-H. GPS measurement of Swedish car movements for assessment of possible electrification. In: Proceedings of EVS27 symposium, Barcelona, Spain. <http://publications.lib.chalmers.se /records/fulltext/ 184575/local_184575.pdf>; 2013.

[99] Jarlemark P, Emardson R, Errors in recorded coordinates from GPS receivers in vehicles and the possibility for a posteriori corrections. SP Technical Research Institute of Sweden; 2014.

[100] Santini D, Gallagher K and Nelson P. Modeling of manufacturing costs of lithium-ion batteries for HEVs, PHEVs, and EVs. In: Proceedings to EVS25, Shenzhen, China; 2010.

[101] Moawad A, Kim N, Shidore N and Rousseau A, Assessment of vehicle sizing, energy consumption, and cost through large-scale simulation of advanced vehicle technologies. Argonne National Laboratory, March 2016, ANL/ESD-15/28

[102] Elgowainy A, Han J, Ward J, Joseck F, Gohlke D, Lindauer A, Ramsden T, Biddy M, Alexander M, Barnhart S, Sutherland I, Verduzco L and Wallington T J, Cradle-to-grave lifecycle analysis of U.S. Light-duty Vehicle-fuel Pathways: A greenhouse gas emissions and economic assessment of current (2015) and future (2025-2030) technologies, Argonne National Laboratory, 2016.

[103] De Vroey, L, Jahn, R, El Baghdadi, M and Van Mierlo, J, 2013. Plug-to-wheel energy balance-results of a two years' experience behind the wheel of electric vehicles. World Electric Vehicle Symposium and Exhibition (EVS27); November 2013; Barcelona, Spain. pp. 1–5.

[104] Karlsson S, Optimal size of PHEV batteries from a consumer perspective – estimation using car movement data and implications for data harvesting, in WEVA World Electric Vehicle Journal, vol. 3, WEVA World Electric Vehicle Journal, 2009.

[105] IEA, Key world energy statistics 2011, ISBN: 9789264179875 (PDF).

[106] IEA, Key world energy statistics 2012, ISBN: 9789264196414 (PDF).

[107] IEA, Key world energy statistics 2013, available at: http://www.energiatalgud.ee/img_auth.php/e/ef /IEA._Key_World_Energy_Statistics._2013.pdf accessed January 2016.

[108] IEA, Key world energy statistics 2014, ISBN: 9789264223998 (PDF).

[109] IEA, Key world energy statistics 2015, available at: https://www.iea.org/publications/freepublications /publication/KeyWorld_Statistics_2015.pdf accessed January 2016

[110] Laurikko J, Granström R, Haakana A. Realistic estimates of EV range based on extensive laboratory and field tests in Nordic climate conditions. In: Proceedings of EVS27 symposium, Barcelona, Spain; 2013.

[111] US department of energy. <www.fueleconomy.com>; 2014 [accessed 27.11.14].

[112] Karlsson S, The potential for a BEV in the two-car household. In: Proceedings of the 29th Electric Vehicle Symposium (EVS29), Montréal, Québec, Canada, June 19–22, 2016.

[113] BIL Sweden. <www.bilsweden.se >; 2017 [accessed 07.02.17].

[114] Power circle. <www.elbilsstatistik.se >; 2017 [accessed 07.02.17].