THESIS FOR THE DEGREE OF LICENTIATE OF PHILOSOPHY

Assessment of PHEV potential to reduce fuel use in Sweden using GPS data for car movements

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Department of Energy and Environment

Division of Physical Resource Theory

Chalmers University of Technology

Göteborg, Sweden 2014

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Printed by Chalmers Reproservice

Göteborg, Sweden 2014

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ABSTRACT

Roughly 30% of Sweden's total greenhouse gas emissions originate from transport. These emissions need to be reduced to be able to reach the by The Swedish parliament adopted goal of a carbon neutral society in 2050. The plug-in hybrid electric vehicle (PHEV) allows 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 insecurity. But the expected share of electric driving for a given battery size is dependent on the individual car's movement. In this thesis we assess the potential to reduce fuel use in Swedish passenger car transport through an introduction of plug-in hybrid electric vehicles (PHEVs) by utilising a comprehensive data set on Swedish car movements logged by GPS.

In paper I we analyse how individuality in movement patterns may affect the battery design and viability of PHEVs and enable electrification of vehicle kilometres in Sweden. We found that both optimal battery sizes and savings vary substantially between individual car movement patterns. As expected better economic conditions meant more cars with batteries, larger batteries and larger savings. Better charging options lead to a higher battery utilization and therefore to more cars viable as PHEVs and higher savings. We also found that the PHEV viability is dependent on the battery-capacity-independent investment cost, which if high can delay the introduction of PHEVs to the market. Due to good possibilities for recharging, regularity in movement pattern and in general higher yearly mileage, the commuters are on average reaching higher savings and their cars are in majority among the first to be viable as PHEVs. Therefore, commuters are likely to be the first drivers for whom the PHEV will be cost-effective.

Paper II focuses on how different actors' interest possibly could influence battery sizing and the resulting fleet TCO savings, electric drive fraction, and number of PHEVs. Our results suggest that different objectives among stakeholder could result in very different optimal battery sizes. Some interest can therefore be conflicting, while others can work together. The resulting fleet could for example reach a high share of PHEVs without reaching a high share of electric driving.

The aim of paper III was to analyse the possibilities for regeneration in Swedish car driving. We found that the individual differences in energy use at the wheel and in braking power are large. Also the discrepancies in braking power profile between test cycles and real world driving were found to be considerable.

Keywords: PHEV, battery size, GPS-logging, Individual movement pattern, PHEV viability, PHEV potential, Sweden, electrification

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”. To be submitted to Applied energy.

II. Lars-Henrik Kullingsjö, Sten Karlsson and Frances Sprei, “Conflicting Interests in Defining an ‘Optimal’ Battery Size when Introducing the PHEV. In proceedings to EVS27, Barcelona, Spain, November 17-20, 2013.

III. Lars-Henrik Kullingsjö and Sten Karlsson “The Possibility for Energy Regeneration by Electrification in Swedish Car Driving”. In proceedings to EVS27 Barcelona, Spain, November 17-20, 2013.

ACKNOWLEDGEMENTS

Thank you Sten for guidance and patience, I am very happy to have you as my supervisor. Thank you Frances for being my assistant supervisor and for many valuable discussions. I would also like to thank the rest of Physical Resource Theory. You all make this a great place to work at.

I also would like to thank my family, you mean a lot to me.

And thank you Christine for everything. You are still the best!

Lars-Henrik Björnsson

Göteborg, May 2014

CONTENTS

1 INTRODUCTION

Roughly 30% of Sweden's total greenhouse gas emissions originate from transport [1]. The Swedish parliament has adopted a vision to reach a carbon neutral society in 2050 [2], and to reduce the greenhouse gas emissions from transport the parliament initiated an investigation on how too reach a fossil independent vehicle fleet by 2030 [3]. 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 to increase the use of fossil free energy and to increase the energy efficiency of vehicles [2]. The work of this thesis is centred around the latter with the aim to assess the potential to reduce fuel use in Swedish passenger car transport through an introduction of plug-in hybrid electric vehicles (PHEVs). This is done by utilising a comprehensive data set on Swedish car movements.

Increased electrification of road transport is one way to increase the energy efficiency of vehicles and to reduce the use of fossil fuels. The overall reduction in CO_2 emissions is also dependent on the emissions in electricity production.[1] In the EU these 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 [2]. Even without a trading scheme, decarbonizing the electricity production is judged a simpler task than decarbonizing for road transport. Switching to electric energy in transport should therefore facilitate an easier transition [4].

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.[2] The gasoline car later became the dominating technology but the electric car has now and then been discussed as a possible alternative. For example as an energy security measure in connection to the oil crises in the 1970's,[3] but also as an option to increase air quality and public health in cities.[4] These advantages are still well recognised and together with the potential to reduce greenhouse gas emissions they make electrification an interesting option to current conventional cars.

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[1] The production of fossil fuels has upside emissions in the order of 20%.

[2] 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 [5].

[3] 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 incentives improvements of batteries, motors and other hybrid and electric components [6]

[4] For example, in the introduction of the Zero-Emission Vehicle mandate adopted 1990 by the California Air resource board further discussed in [7].

1.1 THE PLUG-IN HYBRID ELECTRIC VEHICLE (PHEV)

A major advantage of the electric car is the roughly three times higher energy efficiency (tank to wheel) compared to gasoline and diesel cars. One of the most well known drawbacks of the fully electric car or battery electric vehicle (henceforth BEV) is however the limited range caused by the low energy density and high cost of current batteries. In combination with long recharging times this has since long been seen as a major obstacle for the technology. Different types of hybrid cars combining 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.[5] The today most common hybrid variant, the so called hybrid electric vehicle (HEV), has a rather small battery. It uses the engine as its primary source of energy and cannot be recharged from the grid. Still by temporarily storing energy in the battery, the HEV can recover braking energy and let the engine work more efficiently. The plug-in hybrid electric vehicle (PHEV) is an HEV with a larger energy battery that can be charged with electricity from the grid. Although the battery is smaller than in a BEV, it is large enough to supply grid energy for a significant share of the driving between rechargings. 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. With a PHEV it is thus possible to substitute a large share of the fuel normally used in a conventional or hybrid car by electricity from the grid without being limited in range.

A number of PHEV models are today available on the market such as Toyota Prius PHEV, GM's Chevrolet Volt/Opel Ampera, Volvo V60 and Mitsubishi Outlander. The differences in between models can be substantial since there are many possible driveline designs. In a *parallel hybrid* the electric motor and the engine can individually power the vehicle but they can in many designs also work together simultaneously (Volvo V60, Toyota Prius[6]). In a *series hybrid* only the electric motor can drive the vehicle but an internal combustion engine can via a generator produce electricity to increase the range (Chevrolet Volt/Opel Ampera[7]). It is also possible to combine the two so that the vehicle has both an electric and a mechanical link between the engine and the wheels. These vehicles are then sometimes called *series-parallel hybrids* (Mitsubishi Outlander). [9]

[5] 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 [8].
[6] The Toyota Prius is primarily run in parallel mode but the engine can be used to charge the battery.
[7] The Chevrolet Volt/Opel Ampera is primarily run as a series hybrid but the engine also has a mechanical link to the wheel.

1.2 CAR MOVEMENT DATA

A large variety of data has since long been collected to be able to analyse different aspects of road traffic. Travel surveys have been used to better understand how and where to people travel and the purpose of the trip. Measurements of total traffic flows on roads have been conducted to for example increase knowledge about road capacity limitations. More detailed data have been used to create car emission models and to analyse driving behaviour.

However in the assessment of electric vehicles such as BEVs and PHEVs new types of data become interesting. Because of the limited range of the battery the trip distance becomes important but also the availability of charging infrastructure and time available for recharging. Fast charging is also discussed but its infrastructure is expensive and it might also shorten the battery life. It thus becomes interesting to understand where and for how long the car is parked. For the PHEV this type of data is of great importance to estimate the expected share of electric driving for different battery sizes and the potential societal benefits of the PHEV in terms of reduced fuel use, greenhouse gas emission, local pollution etc. The share of electric driving also affects the total cost of ownership of the PHEV. The cost for battery capacity is still relatively high, resulting in a high investment cost, while the distance driven on electricity results in cheaper running costs. The viability of the PHEV is thus highly dependent on the utilisation rate of the available battery capacity. Data on individual car movement patterns is therefore of importance in battery design and estimation of consumer viability [10, 11, 12]. Since the driving varies over time [13], data covering longer time periods rather than just a day or a week are needed.

Many countries are regularly performing national or regional travel surveys, for example giving data on origin, destination, purpose and time of the travel, but they are in most cases not recording the movements of cars but of persons only. The measurement period is often limited to one day or a week and the quality of this often self-reported (using questionnaires or interviews) data has also been recognized to give an underestimate of the travelling, due to a certain share of non-reported trips [14, 15].

A more detailed picture of car movement is possible to achieve by measurement of time, speed and position with GPS (Global Positioning System) equipment. When conducted such measurements mostly have been sparse, for specific purposes or focusing on a smaller area, though. Earlier measurements include for example a one-day measurement in St Louis [16]. 450 cars were logged before and after (hypothetical) tolls were charged in Seattle metropolitan area [17]. Another example is the Commute Atlanta project involving GPS measurements of commuting in the Atlanta area with the main objective to assess the effects of different cost schemes. The first phase of the project included up to one year of logging of

445 cars from 273 households [18]. In Australia cars have been tracked to analyse driver behaviour such as speeding [19, 20]. In Italy a unique commercial dataset includes at least 650 000 cars logged for insurance profiling. The measurement is performed by the company Octotelematics [21]. Travel surveys improved with GPS equipment, but still not focusing on cars, have been performed or are planned in Baltimore, Washington, Chicago, and California [22-25]. In Canada, Department of Geography at University of Winnipeg has under a number of programs been logging cars in the Winnipeg area with GPS for up to 12 months. This has been done with the purpose to for instance assess the prerequisites for electrification with PHEVs [26 27, 28]. Besides the project in Winnipeg also the data collected in St. Louis, Seattle and Atlanta and part the Italian data have each independently been used in different assessments of viability of either BEVs or PHEVs [11, 29, 30, 31].

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 behaviour and emissions [32]. 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 where the purpose was to analyse the impact and acceptability of Intelligent Speed Adaptation (ISA) equipment [33]. Here about 200 cars were logged for about 100 days. Although valuable, both these datasets are covering limited geographic regions and are today over ten years old.

2 ASSESSING THE POTENTIAL FOR THE PHEV IN SWEDISH DRIVING

There are earlier studies assessing the role of movement patterns for viability and potential societal benefits of PHEVs, for example assessing the benefits of increased possibilities to charging, comparing viability compared to conventional cars and BEVs for different gasoline and battery cost scenarios. For a short review see chapter 2 in [34]. Many studies that have focused on movement patterns have utilized simplified statistics for the movement pattern in the form of statistical distribution of daily driving distances or even only one figure, the average daily driving distance, although there are exceptions [29, 35].

In this thesis we utilize real world driving data to assess the potential to reduce fuel use in Swedish passenger car transport through an introduction of plug-in hybrid electric vehicles (PHEVs).

2.1 THE SWEDISH CAR MOVEMENT DATA PROJECT

This work is based on the utilization of a recently collected database over Swedish car movements gathered with the specific purpose to assess different aspects of electromobility in Sweden. In the measurement project over 700 cars have had GPS equipment installed for between on and three months per vehicle. The logged cars where relatively new (of model year 2002 or newer), they where randomly selected from the Swedish vehicle register from Västra Götaland county and 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. It is probably reasonably representative for Sweden in terms of movement patterns, car ownership and mixture of larger (for example it includes Gothenburg, the second-largest town in Sweden) and smaller towns and rural areas. The loggings were done in campaigns with about 100 cars each and in all seasons from June 2010 to September 2012. The cars where logged with a high relatively high frequency of 2.5 Hz to also make it possible to use the data for more detailed analysis of the driving. The logged data includes for example time, position (latitude, longitude and altitude) and velocity (speed and direction). In a questionnaire sent to all participants some complementary data on the logged cars, their drivers and households, such as for example age of the drivers and number of cars in the household. For a more extensive description of the measurement project see [36, 37].

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

To be able to reach a larger market share one would expect the total cost of ownership (TCO) of the PHEV to be comparable to the alternatives. Compared to a HEV, the PHEV have a higher investment cost but also lower running costs. The higher investment cost can be divided into the cost for extra battery capacity and the cost independent of battery capacity needed for turning an HEV into a PHEV. The latter could for example include the cost for a charger and for any performance increase of the electric driveline, but also possible cost savings from downsizing of the fuel engine. As mentioned above both the investment cost and the savings from the share of electric driving are dependent on the battery size. Making the viability of the PHEV dependent on the sizing utilization of the battery range. It is therefore interesting to study the benefits for the individual driver at different levels of battery range.

The aim of Paper I is to use representative car movement data from Sweden to analyse how individuality in movement patterns, under various charging infrastructure and techno-economic conditions, may affect the battery design and viability of PHEVs and enable electrification of driven distance in Sweden.

METHOD

The modelled PHEV is assumed to have an energy battery able to deliver the power needed to drive the car in a pure charge-depleting (CD) mode until its useful energy is emptied and the driveline goes into a charge-sustaining (CS) hybrid mode.[8] Although the energy use in reality varies with driving conditions as speed, driving aggressiveness, load, etc., the modelled PHEV is for simplicity assumed to have a constant energy consumption e_e [$/km] in CD mode and e_f [$/km] in CS mode.

The battery utilisation for an example car with its individual movement pattern is shown in Fig 1 in terms of marginal electric distance (MED) per extra km of all electric range (AER). The modelled PHEV is assumed to be charged as soon as there is a parking period of 10 h or longer in the measured movement pattern (emulating recharging roughly once a day).

[8] Thus ignoring the possibility of using a blended CD mode where both fuel and electricity is used.

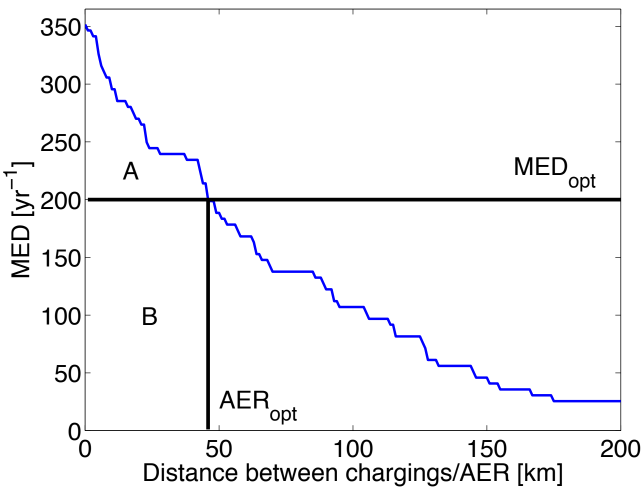

Figure 1: The resulting *MED* as a function of battery size for a real individual movement pattern when assuming the battery is fully charged after every parking period longer than 10h.

In this model the total savings from lower running costs are directly proportional to the total distance driven on electricity and the MED is thus proportional to the marginal savings per extra km of AER. It then becomes natural to discuss different battery cost scenarios in terms of total electric distance needed to offset the investment. The actual cost will however be determined by techno-economic parameters such as marginal battery capacity cost [$/kWh] energy efficiency e_e, depth of discharge, etc. The solid horizontal line in Fig 1 depicts an here assumed constant marginal cost for battery range corresponding to 200 km of electric driving per year. Since the MED curve is monotonically decreasing, the optimal battery size, in terms of minimized total cost of ownership, is found when the horizontal line crosses the MED curve. We denote the marginal cost expressed in extra kilometres of electric driving MED_{opt} since it points out the value of the MED curve that gives the optimal battery size AER_{opt}. Area A+B is then the yearly distance driven on electricity with this battery.

Equipped with an optimal battery size the car will reach its minimum TCO as PHEV. This cost is, together with the yearly cost for the battery-capacity independent investment αI_F, compared to the alternative of purchasing a HEV. The PHEV is economically viable if the TCO is favourable to that of the HEV, Fig 2.

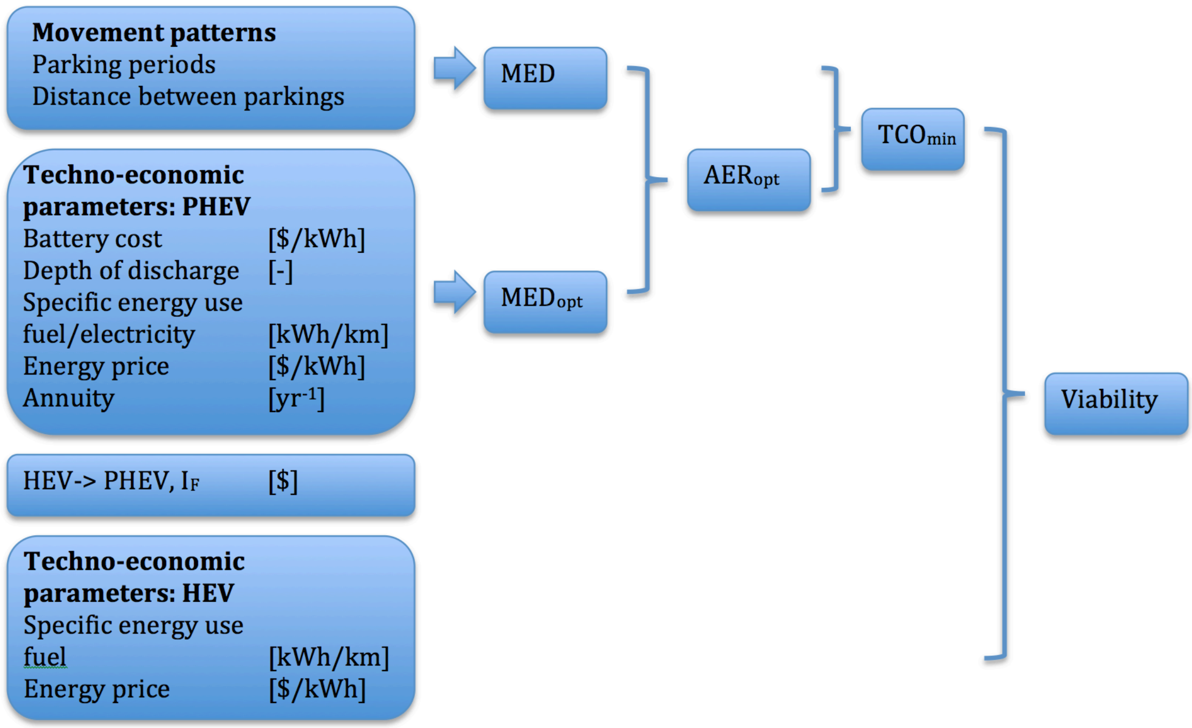

Figure 2: Methodological overview. The MED is derived from the movement patterns and together with MED_{opt} (the minimum MED needed to offset the marginal cost for battery range derived from the techno-economic parameters) an optimal battery size is found. The car is then reaching its lowest TCO as PHEV and if it also can offset the battery independent investment cost it will be favourable to the HEV and considered viable.

MAIN FINDINGS

- Both PHEV optimal battery sizes and savings vary substantially between individual movement patterns and with different levels of $MED_{opt,}$, Fig 3.
- Better techno-economic conditions i.e. the shorter marginal electric distance (*MED*) needed to offset the battery investment means more cars with batteries, larger batteries and larger savings, Fig 3-4.
- Better charging options leads to a higher battery utilization and therefore to more cars viable as PHEVs and higher savings, Fig 3-4.
- The PHEV viability is dependent on the battery-capacity-independent investment cost and a higher cost can therefore delay and slow down the introduction of PHEVs to the market, Fig 4.
- Due to good possibilities for recharging, regularity in movement pattern and in general higher yearly mileage the commuters are on average reaching higher savings and are in majority among the first cars to be viable as PHEVs. Therefore commuters are likely to be the first drivers for whom the PHEV will be cost-effective.

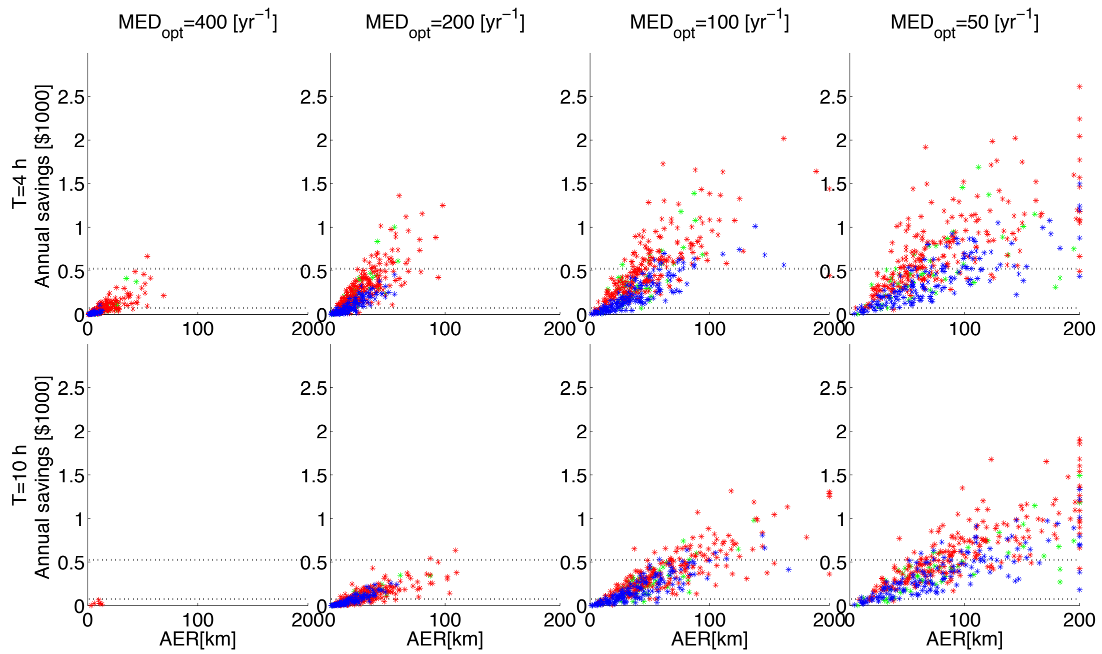

Figure 3: Battery optimization of individual movement patterns and their corresponding yearly savings from the battery investment. Each point represents an individual movement pattern; the color of the marker indicates if the car commutes (red) or not (blue) or if commuting status is unknown (green). Results are shown for minimum marginal electric distance MED_{opt} = 400, 200, 100 and 50 yr^{-1} and minimum parking period T = 10 and 4 hours. The two horizontal dotted lines indicate the savings needed to offset an I_F of $500 and $3500, respectively.

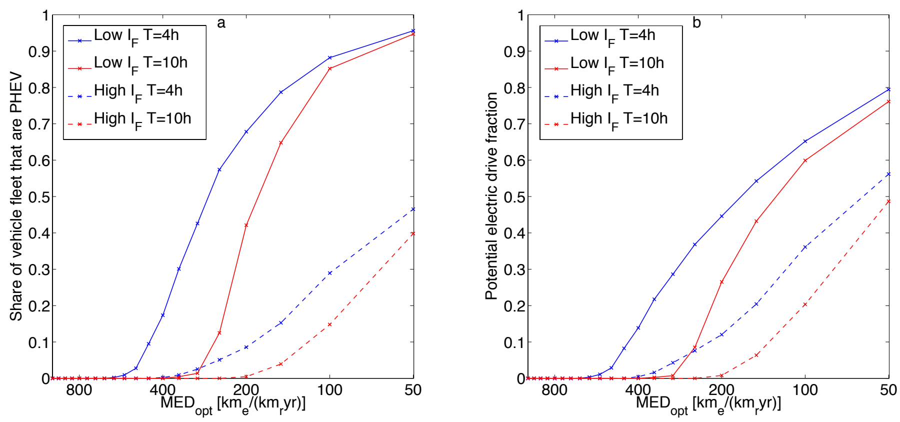

Figure 4: PHEV share of the investigated car fleet (of 432 cars(a) and potential electric drive fraction for the car fleet (b), for different charging options and battery independent investment cost (Low I_F = $500 and High I_F = $3500), as a function of the viability parameter MED_{opt}.

2.3 Paper II: Conflicting interests in defining an 'optimal' battery size when introducing the PHEV?

Different actors can have different interests and therefore have different objectives when for instance a new technology such as the PHEV is introduced. For the society at large, maximising the PHEVs' electric driving is beneficial in terms of reduced greenhouse gas emissions, less local pollution and increased energy security. Most car owners however are likely to favour a lower TCO over a high share of electric driving (i.e. they don't want a too big battery since this would be expensive). Car manufacturers are probably not either primarily interested in the societal benefits of the PHEV, but to make profit and as means to sell as many cars as possible. The manufacturer could also have good reasons to position their brands in electromobility and thereby plan for future increased sales of PHEVs in reaction to anticipated future changes in market conditions and energy/fuel/emissions regulation. The possibility that stakeholders have varying expectations of the PHEV as a technology is interesting. To what extent are theses interests conflicting or converging?

The aim of paper II has been to under a range of economic scenarios explore how different objective functions possibly reflecting different actors' interest may influence the resulting optimal battery size, the fleet TCO savings, electric drive fraction, and number of PHEVs.

METHOD

The method is based on the battery utilization model used in paper I but now with three different objective functions for battery optimization possibly reflecting different actors' interests. The three objective functions are maximization of the vehicle fleet's: TCO savings, total electric drive fraction, and the number of PHEVs.

MAIN FINDINGS

- Possible diverse objectives among stakeholder could result in very different optimal battery sizes. Some interests can be conflicting, while others can work together.
- Maximizing the number of PHEVs results in a smaller battery size and a lower share of electric driving, while the electric driving is maximized with fewer PHEVs with larger batteries.

2.4 Paper III: The possibility for energy regeneration by electrification in Swedish car driving

The ability to regenerate energy when braking is a valuable advantage of most hybrid and fully electric vehicles. Detailed studies of the possibilities for brake-energy regeneration in real world driving increase the understanding of potential gains of car-electrification How much energy that can be regenerated depends mainly on the type of driving and the capacity of the electric driveline. What potentially can be recovered is the energy going into kinetic and potential energy of the car. The data in the car movement database includes the altitude, which makes it possible to also track the potential energy in Swedish driving. In standardised test cycles used in emission labelling the altitude is missing, though.

The aim of paper III has been to analyse the possibilities for regeneration in Swedish driving by utilizing the highly detailed and representative data set of individual car movements and compare to the result on used test cycles.

METHOD

We utilize the highly detailed speed and altitude data from the measured Swedish car movements in a model of the power and energy fluxes at the wheels in a normalized car. The speed profiles of the NEDC and WLTP test cycles are then used for comparison.[9]

To be able to follow the measured movement pattern in terms of speed $v(t)$ and road gradient $\alpha(t)$, the power $P(t)$ at the wheels is given by:

$$P(t) = P_{acc}(t) + P_{air}(t) + P_{roll}(t) + P_{grade}(t) \qquad (1)$$

$$P_{acc}(t) = m * a(t) * v(t) \qquad (2)$$

$$P_{air}(t) = \frac{1}{2}\rho_a * A * C_d * v^3(t) \qquad (3)$$

$$P_{roll}(t) = c_r * m * g * \cos(\alpha(t)) * v(t) \qquad (4)$$

$$P_{grade}(t) = m * g * sin(\alpha(t)) * v(t) \qquad (5)$$

Here P_{acc} is the power needed/gained to accelerate/decelerate the vehicle. P_{air} and P_{roll} are the power required to overcome air drag and rolling resistance respectively and P_{grade} the power required/gained in case of a road gradient. The term m is the mass of the vehicle, $a(t)$ is the acceleration at time t, ρ_a is the density of the surrounding air, A is the frontal area of the car, C_d is the air drag coefficient, c_r is the rolling friction coefficient and g is the acceleration due to gravity.

The total amount of energy that potentially can be regenerated, E_{regpot}, is what is braked away, which is identified by:

$$E_{regpot} = E_{brake} = \int P(t)dt\,,\ when\, P(t) < 0 \qquad (6)$$

[9] The New European Driving Cycle (NEDC), which currently is used in the EU, is a driving cycle designed to assess the emission levels of car engines and fuel economy in passenger cars. A new test cycle is however being developed to better represent the conditions in real world driving, namely the Worldwide harmonized Light vehicles Test Procedures (WLTP).

The share of the braking energy that actually can be recovered is dependent on the driveline design and its efficiency. This is illustrated by the analysis of two simple exemplary drivelines, a battery electric vehicle and a mild hybrid, each with assumed levels of power limitations and energy efficiency.

MAIN FINDINGS

- There are large differences between the individual drivings, both in the distribution of energy losses and in braking power distribution, Fig 5-6. The share of energy lost through braking in the ordinary car varies between 12 and 63 %.
- Although the share of energy lost through braking in general increases with lower average speed (i.e. roughly urban driving), a main determinant for the yearly regeneration potential is the yearly distance driven.
- The inclusion of altitude increases the regeneration potential by over 10%.
- The WLTP and especially the NEDC test cycle have generally a lower power level in the braking compared to real world driving, Fig 6.

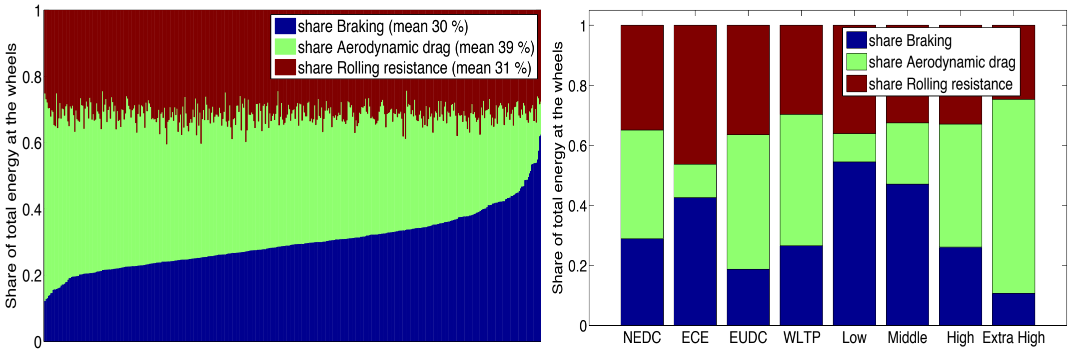

Figure 5: a) For the assumed car, for each movement pattern, the shares of energy lost at the wheels through braking, air drag and rolling resistance, respectively. Sorted after share of energy lost through braking. b) The corresponding shares when the car follows the NEDC, ECE, EUDC, WLTP, WLTP low, WLTP middle, WLTP high and WLTP extra high test cycle, respectively.

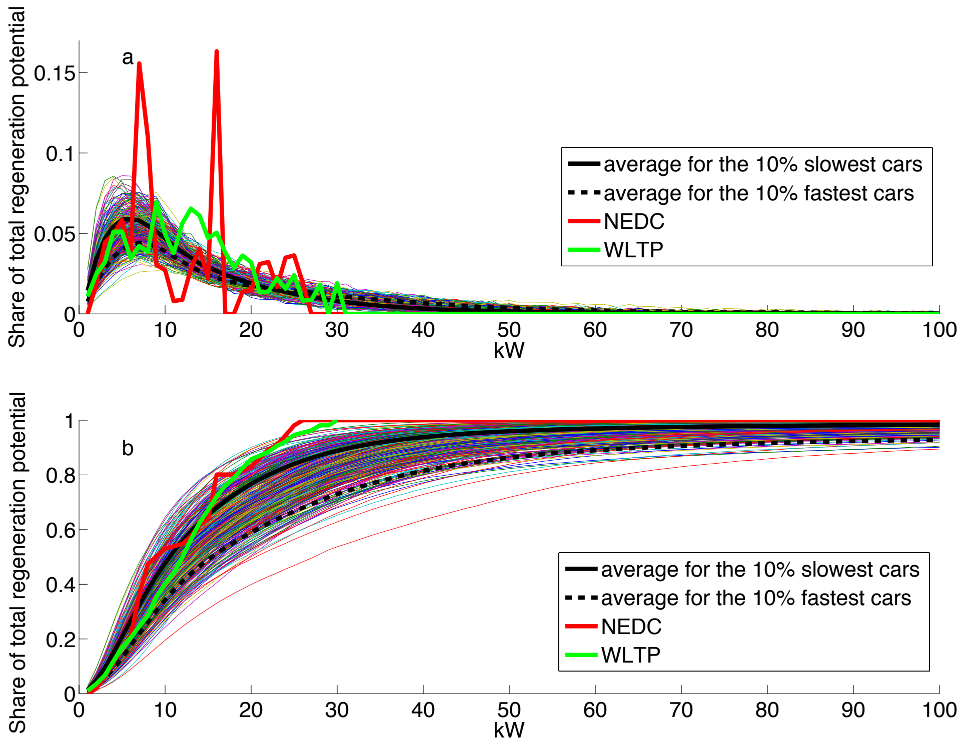

Figure 6: For the assumed car, for each movement pattern as function of power level a) the share, and b) the cumulative share, respectively, of the energy regeneration potential.

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