10

ELECTRIC VEHICLES AND DRIVING PATTERNS

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INTRODUCTION

Neither the magnitude of travelling, nor travelling patterns, are given. The movements of people are developing in interplay between demand for mobility, available transport technology and general economic and environmental constraints in society.

The magnitude of personal travel in the industrialised society has increased tremendously. In Sweden, the average travelled distance per person is currently around 40 km per day (see Figure 10.1). Travelling distances are related to speed. Studies show that the time spent on travel tends to be relatively constant at around one hour a day on average. The historical development of new transport technology such as trains and cars has increased the speed and comfort of travelling, and hence also the distances travelled. Airplanes make it convenient to travel even up to tens of thousands of kilometres for business meetings, visits or vacation. Globalised industries and charter tourism rely to a large extent on the speed of airplanes. And increased globalisation spurs further demand for air traffic.

This development demonstrates that technology and travelling patterns are not independent, nor is one causing the other in a linear way, rather they cause each other and coevolve. It is obvious that the use of oil has had an impact on our travelling patterns. To what extent could a change in technology such as electrification of vehicles reshape our travel behaviour and choice of transport modes? Electric high-speed trains already compete successfully with air transport on medium distances. Can electrification of bicycles lead to an upheaval of biking? Will new types of small electric vehicles transform urban transport? (See also Chapter 2 and 11 on the coevolution of technology and user practices.)

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As mentioned above, the causality also goes the other way around; travel behaviour has an effect on technology choice. This chapter takes the current travelling patterns as starting point. To what extent can the vehicles, now fuelled by oil, be electrified, or, to put it differently, how much of our travelling is suitable for electrification?

Some travelling modes are already extensively electrified, such as various rail traffic systems, which are bound to a track system, making energy supply by electricity technically convenient. Also some vehicles frequently operating specified routes, such as city buses, are already electrified or are now considered for electrification. Personal vehicles, on the other hand, which dominate passenger transport (Figure 10.1), are characterised by their irregular and mostly non-frequent driving pattern. And even if some vehicles are used regularly on specific routes, for instance when used extensively for commuting, the option to also use it for possible upcoming specific, irregular or infrequent trips, is a highly valued feature of the personal vehicle.

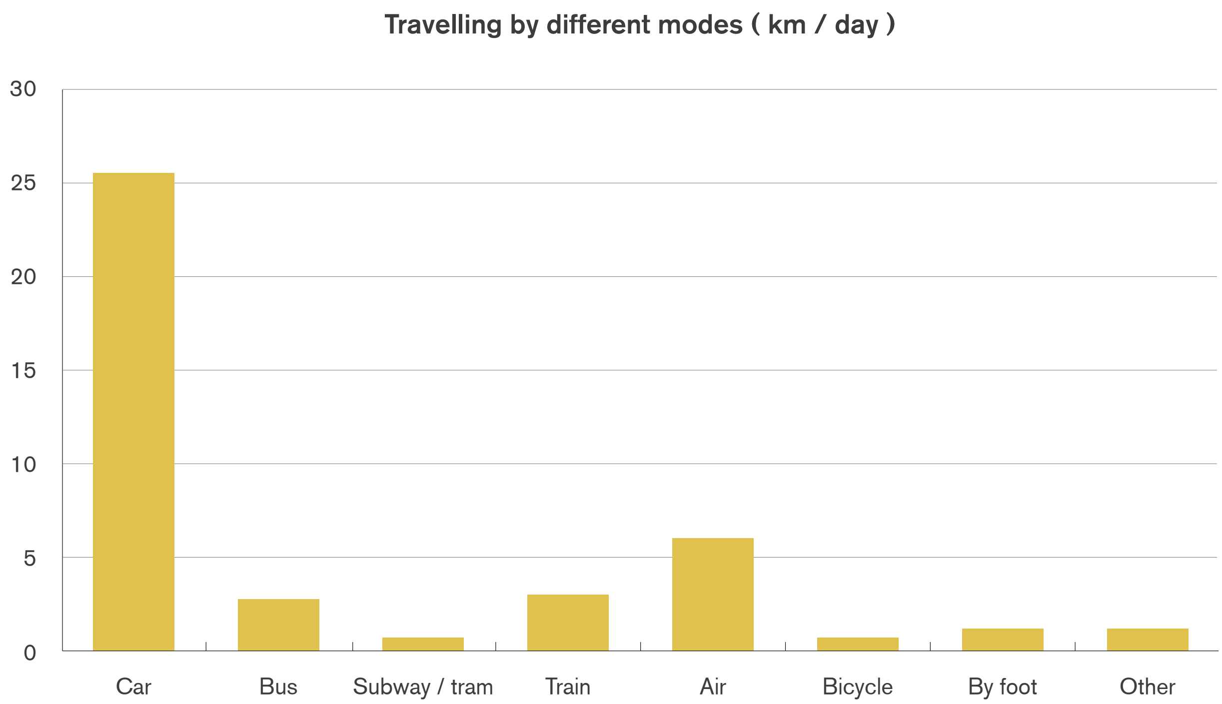


Figure 10.1 Travelling in Sweden divided by transport mode. (Source: RES 2005-2006, The national travel survey. SIKA Statistics 2007:19)

Today the technical option for electrification of personal vehicles is by an on-board battery. The battery cost and energy density limit the range of pure battery electric vehicles. Currently the range for commercially available electric vehicles is often around 150 km under favourable conditions.

The use of bicycles and mopeds is less sensitive to these range limitations. Bicycles are therefore the fastest expanding category of electromobility, with over one hundred millions of electric bicycles in China today. In Europe, a total of 700 000 were sold in 2010.[1] Some cars are not used privately, but are part of fleets with

1 Electric bicycle (Wikipedia)

specific forms of utilization. It can be cars used in various services provided by the municipality, for instance, elderly care. This often implies a reasonably well-known upper limit of the daily driving as well as parking in a specific place during the night. Due to these inherent limitations and the predictability of movements, such fleet vehicles are in many cases among the most appropriate for electrification.

The range limitations of current electric vehicles may also be circumvented by transforming the organisation of passenger transport. Car sharing schemes are now increasingly attracting attention in different cities in the world. By such schemes the user may have access to a range of vehicles more suitable for each specific occasion. For instance, electric vehicles could be used for the many short trips demanded and a fuel-driven car for the few long journeys (compare the discussion on business models in Chapter 12).

In the remainder of this chapter we focus on privately owned cars which make up the major share of travelling. Instead of reorganising transport, there is an option to adapt vehicle technology to prevailing driving patterns. Plug-in-hybrids (PHEVs) is a technology that allow for some adaptation and partial electrification. Taking departure in the current use of cars, we discuss the opportunities to electrify car travel with a focus on PHEVs.

CAR MOVEMENT DATA AND ELECTRIFICATION

What pattern characterises the movement of our cars? Information about vehicle movements over longer periods of time is of major importance for the sizing of batteries, estimation of the economic viability from a consumer perspective and assessment of the potential of electric vehicles to replace fuel-propelled cars. We need data on the distribution of trip lengths and trip characteristics, such as speed and topography, to be able to determine the energy use for individual trips and the need for battery capacity. Moreover, the knowledge of timing and duration of trips and parking between trips is required to evaluate the availability of charging capacity and potential impact on the electricity grid (see Chapter 9 for a discussion on the interaction with electricity production and the grid.) Since the travel patterns of individuals vary considerably over time, which will influence the discharging and recharging patterns and options, data needs to be collected over a long time period.

It can be argued that measurement of today's car movement will not be representative for the near future's battery electric vehicles, which have a limited driving range and hence will impact the travel behaviour of drivers (see introduction above and Chapter 11). However, for plug-in hybrid electric vehicles, a reasonable assumption can be that these vehicles will be used in a similar way as today's cars.

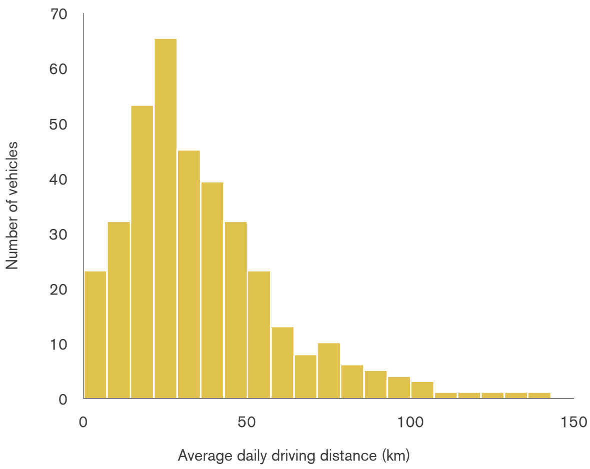
Publicly available data of good quality on car movement patterns are generally lacking. National or regional travel surveys are regularly gathered in many countries. However, in most countries, including Sweden, there is no tracking of the movements of cars, only of persons. It has also been recognised that this often self-reported data (using questionnaires or interviews) provide an underestimate of the travelling, due to a certain share of non-reported trips. Nor does this type of data give the exact position of vehicle movements. Finally, the measurement period in travel surveys is often limited to one day.

GPS-assisted travel surveys have been discussed in several countries. Continuous measurement of position, speed, and time with GPS equipment offers the possibility to gather more thorough information on car movements, although it lacks explicit information on trip purposes, often available in travel surveys. This can to some extent be derived from the available positioning data.

Measurements of car movements with GPS equipment have been scarce, and when done it has been for specific purposes or focusing vehicles in specific areas. For instance, in Australia, cars have been tracked for the purpose of investigating driver behaviour such as speeding. In Italy, a unique commercial dataset of car movements are derived by the company Octotelematics from the GPS tracking of around 650 000 cars (in 2009) in order to inform insurance profiling. In the USA (Seattle area), a GPS logging of 450 vehicles from around 275 households was performed in an assessment of road tolls. In the Atlanta area, 445 cars owned by 273 households where tracked for up to one year in order to assess the effects of different cost schemes on travel behaviour.

In Sweden, in a project in 1998 (Körsätt 98) with the purpose of verifying the role of driving behaviour in emission models, GPS equipment was installed in specifically prepared vehicles. These were placed in 29 families for two weeks, replacing cars of similar size. In another project (LundaISA) about 200 cars in Lund were tracked for about 100 days during 2000-2002. The purpose was to evaluate the impact and acceptability of Intelligent Speed Adaptation (ISA) equipment.

In Canada, a measurement was specifically devoted to electrification. 126 cars in Winnipeg and rural vehicles often commuting into Winnipeg were logged with GPS for up to a year, to be able to, for instance, assess the prerequisites for electric propulsion of PHEVs. Also the data from the two US studies mentioned above have later been used for assessment of electrification opportunities.



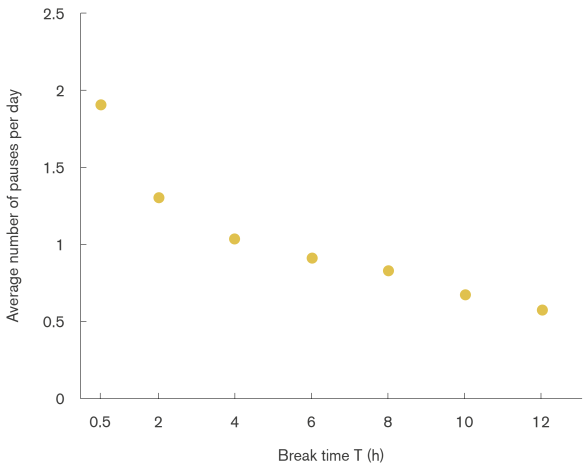


Figure 10.2 For the logged 212 vehicles, the average daily driving distance and the average number of daily breaks between consecutive trips longer than *T* hours. Source: Kullingsjö, L-H, S Karlsson, 2012. *The Swedish car movement data project*. In Proceedings to EEVC 2012, Brussels, Belgium, November 19-22, 2012.

To improve the data situation, a GPS measurement project was recently carried out in Sweden.[2] The aim was to get representative data for privately driven cars in Sweden. The cars come from the positive responses to a request for participation in the project sent to a random selection of owners/drivers of newer cars (≤ 9 years old) from the motor-vehicle register in a region composed of the county of Västra Götaland and Kungsbacka municipality. This project resulted in movement data for around 500 cars for at least one month each. In the following we will use results from this project.

Figure 10.2 shows the distribution of the average daily driving distance. The distance driven by the different vehicles varies considerably, which will affect their individual viability for electrification. Depicted is also the average number per day of stops longer than a certain minimum break time *T*, a parameter, which influence the type of charging that is possible. The frequency of breaks naturally decreases for successively longer breaks. Breaks longer than around six hours, occur less than once a day. This is mainly due to the fact that not all vehicles are driving every day. A knee in the curve can be seen at eight hours, corresponding to the frequent occurrence of break lengths around normal parking times at work places.

POTENTIAL ELECTRIFICATION OF CAR MOVEMENTS

By using the car movement dataset, it is possible to get an estimate of to what extent the movements fit electrification. It is the total distances of all the trips in between the charging occasions that are of importance to electric propulsion. This is determined by the movement pattern as well as the possible utilisation of charging options. Figure 10.3 gives an exemplary yearly distribution of the driving distances between charging options. The driving is sorted with the longest distances at the bottom. The curve therefore shows the annual accumulated number of charging occasions as a function of trip distance, where trip distance means the distance between charging occasions. The area (*S*) under the curve corresponds to the annual distance driven.

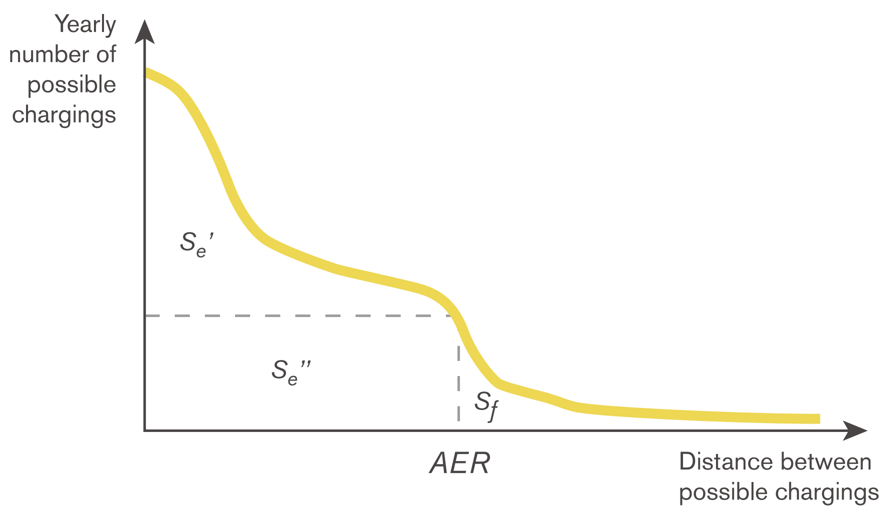


Figure 10.3 A schematic illustration of a vehicle's distribution of distances driven between charging occasions. The vertical axis is the annual accumulated number of charging occasions followed by a driving above a certain distance before next charging option.

2 Karlsson, S. (2013). The Swedish car movement data project, Final report. Energy and Environment, Chalmers University of Technology. See also project website

First we look at a PHEV. We assume it is first propelled by electricity only, and when the battery is emptied it turns to fuel. Hence, it uses a so called Charge Depleting – Charge Sustaining (CD-CS) mode (see Chapter 3) and that the battery is fully charged whenever charged. The battery limits the range the vehicle can drive in the all-electric mode, here termed the *All Electric Range (AER)*. It is then possible to propel the car the yearly distance S_e' with only electricity from the battery.[3] For trips longer than *AER*, the yearly distance S_e'' can be met by battery energy, while S_f must be covered by fuel combustion. The potential share of the yearly distance driven propelled by electricity, the *Electric Drive Fraction* (*EDF*),[4] is thus

$$EDF_{PHEV} = S_e/S$$

where $S_e = S_e' + S_e''$. A battery electric vehicle (BEV) can only be used for trips shorter than the *AER*. The share of the yearly driving in Fig 10.3 possible to cover with a BEV is thus

$$EDF_{BEV} = S_e'/S$$

Generally, for the same battery range (*AER*) and charging options the share of the annual driving distance covered by electric propulsion is thus larger for the PHEV than for the BEV. Of course, a similar relationship holds for the number of trips; the PHEV can with help of the fuel engine cover all trips, while the BEV has to be complemented with another car for trips longer than the battery range. For a specified charging pattern, Figure 10.4 gives the share of current driving in Sweden possibly propelled by electricity as a function of battery range (*AER*) for PHEVs and BEVs, respectively. Here and in the following we assume that data from the Swedish car movement data project is representative for Sweden.[2]

To reach the same *EDF* a BEV needs a battery range more than twice as large as a PHEV. For instance, a PHEV with a range of 60 km can propel roughly half the driven distance with electricity. A BEV will need a range of 130 km to cover the same amount of driving. For the BEV this range must also be a practical utilised range excluding any backup range for the avoidance of running out of battery energy. We must note though, that Figure 10.4 represents the average driving. As demonstrated later in this section, the individual variations are considerable. Many cars may in practice be used in such a way that they never, or at least very seldom, move longer than the BEV range on a daily basis. The suitability of the BEV in such cases is then determined very much by the value of the option to be able to drive longer anyhow.

3 The battery energy use in the driving can vary depending on prerequisites such as driving style, speed, and use of auxiliaries (see Chapter 5). The analysis can be extended to include this but for simplicity we here assume that the driving has one specific energy use per distance.

4 The electric drive fraction is also designated Utility Factor (*UF*) especially in the US, after the concept of (public) utilities providing electricity or other goods based on a (natural monopoly) infrastructure. The electricity may however as well be charged with electricity from a local off-grid, thus non-utility, source. Generally, there are good reasons to avoid concepts that have been framed in a specific historical and socio-economic context in a vocabulary used for discussions on future technologies.

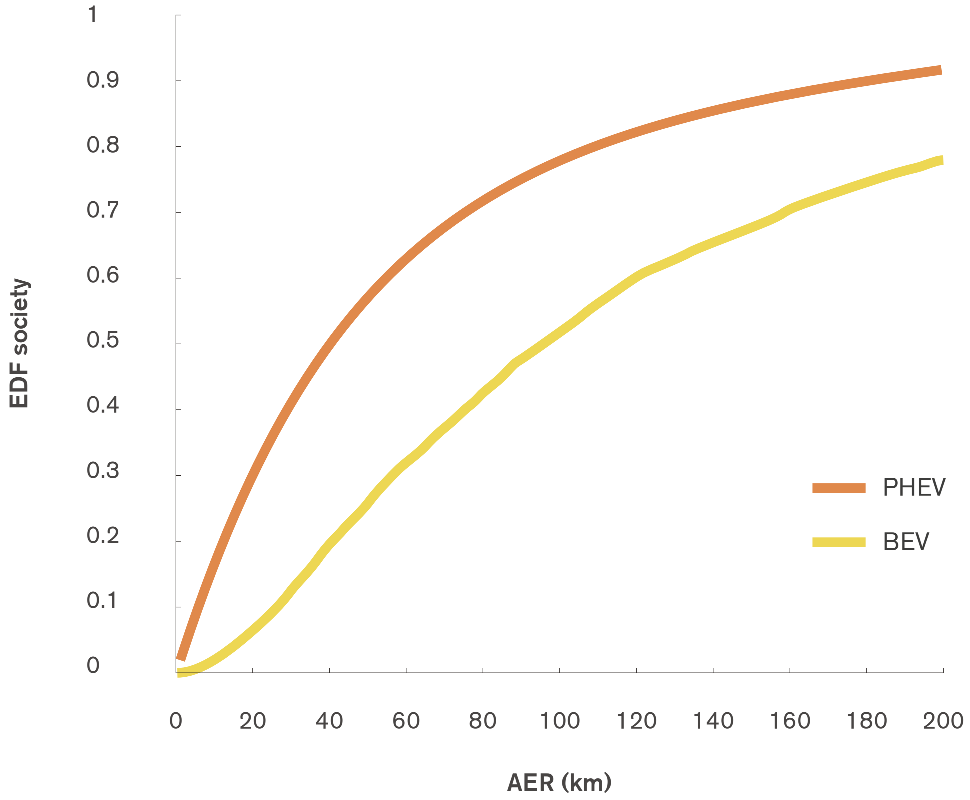


Figure 10.4 The share of current private driving in Sweden possibly propelled by electricity (Electric Drive Fraction, *EDF*) as a function of battery range (*AER*) for PHEVs and BEVs, respectively. The charging is assumed to take place whenever a pause between trips is at least 10 hours ($T = 10$ h).

The range of the BEV can of course be increased by equipping it with a larger battery, but unlike for the conventional car, that comes at a non-negligible cost. Other solutions could be fast charging, battery swapping or charging while driving (see Chapter 2 and 3), all requiring matching infrastructure. If these options are not at hand, the limited range has to be handled by restricting driving to short distances. As mentioned in the introductory section much driving may be facilitated conveniently with BEVs when restricted to specific fleets or when combined with access to other cars: for instance, by membership in a car pool or by renting (see Chapter 12).

Many households have more than one car. In Sweden, almost half of all privately owned cars (not accounting for company cars) belong to households with more than one car. When substituting one of the cars in such a household with a BEV, in many cases the BEV range restriction will be much less of a problem. If the vehicles are really pooled within the household, the BEV can be chosen for the trips that are within its range and the fuel vehicle can be used for longer trips. Moreover, the much lower operational costs, due to the lower energy use per km of the BEV (Chapter 5, 12 and 13), will probably make it the preferred vehicle whenever possible, increasing its share of the household's driving (Chapter 11).[5]

While a BEV battery hopefully never is completely emptied, a PHEV battery can be dimensioned in such a way that its full capacity is frequently utilized. An

5 Measurement of these opportunities are made within a project logging both cars in two-car households in Sweden

important measure or indicator of the utilization of a PHEV battery is the *Marginal Recharging Frequency* (*MRF*). The *MRF* is the number of times a year the PHEV battery is fully emptied and fuel propulsion starts, i.e., how many times a year the last unit of battery capacity is actually used. Besides the driving pattern, the *MRF* is determined by the battery range and the recharging options. Actually, the curve in Fig 10.3 can be interpreted as a movement pattern's *MRF* (y-axis) for different battery ranges (x-axis).

Figure 10.5 illustrates the *MRF*s as a function of battery range for the individual movement patterns of the vehicles in the dataset. The battery is assumed fully recharged every time there is a pause with a length of at least *T* hours (10, 4 and 0.5 hours, in figure a, b and c, respectively). The requirement of a 10 hours pause for charging to occur effectively singles out charging at home during nights. Pauses of 4 to 10 hours length occur particularly at work places when commuting. Thus $T = 4$ hours roughly corresponds to charging at home and at work. Full recharging every time there is half an hour pause ($T = 0.5$) may be seen as an extreme case where fast charging is available and utilised at every stop. (See also Figure 9.2, which shows the distribution of pauses of different duration over the time of day and corresponding possible charging patterns.)

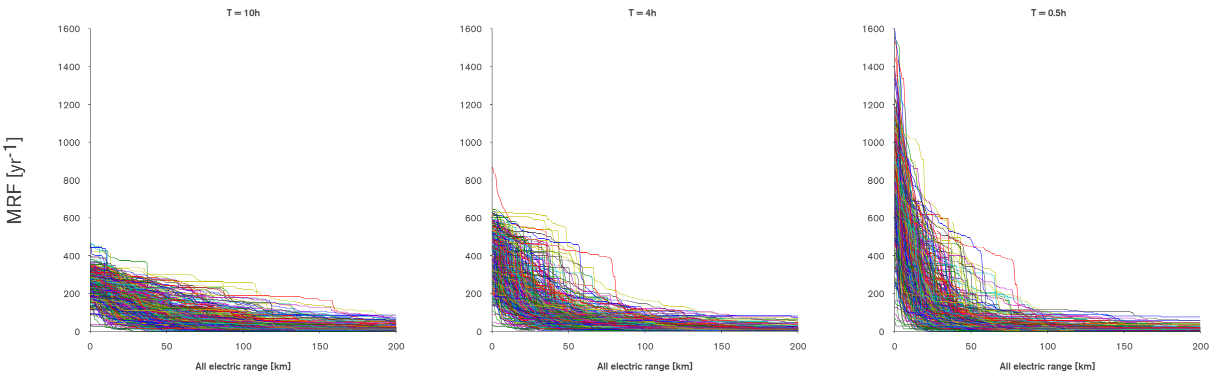


Figure 10.5 For the individual cars driving pattern, the marginal recharging frequency (*MRF*) as function of the battery range (*AER*) and recharging expressed as minimum required break time *T* for recharging the battery. a) $T = 10$ hours; b) $T = 4$ hours; c) $T = 0.5$ hours.

There is apparently a large variation in the *MRF* between different cars depending on their individual movement patterns regardless of charging option; movement patterns matter! For any car movement pattern the *MRF* decreases with larger battery range. That is, all else being equal, the larger the battery in the PHEV the lower the frequency of changes to fuel use due to an empty battery. We can also note that the individual *MRF* curve falls steeply in the cases where the specific movement pattern has a large number of trips around a certain *AER*. This can occur for instance when the driving is dominated by the regular commuting between home and work.

In general, better charging opportunities (here shorter *T*) lead to more recharging occasions and thus to shorter distances covered in between recharging and a higher *EDF*. When the battery range, *AER*, is long, the battery is empty less frequently, that is a smaller *MRF*. For shorter battery ranges, the charging and also the emptying of the battery are more frequent, which implies a larger *MRF*.

FITTING PHEV BATTERIES TO DRIVING PATTERNS

For a PHEV to be economically viable, the higher initial capital cost due to the expensive battery should be compensated for by the lower operational costs due to the higher energy efficiency of the electric drivetrain (see Chapter 5, 12 and 13). A larger battery increases the capital costs, but also the possible share of electric propulsion and therefore lowers the energy costs. Thus, there is a trade-off between battery cost and energy cost. The battery should therefore neither be too large nor too small. Optimally, an extra unit of battery should be (exactly) paid for by the saved operational costs.

Any given set of technical and economic conditions that determine battery cost and saved operational costs corresponds to an optimal marginal recharging frequency, MRF_{opt}. In Table 10.1 some examples derived with help of a simple model are given.[6] With expensive batteries and a relatively small difference between electricity and fuel costs it is economically optimal to switch to fuel more often. The parameters behind an MRF_{opt} of 800 yr^{-1} can be thought of as fairly close to today's situation, while an MRF_{opt} of 200 yr^{-1} requires development of cheaper batteries. A cost somewhere in the vicinity of that predicted for 2020 is required. Similarly, an MRF_{opt} of 50 yr^{-1} corresponds to a possible state further into the future where considerable improvement of battery parameters has taken place, as well as an increase in the energy prices.[7]

Table 10.1 Examples of combinations of techno-economic parameters, which give certain optimal marginal recharging frequencies MRF_{opt}.

	Optimal marginal recharging frequency MRF_{opt} (yr^{-1})				
Techno-economic parameter	**800**	**400**	**200**	**100**	**50**
Annuity (yr^{-1})	0.15	0.15	0.15	0.15	0.15
Utilized share of the nominal battery capacity (-)	0.5	0.5	0.61	0.75	0.8
Marginal battery cost [EUR/kWh)	600	300	185	120	75
Electricity and fuel price (EUR/kWh)	0.11	0.11	0.13	0.15	0.19
Quota of specific energy uses of fuel and electricity [-]	3.0 (0.51/0.17)	3.0 (0.45/0.15)	2.8 (0.42/0.15)	2.6 (0.39/0.15)	2.5 (0.35/0.14)

The optimal battery sizes (ranges), $AER_{opt,i}$, can now be deduced from MRF_{opt}, charging prerequisites and individual driving patterns. Under certain conditions the optimal battery size is zero and hence a HEV (no charging) is preferred over a

6 For further details on the model and the derivation see for instance Karlsson, S. and Jonson, E., (2012). Electrification potential of the car – an estimate from a mid-size Swedish town. *World Electric Vehicle Journal,* 4, 82-90. (2012)

7 Some remarks are in place. Estimated or stated costs of batteries are often given in EUR/kWh for the battery, i.e. total cost divided by the (nominal) energy capacity. But the specific cost of the current PHEV batteries depends on the capacity for both power and energy. For a given power, the additional cost for energy capacity, that is, what is interesting here, can be considerably lower than the specific cost for the whole battery. The marginal cost for battery energy capacity can thus be lower than the today's stated battery specific cost of 450-600 EUR/kWh. On the other hand, stated costs are often production costs and do not include the mark up costs seen by the car buyers. The assumed annuity of 0.15 corresponds to a levelized capital cost over a relatively long depreciation period and/or an assumed low rent. In most countries the actual depreciation in cars' value can be considerably higher in their first years and then decrease for older cars. An assumed doubling of the annuity would result in a doubling of the MRF_{opt}, corresponding to a shifting of one column to the left in Table 10.1.

PHEV. Figures 10.6 and 10.7 show the distribution of optimal battery ranges, and the number and shares of PHEVs in the car fleet. The result is given for different MRF_{opt} in compliance with Table 10.1, and different minimum break times T required for charging to take place.

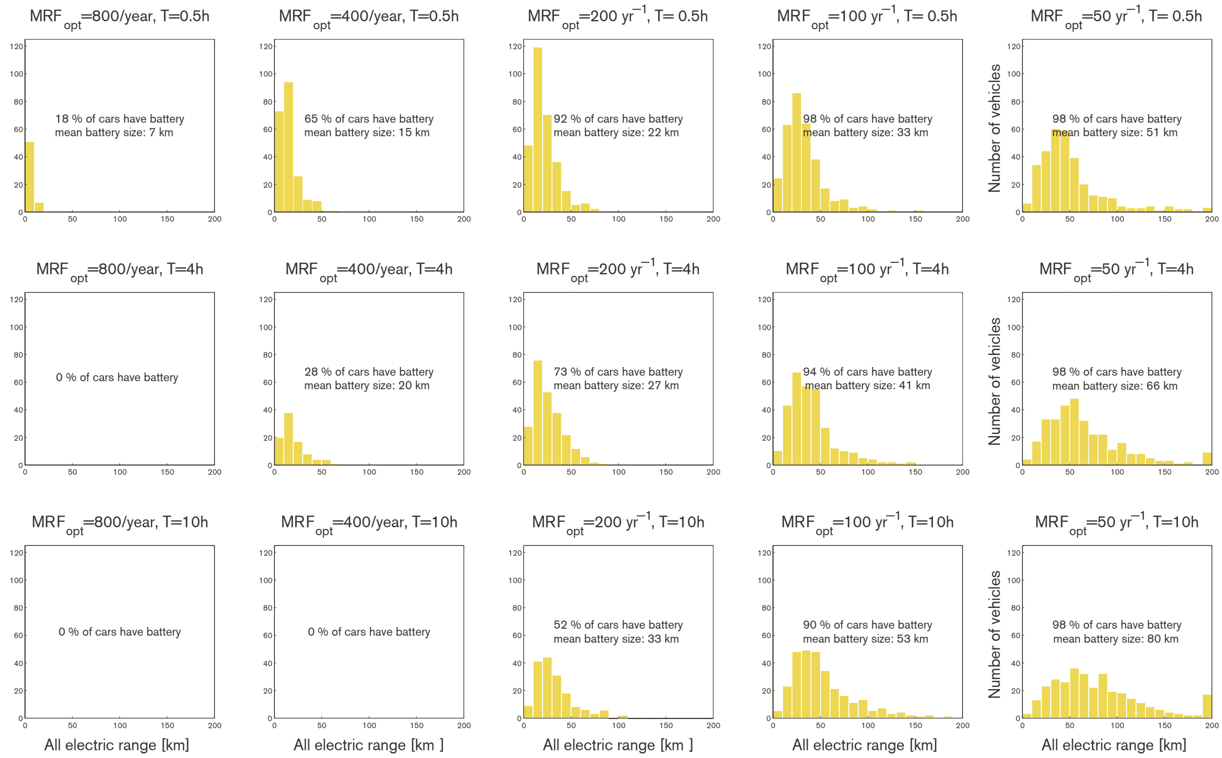


Figure 10.6 For a total of 326 investigated vehicle movement patterns, the distribution of optimal individual PHEV battery ranges *AER*. From left to right: increasing economic viability, that is, decreasing MRF_{opt}. From bottom to top: better recharging options, that is, shorter minimum break time T for recharging.

The viability of PHEVs is strongly dependent on the techno-economic prerequisites, as expressed by the MRF_{opt}. In general, the better the economics of PHEVs, i.e., the smaller the MRF_{opt}, the more viable are PHEVs and the larger are the optimal battery size. Given the conditions of today, if viable at all the optimal battery needs to be small, in the range of 10-20 km, to be able to recover its costs. In a future with possibly very favourable economic conditions, i.e. very small MRF_{opt}, it could be optimal that almost all cars are PHEVs. But their batteries could vary considerably in range due to diverging driving patterns (column to the right in Figure 10.6).

The charging options are of importance for the viability of electromobility. Figure 10.6 demonstrates that for increasing charging opportunities (lower T) the share of viable PHEVs in the vehicle fleet increases. This is especially true for less favourable economic conditions. For PHEV competitiveness, the different charging options are thus most important in the transition from low to high economic viability of batteries. Therefore, development of recharging options is critical to achieve a considerable share of PHEVs in the near future. In addition, the battery should be kept small. For someone not having the ability to charge frequently, PHEVs are unlikely to be an economically viable option without subsidies (Chapter 13).

When charging can take place more often the optimal battery range generally tends to decrease, especially at very benign economic conditions. For instance, our estimates give that for an MRF_{opt} of 50 yr^{-1}, a change of T from 10 to 0.5 h makes the average battery shrink in range with about a third: from 84 to 54 km.

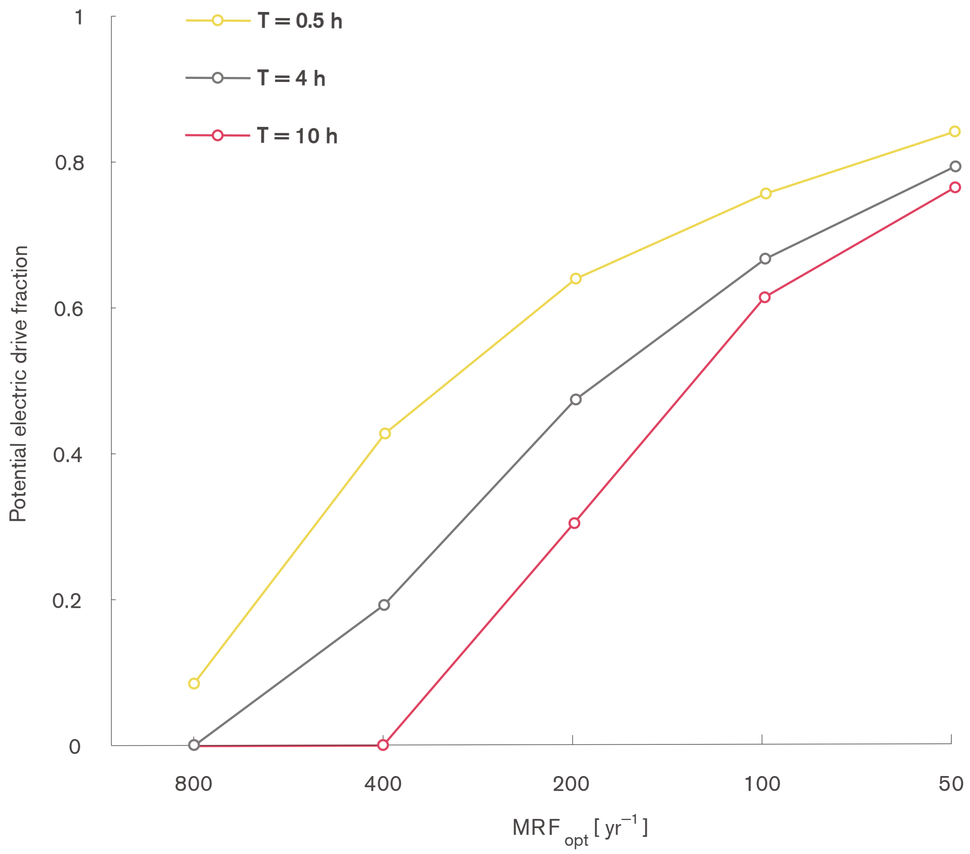


Figure 10.7 The share of the car fleet being PHEVs as a function of the viability parameter MRF_{opt} and charging options expressed as pause time T between trips.

Figure 10.8 gives the estimated overall potential for economically optimized PHEVs to replace fuel with electricity, the fleet *EDF*. Naturally the achieved fuel substitution is smaller than the corresponding share of vehicles being PHEVs, shown in Fig 10.7. For instance, with 60 % of the cars being PHEVs, the electric drive fraction is around 35 %. For conditions when practically all cars are PHEVs and have larger batteries, the substitution of fuel is still limited to around 80 % of the distance driven.

Also the electric drive fraction is very dependent on charging options. Actually, compared to the number of PHEVs, the electric drive fraction is more sensitive to charging condition and battery economics also at very benign economic conditions. Even for MRF_{opt} of 100 or 50 yr^{-1}, the EDF increases considerably for better recharging options and/or further improvements in battery economics. In reality there will not be totally individualised and optimised batteries. We have shown elsewhere that introducing a few battery sizes can be enough to harvest most of the gains achieved by fully individual batteries.[8]

8 Karlsson, S. and Jonson E. (2011). *The effect of PHEV battery range distributions on competitiveness: Implications for design strategy and energy-efficiency policy.* In: Proceedings of Energy efficiency first: The foundation of a low-carbon society, European Council for an Energy Efficient Economy (ECEEE) 2011 Summer Study, 6–11 June 2011, Belambra Presqu'île de Giens, France, pp 1015-1013.

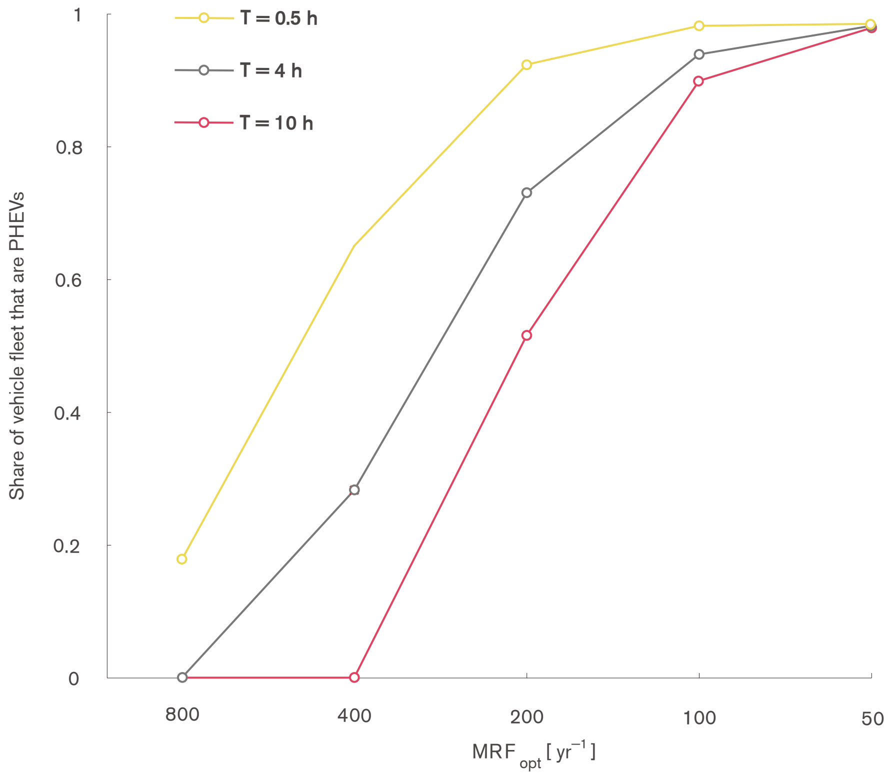


Figure 10.8 Potential electric drive fraction (EDF) for the car fleet as function of the viability parameter MRF_{opt} and charging options expressed as pause time *T* between trips.

DISCUSSION

We have introduced a simple model for assessment of the design, viability and potential for electrified vehicles based on the movement and charging patterns as well as some techno-economic prerequisites related to battery and energy costs. It should be noted that the analysis in the previuos section is restricted to the evaluation of PHEVs with different battery range in comparison to a car with a zero-range battery, that is, the corresponding HEV. To which extent the HEV and the PHEV are superior to the conventional car is of course very important for the competitiveness of vehicle electrification. The conventional vehicle is quickly developing when it comes to energy efficiency and the gap to electrified vehicles is shrinking (see Chapter 5 on energy efficiency). Part if this development is due to the partial electrification of the conventional vehicle by the introduction of for instance stop/start systems and other electric hybridisation technologies (Chapter 2).

The movement patterns in the dataset utilised here cover about one to two months of driving for each car. Still cars can have a movement pattern which varies over the year with season, vacations etc. The pattern could also change over the vehicle lifetime, for instance due to the fact that most cars have several owners during their lifetime.

It is also worth noting that for very small PHEV batteries the power to energy requirements can be prohibitively large if driving in CD/CS mode is what is aimed for. Moreover, turning an HEV into and PHEV will require a charger, a motor and power electronics with higher power rating to avoid blending mode in various normal driving conditions. For viability these extra costs need to be recovered by a high *EDF* in the driving, i.e., a larger battery. PHEV batteries with very short ranges should therefore probably be avoided altogether which to some extent contradicts a conclusion made in the previous section. Still we think that on an aggregated level, the results presented here are valid.

There are now PHEV models available on the market with a long range (≈ 60 km) as well as models with smaller batteries (≈ 20 km). We have pointed to the favourability of relatively small batteries in an introductory phase and then a turn to larger batteries when the costs have decreased further. This conclusion does not rely on an analysis of the current market, but on an assessment from a "rational" total cost of ownership (TCO) perspective. There may still be niche markets for PHEVs with larger batteries targeting specific groups, for instance persons less sensitive to a high TCO. Different forms of subsidies, not least through favourable conditions for company cars may as well be very important for the early development of vehicle electrification (Chapter 13).

CONCLUSIONS

While electrification of vehicles in the longer term may change our driving patterns (Chapter 11), this chapter has analysed how current driving patterns affect to what degree electrification is economically viable.

It can be concluded that data on vehicle movements is useful for assessments of the impact of different techno-economic parameters on market penetration of PHEV, fraction of electric propulsion and optimal battery size.

While PHEVs technically can replace conventional cars, the limited range of current BEVs severely restricts their ability to be an alternative to current cars given the irregular driving patterns of today and occasional long-distance driving, especially in one-car households. However, in car fleets and car pools, the range may not be a problem.

In assessments of economically viable electrification with PHEVs, the marginal recharging frequency is a central concept linking vehicle movements to techno-economic properties. The marginal recharging frequency is determined by the individual vehicle's battery range, movement and recharging opportunities.

From the perspective of a consumer's total cost of ownership an initial electrification by plug-in hybrids should mainly rely on relatively small and therefore cheaper batteries. The focus should be on customers with driving patterns characterised by frequent driving such as commuting. Frequent recharging is also of importance, for instance, by charging not only at home but also at work. Hence, infrastructural investments directed towards workplaces could be beneficial to an introduction of PHEVs. However, without some form of subsidy or other financial alleviation the potential for PHEV for private driving is currently small.