VATTENFALL

Driving a plug-in hybrid

Results from user tests of Volvo V70 plug-in hybrids in 2010

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Foreword

Our society is changing. More and more people realise that we have to change our energy use and adapt to a future with lower carbon emissions. A large share of today's emissions of carbon dioxide stem from the transport sector, which makes that sector important and also challenging to transform to sustainability.

At Vattenfall, we are convinced that electricity plays an important role in the future development of the transport sector. We have worked with electric vehicles in different forms since the 1980's. Today we run projects within E-mobility in Germany, Holland and Sweden. Together with Volvo we have developed one of the first plug-in hybrids that will be sold commercially: Volvo V60 plug-in hybrid.

Vattenfall's cooperation with Volvo on plug-in hybrids started in 2007, and the offset of our common project was to develop and test two V70 plug-in hybrid prototypes. During the test phase we have let a number of test drivers use the plug-in hybrids instead of their ordinary cars. The input from the test drivers has been a valuable contribution in developing the V60 plug-in hybrid. The results of the test project are presented in this report.

The results from the test project have generally been very positive. The test drivers like the plug-in hybrid, and they believe in electric cars and plug-in hybrids for the future. At Vattenfall, we can only agree!

The next step for us at Vattenfall is to continue working with the insights gained in this test project, in order to put the V60 plug-in hybrid on the market in 2012. Then we will be another step closer to a society independent of fossil energy. We hope you want to be a part of that journey!

Enjoy your reading!

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Executive summary

In 2007 Vattenfall started a cooperation with Volvo Cars, ETC Battery and FuelCells and Swedish Energy Agency to develop and test plug-in hybrids. The core of the project has been the two Volvo V70 plug-in hybrids that were developed in the project and tested during 2010 by almost 30 families. This project has given us valuable insight into what role plug-in hybrids can play in the future, and what demands users will put on charging infrastructure. The most important learnings and insights are collected in this report.

The plug-in hybrids were used as family cars and replaced the test drivers' ordinary cars during their test period. The test drivers used the car for the same things they would have done with their ordinary car: going to work, picking up and dropping off kids, going shopping, and so on. The cars have also at some occasions been used for vacations and longer drives. The test drivers agree that plug-in hybrids work well as family cars.

Most of the test drivers report that they have adjusted their style of driving to the plug-in hybrid, and driven in a more calm and economical manner than they would normally have done. The most common reason is that they wanted to save electricity and drive as far as possible without using the diesel engine. Maximal electric range measured during the test was just over 30 km, while most drivers say they have reached around 25 km maximum. Almost all test drivers think the electric range is too short, 50 km is a common wish. On the contrary, logged data shows that full available electric range is seldom used, and that there often is energy left in the battery when the drivers reach their destination.

Many of the drivers have chosen to use electricity in city traffic, and switched to diesel in higher speeds. The reasons given for this are both that it suits the driving characteristics of the car better, and that the environmental benefit of the car is higher if electricity is used in cities. 8 704 km or 35% of the total distance driven during the test has been on electricity.

Vattenfall's focus in the test has been charging and charging infrastructure. All test drivers have had access to charging both at home and at their work place. These have undoubtedly been the most important charging locations: 60% of the charged energy has been charged at home and 25% at the drivers' work places. Only 7% of the charging has been done at other locations where the drivers have gone, for example at family or friends or at public charging stations. The remaining 8% were charged at the car workshop or between test periods.

One public charging station has been put up within the project, but none of the test drivers have used this. Roughly half of the test drivers think they have had sufficient charging possibilities during the test, the other half would have liked to be able to charge at more places. The drivers are generally very positive about charging the car, and think it has been convenient and easy. Many of them point out how useful it is to be able to charge the car where you are parked, compared to going to a specific place to refill diesel.

The cars have mainly been charged by normal charging (230 V, 10 A) which has taken 4-6 h. Many of the test drivers say this is fast enough, since they charge over night or over a working day.

A very important result of the project is that it has contributed to the development of the commercial V60 plug-in hybrid that will reach the market in 2012. Even though the V70 that has been tested in this project is technically quite different from the V60, the experiences and opinions of the test drivers regarding using a plug-in hybrid have been a valuable contribution to the development process of the V60. One example is electric range, which is going to be up to 50 km in the V60.

Main findings

- The test drivers replaced their normal car with the plug-in hybrid, and used it for the same things as they would normally have done.
- The test drivers have driven more calm or economical in the plug-in hybrid than their normal car, mainly in order to save electricity.
- Most test drivers have chosen to use the electric mode in city traffic, and diesel mode in higher speeds. For many, this was an environmental decision.
- The test drivers want a longer electric range, commonly around 50 km.
- There is large variation between test drivers in the electric range reached.
- Logged data shows that all of the electric range is seldom used.
- The most important charging locations have been at home and at work for all test drivers.
- None of the test drivers have used the public charging station installed by the project.
- Half of the test drivers feel charging at home and at work has been sufficient to meet their needs, the other half would like more charging locations in the future.
- Test drivers are generally positive towards charging, and say it has been easy and convenient.
- There have been some unexpected technical problems related to charging, with fuses and other home installations.
- Normal charging (4-6 h) is fast enough for a majority of the test drivers.
- Many test drivers wish for semi-fast charging (2 h) at home.
- Interest in ultra-fast charging (10 min) is fairly low.
- Test drivers generally like the plug-in hybrid, and would recommend it to others.
- The test drivers are very positive towards the environmental performance of the car.
- Before their test periods, the test drivers focus on the global environmental aspects of plug-in hybrids (carbon emission, resource use etc.). After their test periods, they instead refer to local environmental aspects (less particles and local pollution, less noise etc.).
- Most of the test drivers have not experienced silence in electric mode as a safety issue for pedestrians.

Background

The project and the test

From 2007 to 2010, Vattenfall, Volvo Cars and ETC AB cooperated in a project aiming to develop and test plug-in hybrid vehicles and related charging infrastructure. The project was partly financed by the Swedish Energy Agency. The goals of the project were to construct plug-in hybrids and battery systems, to test and evaluate plug-in hybrids and charging infrastructure in everyday life, and to contribute to an increased understanding of how plug-in hybrids can make a difference in society.

This report describes some of the results from that project: the results related to the use of the two Volvo V70 plug-in hybrids. These two cars have been tested during all of 2010, by almost 30 families. They have been tested in the role as family vehicles, and have been used by the test families instead of their normal car.

The test drivers have each had the cars for a period of between one week and two months. The majority of the drivers have used the car for one month each. Four test drivers have used the car during two months. Out of these, two drivers used it two months in a row and two drivers used it one month in the winter and one in the summer.

The test has been running from the beginning of December 2009 to the end of December 2010, which implies that the cars have been used during two cold and snowy winters and one warm summer. The range of weather conditions during the test has thus been large.

The test drivers

Almost all of the test drivers are employees at Vattenfall and Volvo. Volvo used their standard procedures for test driver selection. Vattenfall found their test drivers through asking for interested people over the intranet, and received in total over 600 applications. The test drivers were then selected based on a variety of criteria, in order to have a good representation from both sexes, different driving patterns and needs. All the selected test drivers use their cars often.

During the test, 19 of the test drivers were interviewed before and after their test periods. Selection was based on test period length. The drivers who were not interviewed had test periods of only a week and were therefore judged to have less input to the test. The interview results presented in this report are based on input from the 19 interviewed test drivers. Nine of the interviewed test drivers are women and ten were men. The majority of the test drivers live in the Göteborg-area (12 test drivers), but during parts of the test, the cars were evaluated in the Stockholm-area (4 test drivers) and in Varberg (3 test drivers).

The test drivers are aged 30-59, and have families consisting of 1-2 adults and 0-2 children. Most of the test drivers live in separate houses and some live in terraced houses. None of the drivers in this test live in a flat. Four of the interviewed drivers work at Volvo, and 15 at Vattenfall. They work in very different positions within their organisations, from technicians to top management.

The test drivers were asked to rate their car interest on a scale from 1 (small) to 5 (large), and then answered between 2-5. The distribution of answers is about equal for all grades in the interval. The test drivers were also asked to rate their environmental interest on the same scale (1-5), and also there answered in the interval 2-5. Most test drivers rated their environmental interest as a 3 or 4.

The drivers own between one and three cars each. The most common cars are Volvos or Audis. Almost all of the test drivers use their car to commute to work. Their commuting distances are in the interval of 10-40 kilometres, the majority having a commuting distance of 20-30 km.

The tested plug-in hybrids

The plug-in hybrids that have been tested are two reconstructed Volvo V70 D5, that have been equipped with lithium ion batteries and an electric motor. The cars are prototypes and there is significant technical difference between these and the commercial Volvo V60 plug-in hybrids that will be sold from 2012. This is important to remember when reading the report, since there have been limitations in the cars that have affected the test drivers' experiences.

Technical data

- Electric rear wheel drive: 100 hk
- 5-cylinder diesel front wheel drive: 205 hk
- Normal charging (230V, 10 A): 4-6 h
- Semi-fast charging (230V, 16 A): 2-2,5 h
- Total battery size: 11 kWh
- Usable battery size: 7 kWh
- Battery weight: 150 kg
- Electric range: 25-30 km

There is very limited trunk space in the car, and only four seats, as the trunk and the back middle seat are used for batteries and electric drive line. The diesel tank is smaller than normal, 20 litres. The transition between electric and diesel modes have been fully

manual in these cars, by pressing a button. No real hybrid drive, that is integration of the electric and diesel modes, existed in these cars. The cars have been speed limited to about 100 km/h on electricity. Moreover, the acceleration capacity in diesel mode was limited during parts of the test. A diesel driven cabin heater has been available, that could be programmed to pre-heat the car and to keep the car warm in electric mode.

Evaluation method

The test driving has been evaluated both qualitatively and quantitatively, with data loggers in the vehicles and through interviews with the test drivers. This report focuses on the qualitative results, but also presents some quantitative data for reference and comparison.

Qualitative evaluation

The qualitative evaluation was done through semi-structured interviews with 19 of the test drivers before and after their test driving periods. The interviews before were done to understand the test drivers' driving habits, car use and preconceptions of plug-in hybrids. The interviews after the test periods partly use the same questions as the before-interview, in order to see changes in test drivers' opinions during the test period. Interviews were done using interview manuals with a mix of open and closed ended questions. The "before" interview manual had 46 question and the "after" interview manual 71 questions. The qualitative evaluation has been done in cooperation with Chalmers University of Technology (prof. Elsa Rosenblad). Quotes from the interviews with the test drivers are presented throughout the report for illustration.

The aim of the qualitative evaluation was to answer four overall questions:

1. To what extent can plug-in hybrids fill a role as a family car?
2. To what extent can plug-in hybrids contribute to society's goals of reduced emissions?
3. Is charging a barrier to market development, and in that case, in what way?
4. What misconceptions exist regarding plug-in hybrids, and how can they be changed?

Quantitative evaluation and example drivers

The quantitative data has been collected in the vehicles and compiled by ETC. Certain key figures for both the two cars and all of 2010 is presented. However, since the overall data is based on two cars and a large number of different drivers and driving patterns, interesting features are missed in the averaging. Moreover, the cars have also been used for a fairly large number of events and communication activities, which have affected the averaged results.

In the report, two sets of quantitative data collected from one vehicle during its time with one driver are also presented as a comparison to the overall data. This enables us to see variations between individual test drivers, which can be large. Moreover, data for the example drivers may be more significant for the future, as it only describes test driver usage and does not involve communication activities. The example drivers were chosen

to represent different cities, sexes, driving patterns and seasons; and are briefly presented in Table 1 below.

Table 1: Brief presentation of the two example drivers. Quantiative data in the report is presented as an overall average for all 2010, and for the two example drivers for comparison.

	Test driver March	Test driver September
Test month	March	September
Sex	Male	Female
Age	50	32
City	Göteborg	Stockholm
Family	Partner, one child	Partner, one child
Driving distance to work	27 km	13 km

Driving a plug-in hybrid

Usage pattern

Most of the test drivers have used the plug-in hybrid daily, and have in principle replaced their normal car with the plug-in hybrid completely during their test period. The test drivers have used the plug-in hybrid for the same things they would have used their normal car for: going to work, picking up and dropping of children, going to own hobbies and shopping. A wide range of traffic types and roads have been covered in the test, from city traffic and line-ups to country roads and highways.

When the test drivers occasionally have chosen not to use the plug-in hybrid it was most often because they needed more trunk space, or because they were going far. The recommendation from the project was to stay within a 100 km radius from Göteborg/Stockholm, in order to be close to service shops if any technical problems would occur. Some drivers say that the experienced range, both electric and diesel, felt very short when going long distances, and therefore chose their normal car instead for those occasions. A couple of times the plug-in hybrid have been used for holiday trips e.g. to the mountains, and they have been driven longer distances on a number of occasions.

The test drivers have in general parked and charged at home during night, and at their workplace during day. They have also been parked shorter times at other locations mainly in the afternoons and evenings, such as at family and friends' homes, at gyms, at stores, at day care etc.

Logged data shows that the longest distance driven without turning off the engine is 225 km. The longest trip done was 470 km, between Göteborg and Stockholm.

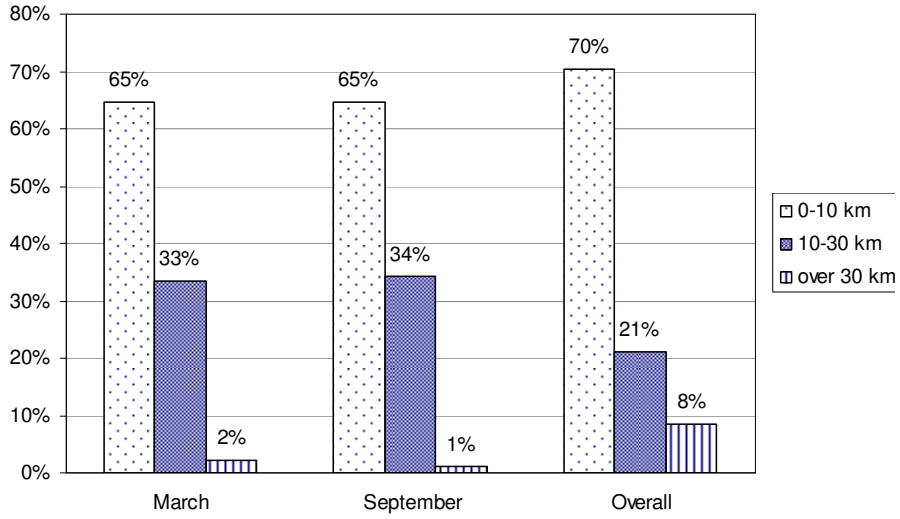

Figure 1: Share of driving occasions in different distance intervals, in the two example drivers' months and during the whole test.

From Figure 1 it can be seen that the large majority, 70%, of all individual driving occasions are short, below 10 km. Only 8 % of the distances driven are longer than 30 km. One important implication of this is that in theory, over 90 % of the driving in the test could have been done in electric mode. The pattern is similar for both example drivers, but the share of distances in the interval 10-30 % is larger, and the share of distances longer than 30 km is even smaller, 1 and 2 % respectively. Both the example drivers did only one trip longer than 30 km during their test period. Moreover, both of them had between 10-30 km to work, which explains their higher share of driving occasions in that interval.

Figure 2: An example of how the car has been driven. Yellow represents electric mode and blue diesel mode.

Figure 2 is a typical example of how the car has been used, in this case from the March driver's home in the suburbs of Göteborg to his work place in the city centre. The yellow distances represent electric mode and the blue diesel mode. The example driver has chosen to use the electric mode in city traffic close to his home and work, but used diesel mode on the highway in between. This has been a common usage pattern, see below.

Main findings:

- The test drivers replaced their normal car with the plug-in hybrid, and used it for the same things as they would normally have done.
- The plug-in hybrids have worked well as everyday family cars.

Driving style

Almost all of the test drivers report that they have adjusted their style of driving to the plug-in hybrid, and driven more calm or economical than they would have done with their normal car. Most of the drivers expected before the test period that they would adjust their driving style in this manner.

The main reason for adjusting their driving style is that the drivers wanted to make the electricity last longer. Several talk about how they get very conscious of the energy consumption when driving on electricity, and note how they can affect the energy consumption by changing their style of driving. Other test drivers say they have driven calmer than usual because the car was not able to support their normal style of driving. This is mainly the same drivers who before the test describe their own driving style as "sporty" or faster than average. A third reported reason for calm driving is that the car is more difficult to control than the normal car, especially on slippery roads. The centre of mass is higher and further back in this prototype than normally, due to the placement of batteries in the trunk. Some test drivers feel this affects the road grip. Others say that the rear wheel drive on electricity affects the driving characteristics on slippery roads.

"I adjusted my driving almost automatically because it was an electric car. I kept track of the Ampere number shown on the display, and I tried to keep that figure down. I avoided some take overs I would normally have done. Drove a little calmer. Because I wanted the electricity to last longer."

- Test driver 6

"I was more careful with the gas pedal, I was not in a hurry. The car did not have as much to give as my normal car, but there was also no reason to be stressed. I was relaxed in this car. I think I wanted the electricity to last longer."

- Test driver 11

"I've been planning my driving more carefully. Avoided accelerations, I took it easy going up hills. Because the incentive to save electricity is so obvious, for me it became a competition. I was just on the limit of making it all the way home in electric mode, so I really wanted to do that."

- Test driver September

The test drivers have generally not chosen different streets or parking lots compared to what they normally would. One driver says she has driven this car less than she would have with her normal car, because it made her think more environmentally and sometimes walk or take the bicycle instead. Another driver instead says she felt it was more okay to take this car for short distances than her ordinary car, because of its good environmental properties. Some drivers say they have occasionally parked in different locations compared to normally, to be able to charge the car. One driver has chosen restaurant based on where she could charge.

> "I have varied my driving. Sometimes I wanted electricity for city driving, then I changed to diesel on roads with higher speeds. It felt natural to use electric mode in the city. It might be better for the local environment to do it that way."
>
> - Test driver 4

> "I have gone over to diesel mode when I drove onto the highway, or some kilometres before the steep hills close to where we live, to be able to roll the last part through our neighbourhood on electricity."
>
> - Test driver September

> "It feels fun to use electric mode in villages and cities, because it doesn't smell and doesn't make any noise. And it feels like a better use for it, to drive on electricity where people live. On the highway it feels like it doesn't make a big difference."
>
> - Test driver 13

> "I have made active choices. Started on electricity, gone over to diesel on the highway, gone back to electricity the last bit. It's important to glide into work on electricity of course, and the same thing in the neighbourhood at home. Because it makes you feel proud."
>
> - Test driver 15

Most of the test drivers have chosen to drive on electricity in lower speeds and in city traffic, and switched to diesel in higher speeds and on larger roads. Some test drivers have chosen to use electricity until the battery was empty, and then gone over to diesel. The two most common reasons for switching between electricity and diesel are:

- A wish to use electricity where it makes the largest environmental difference, in terms of local air pollution and noise.
- Adjusting to the driving characteristics of the car. The speed was limited to around 100 km/h in electric mode.

Table 2: Share of driving distance that has been done in electric and diesel modes, in different distance intervals.

		<10km		10-30km		>30km		Total	
		km	%	km	%	km	%	km	%
Test driver March	Electric mode	24	47%	131	44%	30[1]	99%	**186**	**49%**
	Diesel mode	27	53%	168	56%	0,3	1%	**196**	**51%**
Test driver September	Electric mode	184	66%	399	85%	26[2]	82%	**609**	**78%**
	Diesel mode	95	34%	68	15%	6	18%	**169**	**22%**
Overall	Electric mode	2 218	57%	4 114	43%	2 372	21%	**8 704**	**35%**
	Diesel mode	1 698	43%	5 454	57%	8 895	78%	**16 047**	**65%**

As seen from Table 2, the share of the distance done in electric mode can vary significantly between different drivers, and between different distance intervals. The example driver in September has done 78% of her total driving in electric mode. The example driver in March has done 49% of the driving in electric mode, and the overall value for the whole test period is 35%. In comparison to the driving distances presented in Figure 1, where it can be seen that the vast majority of driving theoretically could have been done in electric mode, the share of driving in electric mode is surprisingly low. Only the September example driver is close to achieving that potential. The low share of electric mode is likely explained by the common behaviour to use electricity only in city traffic, and drive the longer distances on faster roads in diesel mode.

For driving distances shorter than 10 km, 57% of the total distance is done in electric mode. This equals a total of 2 218 electric kilometres, as can be seen in Table 2. For distances between 10-30 km 43% of the total distance (or 4 114 km) is done in electric mode, and for driving distances longer than 30 km only 21% of the distance is done in electric mode, or a total of 2 372 km in absolute numbers. Both the example drivers have a very high share of electric mode for distances longer than 30 km. The explanation is that they each only made one trip longer than 30 km, which they did almost completely in electric mode.

Main findings
- The test drivers have driven more calm or economical in the plug-in hybrid than their normal car, mainly in order to save electricity.
- Most test drivers have chosen to use the electric mode in city traffic, and diesel mode in higher speeds. For many, this was an environmental decision.

The largest absolute number of electric kilometres is driven during trips that are in the distance interval 10-30 km. During the test, a total of 8 704 electric kilometres and

[1] One trip, 30 + 0,3 km
[2] One trip, 26 + 6 km

16 047 kilometres on diesel have been driven by the two cars.

Electric range

The electric range, that is the maximum distance the car can go on electricity without recharging, is an issue the test drivers talk a lot about during the interviews. There is a large spread between the test drivers in the reported maximum electric range, from 20 to almost 40 km. In general, the test drivers report a maximum distance of around 25 km on electricity. Two drivers have had test periods both in summer and in winter, and they both report longer electric range during the summer. However, variations in reported electric range are larger between individual drivers than between seasons. No general seasonal variations in reported range can be seen. Neither can any co-variation between reported electric range and driving style be seen (drivers were asked to lable there driving style as “calm”, “in pace with the traffic” or “sporty”). The longest electric ranges are reached when the driver keeps a steady speed of approximately 70 km/h, on a road with little traffic and few slopes. A couple of test drivers do not know their maximum electric range, because they never drove the car in electric mode until the battery was empty.

"The range is long not enough for a car you would want to buy for yourself. It needs to be the double at least, 50-60 km, to work in daily life. To be able to drive in the city on electricity only."

- Test driver 6

"It discharged very quickly, I didn't get far. I would have needed 60-70 km on electricity. To be able to go to work and back again and go to the gym in between, and only charge once a day. In order not to feel limited. So the double range compared to what I had."

- Test driver 7

"50 kilometres is a good limit. Especially if you drive home, and then go to do some errands afterwards. The errands are in city traffic, and then you want to drive in electric mode, but then you're out of electricity."

- Test driver March

"It actually felt enough for me. Because what you drive the most, that's back and forth to work, and then it's good to be able to go the whole way on electricity. Then it would've been good to have some kilometres more if you want to do something else – go to a friend's place, go shopping. But it's to work you drive the most. 40-50 kilometres on electricity would have been really good."

- Test driver September

All test drivers except one feel that the electric range is too short. When asked what electric range they need, the test drivers answer from 30 to 150 km. Most of the drivers report a need of around 50 km electric range, which is the double distance compared to what many of them have experienced. The same finding has been the result of several tests of electric vehicles before[3]: drivers wish for twice as many electric kilometres as they have. Many test drivers want to be able to do all their daily driving on electricity and preferably also have some electricity left as a reserve at the end of the day, while only charging the car at home over night. A longer electric range is a criterion most test drivers set for wanting to buy a plug-in hybrid themselves, or to recommend it to others.

Before their test driving period, some drivers expected the electric range to be longer, up to 50 km, but most expected the electric range to be around 30 km. Around half of the drivers claim to need a shorter electric range after their test period than before. Around half of the drivers claim to need a longer electric range after their test period than before.

From data recorded in the vehicle data loggers, it can be seen that contrary to this wish for longer electric range, the test drivers seldom use all of the available electricity. The main reason for not emptying the battery seems to be that test drivers use the electric drive only in city traffic, where the driving distances are not long enough to need all the available electricity. However, several drivers also report that they consciously have not completely emptied the battery. Some of them wanted a little electricity left as back-up, if the diesel engine would stop working (which has happened for a few of the drivers of this prototype car). Others saved some electricity because they wanted to be able to use the semi-fast charging (16A), which does not work if the battery voltage goes below 320V.

[3] Hammarlund T., Iivari M., Liljemark S. *Mer än 1 000 000 km! Elbilar i Göteborg 1992-1999* KFB-rapport 2002:12. Accessible at www.kfb.se/publ/main.htm.
Rosenblad, E. Utvärdering av O-seriebilar. Slutrapport till SEHCC/Nutek, 1996-09-15

When asked how large share of their driving that was done on electricity, most test drivers answer a number in the interval 50-75%. Some say lower than 50% and some say up to 90%. On average during the year, the actual distance in electric mode from the vehicles' data logging system is 35% (see Figure 5). It thus seems that the drivers over-estimate the share of driving in electric mode.

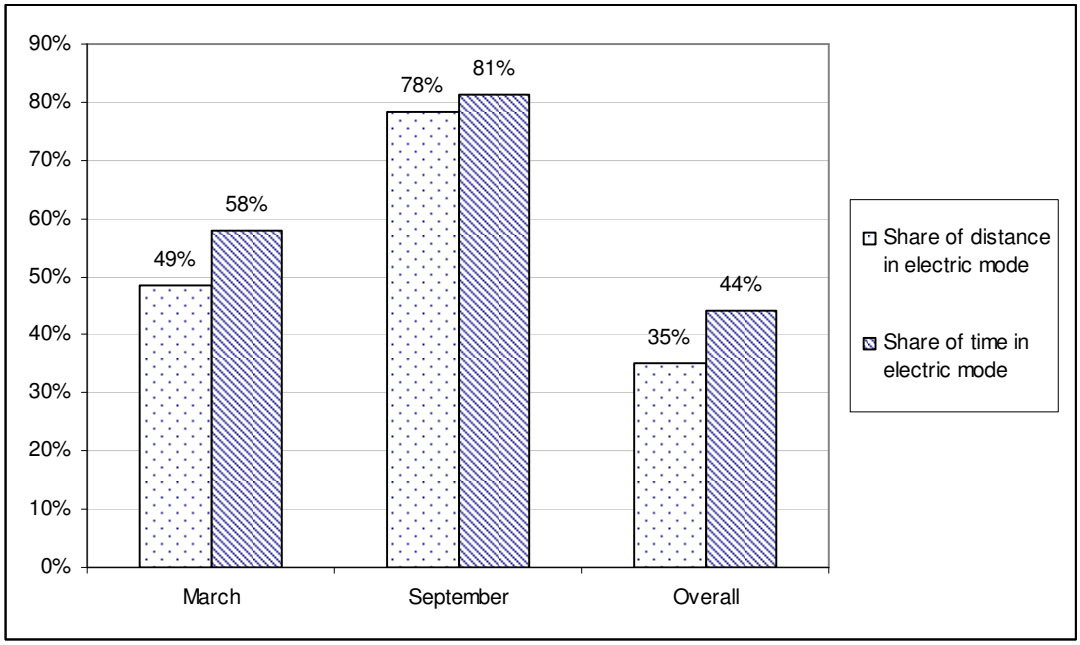

Figure 3: Comparison of the share of time and distance spent in electric mode, in the two example months and during the whole test.

Figure 3 shows that for both the example months and for the overall data, the share of time spent in electric mode is larger than the share of distance driven in electric mode. This indicates that the drivers have used the electric mode in lower speeds, such as in city traffic or traffic build-ups. The larger the difference is between the two bars, the more common the pattern to switch to diesel mode in higher speeds has been. For the example driver in September, this behaviour has been less common than for the example driver in March.

Main findings

- The test drivers want a longer electric range, commonly around 50 km. A longer electric range is a criteria for many test drivers for consider buying a plug-in hybrid.
- There is large variation between test drivers in the electric range reached.
- Logged data shows that all of the electric range is seldom used.

Charging

Where and when?

All the test drivers were able to charge at home and at their workplace during their test period. All test drivers have used this opportunity. Two test drivers frequently parked at Landvetter Airport, and a charging facility was arranged for them there during their test periods. One public charging spot was installed within the project, at Lindholmen Science Park in Göteborg. None of the test drivers has used this public charging spot.

The home and workplace have been the most important charging locations for all test drivers. Some test drivers have also charged at other locations, most commonly at their family and friends' homes. A couple of test drivers report to have used public charging at gas stations, hotels and restaurants. When asked before the test period if they would use public charging, more test drivers believed that they would use public charging than have actually used it. However, almost all of the test drivers still believe that public charging will be widespread in the future.

"I would have wanted charging stations everywhere. Then I would have plugged in everywhere, because I like driving on electricity."

- Test driver 3

"I had enough charging possibilities now, because I've driven short distances and it takes a long time to charge. In the future it would be great if there was charging stations everywhere where you're parked for some time – cinemas, malls, gyms."

- Test driver 14

"It's connected to the electric range. With this range, I would have needed some more charging opportunities. But I don't know if the solution is to be able to charge at the food store, it doesn't charge much on 20 minutes. At bigger malls would be better, where you're parked for a couple of hours."

- Test driver March

Around half of the test drivers say that their charging possibilities have been sufficient to meet their needs. Some of them would like to have more places to charge in the future, if they owned an electric vehicle themselves. Some of them say that the charging is too slow to benefit from charging elsewhere, or that it is more important with a longer electric range than more charging opportunities. The other half of the test drivers would have liked to have more charging possibilities during the test. They generally wish for charging stations at locations where they would park for a couple of hours, such as shopping centers, central parking garages, places where themselves or their children do sports and large food stores. For most drivers, their opinion on how many charging locations they want and where they want them has not changed from before to after their test periods.

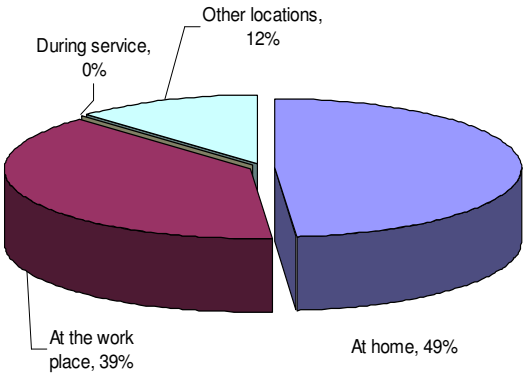

Figure 4: Share of the energy charged at different types of locations for the test driver in March.

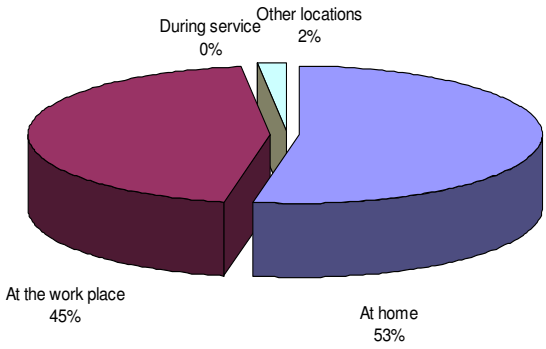

Figure 5: Share of the energy charged at different types of locations for the test driver in September

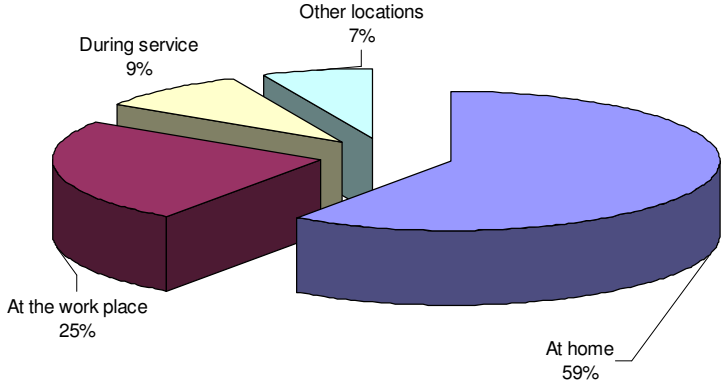

Figure 6: Share of energy charged at different locations during all 2010

Figure 4, Figure 5 and Figure 6 show the share of the total energy charged at different locations during the example periods March and September and during the whole test. Clearly, home and work have been the two major places for charging. During the test, the two cars have charged a total of 4 653 kWh.

Table 3: Amount of energy and number of charging occasions at different types of locations during all 2010.

	Energy charged (kWh)	%	Charging occations (no.)	%
At home	2 778	60%	433	47%
At the work place	1 141	25%	280	30%
During service	423	9%	127	14%
Other locations	311	7%	87	9%
	4 653	**100%**	**927**	**100%**

In Table 3, the share of electricity charged at different locations during the entire test can be seen. It is clear that the large majority of charging has been done at the test drivers' homes (59%) and at their work places (25%). The general pattern is similar to that seen from the example drivers.

9% of the total energy has been charged while the car has been at Volvo or other workshops for service, driver changes and test drives with e.g. media and politicians. Other charging locations represent only 7% of the total energy. The other locations include public charging, but are more commonly at the homes of friends or family. Very few of the test drivers report to have used public charging.

Main findings

- At home and at work have been the most important charging locations for all test drivers.
- None of the test drivers have used the public charging station installed by the project.
- Half of the test drivers feel charging at home and at work has been sufficient to meet their needs, the other half would like more charging locations in the future.
- Uncontrolled charging is likely to reinforce existing peaks in the power system.

The share of charging occasions at home is smaller than the share of energy charged at home, 47% compared to 60%. This indicates that the charging done at the drivers' homes have been for longer periods than at other locations, and that the battery has been filled up more completely at home.

In Figure 7, the average load profile from charging of both the cars is shown. The trend shows that the cars have generally been plugged in at arrival to work in the morning, and in the afternoon when coming home. Overnight charging has been slightly more common than day charging. An important implication of Figure 7 is that when charging is done freely (as in this test), it is likely to reinforce already existing load peaks in the power system.

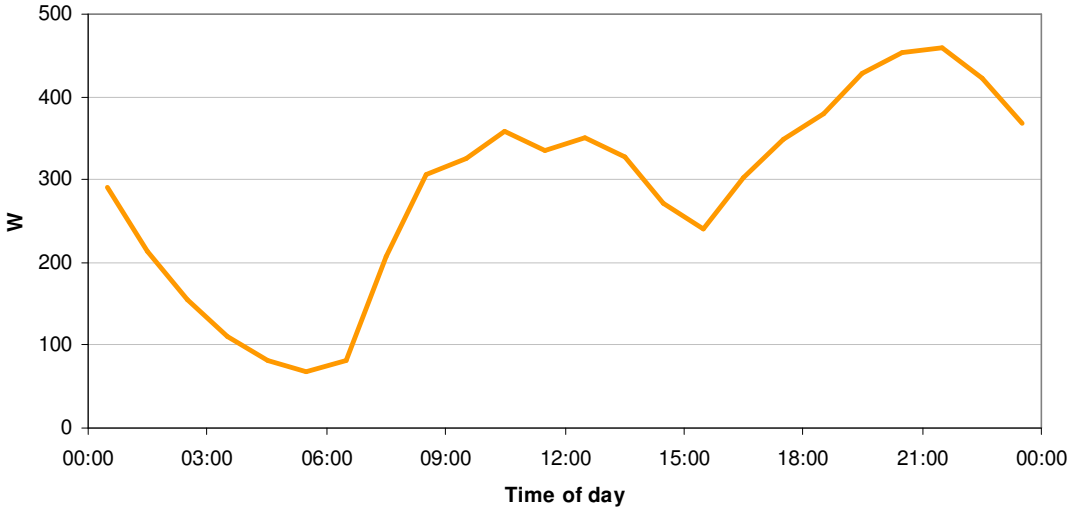

Figure 7: Average load profile during the test. Average power drawn from the grid by the cars versus time of day.

How?

Generally, test drivers say it has been easy and convenient to charge the car. When asked to rate their impression of charging on a scale from 1-5 (where 1 is the worst and 5 is the best), most of them say 4 or 5. In the comparison between charging and refilling the car with liquid fuel, the majority of the test drivers feel that it is easier and more convenient to charge the car. The main reason is that they do not have to go out of their way to go to the gas station. Several also comment on that charging is cleaner than refuelling, or that gas stations are boring places to be.

As for handling the cable, many report that it has not been a problem and that it quickly becomes routine, whereas some feel that it is added work to plug in and out. Some test drivers say that it was difficult to handle the cable when it was wet and dirty and they were a dressed in their office outfit. One of the drivers who had a car both during summer and during winter said that this was a much larger problem in the winter, when the cable was wet and the charging outlet and the trunk door were salty and dirty.

"I avoid refilling if I can, because it's an extra trip to go to the gas station. To charge the car is no extra trip, it's charged when the car is parked at places I was going to. To me that's a great thing, that it's being charged while I'm parked and I don't have to go anywhere."
- Test driver 7

"It's a lot easier to charge than to refill. Charging doesn't go as quickly of course, but the car is minding itself while doing it, so that makes it a lot better than to have to go to the gas station."
- Test driver 12

"The cable is superior to the hose. Diesel is a little messy, and of course it's a lot easier to do it at home compared to going to the gas station."
- Test driver 15

"I like 'refilling with a cable'. It's easy and nice, it's minding itself, I don't have to stand there waiting, I don't have to go anywhere extra. To go to the gas station for refilling is just one more thing you have to make time for."
- Test driver 16

Main findings

- Test drivers are generally positive towards charging, and say it has been easy and convenient. Many feel it is a large advantage to not have to go to the gas station.
- There have been some unexpected technical problems related to charging, with fuses and other home installations.

A couple of drivers have reported technical problems with the charging. These include that the car did not charge or that charging was very slow, and that fuses blew during charging. Most of the test drivers did not expect to have any technical problems with the charging beforehand.

How fast?

The cars in the test have two charging modes: normal (230 V, 10 A) and semi-fast (230V, 16A). The most common charging mode has been the normal mode, since only a smaller number of test drivers had access to a semi-fast charging installation. 16 A outlets were arranged at two work places during the project (the Volvo office in Göteborg and the Vattenfall office in Råcksta, Stockholm).

In normal charging mode, the cars have taken 4-6 hours to charge, according to the test drivers. Roughly half of the test drivers feel that normal charging is fast enough to cover their charging needs. Some more say that it would be fast enough if the electric range was longer. Many of the others report that a charging time of 2 h would be needed to cover their charging needs. This is approximately the time the car uses to charge during semi-fast charging. The most common wish for a faster charging location is at the test driver's home. Many of the test drivers say that they would like to be able to come home in the afternoon, charge the car while eating dinner, and then drive on electricity to the food store or to the kids' or their own activities.

"The need for charging speed is a matter of electric range. I often felt that I drove home and then needed to drive more. You can solve that either by having a longer range, or by charging really quickly, in less than one hour. Otherwise I think it's functional to charge like I did, during the working day."

- Test driver March

"This car definitely charges fast enough if you can charge at work and at home. Then it could take eight hours, it doesn't matter, if it charges while I'm working or sleeping."

- Test driver 12

Some of the test drivers say it would be useful with ultra fast charging, to charge the car in 10 min or less. Wished-for locations for ultra fast charging are at home or at the food store. A number of drivers connect this to the short electric range, and say that they would not need ultra fast charging if the electric range was longer. Most of the drivers have not changed their view on how fast they need to charge from before to after their test period.

Main findings

- Normal charging (4-6 h) is fast enough for a majority of the test drivers.
- Many test drivers wish for semi-fast charging (2 h) at home.
- Interest in ultra-fast charging (10 min) is fairly low.

Everyday life with a plug-in hybrid

Opinions regarding the car

The drivers generally have a good overall impression of the car. When asked to rate their overall impression on a 1-5 scale (where 1 is the worst and 5 is the best), they almost uniformly rate it 4. Almost all of the test drivers would recommend the car to others, but all add conditions to do so. A longer electric range is an almost unanimous condition. More space in the trunk is also an important condition for many of them.

Most test drivers say that the pre-conception they had of plug-in hybrids matched their experience of the car quite well. Several are pleasantly surprised by how easy the car is to use, and by the driving characteristics in electric mode. Several are disappointed with the short electric range, and that the car is not completely silent in electric mode.

The drivers generally appreciate the driving characteristics on electricity and in city traffic. On the 1-5 scale, city driving characteristics are rated by mainly 4:s and 5:s Several drivers comment on how appropriate electric drive is for city traffic, being fast at traffic lights, smooth in line-ups and silent. The drivers are a little less satisfied with the driving characteristics on diesel and on larger roads. On the 1-5 scale, highway and country road driving characteristics are rated by mainly 3:s and 4:s. Several drivers say they felt limited by the car in diesel mode, in acceleration and speed.

"The biggest difference between this car and my normal car was the smoothness of driving in city traffic on electricity. That was phenomenal."

- Test driver March

"This 'one with nature' feeling in the city was incredibly great. It felt like you were riding a bike because it was so smooth and convenient. It was silent, you didn't have to change gears, it was fast at traffic lights – it was a fantastic feeling. That definitely was the best thing with this whole experience, driving in the city and the silence."

- Test driver 3

"It was really slow in diesel mode; I felt that other cars almost blinked at me. I think that has to do with the prototype. But on electricity I have to say it was impressively sharp."

- Test driver 9

Main findings

- Test drivers generally like the plug-in hybrid, and would recommend it to others. Driving characteristics in electric mode and city traffic are highly appreciated.
- The silence in electric mode is a feature many test drivers appreciate.
- Many of the test drivers have experienced prototype related problems with the plug-in hybrids.

Several test drivers comment on how comfortable it is to sit in a car with a much lower sound level than usually. Many of the test drivers who have had the car during cold periods comment on the climate system. The diesel heater that can be used in electric drive mode does not make the car as warm as the drivers would like, and some drivers have not understood how to use it. Several say they dressed warmer when driving this car. Some drivers have also, even during the coldest times, refrained from using the electric heating in seats and windows in order to save electricity.

Almost all of the drivers have experienced prototype

related problems with the car, such as engine failure, difficulties to switch between electricity and diesel, or display failures. Many drivers did expect before their test period that they would have smaller or larger problems with the car.

Almost all test drivers say that people around them have been generally curious and positive about the car. The most common questions are around the price and the electric range. People generally seem to believe that plug-in hybrids will be very expensive, and they are disappointed with the short electric range.

Environmental and economic aspects

The test drivers are generally very positive towards the environmental performance of the car. The majority of the drivers mention the good environmental performance as one of the main advantages with plug-in hybrids. Almost all of the test drivers think that it is a good environmental investment with plug-in hybrids. Before the test the drivers refer to climate, carbon dioxide emissions and resource use as the reasons for plug-in hybrids being a good environmental investment. After the test, almost all the drivers instead point out the local environmental benefits of the car as the main reason, less local pollution and particles and less noise. Almost none of them mention this aspect before the test.

As mentioned above, the test drivers generally have adjusted their style of driving to be more calm and gentle. This is in most cases due to a wish to make the electricity last as long as possible, which is environmentally positive in itself, but irrespective of the reason the effect of this changed behaviour is positive for the environment.

The test drivers have not been offered a special, more environmentally friendly, electricity contract during the test, but have instead charged on their normal contract. Very few of the test drivers say they are interested in a special electricity contract for the car, with eco-labelled energy. The general reason is that they consider Swedish electricity to be clean enough as it is.

"Using the diesel mode in higher speeds might not give the absolutely lowest CO2-emissions; you'll get that if you use up every kWh electricity every time. But there are other issues, like the local environment, and how comfortable it is to drive. Noise. If you drive on electricity at schools and offices, where people walk and breath, you gain other things than the last millimetre of diesel."

- Test driver March

"I felt 'I'm driving an environmentally friendly car, that's really good for all the people who walk around here'. And I thought 'it gets so quiet!', think of all the noice barriers being constructed every-where, no noice barriers would be needed if everybody drove an electric car."

- Test driver 3

"I really felt when going over to electricity that 'wow, I'm environ-mentally friendly now.' I looked at the cars around me and saw how they were spewing out exhaust gas, but I was green. I thought of how good it would be if all cars were electric, especially in the winter, we would get rid of this pungent air in the city. What a lovely environment we would have."

- Test driver 9

None of the test drivers have noticed the extra electricity consumption of the car on their home energy bill. Some have noticed a higher bill than normally, but think that it is mainly because their test period was cold and with a high energy price. Some say the car's consumption is very small compared to the consumption of the rest of the household. This is particularly true for test drivers who have electric heating in their homes. Some have not yet received the bill for the test period at the time of the interview.

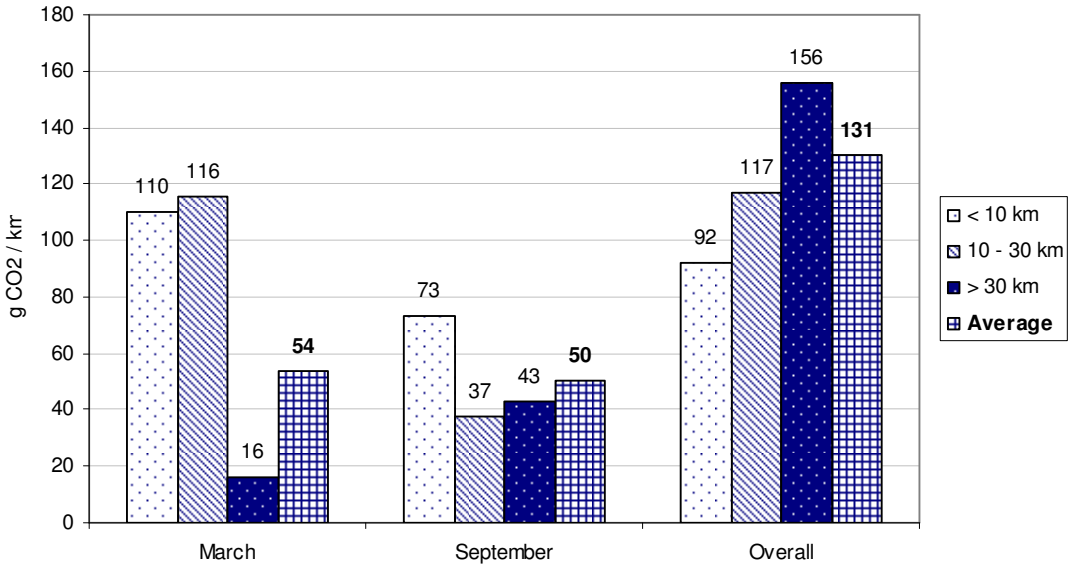

Figure 8: Emissions of carbon dioxide in different distance intervals and in average, during the two example months and the whole test.

Figure 8 shows the carbon emissions in different distance intervals and in average. The calculations for diesel are based on the certified diesel consumption and related carbon emissions for a standard Volvo V70 D5 (7,4 l/100 km and 195 g/km). The calculations for electricity are based on measured consumption during the test. The electricity is assumed to be Swedish electricity mix with a carbon emission of 24 g/kWh.

The average carbon emission for the whole test period is 131 g/km, slightly over the Swedish limit for environmentally friendly vehicles of 120 g/km. The average emissions for the two example months are significantly lower, 54 and 50 g/km, which is explained by a larger share of driving in electric mode. The emissions are closely related to the driving pattern which varies for each driver, depending for example on where they live and work. The higher overall average emissions during the test are partly explained by that the cars have been used for demonstrations and events, sometimes located far away, that have disrupted the normal driving pattern.

The general trend for the overall data is that shorter distances have lower carbon emissions, because the share of electricity is larger for short distances. This is not true for the example months, see Table 2.

Table 4: Comparison of energy consumption, costs and carbon emissions from electric and diesel mode, and averaged values for all driving during the test. Based on data from all 2010.

	Consumption for propulsion	Total consumption	Cost /km	Carbon emissions
Electricity	0,33 kWh/km	4 653 kWh	0,58 kr/km	13 g/km
Diesel	7,4 l/100km	1 187 liter	0,91 kr/km	195 g/km
All driving	0,19 kWh/km + 5 l/100km	4 653 kWh + 1 187 liter	0,79 kr/km	131 g/km

In Table 4, energy consumption, cost and carbon emissions can be compared for electric and diesel drive. The total electricity consumption is higher than the electricity consumption for propulsion, which only includes the energy used for propelling the vehicle forward. The total consumption also includes energy losses, which are large in these prototypes, but are expected to be significantly lower in production vehicles. Costs and carbon emissions from electricity are calculated based on the total electricity consumption. The diesel price used is the 2010 average price for diesel which was 12,35 kr/l, and the electricity is assumed to cost 1,086 kr/kWh (Vattenfall 1 year fixed price). It has been less expensive for the test drivers to drive on electricity compared to on diesel (but the expected electricity consumption and related costs are expected to be lower for production versions of electric vehicles, see above.)

Main findings

- The test drivers are very positive towards the environmental performance of the car.
- Before their test periods, the test drivers focus on the global environmental aspects of plug-in hybrids (carbon emission, resource use etc.). After their test periods, they instead refer to local environmental aspects (less particles and local pollution, less noise etc.).
- The actual emissions from the plug-in hybrids have varied significantly between different test drivers based on driving pattern and driving habits.

Safety aspects

The test drivers generally feel that the car is as safe as a normal car, for both themselves and their passengers. They have not been worried about batteries and high voltage systems.

Before their test periods, most of the test drivers think that the car will be less safe for pedestrians and cyclists because it is silent in electric mode. After their test periods, the majority of the test drivers say that the silence in electric mode not was a problem for pedestrians, and that they had been noticed anyways.

Main findings

- Most of the test drivers have not experienced silence in electric mode as a safety issue for pedestrians.

Conclusion

The qualitative evaluation aimed at answering four overall questions. The conclusions that can be drawn for each of these questions are presented below.

To what extent can plug-in hybrids fill a role as a family car?

During the test, the two cars have been used as family cars in around 30 families. All of the 19 interviewed test drivers have, to a large extent or completely, replaced their normal family car with the plug-in hybrid during the test. They have used the test car for the same things as they would use their normal car, and generally driven the same distances. In practical daily use, the plug-in hybrids in the test thus can be said to work well as a family car.

Before the test, the drivers were asked what defines a family car to them. Their answers often include features such as spacious, safe, comfortable, low fuel consumption and environmentally friendly. After the test, they all agree that plug-in hybrids are generally suitable as family cars. However, the cars in the test have some prototype related issues such as no space in the trunk that make them less suitable. Once these are solved, the test drivers in general think that plug-in hybrids will be good family vehicles.

To what extent can plug-in hybrids contribute to society's goals of reduced emissions?

When it comes to emissions, it is clear that a car which uses Swedish electricity mix for propulsion emits significantly less carbon dioxide than a car that uses diesel. For the plug-in hybrid in the test, the emissions in electric mode are 13 g/km, compared to 195 g/km in diesel mode. The number of kilometers that the cars have been driven in diesel mode is larger than the number of kilometers in electric mode. However, the electric mode has mainly been used in city traffic where people live and breathe, and many of the test drivers point out what a large difference it makes to have zero emissions in such areas. Almost all of the test drivers report that they have changed their style of driving to be calmer and more economical. This also has an environmental impact, as it implies that the energy consumption goes down.

Many of the test drivers talk about how environmentally friendly they feel when driving the plug-in hybrid. This environmental feeling can be one important aspect when deciding whether or not to buy a plug-in hybrid, and thus how large the break-through of plug-in hybrids will be.

The potential break-through of plug-in hybrids also highly affects to what extent they will contribute to reduced emissions. All of the test drivers believe that plug-in hybrids will make it to the mass market and be one of the main vehicle types in the future. Most drivers also believe in pure electric cars in the future. Some think that pure electric cars will replace plug-in hybrids when battery technology has developed further, and some think they will be a city car option.

Moreover, all of the test drivers would consider buying a plug-in hybrid themselves, but most also add conditions. The most important condition is the price level. The test drivers generally wish for a car that would have roughly the same total cost of ownership as a standard car. The investment can thus be somewhat higher, since the running costs will be lower. Many test drivers also want a longer electric range to be willing to buy a plug-in hybrid.

Is charging a barrier to market development and in that case in what way?
The test drivers generally say that charging is easy, and have a good overall impression of charging. They appreciate being able to charge at home, compared to going to the gas station to refill the car. Some of the drivers are not pleased with the design of the charging cables and outlets.

The test drivers have done almost all of their charging as normal charging at home and at work. Many of them feel that this is sufficient, while others wish for more opportunities to charge publically, or faster. Several of the test drivers connect the need for charging places and higher charging speed with the electric range, and all of the test drivers wish for a longer electric range in the car. If this is achieved in future cars, the need for fast charging and charging in many locations is likely to be very small. However, the ability to charge at home and preferably also at work places, will probably be an important factor in market development for electric vehicles in general.

What misconceptions exist regarding plug-in hybrids, and how can they be changed?
Most test drivers say that the pre-conception they had of plug-in hybrids matched their experience of the car quite well. Several are pleasantly surprised by how easy the car is to use, and by the driving characteristics in electric mode. This could indicate a misconception regarding electric cars as difficult, complicated and boring cars. Changing this view can be done by letting more people gain personal experience of plug-in hybrids or other electric vehicles, and by communicating – e.g. in reports such as this one – that modern electric vehicles are indeed easy and fun to drive.

On the other hand, several test drivers are disappointed with the short electric range. The electric range seems to be the largest overall concern the test drivers have with the car, as they almost unanimously agree that the electric range is too short, and many say that a longer electric range is a criterion for wanting to buy a plug-in hybrid or recommending it to others. This concern has been expressed in several tests of electric vehicles before, contrary to the fact that (like in this test), the electric range is often not fully used. However, hard numbers are not the major determinant when people buy cars, but rather their subjective view on needs and priorities. This implies that the electric range could well be a make-or-break factor for electric vehicles in general.