TØI report 1226/2012

Rolf Hagman
Terje Assum

Institute of Transport Economics
Norwegian Centre for Transport Research

Plug-in Hybrid Vehicles

Exhaust emissions and user barriers for a Plug-in Toyota Prius

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Quality manager: Ronny Klæboe

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Summary:

Plug-in hybrid vehicles (PHEV) can contribute to reduced fuel consumption and to lowered CO_2 emissions. A total of 10 plug-in hybrid vehicles have been tested in Denmark, Finland, Norway and Sweden for two years by ordinary users to assess what reductions will be achieved in realistic driving and to study user experience. The petrol consumption of the vehicles varied between 2.5 and 3.8 litres per 100 km, depending on charging frequency and driving style. Laboratory tests showed that emissions of CO_2 were low and local pollutants extremely low for a PHEV Prius. The users of the PHEVs reported general satisfaction with the vehicles. However, most users reported problems handling and storing the charging cable. Most users also wanted a larger driving range in electric mode.

Tittel: Ladbare hybridbilder - Utslippsreduksjoner og barrierer for bruk av en ladbar Toyota Prius

Forfattere: Rolf Hagman
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Sammendrag:

Ladbare eller plugg-inn hybridbiler (PHEV) kan bidra til redusert drivstofforbruk og CO_2-utslipp. 10 ladbare hybridbiler er testet i Danmark, Finland, Norge og Sverige for å finne ut hvilke reduksjoner som kan oppnås i normal kjøring og for å undersøke førernes erfaringer. Bensinforbruket varierte fra 0,25 til 0,38 liter per mil, avhengig av ladefrekvens og kjøremåte. Avgasstesting av en ladbar Prius ved VTTs avgasslaboratorium viste at vi her får både lave utslipp av klimagasser og at utslippene av helseskadelige avgasser var ekstremt lave. Førerne av PHEV Prius rapporterte generell tilfredshet med disse bilene. Imidlertid rapporterte de fleste førerne om problemer med håndtering og lagring av ladekabelen. De fleste førerne ønsker en lengre kjørelengde i elektrisk modus.

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Preface

Plug-in Hybrid Electric Vehicles (PHEVs) are vehicles that have both an internal combustion engine, electric propulsion and batteries, which can be charged from the electricity grid. In this project the Institute of Transport Economics (TØI), in cooperation with Toyota Motor Company, has undertaken an evaluation and literature review of PHEVs. Based on a small number of PHEVs, typical usage patterns have been logged and analysed, while users have been interviewed about their experience. In cooperation with Finnish VTT, TØI and Toyota Norway have undertaken comparative tests of the exhaust emissions from a PHEV Prius versus an ordinary HEV Prius and versus modern diesel and petrol engine vehicles from Toyota.

The project has been funded by Transnova, the Norwegian body for climate friendly transport, and by Toyota Norway. The latter, represented by Quality and Environment manager Per Løken, has been project owner, while Senior Research Engineer Rolf Hagman has acted as project manager. He has been responsible for the technological assessments, while Senior Research Sociologist Terje Assum has been in charge of opinion surveys and behavioural studies.

The report has been authored by Rolf Hagman and Terje Assum. Chief Research Officer Ronny Klæboe has been responsible for quality assurance, while the secretary Trude Rømming has been in charge of the final editing.

Oslo, August 2012
Institute of Transport Economics

Lasse Fridstrøm	*Ronny Klæboe*
Managing Director	Chief Research Officer

Contents

Summary:

Plug-in Hybrid Vehicles

Exhaust emissions and user barriers for a Plug-in Toyota Prius

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Plug-in Hybrid Electric Vehicles (PHEVs) are vehicles that have both an internal combustion engine, electric propulsion and batteries, which can be charged from the electricity grid. Plug-in Hybrid vehicles are the possible next step in the evolution of Hybrid Vehicles (HEVs). Plug-in Hybrid Vehicles being available as prototype and demonstration vehicles, a few production models are now entering the market. Plug-in hybrid vehicles come in many different designs with quite different technical concepts and characteristics. PHEVs can be used for longer trips without charging, meaning that there will be no "range anxiety". The same car can be used for both short and longer trips and still save fossil fuel and CO_2 emissions.

The commercial PHEV version of Prius, a medium sized family car with the possibility of driving about 25 km in the pure Electric Vehicle (EV) mode, will be marketed in all of Europe in 2012. Key questions in plug-in hybrid vehicle design and marketing are what will be the optimal battery size and the optimal range for a PHEV in EV mode. The parameters involved to answer this question are convenience of battery charging, vehicle purchase price, fuel savings, CO_2 reductions and the customers' willingness to pay for a greener image.

This project, carried out for Toyota Norway and supported by the Norwegian body "Transnova", focuses on a pre-commercial test series of the PHEV version of Prius as operated during two years by ordinary users in Denmark, Finland, Norway and Sweden. This Nordic pre-commercial trial of PHEV Prius vehicles has shown a fuel consumption in real life traffic ranging between 2.5 and 3.8 litres per 100 km.

A disadvantage of some engine solutions to reduce CO_2 emissions is that they may have undesired side effects such as increasing the level of hazardous local pollutants like NO_2.This poses a dilemma for national authorities that need to meet both global and local emission targets. Hybrid vehicles generally have the potential of low greenhouse gas (GHG) emissions as well as few locally harmful pollutants.

City driving tests in the emission laboratory of VTT in Finland proved that for an ordinary Toyota Prius, CO_2 emissions were low in comparison with traditional petrol and diesel engine cars, while the emission of local pollutants was virtually nonexistent. A pre-commercial PHEV Prius showed, at a short simulated city traffic round trip with a total length of 15.6 km, CO_2-reductions (at 23°C) of about 80-90 % compared to the ordinary Prius. These reductions are possible on short trips due to the uploaded electric energy in the plug-in batteries. The amount of local pollutants was as from the ordinary Prius – virtually nonexistent at all driving conditions.

New plug-in Prius

The two dominating ways to power a road vehicle are by an electric motor or by a combustion engine. Hybrid technology combines the two worlds by utilising the electric drive system characteristics to improve the efficiency of the internal combustion engine system and the ability to reuse brake energy. Plug-in hybrid technology provides in addition the possibility of exhaust emission free drive by electricity from the grid stored in an enlarged battery in the vehicle.

The new PHEV Prius has a battery capacity of 4.4 KWh. It can be used as a slightly more energy efficient HEV for longer trips, and as a Electric Vehicle (EV) for trips up to 25 km. It has a certified petrol consumption of 2.1 litres/100km in the New European Driving Cycle (NEDC), which corresponds to CO_2 emissions of 49g/km. The time required for full charging of the batteries is about 90 minutes at 220 V. As the vehicle enters the market, key questions are if the vehicle specifications meets the demand of the customers and whether they will pay the extra NOK 40 000 (ca. € 5 300[1]) for the plug-in version of Toyota Prius compared to the existing HEV Prius.

Pre-commercial PHEV Prius

The purpose of testing pre-commercial series of vehicles is to optimize and adjust technical functions and explore the customer acceptance. Ten pre-commercial Toyota Prius PHEVs equipped with data logging of essential parameters were deployed in the Nordic countries from June 2010, three in Norway, two in Denmark, two in Sweden and three in Finland.

After being fully charged with electricity from the grid, the pre-commercial Prius PHEVs basically run as electric vehicles for the first 20 km. Subsequently they after that run as hybrid vehicles. Of all the trips recorded with PHEV Prius in the Nordic countries, 66 % were shorter than 20 km but longer than 5 km, while 88% were shorter than 50 km but longer than 5 km. These statistics suggest that, if charging possibilities and sufficient charging time are available, it should be possible to drive the vehicles in pure EV mode on 66 % of the trips.

The Prius PHEVs in the Nordic countries had a real life average petrol consumption of between 2.5 and 3.8 litres per 100 km. Fuel consumption is highly related to how and where a vehicle is driven. In the field tests there were no instructions and no control of where and how the PHEVs should be driven or when and how often they should be plugged into the electric grid. The vehicle with an average petrol consumption of 2,5 l/100 km was plugged into the grid much more often than the other PHEVs in the test programme. The real life fuel savings were substantial compared with conventional vehicles.

Our experience of fuel consumption, emission testing, driving patterns and vehicle technologies indicates that the CO_2-emission reductions with the pre-commercial Prius PHEVs were in the order of 30 percent compared with a Prius HEV, 45 percent compared with a corresponding efficient diesel engine vehicle and 60 percent compared with an efficient petrol combustion vehicle.

Laboratory emission tests

A pre-commercial Prius PHEV was tested in the emission laboratory of VTT in Helsinki in order to examine and understand its performance in city traffic and cold climate conditions. In order to compare the emissions from the plug-in hybrid to more conventional vehicle models, a Prius HEV, a Toyota Avensis with 2.0 l D-4D

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[1] Exchange rate 7.50

diesel engine, and a Toyota Avensis with 1.8 l petrol engine were tested as well. The four vehicle models were tested at the temperatures -7 °C and +23 °C when driving a cycle called Helsinki city driving cycle, which is designed to be representative of real world traffic in Helsinki.

As compared to the ordinary Prius HEV, the PHEV version, with a fully charged battery, reduced the emissions of CO_2 by 80-90 % on a short simulated return city traffic trip with a cold start, a 15 minutes stop, a warm start and a total distance of 15.6 km at 23 °C. In comparison with the Toyota Avensis with a 1.8 l petrol engine, the CO_2 reductions were 90-95 %, and somewhat lower compared to the Toyota Avensis with a diesel engine. These high CO_2 reductions are possible only on short trips when the battery is depleated.

High CO_2 emissions was observed from the Prius PHEV at cold and warm engine start, at -7 °C and can be explained by the fact that the vehicle is programmed to warm the compartment at low ambient temperatures by starting the combustion engine.

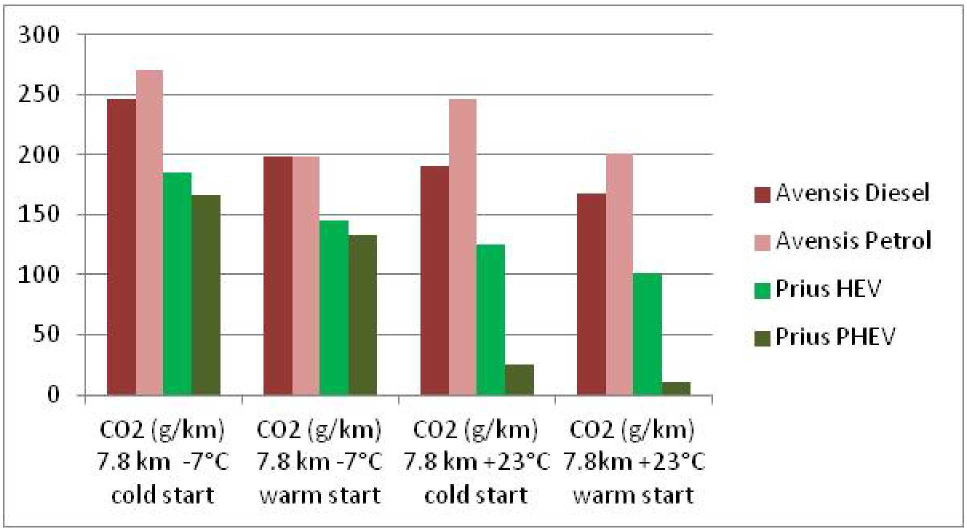

Figure S.1: Measured CO_2 emissions from a pre-commercial PHEV Prius and reference cars at -7 °C and +23°C from full Helsinki city driving cycles

The hypothesis that the Prius PHEV will have only minor and probably harmless emissions of NO_x, PM and volatile hydrocarbon compounds (HC) in city traffic conditions was confirmed. Any emissions of NO_x, PM and HC from the Prius PHEV are hard to detect after the initial "starting engine emissions", even when the vehicle was driven aggressively in city traffic conditions.

PHEV purchase

It is difficult to study the purchase and use of PHEVs until experience has been gained with commercial marketing. Some consumer behaviour studies concerning the hypothetical future purchase of such a vehicle show that a basic knowledge of the technical functioning of PHEVs is critical to the willingness to buy. Moreover, people are more willing to buy a PHEV if they are in a transitional state of their lifestyle practices and find support within their social network.

There is a clear difference between “early adopters”, in this case people interested in technology and environment, and “mainstream buyers”. Presumably, PHEVs will have to be on the market for several years before mainstream car buyers will be likely to buy them.

The potentials of the widespread use of PHEVs are enhanced by technological and environmental interest, support from personal networks, gas price dynamics, and tax incentives. Barriers to their widespread use are lack of knowledge about the technology, uncertainty about the its future, access to charging facilities, and the relation between driving range and price.

Users’ experience of pre-commercial Prius PHEVs

The user surveys in Europe and in the Nordic countries in this project indicate that the users in general are satisfied with the pre-commercial Prius PHEVs. Two challenges or barriers appear – the electric driving range is considered too short, and the handling and storing of the charging cable is cumbersome. The former challenge involves a trade-off versus cost, charging time, and/or luggage space. Longer driving range requires more battery capacity, which is costly. More battery capacity will also require longer charging time. The field test showed that charging time always was less than two hours and that average charging time was 71 minutes. The Finnish survey showed that most users connected the vehicle to the grid for 2-3 hours or, more often, for more than five hours. Consequently, longer charging time for a battery pack larger than 4,4 kWh should not be a big problem for most users.

Oslo City’s agency for “*Road safety, mobility and accessibility*”, which includes the parking regulation services, has chosen Toyota Prius Hybrid vehicles (HEV) for their normal operations, and has also leased a pre-commercial PHEV Prius. Within this agency, five drivers and two managers were interviewed about their experiences.

Both the drivers and the middle managers were positive to the Prius PHEV, considering it a high quality vehicle well fit for their operations, mainly because it was the newest car with the most modern accessories. The Prius PHEV was accepted as a good modern car, a fact indicating that there were no major objections to the vehicle itself or to the plug-in function.

All the users were positive to the reduced consumption of fossil fuel, even though they did not benefit economically from it themselves. The few objections to the Prius PHEV had nothing to do with the plug-in hybrid technology itself. The fuel consumption was, in the way they used the Prius PHEV, said to be some 10 per cent lower than that of the HEVs. Being environmentally friendly is a formal objective of the agency, and reduced CO_2 emissions are seen as positive to the drivers and managers.

The testing of the PHEV within this agency show no barriers to the use or charging of the vehicle. The charging was well organised, and none of the drivers interviewed considered the charging a problem, not even a hassle. Even though the drivers did not benefit economically or in any other way from charging the PHEV after use, they all did it as part of normal routine. Consequently, if the charging is well organised, as it was in this organisation, it should not be a barrier to the effective use of the PHEV.

These results must be considered positive, indicating that organisations using cars for their operations can be an important market for the future PHEV, especially when an environmentally sound image is desired. These test results do not, however, tell us how private consumers would behave as possible PHEV owners.

Battery capacity

Many of the drivers accepted the pre-commercial PHEV Prius' battery capacity as it is, revealing little interest in higher capacity. One of these drivers thought that his employer in Oslo would be willing to pay more for a PHEV with higher battery capacity, because the agency wants an environmentally friendly image. Another driver thought that the agency would refrain for buying more expensive vehicles.

Almost half of the Finnish users of pre-commercial PHEV Priuses stated that they were willing to pay more for a vehicle that is less harmful to the environment. Two thirds agreed that this vehicle satisfied their daily needs for transport. If two versions of the PHEV were marketed, one reasonably priced with the present battery capacity, and another more expensive version with higher capacity, it is likely that most consumers should be able to satisfy their travel needs with one or the other PHEV version.

For companies and organisations that are in business around the clock seven days a week, fully Electric Vehicles (EVs) are difficult since they might have to be charged at inconvenient times. To these companies, limited driving range is a disadvantage as well. With a PHEV you can always continue with the help of a combustion engine, when the batteries are low.

PHEVs will, with a competitive purchase price, be an attractive option in many applications, including family cars. For environmentally focused customers, wanting zero emissions for daily short distances and the convenience of unlimited distance travel without charging batteries, plug-in hybrid vehicles are a fine solution.

Transportøkonomisk institutt
Stiftelsen Norsk senter for samferdselsforskning

Sammendrag:

Ladbare hybridbiler

Utslippsreduksjoner og barrierer for bruk av en ladbar Toyota Prius

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Forfatter(e): Rolf Hagman og Terje Assum
Oslo 2012 40 sider

Ladbare hybridbiler (Plug-in Hybrid Electric Vehicles - PHEVs) er biler som har både en forbrenningsmotor, elektrisk fremdrift og batterier, som kan lades fra strømnettet. Ladbare hybridbiler er det mulige neste trinnet i utviklingen av hybridbiler (HEVs). I 2012 er ladbare hybridbiler tilgjengelige som demonstrasjonsbiler, prototyper, forseriebiler og i form av noen få modeller i kommersiell serieproduksjon. Mange forskjellige utførelser og svært ulike konsepter blir testet. Ladbare hybridbiler kan brukes til lengre turer uten lading, noe som betyr at elbilbrukernes "rekkeviddeangst" ikke er et problem. Den samme bilen kan brukes til både korte og lengre turer, spare fossilt drivstoff og kjøres helt uten avgassutslipp når den kjøres som en Elbil.

Den nye kommersielle ladbare versjonen av Toyota Prius blir en middels stor familiebil med mulighet for å kjøre ca 25 km i elektrisk modus (EV mode), og vil bli markedsført i hele Europa i 2012. Hva vil virke tiltrekkende i markedet og hva vil være det optimale batteristørrelsen og den optimale kjørelengden for en PHEV i elektrisk modus? Faktorer som må være kjent for å besvare dette spørsmålet er, eventuelle utfordringer med batteriene, innkjøpspris, drivstofforbruk, CO_2-utslipp og potensielle kjøperes ambisjoner om en miljøvennlig profil .

Dette prosjektet er utført for Toyota Norge og er støttet av "Transnova". Prosjektet fokuserer på erfaringene med en prekommersiell ladbar versjon av hybridbilen Prius som ble testet av vanlige brukere i to år i Danmark, Finland, Norge og Sverige. Bensinforbruket i disse ladbare hybridbilene viste seg, for bilene som ble brukt på forskjelle måter, i virkelig trafikk under de to årene å bli mellom 0,25 og 0,38 liter per mil.

En ulempe med noen motorteknologier for å redusere utslipp av CO_2 er at de kan ha utilsiktede ulemper som å gi store utslipp av helseskadelige avgasser, for eksempel NO_x. Dette skaper et dilemma for myndighetene som skal sørge for at både mål for klimagassutslipp og mål for helseskadelige utslipp oppfylles. Biler med hybrid teknologi har generelt de beste forutsetninger for lave utslipp av både klimagasser og lokalt helseskadelige forurensninger.

Avgasstester med simulert bykjøring ved VTTs avgasslaboratorium i Finland bekreftet at den vanlige Toyota Prius har lave utslipp av CO_2 sammenlignet med vanlige bensin- og dieselbiler. Avgasstestene med en av de prekommersielle ladbare Prius-bilene viste at vi ved en simulert tur frem og tilbake til butikken (15,6 km) i bytrafikk kan få reduksjoner av CO_2-utslippene med 80-90% i forhold til en vanlige Prius. Disse reduksjonene er mulige på korte turer med fullt oppladede batterier. For både den vanlige Prius og den prekommersielle PHEV Prius var utslippene av helseskadelige avgasser under alle kjøreforhold ekstremt lave.

Ny ladbar Prius

De to hovedmåtene for fremdrift av et kjøretøy er ved hjelp av en elektrisk motor eller med en forbrenningsmotor. Hybridteknologien kombinerer de beste egenskapene med de to fremdriftsformene. Ladbare hybridbiler gir i tillegg mulighet for kjøring på strøm fra nettet. Den nye kommersielt tilgjengelig ladbare Prius har en batterikapasitet på 4,4 KWh. Den kan brukes som en energieffektiv hybridbil på lengre turer og på korte turer som en elbil. Bensinforbruk er på 0,21 liter per mil (NEDC, europeiske kjøresyklus for ladbare hybridbiler) noe som tilsvarer CO_2-utslipp på 49 g/km. Full lading av batteriene trenger 90 minutter med bilen tilkoblet til strømnett (220 V, 16 A).

Er det disse egenskapene hos en ladbar hybridbil som det markedet ønsker? Vil markedet betale en ekstra pris på ca. 40 000 kroner for den ladbare versjonen av Toyota Prius i forhold til den siden mange år etablerte hybridbilen uten mulighet for lading via nettet?

Prekommersiell ladbar Prius

Hensikten med å teste prekommersielle serier av biler er å optimalisere tekniske funksjoner samt å kartlegge aksept i markedet. Ti prekommersielle Toyota Prius ble utplassert i de nordiske landene, tre i Norge, to i Danmark, to i Sverige og tre i Finland. Etter full lading med elektrisitet fra nettet ble det oppgitt at disse bilene kan kjøres som rene elbiler de første 20 km. Etter en regulert utlading av batteriene kan de kjøres som vanlige hybridbiler.

De ladbare Prius'ene hadde ved testkjøringen i de nordiske landene et gjennomsnittlig bensinforbruk på fra 0,25 til 0,38 liter per mil. Drivstofforbruket henger klart sammen med hvordan og hvor et kjøretøy blir kjørt. I denne praktiske testen var det ingen instruksjoner for og ingen kontroll av hvor og hvordan de ladbare bilene skulle kjøres eller når og hvor ofte de skulle lades. Den bilen med det laveste bensinforbruk (0,25 l/mil) ble koblet til strømnettet mye oftere enn de andre. Innsparingen av drivstoff var generelt høy for bilene i den prekommersielle serien av ladbare Prius.

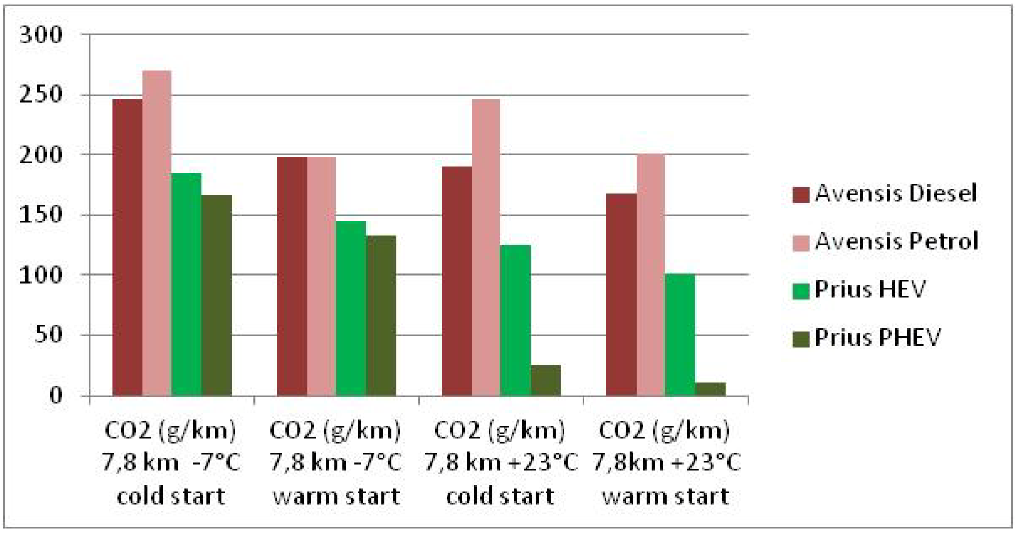
Vår erfaring av drivstofforbruk, avgasstesting, kjøremønster og bilteknologi gir en indikasjon på at avgassutslippene av CO_2 fra de prekommersielle ladbare Prius'ene generelt var i størrelsen 30% sammenlignet med vanlige Prius hybridbiler, 45% sammenlignet med effektive dieselbiler og 60% sammenlignet med effektive bensinbiler.

Utslippstester i laboratorium

For forstå hvor effektiv en ladbar Prius er i bytrafikk og i kaldt klima, ble en av bilene testet ved VTTs avgasslaboratorium i Helsingfors. Den ladbare hybridbilen ble sammenlignet med en vanlig Prius, en Toyota Avensis med 1,8 liter bensinmotor og en Toyota Avensis med 2,0 l dieselmotor. De fire bilmodellene ble testet ved omgivelsestemperaturerene -7 °C og +23 °C og ved kjøring av en bykjøringssyklus, (Helsinki bykjøringssyklus).

Den ladbare Toyota Prius viste lavt bensinforbruk og betydelig redusert utslipp av CO_2 ved kaldstart - kjøring 7,8 km, innlagt stopp på 15 minutter, varmstarten - kjøring 7,8 km. Sammenlignet med en vanlig Prius hybridbil var CO_2-reduksjonen 80-90% ved +23 °C. Sammenlignet med en Toyota Avensis med 1,8 liter bensinmotor var CO_2 -reduksjonen 90-95% og noe lavere sammenlignet med en Toyota Avensis med dieselmotor.

Ved -7 °C hadde den prekommersielle ladbare Prius nesten like store utslipp av CO_2 som den vanlige Prius. Den ladbare versjonens høye utslipp av CO_2 fra start med kald og varm motor ved -7 °C l kan forklares med at bilen var programmert til å varme opp kupeen med varme fra forbrenningsmotoren når omgivelsestemperaturer var lav.



Figur S.1: Målte CO_2-utslipp fra en ladbar Prius hybridbil og sammenlignbare biler ved -7 °C og +23 °C - Helsinfors bykjøringssyklus

Hypotesen om at en ladbar Prius i bytrafikk vil ha meget lave utslipp av NO_x, PM og flyktige hydrokarbonforbindelser (HC) i bytrafikk ble bekreftet. Utslippene av NO_x, PM og HC fra den ladbare Priusen var ekstremt lave. Spesielt var de, når treveiskatalysatoren har tent, lave ved krevende bykjøring[1].

Kjøp av ladbar hybridbil

Det er vanskelig å undersøke attitydene til kjøp og bruk av ladbare hybridbiler før de er kommet på markedet. Noen undersøkelser om hypotetiske fremtidig kjøp av slike kjøretøy viser at grunnleggende kunnskap om den tekniske virkemåten til disse bilene er avgjørende for innstillingen til å kjøpe en slik bil. Dessuten er folk mer villige til å kjøpe en ladbar hybridbil hvis de er i en periode preget av endringer i livsstil, og hvis de finner støtte i sitt sosiale nettverk. Det er en klar forskjell mellom "early adopters", dvs. i dette tilfellet folk som er interessert i teknologi og miljø, og "mainstream” kjøpere. Antakelig må ladbare hybridbiler være på markedet i flere år før det er sannsynlig at ”mainstream” bilkjøpere vil kjøpe dem.

Potensialet for utbredt bruk av ladbare hybridbiler er avhengig av teknologisk og miljømessig interesse hos kjøperne, støtte fra personlige nettverk, endringer i drivstoffpriser og incentiver i form av skattelette på slike biler og høyere avgifter på fossilt drivstoff. Mulige barrierer mot utbredt bruk av ladbare hybridbiler er mangel

[1] Det er på grunn av fet blandning ved start av motoren alltid et relativt stort kaldstarttillegg for bensinbiler som har treveiskatalysator

på kunnskap om denne teknologien, usikkerhet om framtiden for denne teknologien, tilgang til ladepunkter, og forholdet mellom elektrisk kjørelengde og prisen på bilene.

Brukererfaringer med ladbare hybridbiler

Brukerundersøkelsene i Europa og i de nordiske landene i dette prosjektet indikerer at brukerne generelt er fornøyd med den prekommersielle ladbare Prius hybridbilen. To utfordringer eller hindringer kom fram - den elektriske kjøreavstanden anses for kort, og håndtering og lagring av ladekabelen er tungvint. Førstnevnte er primært et spørsmål om kostnad, ladetid og plass i bilen. Lengre kjørelengde i elektrisk modus krever mer batterikapasitet, noe som er kostbart. Mer batterikapasitet vil også kreve lengre ladetid. Undersøkelsene viste at gjennomsnittlig ladetid var mindre enn to timer. Den finske undersøkelsen viste at de fleste brukere hadde bilen koblet til nettet i 2-3 timer, og ofte under lengre tid enn fem timer. Den tiden det tar å lade batteriene var kortere enn den tid bilen faktisk var tilkoblet strømnettet. Derfor bør en ladetid på opptil 3-4 timer ikke være et stort problem for de fleste brukere.

Oslo kommune har leaset en ladbar Toyota Prius til bruk for trafikkbetjentene. Fem trafikkbetjenter og to mellomledere ble intervjuet om bruken av denne bilen. Alle var positive, og vurderte den som et kjøretøy av høy kvalitet, godt skikket for det arbeidet de skulle utføre. Den positive innstillingen skyldtes hovedsakelig at dette var den nyeste bilen med det mest moderne tilbehøret. Den ladbare hybridbilen ble akseptert som en god moderne bil, noe som viser at det ikke var noen viktige innvendinger til selve kjøretøyet eller ladefunksjonen. Alle brukerne var positive til redusert forbruk av fossilt drivstoff, selv om de ikke hadde økonomisk fordel av dette selv. De få innsigelsene som kom hadde ingenting å gjøre med hybridteknologien eller ladingen. Drivstofforbruket ble sagt å være rundt 10 prosent lavere enn for vanlige hybridbiler som trafikkbetjentene også brukte. Godt miljø er et formelt vedtatt mål i Oslo kommune, og redusert CO_2-utslipp er derfor positivt både for trafikkbetjentene og lederne.

Resultatene fra utprøvingen av den ladbare hybridbilen i Oslo kommune viste ingen hindringer for bruk eller lading av bilen. Ladingen var godt organisert, og ingen av de intervjuede betjentene vurdert ladingen som et problem, ikke engang som bry. Selv om betjentene ikke hadde økonomiske eller andre fordeler av å lade bilen etter bruk, gjorde alle det som en del av vanlig rutine. Det vil si hvis ladingen er godt organisert, som den var i Oslo kommune, bør lading ikke være en hindring for effektiv bruk av ladbare hybridbiler.

Disse resultatene må vurderes som positive, og det viser at bedrifter og organisasjoner som bruker biler i sine virksomhet kan være et viktig marked for fremtidige ladbare hybridbiler, særlig organisasjoner og bedrifter som ønsker å gi et miljøvennlig inntrykk. Resultatene fra utprøvingen i Oslo kommune kan ikke gjøres gjeldende for bilmarkedet for private husholdninger.

Batterikapasitet

Flere brukere i Oslo kommune aksepterte den ladbare hybridbilens batterikapasitet som den var og syntes å ha liten interesse i større kapasitet. En av trafikkbetjentene mente dog at kommunen ville være villig til å betale mer for en ladbar hybridbil med høyere batterikapasitet fordi kommunen ønsker å gi et miljøvennlig inntrykk. En annen betjent mente at kommunen ikke ville kjøpe dyrere biler.

Omtrent halvparten av de finske brukerne sa at de var villige til å betale mer for en bil som er mindre skadelig for miljøet, og to tredjedeler var enige om at de ladbare hybridbilene hadde oppfylt deres daglige behov for transport. Hvis to versjoner av PHEV ble markedsført, en rimelig versjon med dagens batterikapasitet og en dyrere versjon med høyere kapasitet, ville de fleste forbrukere kunne tilfredsstille sine reisebehov med ladbare hybridbiler.

For bedrifter og organisasjoner kan rent elektriske biler være vanskelig å bruke hvis de skal være i drift 24 timer i døgnet 7 dager i uken. Ladetiden og for lang reiseavstand kan være en utfordring med elbiler, men er ikke et problem for ladbare hybridbiler som kan kjøre videre uten fulladet batteri og med hjelp av alternative fremdriftskilder. Ladbare hybridbiler vil være attraktive familiebiler hvis de er i stand til å konkurrere på pris. For miljøinteresserte kunder som ønsker null avgassutslipp på daglige korte reiser og samtidig har mulighet for ubegrenset reiseavstand, vil ladbare hybridbiler være en god løsning.

1 Introduction

1.1 Background

A chargeable or Plug-in Hybrid Electric Vehicle (PHEV) has an internal combustion engine and batteries that can be charged from the electricity grid propelling the vehicle electrically. Electric Vehicles (EVs) are defined here as vehicles with all energy for propulsion stored in chargeable batteries. A PHEV may run as an EV[1] in EV mode and as a Hybrid Electric Vehicle (HEV) in HEV mode.

With this project, the Institute of Transport Economics has undertaken an evaluation and literature review of PHEVs and a study of the typical usage patterns of a small number of PHEVs in cooperation with the Toyota Motor Company. Users were afterwards interviewed about their experiences. In cooperation with VTT, an internationally well-known emissions laboratory, we carried out comparative tests of the emissions from a PHEV Prius versus an ordinary HEV Prius without an extra battery, and versus modern diesel and petrol alternatives.

The vehicles in the field test were pre-commercial Toyota Prius PHEVs with a 73 kW petrol combustion engine, a 60 kW electric motor and lithium-ion batteries. When driven in EV mode on electric power only, these vehicles have a range of about 20 km, a top speed of 100 km/h and zero tailpipe CO_2 emissions. Charging time for discharged batteries is less than 2 hours. The vehicles, which were not yet available on the open market, were driven by ordinary users in open road traffic in the Nordic countries (Denmark, Finland, Norway and Sweden) in the period 2010 to 1212.

Although these PHEVs are capable of zero tailpipe local pollutants and CO_2 emissions during the first 20 km after charging, the actual reduction in local pollutants and CO_2 emissions and the impact on climate depend on several factors. Firstly, a PHEV may use the combustion engine even when batteries are fully charged – for example, when accelerating or driving along steep uphill roads. Secondly, reduced CO_2 emissions also depend on the amount of electricity left before the vehicle has to be recharged. If PHEVs are driven considerably longer between recharging than the capacity of the battery allows, the combustion engine power kicks in and the full potential of emission-free driving is not realized.

Whereas the reduction in local emissions is achieved relatively independently of how the electricity is produced, CO_2 emissions from the burning of coal, gas or oil must be taken into account in a Life Cycle perspective of benefits from driving in EV mode. Here there can be important regional and national differences. While most of the electricity in Norway is produced by hydropower, the main source of electricity in most other countries is by fossil fuels. Denmark has substantial wind-power generation, while in Sweden and Finland nuclear power is an important source. Since

[1] The more general term Charge Depletion (CD) mode may be more adequate since this is a mode where the battery is depleting (the combustion engine may still kick in when the need arises.)

the Nordic countries are connected in a common grid, there is a mix of electricity sources operating in each country.

1.2 Market acceptability and emission savings

As for all new vehicle models, the purpose of launching pre-commercial series is to be able to optimize and adjust technical functions and measure customer acceptance.

A crucial aspect of vehicle electrification, and a main point of interest in this project, is the extent to which the technical CO_2 reducing potential of PHEVs can be realized in the practical, normal use of these vehicles. Compared to conventional vehicles which use fossil fuels, PHEVs are assumed to have a CO_2 reduction potential of about two-thirds under common, mixed use involving commuting and weekend trips. PHEVs are assumed to be attractive because they do not have the disadvantages of EVs in terms of limited mileage between charging.

One ambition in the project is to analyse and understand the fuel savings and reductions of greenhouse gas (GHG) emissions that can be achieved with hybrid and plug-in hybrid technology in light vehicles.

Through measuring fuel consumption, testing emissions and assessing driving patterns we attempted to demonstrate the magnitude of CO_2 emission reductions with the Prius PHEV when used in Nordic field tests. Laboratory emission tests at VTT in Finland have made it possible to compare field test fuel consumption with that of other vehicles and technologies under controlled conditions.

In order to be able to examine the practical reductions and the potential CO_2 savings of PHEVs, the vehicle use in EV mode is recorded separately from traditional Prius Hybrid HEV mode.

Another purpose of the project is to detect any barriers to the regular use of PHEVs, and to assess the extent to which batteries are charged, and how often. Possible barriers may be access to the electric grid and plug-in possibilities where the vehicle is parked. Other possible barriers are inconvenient plug-in locations at home and at the workplace, low private economic benefits when driving on fully charged batteries compared to driving on petrol, or high vehicle purchase price compared to vehicles with competing technologies.

1.2.1 International and national CO_2 reduction targets

Increasing proportions of CO_2 and other greenhouse gases in the atmosphere contribute to global warming and produce regional changes in weather patterns that can lead to extreme weather conditions. Norway has set targets for reducing CO_2 emissions in a White Paper on climate policy (St.meld.nr 21 (2011-2012)) and in an agreement on climate policy reached by the Norwegian Parliament in 2012. In the so-called Soria Moria II declaration (Gilja 2009), the Norwegian government has set a goal of 40 percent cuts in emissions by 2020 compared to 1990. In this context it is therefore important to reduce CO_2 emissions from road traffic.

Potentially, chargeable or plug-in hybrid vehicles can reduce the consumption of fossil fuels substantially and contribute to the success of the Norwegian initiatives. In this project we examined the extent to which the emission reductions are obtainable under field test conditions and in an emissions laboratory.

1.2.2 Local pollutants

Exhaust emissions from motor vehicles are a problem in major cities, and nitrogen oxides (NO_x), together with particulate matter (PM), are the two dominant, directly harmful components of exhaust gases. Concentrations of NO_2 in the air have increased in the past 10 years in some of the major cities in Norway, particularly in Oslo and Bergen, where limit values for acceptable air quality were exceeded several times in 2010. A problem for the authorities is that the financial incentives introduced to encourage a switch to vehicles with lower GHG emissions have proved problematic from a public health perspective (Hagman, Gjerstad, Amundsen 2011).

Ideally, the authorities would like to introduce further innovative technologies that would solve both local and global emission problems.

1.3 Hybrid and plug-in hybrid technology

1.3.1 State of the art

One of the ambitions of the project was to analyse and understand what fuel savings and reductions of GHG emissions are possible with hybrid and plug-in hybrid technology in light vehicles. To obtain an overview of the technical opportunities available, right from the start of the project we gathered information from various automotive companies and auto shows, as well as from independent research and scientific papers. In addition, we discussed and tested our understanding and conclusions with key technology expertise from leading automotive companies.

The Toyota company, and Toyota Norway as project owner, generously shared their views on vehicle electrification and on the possibilities and challenges related to costs and batteries. In addition, we received valuable information and had interesting communication with representatives of GM/Opel, the Ford Motor Company, VW/Audi, Mercedes and the Volvo Car Company.

It became clear to us during the project period that electrification of light vehicles to varying degrees would be part of the future of the automotive industry. Technically, PHEVs can have a "Tank to Wheel" energy efficiency of over 80 percent from stored energy in batteries if they run on electric power only (Hagman et al. 2011). However, EVs are the vehicle of choice over short distances on electric power, and not PHEVs. In an assumed real-life case, the use of PHEVs can have an energy efficiency of almost 60 percent "Tank to Wheel" (Hagman et al. 2011).

Comparisons between real-life fuel consumption and CO_2 emissions are difficult, since they very much depend on how, where and by whom the cars are driven. An average fuel consumption for the 9 PHEVs in the Nordic tests of 3.25 l petrol per 100 km, corresponding to 75 g CO_2/km, indicates up to 60 percent reductions of tailpipe CO_2 emissions ("Tank to Wheel") compared with similar petrol engine vehicles in real-life daily driving conditions.

This section gives a short overview of the background for, and our view of, the state of the art for plug-in hybrid vehicles in the Nordic countries in 2012.

1.3.2 Propulsion systems

The two dominant ways of powering a road vehicle are electricity and combustion.

The main argument for electricity is that energy efficiency is much higher than with combustion. Electric drive may have an efficiency of about 85 percent from energy storage inside the car to useful power to the wheels (Tank to Wheel), which is superior to competing alternatives (Hagman et al. 2011). Another argument for electric drive is the absence of tailpipe emissions.

The major challenge with electricity-to-road vehicles is coping with batteries that are heavy, expensive and with durability still unproven. For traditional car-use, including over longer distances, the batteries weigh about 200 kilograms (including the control electronics) and costs are a heavy burden. In 2012, batteries even for a small car often cost more to produce than the rest of the car put together. The potential for development and improvement is there, but the cost of battery packs with long-range capacity remains an obstacle. EVs have simple technology and inexpensive propulsion systems, and since small vehicles can function with a smaller, lighter and less expensive battery pack than larger vehicles, competitive EVs should be as small and as light as possible.

The main argument for combustion engines in cars is the convenience of high energy density carbon based fuels, reliable vehicles, mature low cost engine technology and sufficient infrastructure for fuel.

Up to 50 available models of Hybrid Electric Vehicles (HEVs) in 2012 reflect the focus of manufacturers on finding new efficient technology and reducing cost, both of which are critical issues if hybrids are to be accepted as mainstream vehicles (New York Times 2012).

The torque and efficiency of electric drive along with the practical advantages of a combustion engine in an HEV combines well to achieve a vehicle that uses fossil fuels effectively. HEVs are essentially vehicles powered by petrol or diesel with an additional electric power line. HEVs can get longer driving distances out of a litre of carbon-based fuel and usually create less locally harmful exhaust emissions than corresponding conventional combustion engine vehicles.

Vehicles with two power sources naturally cost more to develop and manufacture than those with just a conventional engine, which means hybrids carry a price premium. There really is no single answer to how long it will take before a HEV's better fuel economy will offset its higher initial cost. To compensate for the extra costs, authorities often offer tax advantages and other incentives to stimulate sales. Tax advantages and incentives in Norway have created a unique high demand for EVs compared with the rest of the world. For Norwegian authorities it will be a challenge to adjust tax advantages and incentives so that new partially electrified vehicle models are treated fairly.

Marketing of new EV, HEV and PHEV models and associated new technologies has created confusion in the market. The new systems range from simple "start and go" giving small savings at low cost to so-called full hybrids and EVs with range extenders costing much more. The EV, HEV and PHEV systems not only vary in the way the power is routed, in the degree of electrification and in mechanical layouts, they also resist any precise classification of their designs (New York Times 2012). There are some commonalities, however. At their most basic, hybrid systems increase fuel efficiency by pairing a combustion engine with one or more electric motors or generators. There is also a high-capacity battery for storing and releasing electrical energy to the motor when needed. Power split units, clutches and electronic controllers to regulate the flow of engine power and electricity are components used to design partially electrified vehicles.

The first HEV sold in high volumes was the Toyota Prius. This car has a hybrid system with an electric motor, a combustion engine and a separate generator. In differentiated driving conditions, the hybrid system will reduce petrol consumption by approximately 30 percent. With a rechargeable and larger battery pack there is more energy to save. Commercial production and public sale of the PHEV version of the Toyota Prius is starting in 2012.

PHEVs have all the qualities and comfort of traditional combustion engine vehicles and, in addition, the potential of great fuel savings. Batteries are the critical key component of the successful electrification of light vehicles. Thanks to a limited need for expensive, large and heavy batteries, PHEVs will reduce CO_2 emissions from light vehicles at a more affordable cost than wholly electric vehicles (Hagman et al. 2011).

1.3.3 Hybrid and Plug-in concepts

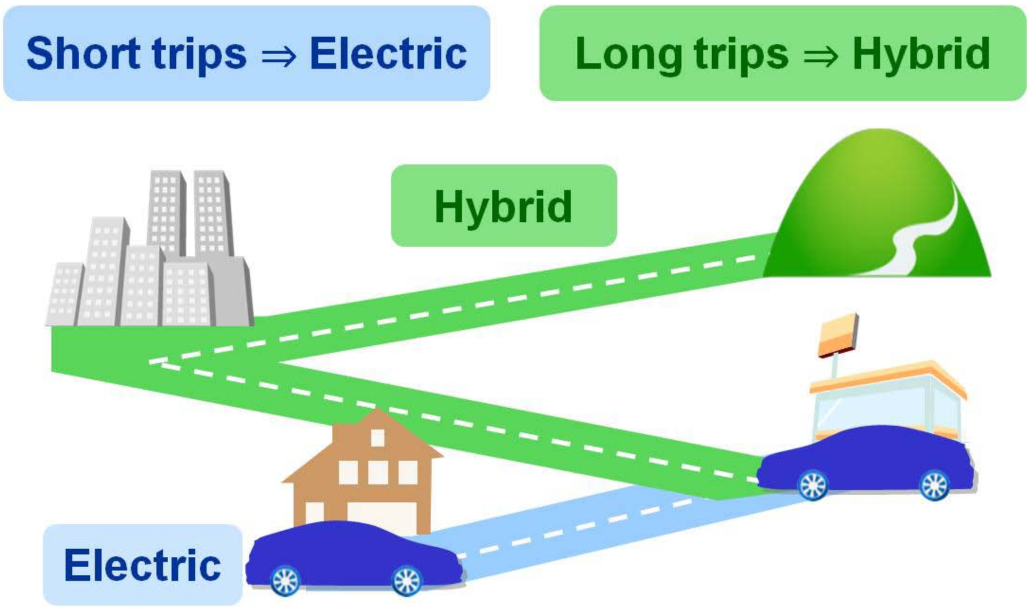


Figure 1: Toyota Europe

The basic idea is an EV for short trips and an energy-efficient HEV for long trips in one and the same vehicle. Battery size is important, as this limits wholly electric driving mode range.

Considering global warming and the environment, one's economy and practical use of a car, the private car of the near future could be:

- *EV* – a smaller vehicle driven over short driving ranges
- *PHEV* – vehicles driven over short, but also longer, distances

HEVs and PHEVs are more likely than EVs to be the vehicle of choice in single-car households, because these cars can be used over both short and long distances, and at the same time lower petrol consumption than conventional cars. Until the distance that EVs can travel between each battery charge is much greater, and charging much quicker, these cars are suitable primarily for shorter and predictable journeys between places where the driver spends some time and where there are charging facilities in place. Depending on travel patterns, an EV may prove a better fit as the second car in two-car households.

PHEVs are available as demonstration, prototype and production models in many different designs with very different concepts and characteristics.

The Opel Ampera is a PHEV (or EV with petrol-powered generator) introduced onto the Norwegian market in 2012. Opel/GM say that their Ampera will have re-chargeable batteries giving 60 km on electric drive, and that the combustion engine will re-charge the batteries when they are about to run out. The Opel Ampera drive system concept is expected to become available for a range of cars with different engine size and battery capacity.

The Volvo V60 plug-in hybrid is another concept that will be available in small production volumes on the open market in 2012. It focuses on the plug-in option and less on the combination electric motor and diesel engine. Volvo describes it as three cars in one. First, a rear-wheel-driven EV giving about 50 km on electric power stored in batteries, and, second, a front-wheel-driven diesel car. To some extent front and rear wheel drive can be combined in four-wheel hybrid mode.

1.3.4 Toyota PHEV Prius

Figure 2: Toyota Europe

Table 1: Toyota Motor Company's 2012 key specifications for the new commercial PHEV Prius:

Fuel consumption (EU approval figure)	2.1 l petrol/100 km
CO_2 emissions (EU approval figure)	49 g/km
NO_X emissions (EU approval figure)	0,0009 g/km
Electric mode cruising range	Approx. 25 km
Charging time	Approx. 90 min (AC 220V, 16 A)
Battery	4.4 kWh Lithium-Ion

Toyota is developing EVs, HEVs, PHEVs and also fuel cell vehicles (FCEVs) with hydrogen as energy carrier. The company started hybridization of their vehicles with the Prius in 1997 and have gradually been continuing with hybridization of other models with a system called Hybrid Synergy Drive, where a key component is the power split unit, which gives the vehicles strongly increased energy efficiency in urban traffic. Toyota state that, at some point, all their cars will have hybrid drive.

After development and gradually increased test fleets since 2007, Toyota is now introducing a plug-in Prius model onto the open market.

Challenges with batteries and lack of carbon-neutral-produced electric power are the main reasons why EVs are not produced and sold in high volumes world-wide. The reason FCHEVs are not sold on a commercial basis is simply that the technology has not matured to a commercially viable level. The extent to which EVs and PHEVs will be sold in large numbers depends on national taxation and sales incentives on these vehicles (Webiner, July 2012).

The 2012 Prius PHEV is basically a regular Prius that has been upgraded with a larger battery pack. The batteries are a newly developed 4.4 kWh lithium-ion battery pack (weight 80 kg) replacing the old nickel metal hydride (NiMH) battery for an ordinary 2012 HEV Prius. Some new weight-saving methods reduce the drawbacks with the larger battery, making the PHEV version of the Prius a modest 56 kg heavier than the regular HEV version.

The biggest fuel savings, and thus CO_2 savings, will be realized by those who mostly travel short distances, frequently re-charge the batteries and keep the 2012 Prius PHEV in electric mode as much as possible.

1.4 Literature on purchase and use of PHEVs

Although PHEVs are fairly new, there is already some research literature concerning both the technology itself and the use of these vehicles.

The TOI library searched international literature databases using the key words

- Plug-in hybrid electric vehicle or PHEV
- Plug-in hybrid vehicle – PHV
- Ladbar hybridbil (Norwegian/Scandinavian)

Between 150 and 200 publications were found on the use of PHEVs, but only about 50 were considered relevant and therefore checked. A few are cited below. Most of the literature was published in the period 2009–2012, i.e. after the proposal for this project was written.

1.4.1 Topics in the literature concerning the use of PHEVs

Four relevant questions emerged from the literature:

1. Will people buy PHEVs? Who will buy them and will they be early adopters or mainstream car buyers?
2. Will people charge these vehicles? To what extent, how often, how much?
3. What reduction in fossil fuel consumption and CO_2 emissions can be expected from the use of PHEVs?
4. What public policy implications will there be?

1.4.2 The use of PHEVs – buying and charging

According to Schwanen and Lucas (2011, p. 3), "*.... a complex combination of factors is at play"* in travel choices and preference for the automobile over other modes of transport. These authors describe the many theories applied in predicting and understanding car-use. Concluding, they list seven important factors found in different theoretical perspectives of car-use, the last of these being: "*Car-use is heterogeneous in that there are important differences in motives and drivers between individuals and between situations experienced by one and the same individual*" (p. 31). Consequently, finding a simple explanation as to why people would use a car, not to speak of a car with new technology such as the PHEV, seems unlikely. However, several authors have tried to find important aspects of the use of PHEVs.

The main questions are whether people will buy such vehicles, and, if they do, to what extent will they make full use of the EV mode by charging the batteries from the electric grid (Assum, 2011)? If drivers do not bother to plug in, the plug-in PHEV Prius will function as a traditional hybrid vehicle, and there would be little point in paying an extra purchase price of about NOK 40 000 (about €5300[2]).

For a new PHEV Prius, plugging in the vehicle after use will save about a litre of petrol during the next trip, i.e. about NOK 15 or €2, and perhaps give drivers a feeling of being environmentally friendly. Other PHEV models may have much larger battery packs and be able to run for much longer distances in pure EV mode.

Other PHEV models are delivered with about three times larger battery pack and the potential for three times longer EV mode. What will attract the market? Will it be the optimal battery size and the optimal distance for a PHEV driving in EV mode only? The parameters involved in answering these questions are probably ease of charging, vehicle purchase price, fuel savings, CO_2 reductions and green image.

Kurani (2009; p. I), studying 34 households in Sacramento, California, provided with PHEVs, asked "*Why would consumers buy plug-in hybrid electric vehicles ...?"* and *"whether or not people will plug-in a vehicle that does not have to be plugged-in"* (p. V). The answer to the latter question was "*Yes, we will*", but *"with a large variation in the mean frequency of PHEV charging across households – from zero to 2.6 times per weekday and zero to 1.5 times per weekend day"* (pp. V-VI). However, the sample of households was small and not representative of the population (p. IV). In a later report, Kurani (2010) found more or less the same charging frequencies with a sample of 67 households (p. 2) which "*does not attempt to represent a population, but rather to illustrate observed behavior of specific groups"* (p. I).

Axsen & Kurani (2011) list five models for purchasing behaviour concerning PHEVs:

1. Expectancy-value model,
2. Adjusted-expectancy-value models,
3. Normative models,
4. Habit models,
5. Sociality models.

[2] Exchange rate 1€ = 7.50 NOK

Ten households, i.e. a total of 18 persons, as well as the social networks of these households formed the basis of the empirical data. Axsen and Kurani found that discussion within social networks influences not only perceptions of the PHEV and purchasing behaviour, but also more basic values concerning the environment and social valuation.

The main conclusion is that there are three conditions to buying a PHEV. "*Households are likely to develop such values in this PHEV trial if they:*

i) already have or easily come to a basic understanding of functional aspects of PHEV technology, ii) are in a transitional state of their lifestyle practices, and iii) find supportive pro-societal values within their social network. Thus, to capture value change, behavioral models should account for perceptions of functional and symbolic benefits, as well as identity and lifestyle practices.... " (p. 22).

A basic condition of having a PHEV is local access to charging facilities, i.e. an electricity outlet. The primary charging place is assumed to be the home (Davies and Kurani 2010; pp. 76 and 81). Axsen and Kurani (2012) find that "*about half the population of new car households in the US have the potential to charge a vehicle at home ..."* (p. 352). Eighty percent of households living in detached houses have this access, whereas only about 10 percent living in apartments have the same access (p. 350). Access to charging facilities will of course vary both within and between countries. In 2001, some 90 percent of Norwegian households with one or more cars had their own parking space, car port or car shed (Statistics Norway 2002).

The impact of workplace charging on charge-deplete (CD or EV[3]) driving appears to depend "*on a number of other factors, including CD-range, at home charging behaviour, driving distances between charging events, the frequency with which households drive to work and the amount of time the vehicle remains there*" (Davies and Kurani 2011, p. 12). Workplace charging increased "*the total percentage of miles in CD mode between 0 and 42 percentage points."*

As mentioned above, knowledge and attitudes towards PHEV are important when buying a PHEV. Graham-Rowe et al. (2012) find six core categories of response to electric cars in general, including PHEVs. The most important is the perception of *"electric cars generally as ' work in progress' products"* (p. 140). *"Drivers were unwilling to purchase EVs while they remained 'under development', because of the assumed risk of current vehicles rapidly becoming outdated, ..."* (p. 149). An important aspect is that Graham-Rowe et al. (2012) studied mainstream car consumers, whereas a large amount of research on the use of PHEVs is based on 'early adopters', or people who have a special interest in technological development of motor vehicles (p. 141).

The Indiana University Expert Panel (2011, p. 5) also made a distinction between early adopters and mainstream car buyers, saying that "*Mainstream car buyers are careful about investing in new technologies that are not fully understood. There are a variety of uncertainties about exactly how much money will be saved by PEVs ...., how reliable and safe the batteries will be, how convenient and costly it will be to charge a PEV, how easy it will be to have the vehicle serviced, and how difficult it will be to resell the vehicle."*

Baptista, Rolim and Silva (2012) found that whereas 90 percent of their sample were aware of hybrid electric vehicles and fully electric vehicles, only 56 percent were aware of PHEVs in Portugal in 2009 (p. 69), even though this sample had a higher level of education than average, tended to live in urban areas and were mainly between 25 and 50 years old. "*After a brief explanation of both technologies, the respondents*

[3] See footnote page 1.

preferred the PHEV over the EV.... Potential buyers of EV and PHEV technologies are extremely sensitive to fuel prices/electricity prices" (p. 73). This study, however, is purely hypothetical in the sense that the respondents have no experience of driving PHEVs or EVs.

Yabe et al. (2012) found for the market penetration of PHEVs and EVs that "*Though the large-scale introduction of PHEVs/EVs has the potential to significantly reduce the CO_2-emissions, the penetration speed is not so fast considering the economical viewpoint of vehicle owners..."* (p. 537).

Sovacool & Hirsch (2009) emphasized the many barriers for customers as well as for business to plug-in hybrid vehicles. Even though PHEVs may offer long-term economic benefits to car buyers in terms of lower travel costs, the higher purchase costs may serve as an economic disincentive (p. 1098). Moreover, most car owners did not analyse fuel costs in a systematic way (p. 1099), and fuel-efficient vehicles may have a negative social stigma as being "cheap", "light" and "small". The automobile, oil and other industries *"have huge stakes in maintaining the status quo"* because they have vested interests in the existing technology, organization and know-how in their present businesses. Such barriers may be just as important as the technological problems of batteries.

Musti and Kockelman (2011) developed a micro-simulation model for future greenhouse gas emissions in Austin, Texas, and found two and three-vehicle households *"to be the highest adopters of HEVs and PHEVs across all scenarios"* (p. 707).

Hagman, Assum and Amundsen (2011; pp. 44–59) studied 991 owners of Toyota Prius Hybrid Electric Vehicles in Norway. When asked what kind of car they would buy next time, 35 percent answered "plug-in hybrid electric vehicle" even though PHEVs were not marketed in Norway at the time of the data collection. Only 1 percent would buy a purely electric vehicle. Twenty-five percent would buy a traditional hybrid vehicle and 4 per cent a combustion-engine vehicle.

The development of PHEV was well known by 37 percent of Prius owners and another 40 percent knew a little about it. As stated above, knowledge about the basic functioning of the PHEV is a precondition to purchasing such a vehicle. The Prius owners were also asked about the conditions that had to be met if they were to buy a PHEV. Thirty-one percent answered "longer driving distance between charging"; 22 percent mentioned lower purchase price. Forty-eight percent said they were not willing to pay more for a PHEV than for a combustion engine vehicle. The demand for both a long driving distance between chargings and prices similar to combustion engine vehicles may be difficult to reconcile, consequently posing a barrier to the introduction of PHEVs. Of those who said they would buy a PHEV next time, 60 percent thought they would charge the vehicle in the normal way, and 20 percent said they would do so only "sometimes".

1.4.3 Possible reductions in fuel consumption and CO_2 emissions

In addition to possible technical potential, the attractivity of PHEVs and how they are used is essential if fuel consumption and CO_2 emissions are to be reduced. A report from an expert panel (Indiana University 2011) emphasized that "... *the net effect* *of PEV*[4] *on greenhouse gases will be limited and will vary by region. As electricity production shifts to low carbon-emitting sources, the environmental promise of PEVs will be enhanced significantly"* (p. 6). This expert panel report relates to USA conditions. In Norway, where almost all electricity is produced by hydro power, i.e. no carbon-emitting production, the situation is quite different. However, the electricity used for vehicles in Norway could otherwise have been exported to other European countries and thus have replaced electricity produced by carbon-emitting sources there. However, this would have no practical impact presuming that the EU Emission Trading Scheme works as supposed.

1.4.4 Public policy implications

The expert panel of the University of Indiana (2011) listed a number of policy instruments that would improve the prospects for initial commercialization of electric vehicles. These are "*generous tax credits for consumers and producers, new regulations for vehicle manufacturers, special access to high occupancy vehicle lanes and city parking, loan guarantees and subsidies for companies in the PEV industry, grants for charging infrastructure, and federal R&D support for more advanced battery technologies"* (p. 5). The panel also states that a national goal of a certain number of PEVs is not sufficient if consumers are not willing the buy the PEV. Furthermore, the main market drivers for these vehicles are energy prices, battery characteristics, availability of charging infrastructure and technological progress of PEVs compared to competing technologies. Each of these market drivers can be influenced by public policy (p. 5).

Musti and Kockelman (2011; p. 707) conclude: "*In the longer term, gas price dynamics, tax incentives, feebates*[5] *and purchase prices along with new technologies, government-industry partnerships, and more accurate information on range and charging times ... should have added effects on energy dependence and greenhouse gas emissions."*

Using subsidies promoting special products is not without problems. There is a risk that subsidies, especially if promoting special solutions, can hinder competing and superior solutions to gain market acceptance or lead to premature changes in environmental policies (*Financial Times* 2011). The use of subsidies, especially when there is a high degree of uncertainty about future developments, has backfired in many cases and tied authorities to schemes that in retrospect seem ill advised (Spiegel 2012).

A well-known human failing is that immediate costs are weighted disproportionately relative to benefits obtained at a later point in time. This can be a hindrance for many solutions that require additional expenses up front - such as a more advanced power solution. For the authorities there is a challenge to counteracting this type of misperception through financial or other means to bring perceptions into line with what is considered rational choice (Kahneman and Tversky 1979). Here the authorities are simply remedying market imperfections and in theory should run a smaller risk of undesired consequences.

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[4] PEV = plug-in electric vehicle, i.e. both battery electric vehicle or fully electric vehicle and plug-in hybrid electric vehicle (PHEV)

[5] "Feebate" is a combination of the words "fee" and "rebate". A feebate programme is"*a self-financing system of fees and rebates that are used to shift the costs of externalities ......onto those market actors responsible. Originally coined in the 1990s, feebate programs have typically been used to shift buying habits in the transportation and energy sectors*." (Wikipedia 2012)

1.4.5 Purchase and use: literature conclusion

It is difficult to study the purchase and use of PHEVs before they are commercially produced and marketed. Nevertheless, some studies concerning the hypothetical future purchase of such a vehicle show that a basic knowledge of the technical functioning of PHEVs is critical to willingness to buy. Moreover, people are more willing to buy a PHEV if they are in a transitional state of their lifestyle practices, and find support within their social network.

There is a clear difference between “early adopters”, in this case people interested in technology and environment, and “mainstream buyers”. The former are willing to buy a PHEV given a reasonable price and a minimum driving range in electric mode, whereas the latter are hesitant to buy vehicles they consider to be under development because of an assumed risk of these vehicles rapidly becoming outdated. Consequently, PHEVs will have to be on the market for several years before mainstream car buyers are likely to buy them. Households with two or more cars are more likely to buy a PHEV than one-car households.

People who drive PHEVs seem to charge them on average a little more than once a day, more often during weekdays than at weekends. However, the variation in charging frequency is large.

Barriers to the widespread use of PHEVs are: lack of knowledge about the technology, uncertainty about the future of the technology, access to charging facilities, and the relation between driving range and price.

The conditions for the widespread use of PHEVs are technological and environmental interest, support from personal networks, gas price dynamics and tax incentives, easily accessible information on range and charging, as well as the technological development of batteries, i.e. batteries that can produce a longer electric driving range at a lower price.

Public policy can influence important market drivers for PHEV, such as the price of petrol and electricity as well as charging infrastructure. Public policy can also contribute to reducing barriers by information campaigns and supporting technological development of batteries.

1.5 Research questions

Conventional hybrid vehicles have been produced for the commercial market ever since 1997. Compared to conventional petrol engine vehicles, HEVs may give an energy consumption reduction of about 40 percent and a corresponding reduction in CO_2 emissions in city driving. When driving on highways the reduction could be about 10 percent, but depending on topography and driving style it could be higher or lower.

Chargeable or PHEVs are the next step in the development of hybrid vehicles, and according to the WWF (2008) the best alternative to traditional vehicles. PHEVs can be practical and functional in EV mode for all daily travel of shorter distances, and at the same time for longer trips at weekends and holidays. A PHEV will thus be a vehicle for daily trips to work as well as for long trips. Future PHEVs will combine zero emissions on shorter trips with the possibility of longer trips.

New more efficient and lighter-weight batteries 10 years from now are still expected to be relatively costly, volume demanding and heavy.

How the PHEV is used in practice and the possible practical problems that might arise were examined in the project, i.e. by data-loggers installed in the vehicles. The opinions and experiences of users of the vehicles were surveyed and analysed using questionnaires and interviews.

More precisely, the questions raised by the project were:

- What do possible customers want and expect?
- How should the first chargeable hybrid vehicles be designed to be environmentally friendly and successful in the market?
- How do PHEVs perform in the Nordic and Norwegian conditions with regard to factors such as cold climatic conditions, demanding hilly topography, rather low speeds limits, poor road standards in some areas, and so on?

2 Methods

2.1 Project design

Ten Toyota Prius PHEVs were deployed in the Nordic countries: three in Norway, two in Denmark, two in Sweden and three in Finland from June 2010. Six of the vehicles were leased to companies, agencies or organisations and four in use as demonstration vehicles by the Toyota importers in the four countries were lent to environmental organisations, research institutes, media and others interested in sustainable transportation technology.

The ten PHEVs were equipped with sensors and data-logging equipment recording and storing technical data. In addition, data were collected through questionnaires and interviews. Relatively brief questionnaires were sent to all users.

The pre-commercial field test interviews were divided into three phases

- Initial
- Middle
- Conclusions after finished tests

Two questionnaires were developed in collaboration between the Toyota Motor Company (TMC) and TOI. The questionnaire for Phase 0 contained questions concerning travel patterns in general, attitudes and expectations as well as some questions about use of the PHEV. The questionnaire for Phase I concerned use of the PHEV and future car purchase behaviour.

TMC distributed and collected the questionnaires in each country and was responsible for analysing the data from the data-loggers and the questionnaire. TOI received the results mainly in the form of tables and diagrams.

TOI carried out interviews with the users of one PHEV in one organisation to get more in-depth information concerning its use. On the basis of the results and the results of the interviews, TOI has written this report.

Important data recorded in the data-loggers were:

- Use of PHEVs in EV mode
- Use of PHEVs in HEV mode
- Distances driven
- Temperatures
- Fuel consumption
- Battery and charging status

The design for the entire survey was prepared in cooperation with TMC Europe and adapted to Northern conditions. After the two years of testing the PHEVs will be evaluated technically and scrapped.

On the initiative of Toyota Norway and TOI, independent laboratory exhaust emissions were tested at VTT in Finland.

2.2 Data collection

2.2.1 Field testing

Collection of technical data was prepared for 10 PHEVs, two in Denmark, three in Finland, three in Norway and two in Sweden, in the period summer 2010 to autumn 2012. TOI received 11 Excel files with data read from the data-loggers in the PHEVs. One of the Danish vehicles had problems with the data-logging system, so the data from only nine vehicles are included in the technical dataset.

The files consist of tables and figures and are assembled and presented in Power Point charts. In addition, TOI has four files with the presentation of preliminary results. TOI has analysed recorded technical data in ways initiated by TMC.

2.2.2 Questionnaires and interviews

TOI received five data files with results from the questionnaire surveys:

FinlandPhase I 30 respondents

Germany	Phase 0	36 respondents
Germany	Phase I	8 respondents
Norway	Phase 0	3 respondents
Norway	Phase I	6 respondents

Moreover, TOI received a file containing some results for Europe of Phase 0 based on 128 questionnaires returned and the results from Phase I based on 60 questionnaires. These data files were provided as tables and figures, and consequently TOI could only comment on them. A file of raw data for 158 respondents throughout Europe was also received, but considering the fact that these respondents represented 10 countries plus country not stated, analysing the data further was not considered meaningful. The German respondents are included in the European results. Because the primary purpose of this project was to analyse the results of the PHEV tested in the Denmark, Finland, Norway and Sweden, the German results are only shown as part of the European results. No results were received from Denmark and Sweden.

Qualitative face-to-face interviews were carried out with five drivers within an organisation that has used one of the PHEVs in their regular operation for more than two years. Moreover, two middle managers in the same organisation were interviewed by telephone.

2.2.3 Laboratory exhaust emission tests

A good understanding of the Prius PHEV functioning in city traffic is essential, since electric drive and hybrid technology are assumed to offer substantial advantages in city traffic. Thus one of the PHEVs was tested in the emission laboratory of VTT in Helsinki. Reference values for the exhaust emissions from comparable vehicles are required for the evaluation of PHEVs.

To be able to compare the CO_2 emissions from the PHEV with a corresponding HEV, our method was to test an ordinary Prius HEV. In addition, more conventional vehicle models, such as a Toyota Avensis with a 2.0 l D-4D diesel engine and a Toyota Avensis with a 1.8 l petrol engine were tested in the same ways as the PHEV and the HEV. The four vehicle models were tested on a vehicle dynamometer at temperatures –7°C and +23°C, when driving a city driving cycle known as the Helsinki city cycle.

The Helsinki driving cycle was created to simulate typical Helsinki city driving patterns (see figure 3). It is 7.8 km and lasts for 23 minutes. In order to separate the effects of cold start, the emissions were measured separately for the first 3.7 km, including the key turn on emissions and the rest of the driving cycle (3.7-7.8 km).

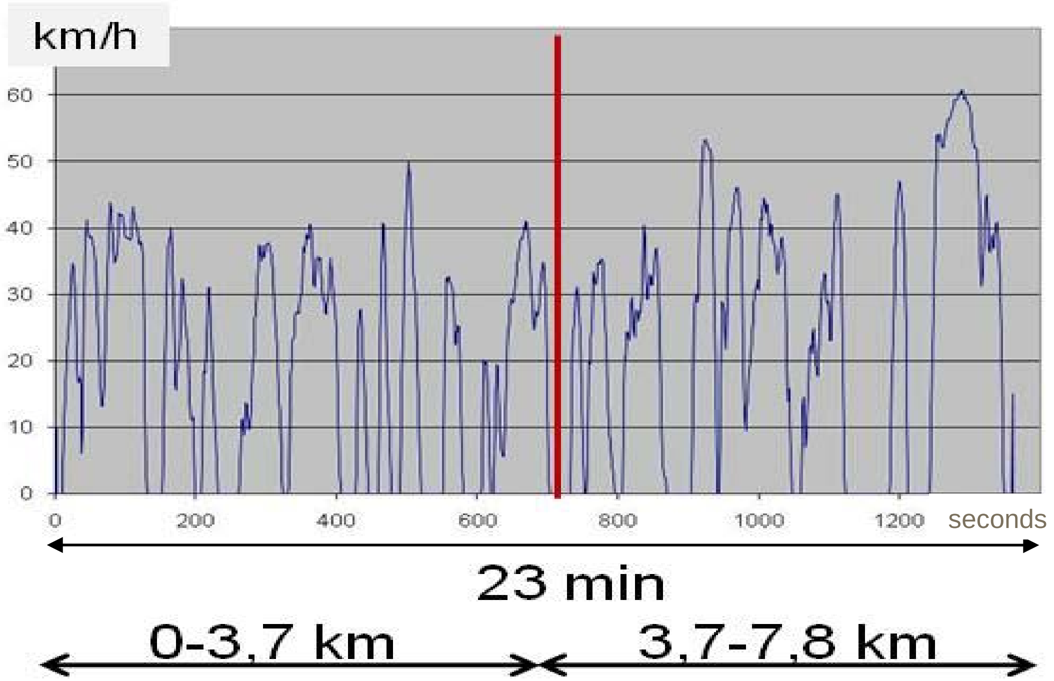

Figure 3: The Helsinki city driving cycle – vehicle speed versus time and distance

2.3 Data analysis

As mentioned above, the data from the data-loggers and the questionnaires were analysed by Toyota, and the results presented in this report are the results of these analyses.

The data from the emission tests at VTT in Helsinki derive from a TOI initiative and are supported by Toyota Norway AS. The exhaust emission test design and analysis methods are the result of a cooperation between TOI and VTT.

3 Results

3.1 Field test information from the Nordic countries

3.1.1 Fuel consumption and CO_2 reductions

From 2010 to 2012 pre-commercial PHEVs in Denmark, Finland, Norway and Sweden were instrumented and driving information was collected on data-recorders. The purpose was to gain experience about how the 10 pre-commercial PHEV Prius vehicles were used in the field trial tests, and to get essential technical information.

In this section we present essential information and discuss the results obtained from 9 of the 10 pre-commercial PHEVs so far in the project period. Because of technical problems, driving information data are unfortunately not available from one of the Danish PHEVs.

The information presented covers 77 000 km of driving in the Nordic countries and the time span includes the winter season 2010-2011.

3.1.2 Fuel consumption and CO_2 emissions

The pre-commercial Prius PHEVs basically run as electric vehicles for the first 20 km after the batteries are fully charged with electric energy. After that, they run as hybrid vehicles.

The main purpose of hybrid and plug-in hybrid vehicles is to reduce fuel consumption and CO_2 emissions. For the 9 PHEV in the Nordic countries as used in real life by different drivers, fuel consumption was in the range 2.5-3.8 l petrol per 100 km, which corresponds to CO_2 emissions of about 60-90 g/km. The average petrol consumption of 3.25 l/100 km in the Nordic countries was slightly lower than the 3.76 l petrol per 100 km average for the entire TMC field project for the EU (including all EU27 member states).

Fuel consumption is generally highly related to how and where a vehicle is driven. In the TMC field test there is no instruction and no control of where and how the PHEVs should be driven or about when and how often they should be plugged into the electric grid. The fuel saving compared to conventional vehicles and the ordinary Prius HEV is evaluated more precisely in an emission laboratory where it is possible to have control of the driving parameters, as described in section 3.3. The field test was carried out to find out how the PHEVs were used and how they function in real-life with different drivers. The drivers were asked about their experiences and opinions of the PHEVs, as described in section 3.2.

An average petrol consumption of 3.25 l/100 km in the field tests is much lower than can be expected with conventional vehicles and combustion engines and with an ordinary Prius HEV. PHEVs have been used in many different ways and have had very different driving patterns. Short trips, especially with conventional vehicles, are generally more energy demanding than long trips. In the field tests the PHEVs have mainly been driven on short trips.

Short trips, moderate acceleration, outside temperature around 15 ± 10°C and frequent charging make it possible to drive PHEVs with extremely low or even zero petrol consumption and low emissions of CO_2. With long-distance trips, high constant speed and at outside temperatures requiring air conditioning or heating, the potential for reduced CO_2 emissions and limited battery capacity is limited with PHEVs.

Our experience of fuel consumption, emission testing, driving patterns and vehicle technologies indicates that, when used like the usage pattern in the Nordic field tests, the CO_2 emission reductions with the Prius PHEV are in the order of:

- 30 percent compared with a Prius HEV
- 45 percent compared with a corresponding efficient diesel engine vehicle
- 60 percent compared with a petrol combustion vehicle

We followed each of the nine vehicles and how they were used, and named them "DK-1 ... SE-2" as indicated in figure 4. Average figures for how the nine vehicles were used are:

- The average speed was 47.5 km/h
- The average distance between charging was about 36.4 km
- The average distance per trip was 12.9 km

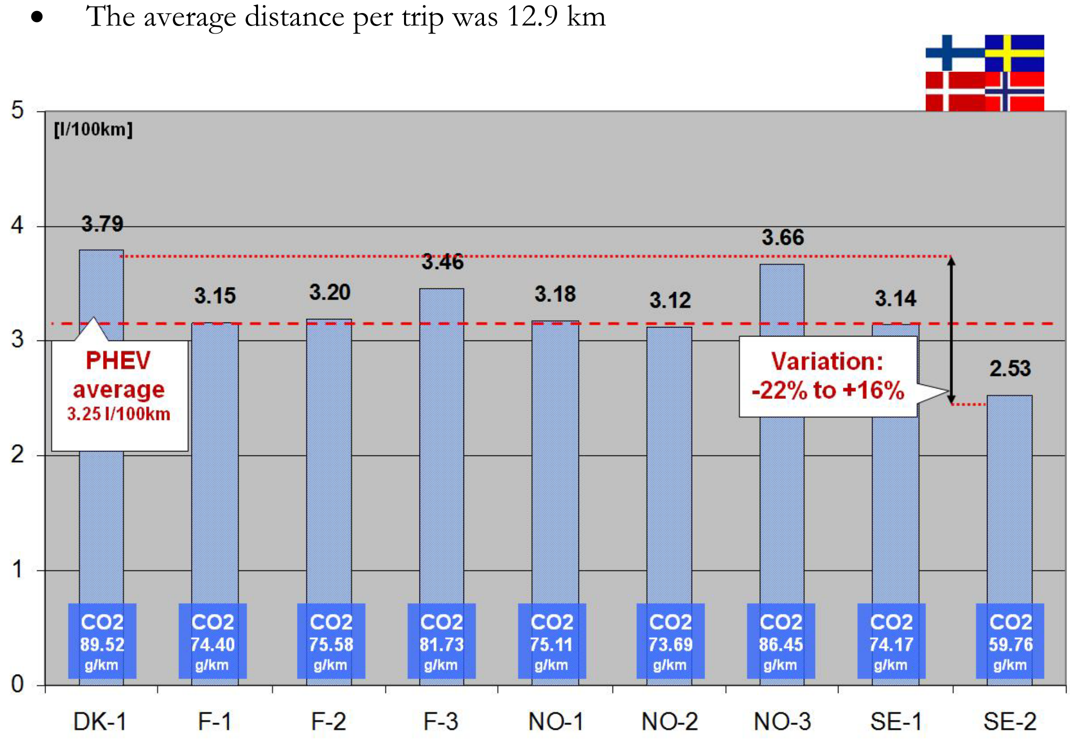

Figure 4: Average measured petrol consumption and CO_2 emissions for each of the 9 PHEVs in the Nordic project

3.1.3 Average distance per trip

A trip in the data-recording analyses is defined here as an event between turning the vehicle on with the "start/stop button" and turning it off with the "start/stop button".

When analysed, the data-recordings show that there are more trips of less than 2 km than there are longer than 2 km. The explanation may be that the PHEVs in these field tests were used very much for demonstration purposes, and that use of the "start/stop" button was much more frequent than might be expected in real life. The Norwegian Travel Survey (Vågane, Brechan, Hjorthol 2011, pp. 28-30) shows that, in 2009, the average trip as a car driver was 13.6 km. Seven percent of all trips as a car driver were less than 1 km and 31 percent were less than 2.9 km. Short trips are fairly normal, but in this project more than half the trips less than 2 km indicate some special use of the PHEVs.

There is therefore a high degree of uncertainty related to how relevant the number of counts is for short trips under 2 km. For this reason, the numbers of very short trips are not used in figure 5 showing the average distance per trip, nor, in figure 7, the percentage of trips of less than 50 km.

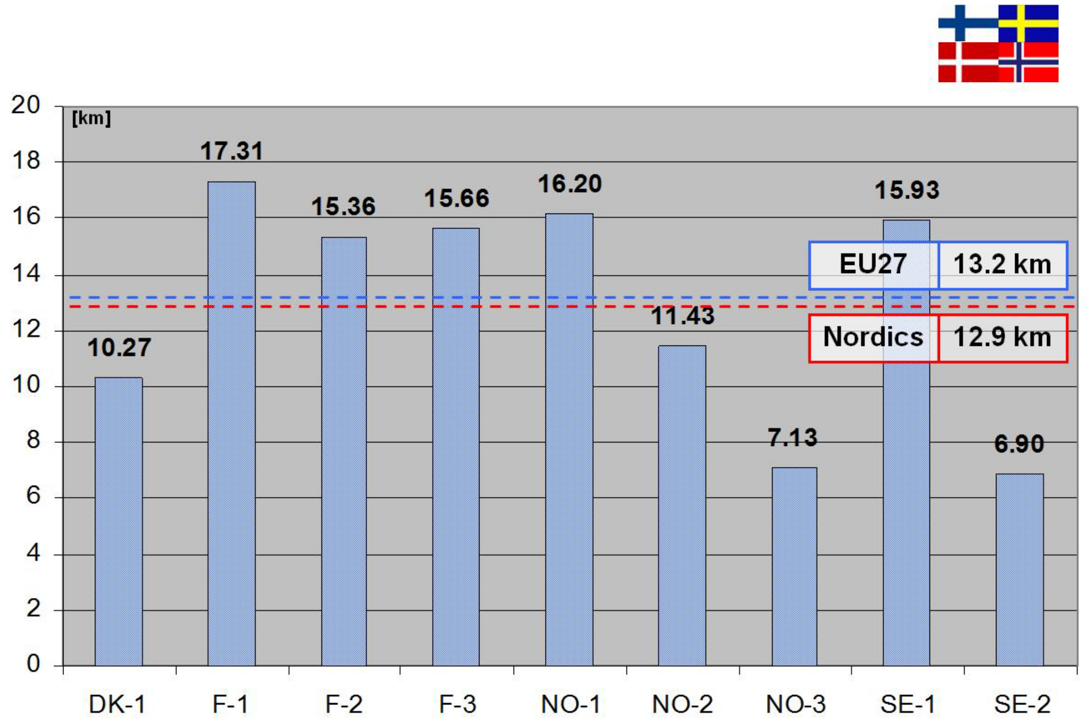

Figure 5: Average distance in km per trip for each of the 9 PHEV in the Nordic countries (trips shorter than 2 km are excluded)

3.1.4 Potential for trips in EV mode

The number of trips over a distance under 20 km is essential, since 20 km is a practical upper limit for a trip in pure Electric Vehicle (EV) mode. Since the PHEV management system under special conditions, such as demand for extra power or need for heating, turns on the combustion engine it might be more correct to call the EV mode the Charge Depletion (CD) mode. When the charge level of the battery has decreased to the specified level, the PHEV turns over to ordinary Prius HEV operation, which is a Charge Sustainable (CS) mode.

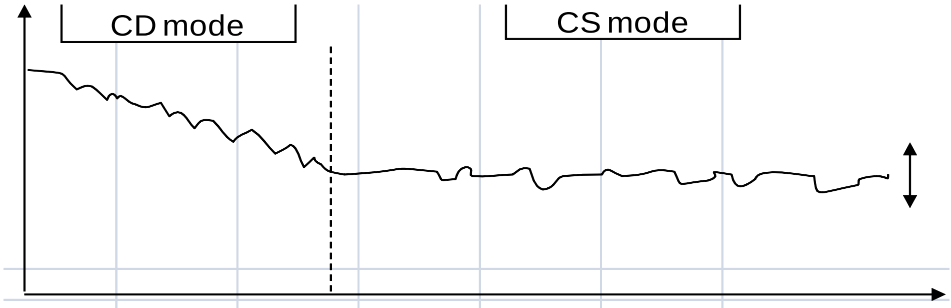

Figure 6: The PHEV Prius with batteries charged over a specified level will run as an Electric Vehicle in EV or Charge Depletion (CD) mode, but after the battery charge has decreased below this level the vehicle will turn to HEV mode.

Because of uncertainty about the number of very short trips, we only calculate trips longer than 5 km in the calculations leading to figure 7.

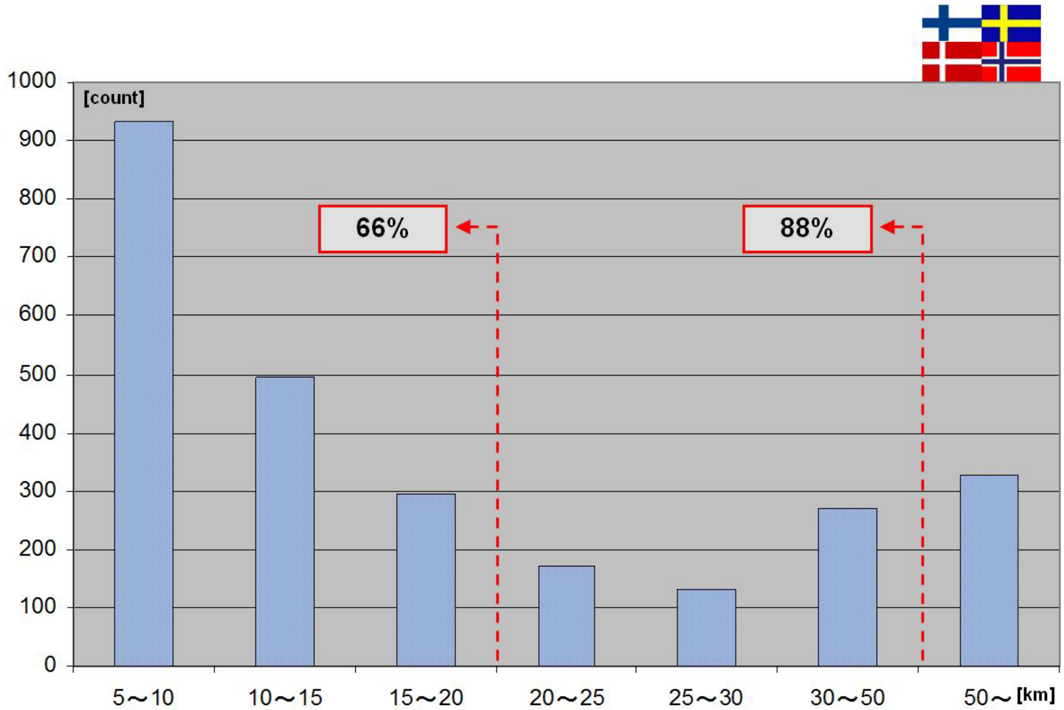

Figure 7: Number of trips (counts) over a distance shorter than 50 km (but longer than 5 km)

It appears from figure 7 that pure EV mode is a possibility for about 66 percent of all trips (over 5 km). A condition is that the driver charges the vehicle after all trips over 5 km.

3.1.5 Average speed and speed distribution

Average speed is important for determining how the different PHEVs are used and indeed whether a PHEV is the right type of vehicle for a certain type of application. For example, the PHEV NO-3 is a vehicle with very low mean speed and is used by street parking control authorities to check and issue fine tickets when parking regulations have been violated. Relative to other PHEVs, NO-3 has high petrol consumption (see figure 4).

An average speed of 16 km/h is low, but normal for a street parking control vehicle. Since we include only trips over 5 km in the calculations, it can be expected that the real average speed of NO-3 is even lower than the 16 km/h indicated in figure 8.

Low average speed, short trips, low consumption of petrol compared to conventional combustion engine vehicles, charging time and distance between charging all indicate that street parking control service vehicles are a good application for PHEVs. However, whether the battery capacity of 4.4 kWh is optimal or should be higher for a PHEV used for this application is a moot point.

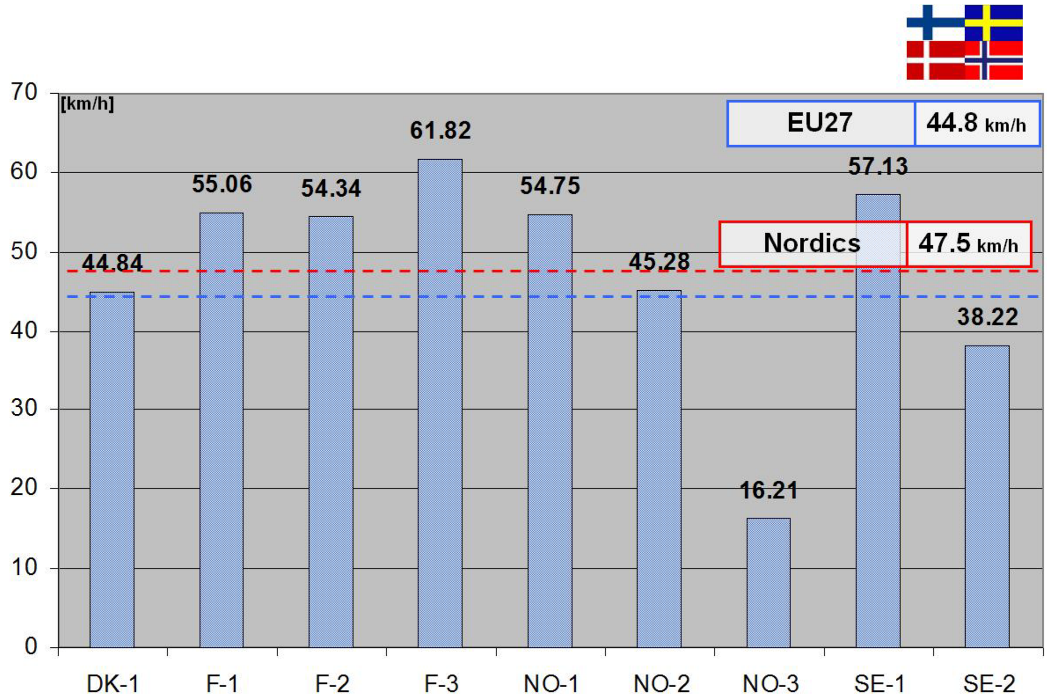

Figure 8: Average speed for the 9 PHEVs

The distribution of speed for all 9 PHEVs is shown in figure 9, indicating that most of the time the Nordic PHEVs were driven at speeds below 30 km/h. The distribution of speed is an indication of how these vehicles were used. As mentioned, the drivers used the vehicles as they pleased. They may have ideas about comfort economy and convenience with charging, but the PHEVs may not fulfil their wishes.

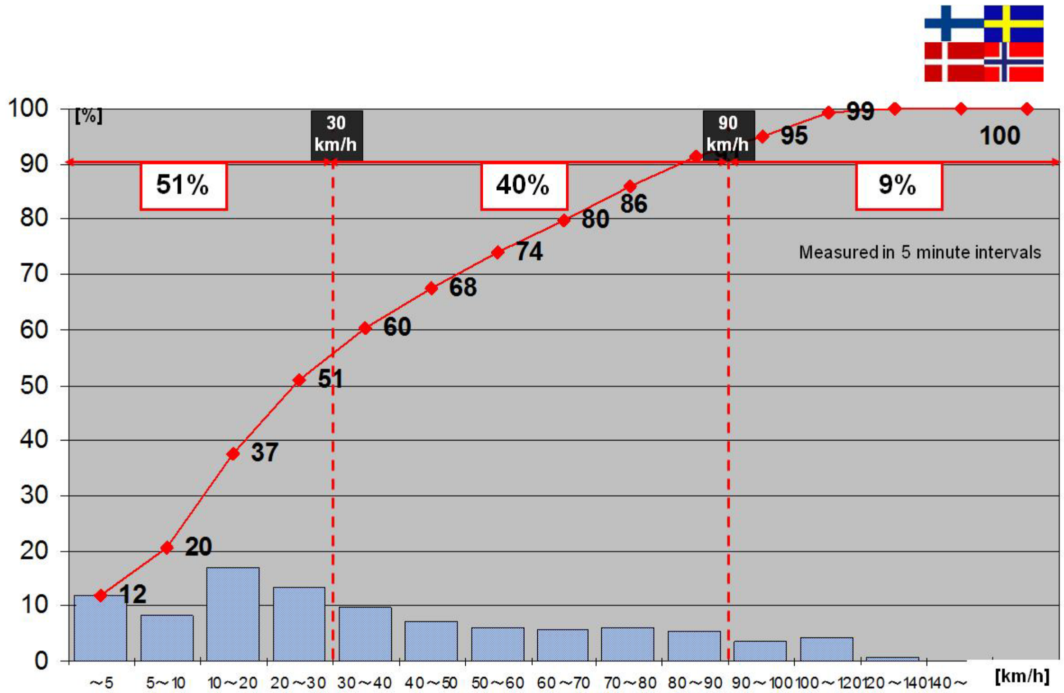

Figure 9: Distribution of speed for the 9 PHEVs

3.1.6 Batteries and charging

Batteries and charging of batteries are the essential challenges with electrification of vehicles. For PHEVs, the question is how high the battery capacity should be. The advantages are energy and fossil fuel savings with electric drive.

A battery capacity in the order of 1-2 kWh, as in the Prius HEV, is capable of petrol savings of 30 percent relative to corresponding vehicles without hybrid technology. With higher battery capacity and charging from the grid, as in the PHEV vehicles, the possibility of energy savings and reduction of greenhouse gas emissions is much higher.

A battery charging capacity in the magnitude 5 kWh makes it possible to drive about 20-25 km in EV mode and to save about 1 litre of petrol per trip for a PHEV Prius. The battery capacity allowing these savings, on the other hand, adds about NOK 40 000 (ca. €5,300[6]) to the purchase price. However, the higher purchase price for a new PHEV is to some extent compensated by petrol savings. The right and optimal battery capacity is not just a simple economic optimization question. The driver needs to have the possibility and be motivated to plug in the PHEV after every trip if maximal energy and greenhouse gas savings are to be obtained. Charging time, distance for each trip and distance between charging are all essential when choosing the right battery capacity for a PHEV application.

Essential information about charging behaviour for the 9 Nordic PHEVs was:

- the batteries were always fully charged in less than 120 minutes
- the average time for active charging was 71 minutes if very short plug-in charges are excluded (less than 12 minutes)

[6] Exchange rate 1€ =7.50 NOK

- the users charged the batteries on average after 36 km rather than after the optimal 20 km
- there is a spread from about 17 to 52 km in the average distance between charging

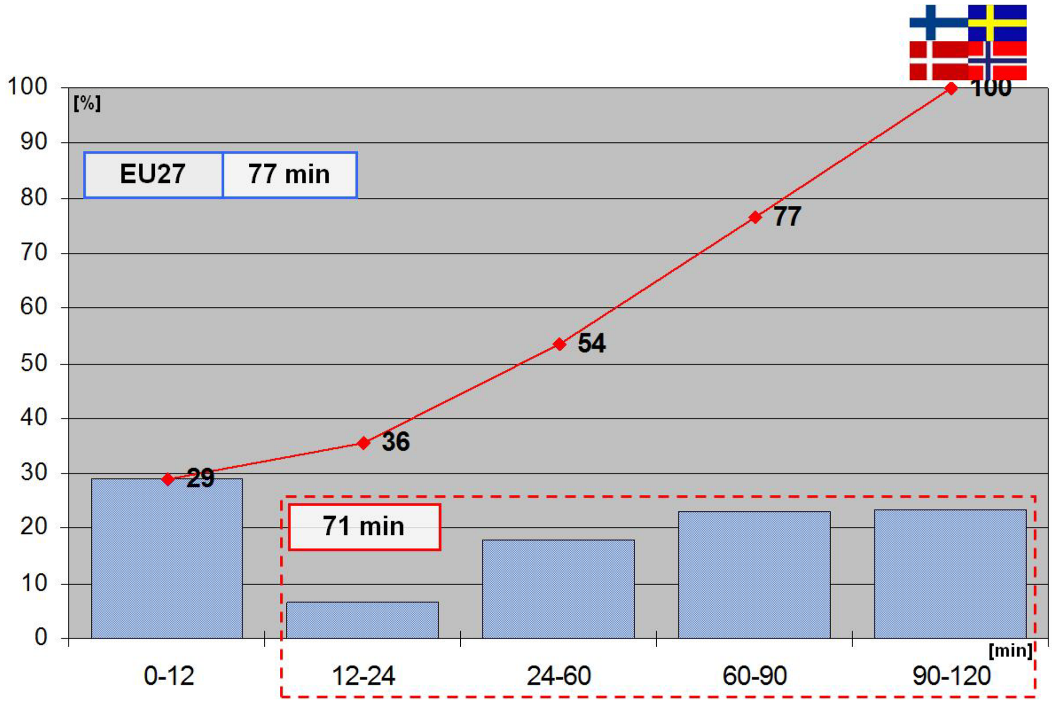

Figure 10: Distribution of real charging time in minutes for the 9 PHEVs

Was a battery capacity that allowed 20 km of driving in EV mode right for the 9 Nordic PHEVs?

As an example, let us look a bit more closely at PHEV NO-3. We can see from figure 11 that this PHEV, which was used for street parking control activities in Oslo, was charged for 75 minutes on average. The average distance between charges was about 30 km (figure 10). Since the maximum driving distance in energy efficient EV mode is 20 km, it is possible that, for this street parking service application, a battery capacity allowing 30 km or more in EV mode should be the optimal choice. With larger battery capacity the city of Oslo would benefit from reduced emissions of CO_2, reduced climate impact and be compensated to some extent for the extra costs.

For applications such as commuting to a work location about 10 km away from home and using the PHEV for longer weekend trips, a 20 km EV mode range could be optimal for the battery capacity. For someone with a work location where it is possible to charge the car, a 20 km EV mode range would be sufficient for travelling to work. For this subset of employees, a charging station at work would spare them the cost of purchasing larger batteries.

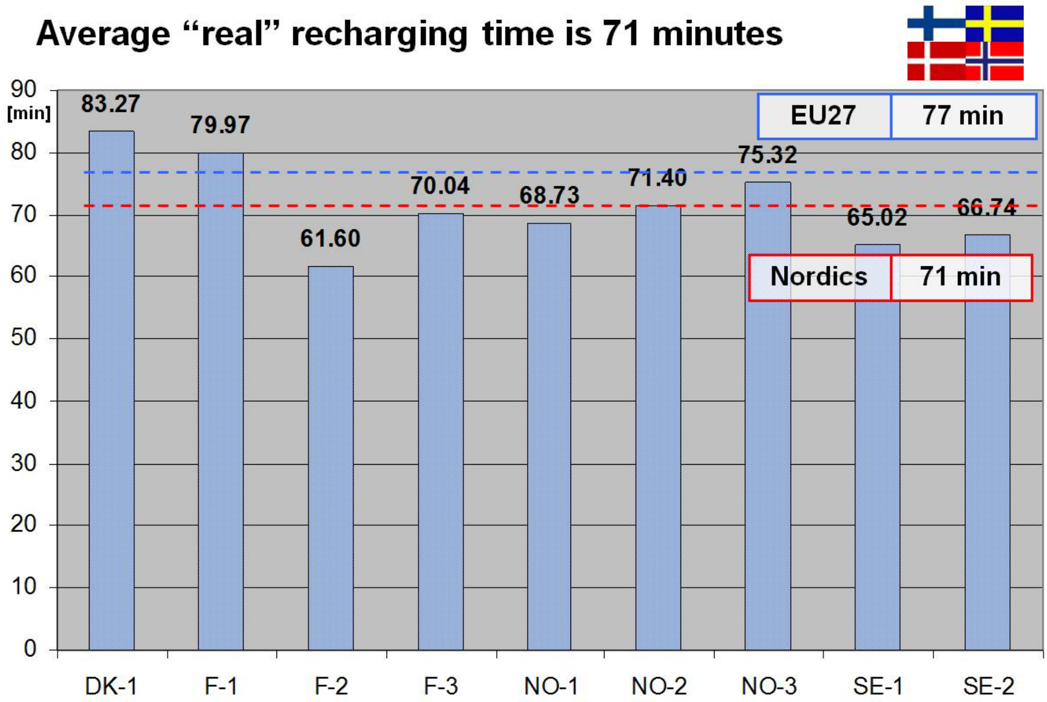

Figure 11: Average "real" charging time for each of the 9 PHEVs

When the PHEV NO-3 is driven about 30 km between every charging, and the average trip is 16 km, this does not automatically mean that it could be driven with much lower petrol consumption. The PHEV NO-3 might have to be in service to such an extent that there would not be enough time left for charging as often and as long as would have been optimal from environmental aspects.

As discussed earlier, higher battery capacity than for 20 km in EV mode could help to reduce fuel consumption. However, to charge a battery pack with double capacity takes about twice the time. Fast charging was not available in the Nordic countries during the period of testing that we analyse in this report.

Fast electric charging might be an option for some applications in the future. However, the practical consequences and opportunities are not well known today, but improved fast-charging opportunities could influence electrification of vehicles and optimal battery capacity in future PHEVs.

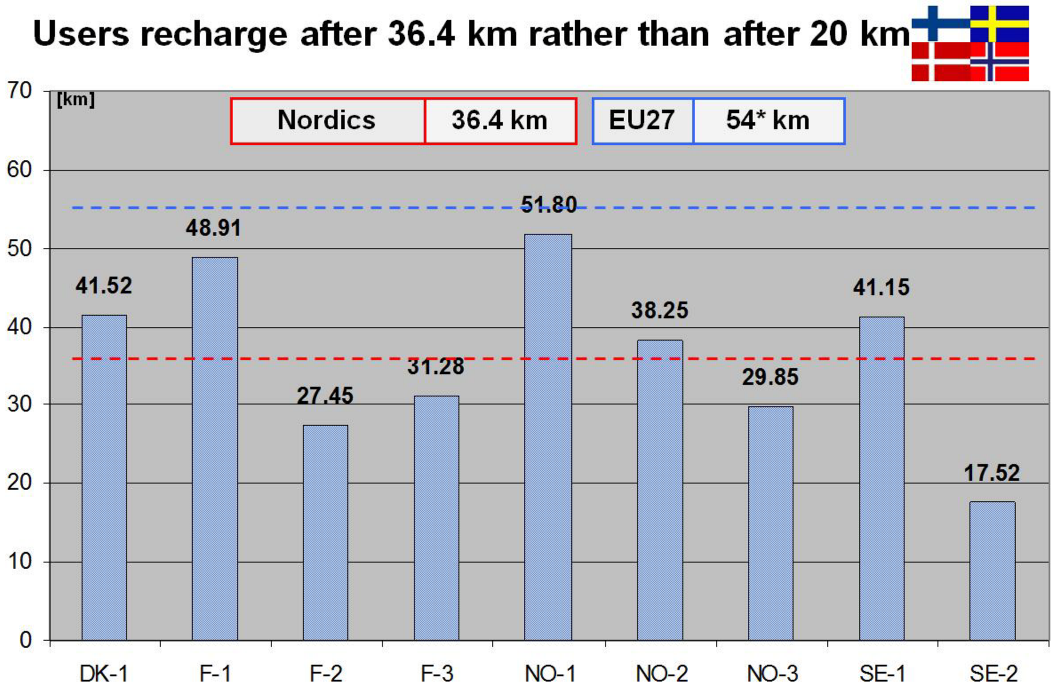

Figure 12: Average driving distance between charging for the 9 PHEVs

3.2 User experiences and attitudes

As mentioned, another purpose of this project is to find out whether there are any barriers to the purchase and regular use of PHEVs and also to what extent and how often charging of the batteries is done and is possible. Barriers may be access to the electric grid and plug-in possibility where the vehicle is parked for a long time. Inconvenient plug-in locations at home and at the workplace, low private economic benefits driving on fully charged batteries compared to driving on petrol, high vehicle purchase price compared with traditional vehicles, etc., are other possible barriers.

Data concerning user experiences and attitudes were collected through questionnaires to users of the PHEVs. As described in section 2.2.2, data for a limited number of users in the Nordic countries were received and a large number for Europe.

3.2.1 European users and PHEV Prius

The questionnaire data for Europe about the pre-commercial PHEV Prius show that 77 percent of users perceived the comfort level as high, while 70 percent thought that fuel consumption was good or very good. Sixty-seven per cent found the electric mode driving performance good or very good, but 79 percent thought that the range was too short.

Fifty-three percent of the users were concerned with the availability of charging locations; either that the charging spaces were taken by other vehicles or that they did not work. Limited electric driving range was a main disadvantage for 79 percent of the users, and only 3 percent were concerned about problems with silent driving.

Fifty-eight percent struggled with the ergonomics of the charging cable, while 88 percent stated that storage of the cable in the vehicle was the main concern of the charging equipment. Another problem was the size of the boot (trunk) when travelling long distances or with business equipment.

Sixty-three percent rated acceleration of the PHEV from 0 to 50 km/h as good or very good. Seventy percent rated fuel consumption as good or very good. Fifty-one percent stated that petrol consumption was 3-4 litres per 100 km or less, whereas 39 percent stated that it was 4-5 litres or more per 100 km. Sixty-seven percent thought that acceptable fuel consumption for a PHEV vehicle of this size was 3-4 litres or less.

Air conditioning in vehicles consumes quite a lot of electricity, and in electric cars heating consumes a considerable part of the available electricity. The emission test results given in section 3.3 indicate that in the PHEV Prius the combustion engine takes over automatically when the heating is turned on to avoid extra electricity consumption. A temperature difference of 10°C between the desired temperature inside the vehicle and the outside temperature may reduce the electric driving range by about 4 km. Fifty-six percent of the users stated that they use air conditioning or heating all the time or at least most of the day. If it comes from the combustion engine, the use of heating should have no influence on the driving range. However, the question can be asked whether PHEV users would realise that the use of A/C reduced the electric driving range.

3.2.2 Finnish users

A total of 30 users in Finland answered the Phase I questionnaire about the pre-commercial PHEV Prius. More detailed data were received from Finnish users than from the other European users.

Of the 30 users, 80 percent stated that they perceived a change in their own driving behaviour; 54 percent of them had economic driving as their main focus and 46 percent had become more ecologically conscious.

Forty-three percent of the Finnish drivers experienced no problems during their use of the PHEV, while the remainder experienced problems such as body noise, wind noise, vibration, problems with the interior of the vehicle, with electrical equipment, with brakes, with charging the vehicle or other problems.

Of the respondents who had driven the PHEV during winter, 87 percent stated that their winter experience with the PHEV was about the same as with other vehicles. Nine percent considered it worse than other cars, and 4 percent considered it better than other cars. However, these winter drivers also experienced advantages such as “easier to start” (39 percent), “better uphill grip” (22 percent), “easy to charge battery during winter” (22 percent) and low fuel consumption (54 percent). Fifty-eight percent stated that “the cable is hard to handle in low temperatures”, and 25 percent experienced problems with temperature inside the car, i.e. too cold, steamed up windows, etc. Thirty-eight percent experienced no particular winter problems.

All the Finnish drivers rated the silent driving of the PHEV as enjoyable in the inner city environment as well as in the outer city environment and on highways.

Two-thirds of the Finnish users rated their own knowledge of the high-tech features of the vehicle as “good” or “very good”.

Fifty-nine percent were satisfied with the load capacity, and 62 percent with the comfort level. The most frequently mentioned advantages were silent driving and technical innovation, while the most frequently mentioned disadvantages were the limited capacity of the batteries (90 percent) and the ergonomics of the cable (62 percent).

Eleven percent of the Finnish users rated the EV mode range as good or very good, 57 percent as moderate and 32 percent as "poor" or "very poor". Fifty-six percent of the users thought that the EV range would in reality be 15 - 20 km; 22 percent thought that it would be more than 20 km and 23 percent 15 km or less.

Only 20 of the users considered 20 km or less as adequate for daily use, so there is obviously a demand for longer EV mode range than the present 20 km.

Sixty-eight percent of the Finnish users said they charged the vehicle at least twice a day, and 29 percent once a day. Thirty-six percent charged the vehicle for 1 – 2 hours on average each time, 18 percent for 2-3 hours and 40 percent for more than 3 hours. Sixty-one percent considered the charging time as acceptable, and 71 percent the charging procedure as "easy" or "very easy" at work, whereas 80 percent considered it "difficult" or "too difficult" in public places.

The most frequent reason for not plugging in the vehicle in places where it was possible was "battery not empty" (56 percent), and the most frequent concern about charging was availability of charging places (79 percent); 32 percent mentioned "vandalism". Twenty-nine percent mentioned "anxiety about possibly not finding a charging point" and 25 percent mentioned "adding tasks to daily routine".

As to the main concerns about charging equipment: 54 percent were concerned about storage of the cable and 57 percent mentioned flexibility of the cable. Eighty-six percent found charging the vehicle at home "very" or "quite" appealing. Other than at home, 96 percent considered "at work" to be the most useful place to charge the vehicle. About two-thirds of the users had made between 0 and 10 percent of their charges at a public charge point.

Eighty-six percent of the users wanted to know how much energy was being consumed when charging, i.e. mainly out of curiosity and concern for the electricity bill.

The perception of the average fuel consumption varied greatly. Eighteen percent of the Finnish respondents said this was 2 – 3 litres per 100 km, 18 per cent said 3 – 4 litres, 36 per cent stated 4-5 litres, 18 per cent said 5-6 litres, and 11 per cent said 6 – 7 litres per 100 km.

Forty-six percent of the users said that 2 – 3 litres per 100 km would be acceptable fuel consumption for a car of this size, and 36 percent that 3-4 litres per 100 km would be acceptable.

The most frequently mentioned considerations in any possible future purchase of a PHEV would be the price of the vehicle, the electric driving range and fuel consumption.

Forty-seven percent of the users would be willing to pay more for a vehicle that was less harmful to the environment. Seventy-eight percent agreed with the statement that "the vehicle I have in this trial would satisfy my daily needs", and 79 percent considered a supportive public charging infrastructure as essential for people with electric vehicles. Seventy-five percent liked the lack of engine noise, but considered this as a possible danger to pedestrians.

Both European users and Finnish users were highly satisfied with the pre-commercial Prius PHEV. The main disadvantages mentioned were handling and storage of the cable as well as the short driving range. Special questions about winter driving were put to the Finnish users. A great majority of those who had driven the PHEV during winter said that performance was about the same as other cars.

3.2.3 Use of the PHEV Prius in a Norwegian local authority

The purpose of the Oslo city administration authority is "*road safety, mobility and accessibility*", including parking regulations (Oslo kommune, 2012). Protection of the environment is high on the agenda and consequently this organisation, having chosen Toyota Prius Hybrid vehicles (HEV) for their normal operations, have now leased a pre-commercial PHEV Prius. In addition to the Prius HEVs and the Prius PHEV, the organisation has two fully electric vehicles and one diesel combustion engine vehicle.

Five drivers and two middle managers within this organisation were interviewed, the main topics being:

- Use of the PHEV Prius
- Comparison with other cars
- Running characteristics of the PHEV Prius
- Charging of the PHEV Prius
- Battery
- Maintenance and repairs
- Future purchase of PHEVs

Use of the PHEV

Drivers could choose between the vehicles, all of which for use only within the city limits, mainly in the city centre and areas close to the centre. All drivers interviewed had used the PHEV Prius in the city centre, in surrounding areas and on expressways within the city. Their operations include many stops and starts, with the driver having to get in and out of the vehicle. Normally there would be one passenger in addition to the driver, although sometimes there would be several passengers in the vehicle. The regular use implied no need for luggage. The drivers were not allowed to use the vehicles for their own private use.

All five drivers expressed a positive attitude to the PHEV Prius. Three said they used the PHEV Prius often or "*as often as possible*", whereas two hesitated to some extent about choosing the PHEV Prius. One of these two could not really express why he did not choose the PHEV Prius: "*It just happened*", he said, before adding that he missed a backsword driving assistance on the PHEV Prius, which was an assistance tool on the other Prius models. Another driver said he chose the diesel vehicle because being so tall he found the PHEV coupé too low. All drivers said that the PHEV has low ground clearance which sometimes caused problems when driving in deep snow.

The three positive drivers had some difficulty explaining why they preferred the PHEV, but they substantiated their choice by "*good driving qualities*" or, more specifically, seat heating, big GPS screen and wireless hands-free telephone.

Comparison with other cars

Drivers appreciated the lack of engine noise, which made driving more comfortable. The lack of noise was important when driving in residential areas at night, but could be a problem for pedestrians and bike riders, although none reported accidents.

Driving the PHEV was similar to driving a HEV, which was the other main option. Both the PHEV and the HEV could be difficult when driving on snow, because of the low ground clearance. The possibility to choose between power mode and eco mode was appreciated. One driver wanted an option to be able to turn off the traction control.

The PHEV satisfied the transport needs of the organisation.

Compared to the fully electric vehicles used by this organisation (EV), the drivers felt that there was a great difference. "*The electric vehicle is a tiny, simple car." "EVs are not easy. Prius is like a regular car." "We do not use the EVs regularly." "When using the EV we had to turn off everything, including the heating because the meter showed red."* One driver also mentioned that it took a lot longer to charge the EVs. They did not consider the EVs as real cars.

Running characteristics of the PHEV

Acceleration and speed were considered excellent. The possibility of choosing automatic or manual selection of electric or combustion mode was considered positive. Nobody expressed concern about range. The only problems were the low coupé and the low ground clearance. The front seat could be a bit tight for two grown men with cameras and other equipment attached to their belts.

The HEV could be difficult to start when they had been out of use for some time. This problem never happened with the PHEV.

Some of the drivers said that fuel consumption of the PHEV was lower than that of the HEV. The drivers did not pay for the fuel themselves and consequently fuel consumption was not of great interest to them.

All drivers were positive to driving the PHEV during winter conditions, except for the low ground clearance, saying that the PHEV was stable and worked fine in the hilly conditions of Oslo.

Charging the battery

The most important question concerning the PHEV is whether those who drive these vehicles will charge them regularly. If the PHEV is not charged regularly, it will operate as a HEV. There will be no reduction in fuel consumption compared to a HEV and no reduction in emissions. The cost of the extra battery would not be justified.

The PHEV was only charged in the parking facility of the organisation, with the cable hanging on the wall in the parking facility when not in use. The PHEV was normally charged three times a day: two hours in the morning between duty shifts, 30 minutes during the lunch break and 30 minutes in the evening between duty shifts. If the PHEV was not used by the night shift, it was charged throughout the night.

When the PHEV was first introduced in the organisation, the drivers were instructed in how to use and charge it. Three drivers attended the introductory course and two did not. All five drivers said that charging was easy and not a problem. "*The charging is not a hassle." "It's super easy. Takes two seconds." "Just push the lid and plug it in." "We have to remember to unplug it when we start driving, but I never forgot. There is a light indicating the cable* *is plugged in. The cable is next to the driver seat door, so you have to see it."* These results are quite different from the survey of European users mentioned above, the majority of whom considered handling of the cable a problem and almost 90 percent considered storage of the cable a problem.

The drivers had been instructed to charge the PHEV, but were given no economic motive for doing so. Nevertheless, they all said they charged the vehicle and considered charging no problem. The way the charging was organised nobody objected to charging or even thought of charging as a hassle.

The battery

Most drivers accepted the battery and its capacity as it was, and seemed to have little knowledge about or interest in alternatives such as higher battery capacity. One driver, however, did test the capacity by choosing the electric mode and observing the number of kilometres he could drive in that mode. One of the drivers thought that the organisation would be willing to pay more for a PHEV with higher battery capacity because an environmentally friendly image was an aim. Another driver believed that the organisation would not purchase more expensive vehicles. The remaining three drivers had no answer to this question.

Maintenance and repair

The drivers were not responsible for maintenance and repair of the vehicles. However, that said, there were no particular problems with PHEVs.

Future use

The drivers did not decide on the purchase of new vehicles, but two of them said they had discussed the kind of vehicles the organisation should procure in the future. The low coupé and the short distance from the floor to the road were the two arguments against the Prius in general, whether PHEV or HEV. One of the drivers thought the organisation would purchase PHEVs in the future in order to reduce emissions. "*The environment is a priority in this organisation.*"

The drivers – positive to the PHEV and to charging

All five drivers expressed positive attitudes to the PHEV. The few objections that there were had nothing to do with the plug-in hybrid propulsion itself. All five drivers were also positive to the charging of the battery. None considered plugging in a problem – not even a hassle – even though they had no economic or other personal motive for doing so.

The PHEV – and the HEVs – used in the organisation were considered high-quality vehicles that were pleasant to drive, as opposed to the fully electric vehicles which were not considered as real vehicles at all.

The managers

In addition to the interviews with the drivers, two middle managers were interviewed by telephone, one of whom had worked in the organisation when the PHEV was introduced but had recently left the organisation. The other had recently taken over the responsibility for PHEVs. Both managers had driven the PHEV themselves, confirming the positive impressions of the five drivers interviewed. The managers also said that all the other drivers in the organisation were positive to the PHEV in general. Taking part in the testing of a new kind of vehicle was considered positive by most of the drivers in the organisation.

According to the managers, the fuel consumption of the PHEV was some 10 percent lower than that of the HEVs.

The organisation has a zero emission target for 2017. Fully electric vehicles are difficult to use in an organisation operating 24 hours seven days a week because of the long charging hours of such vehicles. Consequently, the PHEV can be a good alternative for this organisation.

The use of the PHEV in the organisation – conclusion

Both drivers and middle managers were positive to the PHEV, considering it a high quality vehicle well fitted to the operations of the organisation, mainly because it was the newest car with the most modern accessories. The PHEV was accepted as a good modern car, a fact indicating that there were no major objections to the vehicle itself.

All the users were positive to the reduced consumption of fossil fuel, even though they did not benefit economically from it. The few objections to the PHEV had nothing to do with the plug-in hybrid technology itself. The fuel consumption was said to be some 10 percent lower than that of the HEVs.

Being environmentally friendly is a formal objective of the organisation, and positive for the drivers and managers.

The results of tests of the PHEV within this organisation show no barriers to use or charging of the vehicle. Charging was well organised and none of the drivers interviewed considered this a problem, not even a hassle. Even though the drivers did not benefit economically or in any other way from charging the PHEV after use, they all did it as part of normal routine. Consequently, if the charging is well organised, as it was in this organisation, this should not be a barrier to effective use of the PHEV.

These results must be considered positive, indicating that organisations using cars for their operations can be an important market for the future PHEV, especially for organisations wanting an environmentally sound image. However, the test results for this organisation do not relate to the private household car market.

3.2.4 Discussion of findings

Only for Finland did a sufficient number of respondents return the questionnaires from the user survey. However, user survey results from Europe have been included in this report. Moreover, professional users in a Norwegian local authority were interviewed.

Both European and Finnish users, as well as the professional Norwegian users, were satisfied with the PHEV's comfort, energy consumption, acceleration and functioning in EV mode. All three user groups considered the electric driving range too short. Finnish and European users considered the handling of the cable a problem, whereas the Norwegian professionals did not. Moreover, the European users were to some extent dissatisfied with the size of the boot (trunk). The Norwegian professional users did not need the boot for their operations.

No particular winter problems were noted among the Finnish users. Both the European and Finnish users were concerned about the availability of charging places. For the professional Norwegian users there was no need for charging places outside their garage.

The short EV mode range is a main challenge. However, the higher battery capacity required to increase the electric driving range would imply higher vehicle purchase costs, less boot space in a Prius PHEV and longer charging time needed to utilize the higher capacity. Questions were not asked about willingness to pay a premium for longer electric driving range, about giving up boot space or accepting longer charging times. Instead, further surveys will have to deal with these questions.

The other main problem is the ergonomics or handling of the electric cable necessary for charging the battery. A better technical solution should be developed. However, the routine established by the local Norwegian authority seems to have solved this problem. Another possible solution could be some kind of automatic charging device which starts when the vehicle is parked at home or at work. A third solution could be a cable that is automatically stored within the vehicle after use, just like the cable in a vacuum cleaner. Yet another solution could be permanent cables at charging places, just like the petrol hoses at filling stations. Avoiding transporting the cable in the vehicle has advantages in terms of available storage space and convenience.

3.3 Laboratory emission testing

3.3.1 PHEVs, HEVs and conventional vehicles

A pre-commercial PHEV was tested in March 2011 in the emissions laboratory of VTT in Helsinki in order to examine how the PHEV Prius functions in city traffic. Emissions from the plug-in hybrid were compared with emissions from more conventional vehicle models such as a Prius HEV, a Toyota Avensis with 2.0 l D-4D diesel engine and a Toyota Avensis with 1.8 l petrol engine. The four vehicle models were tested on a vehicle dynamometer at temperatures of –7°C and +23°C and when driving a city driving cycle called the Helsinki city driving cycle.

The Toyota Prius PHEV performed well and with significantly reduced emissions of CO_2 for a short simulated return city traffic trip over a total distance of about 15 km at 23°C. Compared with a Prius HEV, the tailpipe CO_2 reductions were about 80-90 percent. Compared with the Toyota Avensis with a 1.8 l petrol engine, the CO_2 reductions were 90-95 percent and a little lower compared with the Toyota Avensis with diesel engine.

3.3.2 Exhaust emission tests

As described in section 2.2.3, the Helsinki driving cycle was created to simulate real world city driving in Helsinki. In order to separate the effects of cold starting, the emissions were measured separately for the first 3.7 km, including the key turn on emissions and the rest of the driving cycle (3.7-7.8 km).

During the emission tests the vehicles were started with the engine cold and driven the 7.8 km cycle twice. After the first cycle the vehicles were left standing for about 15 minutes with the engine turned off, then started again (with warm engines) and driven the 7.8 km driving cycle. This way of testing very much corresponds to a short trip in a city, a stop for shopping or delivery and then returning to the starting point.

The emission tests with both cold and warm starts and the driving pattern shown in figure 13 were done in a cold climate (-7°C) as well as at normal temperatures (+23°C).

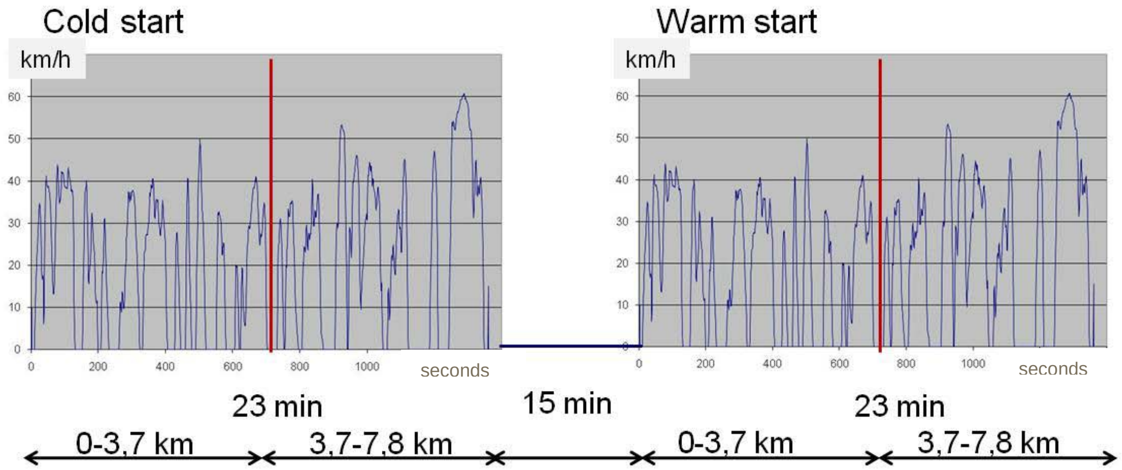

Figure 13: The Helsinki city driving cycle – vehicle speed versus time and distance

3.3.3 CO_2 emissions

The CO_2 emissions were measured from a

- Toyota Avensis with 2.0 l D-4D diesel engine
- Toyota Avensis with 1.8 l petrol engine
- Toyota Prius HEV
- Toyota Prius PHEV

The CO_2 emissions in figure 12 are shown for full cycles of 7.8 km:

- 7.8 km Helsinki city cycle with cold start at ambient temperature –7°C
- 7.8 km Helsinki city cycle with warm start at ambient temperature –7°C
- 7.8 km Helsinki city cycle with cold start at ambient temperature +23°C
- 7.8 km Helsinki city cycle with warm start at ambient temperature +23°C

The Prius PHEV performed well at 23°C and with significantly reduced emissions of CO_2 over a short simulated city traffic "return trip". The total distance travelled in this case was two Helsinki city cycles (15.6 km) and the capacity of the battery seemed to last over this entire simulated "return" trip.

Compared with a Prius HEV, the CO_2 reductions for this "return trip" at 23°C were about 80-90 percent. Compared with the Toyota Avensis with 1.8 l petrol engine and the Toyota Avensis with diesel engine, the CO_2 reductions were higher, as can be seen in figure 14.

However, it should be noted that at –7°C the CO_2 emission from the PHEV is almost at the same level as it is from the HEV. The explanation is that at ambient temperatures of –7°C the electronic management system will prioritize to supply heat to warm up the vehicle compartment and the defroster system. In this case, heat is produced most efficiently by the combustion engine, since the surplus heat energy from the engine at this cold temperature is not an energy waste. It can be expected that stored energy in the battery may be used on longer trips, but for short trips the PHEV will be more climate friendly and energy efficient at +23°C than at –7°C.

An option is to heat the cabin of the PHEV with an electric heater when it is connected to the electric grid for battery charging. To heat the engine and the compartment should really be an even more relevant option for vehicles plugged in for charging than for conventional vehicles with only a combustion engine.

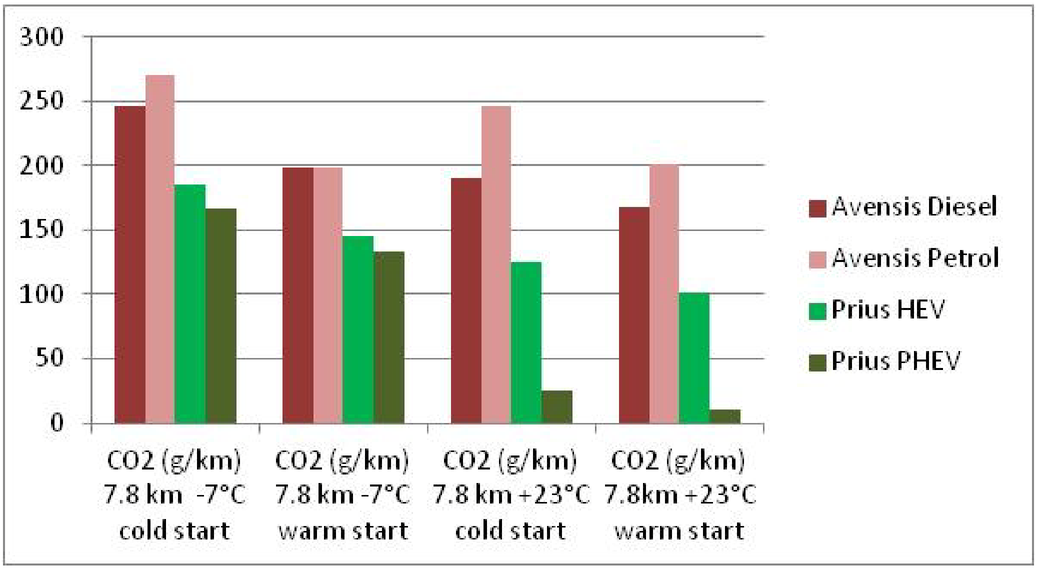

Figure 14: Measured CO_2 emissions at –7°C and +23°C from a full Helsinki city driving cycle

The CO_2 emissions for the full city driving cycles are shown in figure 14, and the separate figures from the first 3.7 km including cold start from the last 4.1 km of the cycle in figure 15.

The following conclusions can be drawn about CO_2 emissions from the four different vehicles:

- A Prius PHEV with fully charged batteries effectively reduces CO_2 emissions on short trips up to 15-20 km in temperate weather conditions
- When driving the Helsinki city driving cycle without the need for heating in a Prius PHEV with fully charged batteries, the CO_2 emissions are in the order of 10-40 g/km
- The Prius PHEV management system prioritizes heat, safety and comfort before CO_2 emission reductions at –7°C
- The Helsinki city driving cycle is so tough that the combustion engine occasionally seems to engage to supply power sufficient to meet the driving cycle acceleration

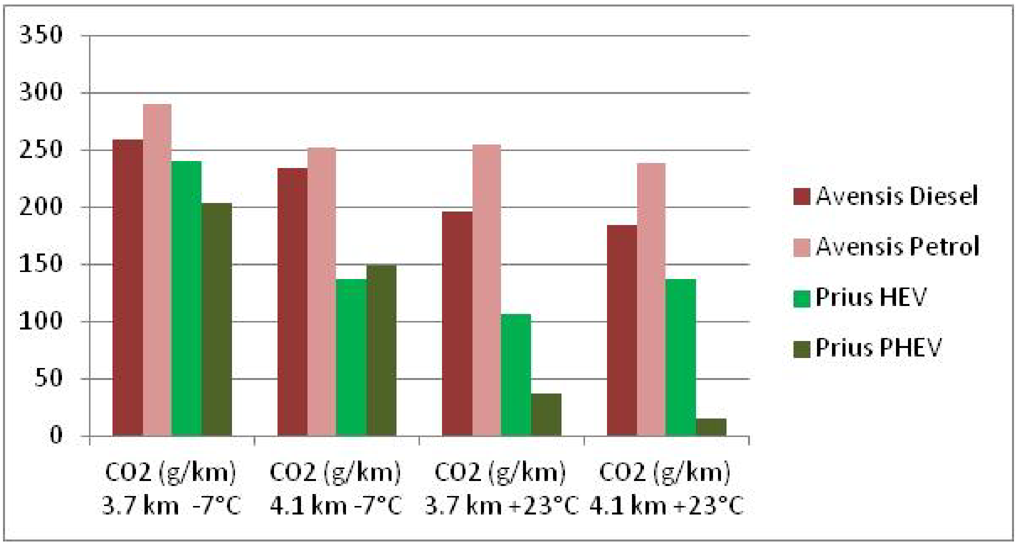

Figure 15: Measured CO_2 emissions at –7°C and +23°C from the two parts of the driving cycle with cold start (the meaning of cold start is specified in figure 11)

3.3.4 Local pollutant exhaust emissions

Exhaust emissions from motor vehicles are a problem in major cities, and nitrogen oxides (NO_x), together with particulate matter (PM), are the two dominant directly harmful health components in exhaust gases. Concentrations of NO_2 in the air have increased in the past 10 years in some of the major cities in Norway, particularly in Oslo and Bergen, where limit values for acceptable air quality were exceeded several times in 2010. The pollutant emissions from vehicles are mostly a problem at low temperatures and in congested city traffic. The Helsinki city cycle at –7°C is thus a relevant test revealing whether harmful local pollutants are a problem with PHEVs.

The hypothesis that the Prius PHEV, in city traffic conditions, will have only minor and probably harmless emissions of NO_x, PM and volatile hydrocarbon compounds (HC) was confirmed. Any emissions of NO_x, PM and HC from the Prius PHEV are difficult to detect after the initial "starting engine emissions", even when the vehicle is driven aggressively in city traffic conditions.

We can see from figure 16 that NOx emissions from the PHEV are low during the first 3.7 km and almost zero after that. Modern new vehicles with petrol engine and three-way catalysts appear to be very clean in terms of local pollutants like CO, PM, HC and NOx when the catalyst has reached "light off temperature".

At –7°C, cold starts, cars with petrol engines (including the PHEV) show relatively high emissions of HC because of the necessarily rich fuel mixture needed to ignite the engine (figure 17). However, this period of unclean emissions is short, and after 3.7 km petrol engine vehicles can almost be considered as zero emitters of local pollutants. The Prius PHEV seems to emit a total of about 3 grams of unburned petrol compounds (HC) during a cold start at –7°C.

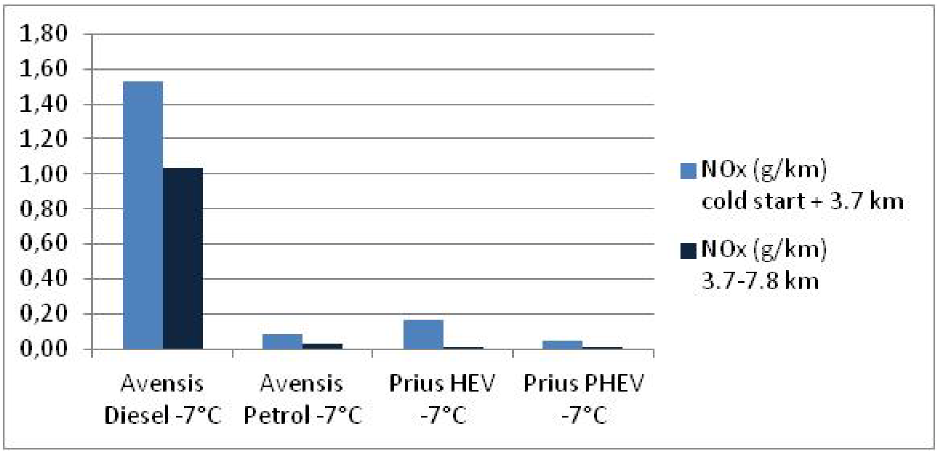

Figure 16: Measured NO_x emissions at –7°C from the two parts of the driving cycle with cold start

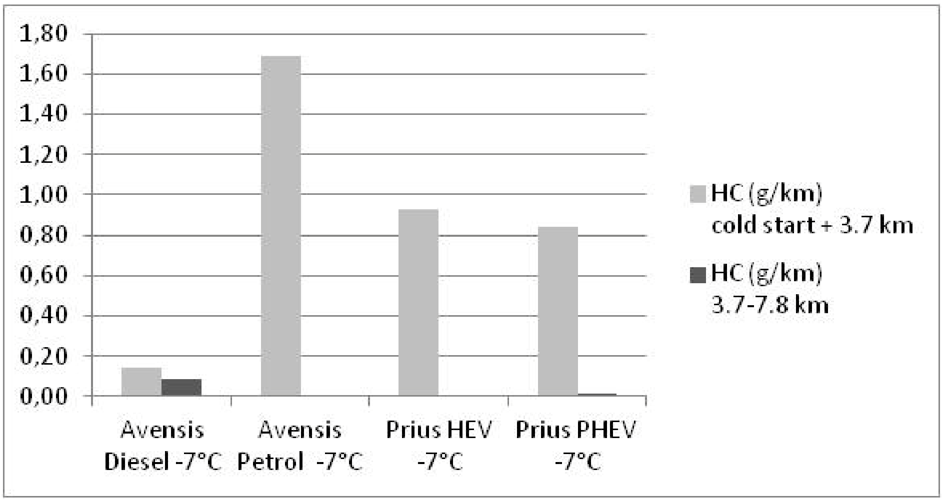

Figure 17: Measured HC emissions at -7 °C from the two parts of the driving cycle with cold start

In addition to pollution from combustion, all vehicles contribute to local air pollution through the abrasion of road surfaces, in some cases through the use of studded tyre, tyre particulates, etc. This type of pollution relates to type of road surface, the tyres used, atmospheric and climate conditions and road maintenance, and consequently is not influenced by the choice of engine and fuel technology, except perhaps slightly through the weight factor.

4 Conclusions

PHEVs can contribute to considerable fuel and CO_2 reductions – especially over travel distances with the vehicle in pure electric (EV) mode. For daily commuting distances shorter than 20-25 km, fuel consumption and CO_2 emissions from a Prius PHEV can be close to zero if electricity is available in car parks where commuters leave their cars. The advantage of the PHEV compared to an EV (pure battery Electric Vehicle) is that a PHEV can be used for longer trips without having to be charged, i.e. there will be no "range anxiety" and the same car can be used for both short and longer trips and still save fossil fuel and reduce CO_2 emissions. In a country like Norway, with almost 100 percent of electricity coming from renewable sources, PHEVs will represent a considerable step towards CO_2 reductions. The challenge is for PHEVs to gain a fair share of the car market.

User surveys in Europe and in Finland indicate satisfaction with the pre-commercial PHEV Prius in general, as do the interviews with professional Norwegian drivers.

A large majority of the Finnish users who had used their PHEV Prius during winter replied that their experience was no different from their experience with other cars; some Finnish users even saw advantages of PHEV in winter use, such as "easier to start" or "better uphill grip". The professional Norwegian drivers were also well satisfied with the PHEV Prius during winter conditions, with the exception of the low ground clearance.

There are two challenges – the electric driving range is considered too short, and handling and storing of the charging cable is cumbersome. The latter will be solved by further product design and development, or by a well-organised charging routine such as the Norwegian professional drivers had. The former are primarily cost, charging time and available vehicle volume constraints. Longer driving range requires more battery capacity, which is costly, and more battery capacity requires longer charging time. However, the survey questionnaires did not include questions concerning willingness to pay for longer range nor questions concerning the consequences of longer charging time and smaller luggage space. The field tests showed that charging time was less than two hours, average charging time 71 minutes, and the Finnish survey showed that most users connected the vehicle to the grid for 2-3 hours or more than five hours. Consequently, longer charging hours up to 3-4 hours should not be a problem.

Almost half the Finnish users said they were willing to pay more for a vehicle that was less harmful to the environment, and two-thirds agreed that the PHEV Prius satisfied their daily needs for transport. Consequently, if two versions of PHEVs were marketed, a reasonably priced one with the present PHEV Prius battery capacity and a more expensive version with higher battery capacity, most consumers should be able to satisfy their travel needs with PHEVs.

As mentioned, the average trip for a car driver in Norway in 2009 was 13.6 km (Vågane, Brechan, Hjorthol, 2011, pp. 28-30) and 31 percent of trips were less than 2.9 km. Even if charging facilities are not available and time does not allow charging at all stops between trips, an electric driving range of 20-25 km should cover a considerable part of the total number of kilometres driven in Norway.

At present, it is impossible to say what customers in general want and expect from PHEVs, since the users of the PHEVs in this project were hardly representative of the average customer in the car market. Moreover, they did not pay for the vehicle themselves.

When the Prius PHEV was driven in city traffic with a fully charged battery for 15 km, tests showed that CO_2 emissions were reduced by 80-90 percent compared with a Prius HEV, and even more compared with conventional diesel and petrol vehicles in temperate weather conditions. In a cold climate, some of the benefits are eroded due to the need to run the engine to provide heat to the cabin. These results indicate clearly the high CO_2-reducing potential of PHEVs but also that cabin acclimatisation requires attention.

The local pollutant emissions from the Prius PHEV, such as NO_x, were reduced to almost nothing after the first 3.7 km. However, local pollutants were also shown not to be a problem from a new modern conventional petrol vehicle, but the reductions produced by the PHEV compared with a conventional diesel vehicle were large.

The emission tests show that the PHEV may reduce CO_2 emissions considerably compared to other vehicles and local pollutants compared to conventional diesel vehicles. Thus, the PHEV is definitely environmentally friendly. If the above-mentioned challenges – the range of electric driving and ease of charging – are solved without too much extra cost to the customer, the PHEV may have a good chance of success in the market.

Most users of the pre-commercial PHEV Prius wanted a longer EV mode driving range, but whether they would be willing to pay the extra costs of higher battery capacity is another question. Both the Finnish users and the Norwegian professionals reported that the PHEVs performed well during winter conditions, but that the low ground clearance was sometimes a problem when driving on snow.

No fundamental barriers to the use of PHEVs were found during the project, but handling and storage of the charging cable were mentioned as a disadvantage. Nevertheless, most users charged the vehicle once or twice a day, which is an indication that the charging itself is not a barrier.

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