Institute of Transport Economics
Norwegian Centre for Transport Research

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

[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.

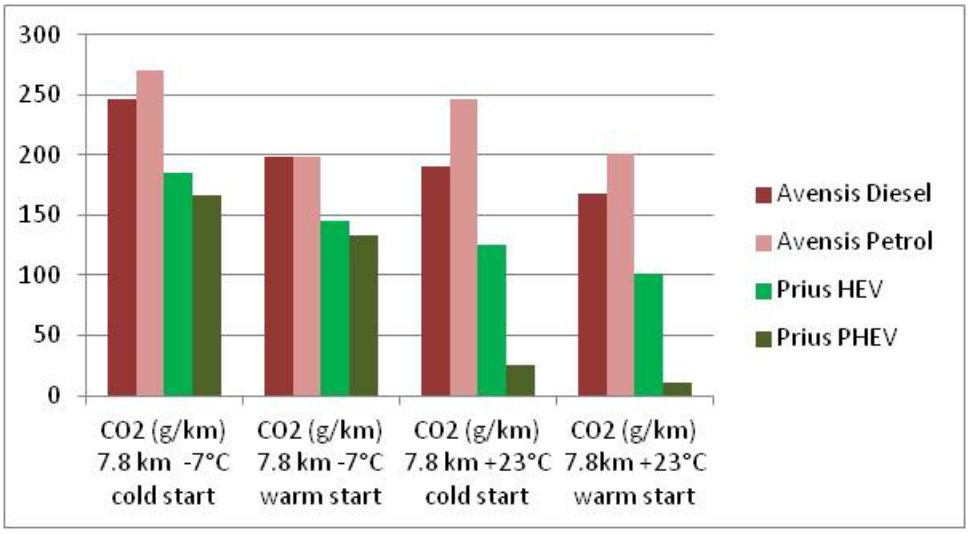

Figure S.1: Measured CO_2 emissions from a pre-commercial PHEV Prius and reference cars at -7 °C and +23°C from full Helsinki city driving cycles

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.