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Norwegian Centre for Transport Research

Experimental testing of Plug-in Hybrid Vehicles

CO_2-emission, energy consumption and local pollution

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Sammendrag:

To ladbare hybridbiler ble testet i et avgass-laboratorium ved 23°C og ved -7°C, i en rekke ulike kjøresykluser og brukervalgbare kjøremoduser, for å avdekke CO_2-utslipp, energiforbruk og utslipp av lokalt forurensende avgasser.

Resultatene ble sammenlignet med måleresultater fra bensin- og dieselversjoner av de samme bilene for å kunne estimere de gjennomsnittlige potensielle utslippsreduksjonene som kan oppnås gjennom ett års kjøring.

Hovedresultatet er at ladbare hybridbiler med en rekkevidde i E-modus kan gi en CO_2-utslippsreduksjon på ca. 30%, mens 50 km rekkevidde kan gi 50% reduksjon, uten at gjennomsnittlig lokalt forurensende avgassutslipp overskrider grenseverdiene i avgassbestemmelsene. Lokalt forurensende utslipp kan imidlertid være forhøyet i enkelte spesifikke situasjoner slik som i kaldt klima, med utladet batteri og høy belastning.

Resultatene må tolkes med varsomhet da det bare ble testet to biler.

Summary:

Two Plug-in Hybrid Vehicles (PHEVs) were tested in an exhaust emission laboratory at 23°C, and at -7°C, using a combination of different drive cycles and user selectable drive modes, to uncover their CO_2-emissions, energy consumption and emissions of local pollutants.

The results were compared with measurements on Internal Combustion Engine versions of the same vehicles (ICEVs) to estimate the average potential reductions that can be achieved over a year of driving.

The overall result is that the PHEV with a range of about 30 km can have 30% less CO2-emission over a year of driving, and a PHEV with 50 km E-mode range can have a 50% reduction, without average local emissions exceeding the limits in the exhaust regulations. Local emissions can however be elevated in some driving conditions, such as driving in cold climate with high loads and an empty battery.

Results should be interpreted with caution as only two vehicles were tested.

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Preface

This report is part of the EMIROAD (Emission from Road Transport Vehicles) project financed by the Norwegian Public Roads Administration. The objective of EMIROAD is to bring forward new knowledge about emission from vehicles, under different driving conditions in Nordic climate, and the potential of cutting emissions in the coming years with new technologies and alternative energy carriers.

The objective of this report is to present exhaust emission and energy consumption measurement results for two Plug-in Hybrid Vehicles (PHEVs). This vehicle type has rapidly gained popularity among Norwegian vehicle buyers, but little has been known about their environmental characteristics under real driving conditions in Norway.

The measurement results are combined with user pattern information gathered in a survey of PHEV users conducted in March 2016 (TØI report 1492/2016), to provide rough estimates of the emissions and energy use of these vehicles over a full year for sample usage patterns.

We want to express our gratitude to VTT Technical Research Centre of Finland LTD, which was responsible for conducting the measurements in their emission test laboratory.

Erik Figenbaum has been responsible for the data-analysis and been the main author of the report, with contributions from the EMIROAD project leader Christian Weber. Christian Weber also organized the test program. Michael W. J. Sørensen has been TØI's quality assurer.

Oslo, April 2017
Institute of Transport Economics

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Content

Acronyms and abbreviations

BEV = Battery Electric Vehicle
HEV = Hybrid Electric Vehicle
ICE = Internal Combustion Engine
ICEV = Internal Combustion Engine Vehicle
PHEV = Plug-in Hybrid Electric Vehicle
SOC = State of charge of the on-board propulsion battery
4WD = Four-wheel drive

Sammendrag

Eksperimentell testing av ladbare hybridbiler

Virkninger på CO_2-utslipp, energiforbruk og luftforurensing

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Energiforbruket, CO_2-utslippet og utslippet av luft-forurensende avgasser fra to ladbare hybridbiler ble, på oppdrag fra EMIROAD testprogrammet, målt i VTT's avgasslaboratorium i Finland, ved +23°C og -7°C, og i ulike kjøremønstre og sjåførvalgte driftsmoduser. Sammen med brukermønstre framskaffet i en spørreundersøkelse blant eiere av ladbare hybridbiler fra mars 2016, kan disse måleresultatene anvendes til å estimere miljøeffektene av å anvende disse bilene i norsk trafikk. Den overordnede konklusjonen er at disse bilene gir substansielle miljøfordeler sammenlignet med bensin- og dieselbiler. CO_2-utslippet reduseres med 30-50% avhengig av bilens konfigurasjon, mens lokal luftkvalitet ikke ser ut til å være en utfordring med disse bilene sammenlignet med bensin- og dieselbiler. De slipper imidlertid ut betydelig mer CO_2 og bruker mer energi enn det som står i typegodkjenningen. Avviket er betydelig større enn for bensin- og dieselbiler og det er urealistisk å tro at typegodkjenningsverdiene skal kunne oppnås av vanlige brukere. Noen spesielle bruksmønstre, f.eks. kjøring i kaldt klima med tung belastning og tomt batteri kan føre til høyere utslipp av lokalt forurensende avgasser enn typegodkjenningsverdiene og til dels også grenseverdiene i avgassbestemmelsene.

Bakgrunn, metode og analytisk rammeverk

Hybridbiler bruker et batteri og en elektrisk motor/generator til å ta vare på bremseenergien. Når bilen bremser fungerer elmotoren som en generator som dermed bremser bilen og lader batteriet. Denne energien kan tas ut igjen av batteriet ved at elmotoren bidrar som en hjelpemotor til bensinmotoren når bilen akselerer. På den måten kan bensinmotoren operere mer energieffektivt og drivstofforbruket og CO_2-utslippet reduseres. Batteriet i hybridbiler kan ikke lades opp fra strømnettet.

Ladbare hybridbiler kan lades fra strømnettet og kjøre mer eller mindre elektrisk i 20-80 km avhengig av hvor stort batteriet er og hvordan bilen er konfigurert. På lengre kjøreturer og ved kraftige akselerasjoner startes bensinmotoren og sørger for framdrift av bilen med assistanse fra elmotoren.

Det doble drivsystemet og tilgangen til to energikilder gjør at ladbare hybridbiler gir brukerne fleksibilitet, noe som forsterkes av at brukeren kan velge ulike kjøremoduser der elmotoren og bensinmotoren anvendes i større og mindre grad. Bruksmønsteret og energiforbruket for disse bilene kan dermed få en mye større spredning enn for bensin- og dieselbiler, og resultere i svært varierte utslipp.

Det er lite kunnskap om ladbare hybridbilers reelle energiforbruk, utslipp og bruksmønster i norske trafikk- og klimaforhold. EMIROAD prosjektet hadde som mål å fylle kunnskapsgapet gjennom to delprosjekter:

1. Målinger utført i laboratorier for å vurdere to ladbare hybridbilers energiforbruk og utslipp, gjennom å simulere kjøring i virkelig trafikk og i kaldt og varmt klima.

2. Spørreundersøkelse blant eiere av ladbare hybridbiler (og elbiler og bensin- og dieselbiler) ble spurt om bruksmønster og lademønster for å se hva som er typiske brukerprofiler.

Ved å kombinere disse resultatene kan en estimere den gjennomsnittlige reduksjonen av utslipp og energiforbruk ved å erstatte bensin- og dieselbiler med ladbare hybridbiler.

Målinger og spørreundersøkelse

Bil A var en kompaktbil med el-rekkevidde på 50 km, CO_2-utslipp på 37 g/km og ett energiforbruk på 117 Wh/km strøm og 0,16 liter bensin/mil. Bil B var en mellomklasse bil med el-rekkevidde på 31 km og ett CO_2-utslipp på 48 g/km, og et energiforbruk på 110 Wh/km strøm og 0,21 liter bensin/mil. Disse tallene er i henhold til den offisielle typegodkjenningen. Testprogrammet var satt opp for å undersøke hvor stort avviket fra typegodkjenningen er i virkelig trafikk. I disse bilene kan brukerne velge ulike kjøremoduser som gir ulik fordeling av bruken av el- og bensinmotoren.

De to ladbare hybridbilene ble derfor testet ekstensivt i avgasslaboratoriet ved å kjøre ulike kombinasjoner av kjøreforhold (kald- og varmstart ved +23°C og -7°C), batteritilstand (fullt ladet og helt utladet) og brukervalgte kjøremoduser i NEDC, Artemis Urban og Helsinki-city test sykluser («snille» og «aggressive» kjøremønstre).

Målinger av gravimetriske (masse) utslipp av karbondioksid (CO_2), nitrøse gasser (NO_X), karbonmonoksid (CO), hydrokarboner (HC), partikler (PM) og antall partikler (PN), samt strømforbruk fra kraftnettet til opplading av bilens batterier, ble foretatt.

Spørreundersøkelsen av 2065 private eiere av ladbare hybridbiler ble gjennomført i mars 2016 og er dokumentert i Figenbaum og Kolbenstvedt (2016). Metodene brukt i den undersøkelsen er derfor ikke repetert her.

Resultater

Målingene var repeterbare. For Bil A varierte CO_2-utslippet og drivstofforbruket innenfor 10% og elforbruket med 4% ved testing i identiske tester over flere gjentatte kjøresykluser. Bil A hadde ikke en rent elektrisk kjøremodus i og med at forbrenningsmotoren startet tidvis. I hybrid modus kunne bilen kjøres delvis rent elektrisk men bensinmotoren ble startet og anvendt til framdrift av bilen under krevende kjøreforhold og lave temperaturer og når batteriet var tomt. Typegodkjenningsverdien for CO_2 er svært optimistisk for denne bilen og kan bare være oppnåelig med et optimalt kjøremønster der mesteparten av kjøringen foregår i E-modus. Noen brukermoduser kan under fordelaktige kjøreforhold og med fulladet batteri gi CO_2-utslipp som er 70% lavere enn for en sammenlignbar dieselversjon av bilen. Over ett gjennomsnittsår med kjøring vil fordelen være mindre.

I spørreundersøkelsen blant private eiere av ladbare hybridbiler fremkom det at bilene i hovedsak lades hjemme hver natt og i liten grad andre steder. Den gjennomsnittlige årlige kjørelengden for disse bileierne var ca. 15000-16000 km. Ut fra disse resultatene og måleresultatene kan en estimere at for ett år kan CO_2-utslippet for denne bilen være ca. 46% lavere enn for en tilsvarende dieselbil. Det gjennomsnittlige årlige utslippet av NO_X og partikler vil trolig være under typegodkjenningsverdiene men i noen spesifikke bruksmønstre, som ved kjøring i kaldt klima med tomt batteri, kan utslippet være høyere.

Bil B fungerte svært ulikt fra Bil A. Den var fullt ut kapabel til å kjøre 100% på elmotoren både i kaldt- og varmt klima. I kaldt klima var imidlertid rekkevidden kort, så turer lenger enn 10-15 km vil sannsynligvis innebære at forbrenningsmotoren må bidra til framdrift av bilen. Denne bilen var tydeligvis programmert til å kjøre mest mulig rent elektrisk også i hybrid modus når kjøreforholdene gjør det mulig. Ved mer «aggressiv» kjøring med tomt batteri og i kaldt klima kunne enkelte av de lokale utslippskomponentene ligge over typegodkjenningsverdiene. CO_2-utslippet vil under slike forhold ligge langt over typegodkjenningsverdien.

Det årlige gjennomsnittlige CO_2-utslippet fra bilen ble estimert ut fra data fra spørreundersøkelsen og laboratorietestene til å være 27% mindre enn fra en 1,6 liters bensinmotorversjon av samme bil og 36% mindre enn en 2,2 liter dieselmotorversjon som også har blitt testet av EMIROAD programmet når årlig kjørelengde er 16000 km.

CO_2-utslippet fra disse ladbare hybridbilene varierer betydelig mer mellom kjøresykluser, temperaturer og bruksmønstre enn det gjøre for bensin- og dieselversjonene. Derfor vil en få en stor spredning i hvor store CO_2-utslippsreduksjoner som kan oppnås med disse bilene.

Konklusjon

Resultatene fra testing av de to ladbare hybridbilene demonstrerer at dette er en teknologi som gir en uensartet biltype. Mengden CO_2 og lokal luftforurensing som disse bilene slipper ut vil avhenge av hvordan de er konstruert men også i mye større grad av hvor, hvordan og når de benyttes enn det som er tilfelle for bensin- og dieselbiler. Dette er biler med høy total motorytelse og en bør derfor sammenligne med bensin- og dieselbiler med mest mulig tilsvarende ytelser for å få et riktig bilde av miljøegenskapene.

CO_2-reduksjonen som oppnås relativt til sammenlignbare bensin- og dieselbiler er proporsjonal med elrekkevidden. 50 km rekkevidde gir om lag 50% reduksjon, og 31 km gir om lag 30% reduksjon. Utslippene er imidlertid omtrent 2,5 ganger høyere enn typegodkjenningsverdien for ett mulig gjennomsnittlig bruksmønster over ett år. Avviket er om lag 1,4 ganger for vanlige 2015 årsmodell bensin- og dieselbiler i henhold til Tietge et al (2016). Enkelte kjøreforhold kan gi økte utslipp av lokal forurensende avgasser, men gjennomsnittlig kjøring i ulike driftsmoduser over ett år leder til gjennomsnittsutslipp under utslippsgrensene.

Bruksmønsteret må passe til bilenes egenskaper for å kunne oppnå maksimale fordeler i form av redusert CO_2-utslipp og lokal luftforurensning.

Institute of Transport Economics
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Summary

Experimental testing of Plug-in Hybrid vehicles

Impacts on CO_2-emission, energy consumption and pollution

TØI Report 1539/2016
Authors: Erik Figenbaum, Christian Weber
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Two Plug-in Hybrid Vehicles (PHEVs) energy consumption, CO_2-emission and locally polluting emissions were tested in VTT's emission laboratory in Finland, at +23°C and -7°C and in different drive cycles and drive modes. Together with data on usage pattern extracted from a survey of PHEV owners in March 2016, the measurements enable an assessment of the environmental impacts of these vehicles in Norwegian traffic conditions. The general conclusion is that these vehicles provide substantial environmental advantages compared with comparable Internal Combustion Engine Vehicles (ICEVs). The CO_2-emission is reduced 30-50% depending on vehicle configuration, and local pollution does not seem to be an issue with these vehicles compared with ICEVs. They do however emit substantially more CO_2 and consume much more energy than the type approval values. The type approval value does not seem achievable in real traffic. Some specific usage modes, for instance driving in cold climates under heavy loads with an empty battery, can lead to excessive local emissions compared with the official type approval limits.

Background, method and analytical framework

The Hybrid Electric Vehicle (HEV) uses a battery and an electric motor/generator to capture brake energy. The motor is when braking turned into a generator producing electricity (and a braking torque) that is recharged into the batteries. This captured brake energy can subsequently be used in the electric motor to assist in the propulsion of the vehicle and thus save fuel. The batteries in these vehicles cannot be externally recharged. Plug in Hybrid Vehicles (PHEVs) can utilize grid electricity charged into the vehicle's larger batteries, for propulsion up to 20-80 km depending on the battery capacity and vehicle configuration. For longer distances and when the power in the electrical system is insufficient, the on-board Internal Combustion Engine (ICE) supports propulsion.

The duality of power sources and engine/motors in PHEVs introduce flexibility for the user, and the user can select different drive modes where the ICE is operating to a larger or lesser extent. The real traffic propulsion system usage patterns can therefore be much more diversified for these PHEVs than for ICEVs.

Little has been known about PHEVs real world energy consumption, emission and usage characteristics under Norwegian road and climate conditions, and typical usage patterns. EMIROAD set out to fill that knowledge gap following a two path approach:

1. Measurements were carried out in laboratories, to assess two PHEVs energy use and exhaust emissions, by simulating real world traffic and climatic conditions.
2. Current users of PHEVs (and BEVs and ICEVs) where surveyed about their usage pattern and charging behavior, to build a plausible Norwegian PHEV usage profile.

The combined results from the laboratory measurements and the survey enables estimation of possible reductions of emissions and energy consumption when PHEVs replace ICEVs.

Measurements and survey

Two PHEVs were tested extensively in the emission laboratory. Vehicle A was a compact sized vehicle which, according to the type approval, has an E-mode range of 50 km, emit 37 g CO_2/km with an average energy consumption of 117 Wh/km of electricity and 0.016 liter of gasoline/km. Vehicle B was a mid-sized plug-in hybrid vehicle, which according to the type approval, has an E-mode range of 31 km, emit 48 g CO_2/km with an average energy consumption of 110 Wh/km of electricity and 0.021 liter/km of gasoline.

These vehicles were tested in different combinations of input conditions in the NEDC, Artemis Urban and Helsinki-city tests, i.e. ambient temperatures of +23°C and -7°C, cold and warm starts, fully charged and fully discharged batteries, and in different user selectable drive modes.

The exhaust gravimetric emissions of carbon dioxide (CO_2), nitrogen oxide (NO_X), carbon monoxide (CO), hydrocarbon compounds (HC) and particulates (PM) as well as the total number of particulates (PN) and the electricity consumption from the grid, were measured.

The PHEV user survey of 2065 private owners is documented in Figenbaum and Kolbenstvedt (2016), and the methods used in the survey are therefore not repeated here.

Results

The tests of vehicle A were fairly repeatable. The CO_2-emission and energy consumption varied within 10% and electricity consumption within 4% over identical tests containing several drive cycles. The vehicle did not have a pure electric drive mode as the ICE started occasionally. In the hybrid mode the vehicle ran partly fully electric, but the ICE was switched on for more demanding driving and at low temperature or when the battery was empty. The type approval CO_2-emission level seems to be a very optimistic value for this vehicle. It seems only reachable for an optimum driving pattern with a very high share of driving in the E-mode. In favorable driving conditions and starting fully charged, the vehicle can however in some user selectable modes achieve 70% less CO_2-emission than a comparable diesel version of the vehicle. Over a year of average driving the advantage will be less.

The user survey showed that most PHEVs are charged at home every day and rarely elsewhere, and the typical average driving length is 15000-16000 km. That results in a CO_2-emission estimate of Vehicle A over a year of driving that is about 46% less than that of a comparable diesel vehicle. The average NO_X and particulates emissions can be below the type approval limits for this usage pattern over the year, and also for the winter season. Some specific usage conditions, such as heavy loads with an empty battery in cold climate, can however lead to elevated emission levels above type approval values.

Vehicle B functioned very differently from vehicle A. It was fully capable of driving in a pure electric mode both in warm and cold climates. However, when driving in cold climate the electric range was short, so trips longer than 10-15 km in cold climates will involve some operation of the ICE. The vehicle is apparently programmed to drive purely electrical in the hybrid mode when vehicle load, driving and climatic conditions make it possible. When driving in high load conditions, with 0% SOC or in cold climate, some of the local emissions were also for this vehicle above the type approval emission limits. Also the CO_2-emission can then be much higher than the type approval value. The average yearly CO_2-emission of the vehicle was estimated to be 27% less than with the 1.6-liter gasoline version of the vehicle, and 36% less compared with a 2.2-liter diesel version of the vehicle, when driven 16000 km per year.

The CO_2-emission level of these PHEVs varied much more between drive cycles and temperatures than for comparable ICEVs. User profiles are very diversified and will generate a large spread in the potential annual CO_2-emission of these vehicles.

Conclusion

The testing of these two vehicles demonstrates that PHEVs are a non-uniform category of vehicles. The amount CO_2 and local pollutants these vehicles emit will depend heavily on how the vehicles are designed, and how, when and where they are used. They are high performance vehicles and care should be taken when identifying vehicles to compare emissions with.

The CO_2-reduction benefit relative to comparable ICEVs, were proportional to the e-mode range, i.e. about 50% reduction for the vehicle with 50 km range and about 30% for the vehicle with 31 km E-mode range. The average yearly estimated CO_2-emission was about 2.5 times higher than the value stated in the type approval. That deviation is much larger than the 1.4 times larger on-road emissions Tietge et al (2016) found for 2015-yearmodel ICEVs.

Some driving conditions caused elevated local emission levels, but average driving in different drive modes should over the year lead to average emissions below the emission limit values.

The testing supports a conclusion that the users driving pattern needs to match the characteristics of these vehicles to reap the maximum benefits in terms of reduced CO_2-emission and less local pollution.

1 Introduction

1.1 Background

Electromobility is high on the political agenda in Norway. The political target is to increase the share of electric vehicles in the fleet, as a contribution towards meeting Norway's climate policy targets. The main climate policy targets are to achieve a 40% reduction of greenhouse gas emissions by 2030 compared with 1990, and that Norway shall be a low emission society by 2050.

Norway had the highest market share of Battery Electric Vehicles (BEVs) in the world the last four years. The BEV market is supported by large incentives, mainly exemption from VAT and registration tax, that reduce the purchase price, and provide buyers with valuable privileges, such as access to bus lanes, free toll roads and parking (see for instance Figenbaum and Kolbenstvedt 2015, Figenbaum 2016).

The incentives for Plug-in Hybrid Vehicles (PHEVs) have been much lower. The registration tax is however reduced, and for some PHEVs even zero, thus leveling out the price difference versus comparable diesel vehicles (see Fridstrøm and Østli 2016). Other incentives have not been available but these vehicles nevertheless gain popularity.

BEVs had a market share of 15.7% in 2016 and PHEVs a market share of 13.4% (OFVAS 2017), as seen in figure 1.1. Most other countries had market shares below 1 percent: Sweden is an exception with a BEV market share of 0.8% and a PHEV market share of 2.8% in 2016 (BilSweden 2017).

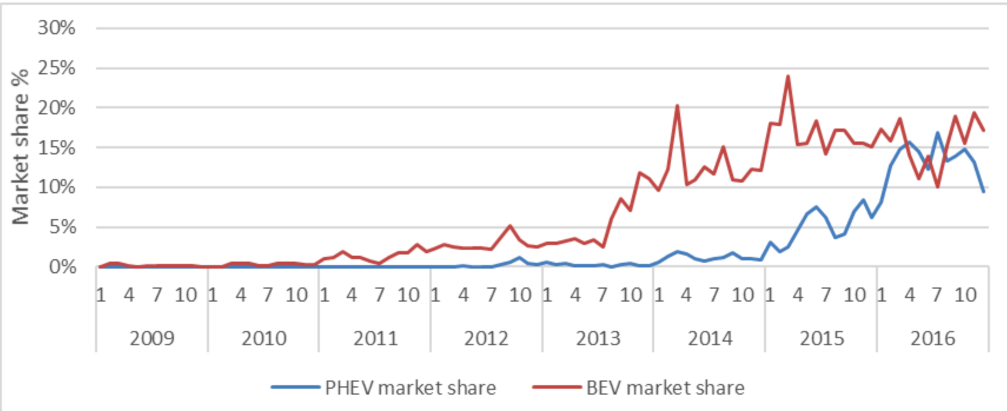

Figure 1.1: Market share of Battery electric (BEV) and Plug-in hybrid (PHEV) vehicles in Norway 2009-2016.

Little is known about PHEVs real world energy consumption, emission and usage characteristics under Norwegian road and climate conditions, and typical usage patterns.

EMIROAD set out to fill the knowledge gap following a two path approach. In the first path, measurements were carried out in laboratory tests, to assess the PHEVs energy use and exhaust emissions, simulating real world traffic conditions under different climatic conditions. Users of PHEVs, BEVs and Internal Combustion Engine Vehicles (ICEVs) where in the second path surveyed about their purchase motivations, usage pattern, charging behavior, attitudes towards BEVs and PHEVs, and their socio-demographic characteristics. The target was to build a plausible PHEV user and usage profile that could be compared to BEV and ICEV owners.

The combined results from the laboratory measurements and the survey make it possible to estimate possible reductions of emissions and energy consumption when PHEVs replace ICEVs.

The laboratory measurements are reported in this report. The survey results were reported in the Institute of Transport Economics report: 1492/2016, "Learning from Norwegian Battery Electric and Plug-in Hybrid Vehicle users" (Figenbaum and Kolbenstvedt 2016). BEV owners were also surveyed in 2014 (Figenbaum et al 2014), establishing a basis for the knowledge about BEVs owners and usage patterns, that was expanded by the 2016 survey.

1.2 Purpose and hypoteses

The purpose of the measurement program of PHEVs at VTT was to obtain a basic understanding of how PHEVs operate in Norway under various real traffic and climatic conditions, in line with the overall targets of the EMIROAD research program.

The questions that prompted the need to measure PHEVs and survey owners were:

1. What is the range and energy consumption when PHEVs are driven in the Electric drive mode?
2. What is the share of driving that is done in E-mode?
3. What is the influence of varying climate and driving conditions on the energy consumption, range and emissions?

An exploratory measurement program was designed to be able to shed light on these questions. The following hypothesis about PHEVs characteristics and environmental impacts were to be tested using the combination of the laboratory measurements and the survey results:

1. PHEVs have a pure battery electric drive mode in warm as well as cold climates.
2. Battery range is sufficient for everyday traffic, i.e. longer than the average round trip distance to work.
3. Due to the heavier weight of the added battery and electrical system, the energy consumption in non-electric modes will be higher than for comparable ICEVs.
4. Frequent start and stop of the drive system in hybrid mode can lead to high emissions.
5. The total energy consumption and emissions of PHEVs will be much lower than for similar ICEVs, for typical Norwegian usage patterns and climatic conditions.
6. A pure E-mode is not necessarily better from a CO_2-reduction perspective than a blended E-mode where the ICE can be on part of the time, on longer distances.

1.3 Boundaries

This report focuses on exploring the potential real world characteristics of PHEVs. The data cannot be used to estimate the average emissions or energy consumptions of the fleet of PHEVs on the road. Only two vehicles were tested, and the tests were deliberately designed to be exploratory, i.e. to also find the unexpected rather than focusing on the average behavior of the vehicles.

1.4 Report structure

Chapter 2 presents the methods and analytical framework of the measurement program. The measurement results are presented in chapter 3. In chapter 4, the measurement results in different user modes are combined with examples of user patterns, to estimate the average emission from the vehicles over a year of driving. Chapter 5 contains the discussion of the results and the conclusions of the report.

2 Methods and analytical framework

2.1 Theory of operation of the Plug-in Hybrid Electric Vehicle

The Hybrid Electric Vehicle (HEV) uses a battery and an electric motor/generator to capture brake energy, by generating electricity that is recharged into the batteries. This captured brake energy can subsequently be extracted and used in the electric motor to assist in the propulsion of the vehicle and thus save fuel. The batteries in these vehicles cannot be externally recharged, and the capacity is much smaller than for Battery Electric Vehicles (BEV) or Plug-in Hybrid Electric Vehicles (PHEVs).

The PHEV can on the other hand utilize grid electricity charged into the vehicle's larger batteries for propulsion over distances up to 20-80 km, depending on the battery capacity and vehicle configuration. For longer distances and when the power in the electrical system is insufficient, the on-board Internal Combustion Engine (ICE) supports propulsion. Some PHEVs use the ICE connected with a generator to produce the electricity consumed in the vehicle's electric motor, others can power the wheels directly.

This duality of power sources and engine/motors introduce flexibility for the user. It however also adds complexity for researchers aiming to understand the environmental impacts of PHEVs. Further complicating the picture, the user can select different drive modes where the ICE may be operative to a larger or lesser extent. Figure 2.1 shows an example of a PHEV lay-out with an overview of typical user selectable drive modes.

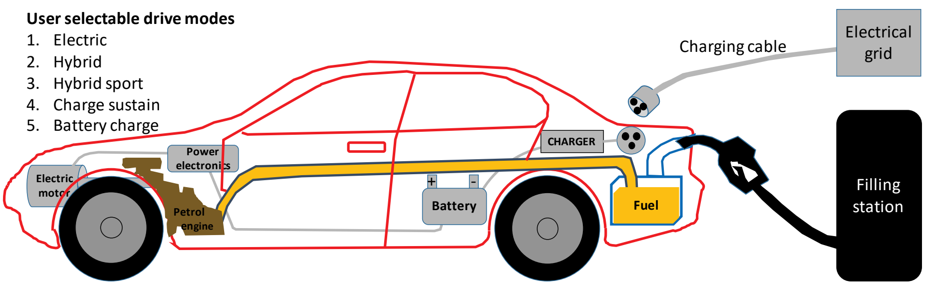

Figure 2.1: Typical plug-in hybrid vehicle lay-out and user selectable drive modes.

The real traffic propulsion system usage patterns can be much more diversified for these PHEVs, with their multitude of user selectable drive modes, than for ICEVs that can only use an ICE for propulsion. It is therefore no longer adequate to measure the energy consumption, the emission of CO_2 and local pollutants in a laboratory simulating real traffic, to establish an estimate of these vehicles environmental impacts. One also needs to take into consideration the actual usage of the vehicles.

The potential to reduce the environmental impact of PHEVs rests on the share of driving that can be, and is, accomplished in the most electric drive mode. In drive modes where the ICE is activated, the emissions may be higher than for comparably sized HEVs due to the extra weight of the larger batteries, the battery charger and other extra components.

The usage profile will influence emissions. Owners can for instance charge frequently or infrequently or drive so long distances that even frequent charging will lead to a low share of electrically driven kilometers. Some could be driving the vehicle continuously in the hybrid mode. Others maximize the share of driving in the electric drive mode by charging whenever possible.

The combination of laboratory measurement results and the user profiles obtained from user surveys, provide the basis for an estimate of the environmental impacts of these vehicles over a year of driving. In the EMIROAD project both laboratory measurements and surveys were therefore carried out to assess how much PHEVs' contribute to environmental impacts. The measurements of energy use and emissions were done in laboratory tests simulating real world traffic conditions under different climatic conditions. In an internet survey users of PHEVs, BEVs and ICEVs where asked about their purchase motivations, usage pattern, charging behavior and socio-demographic parameters.

This report presents the methods and results of the vehicle measurement program. The user pattern survey results are found in an already published TØI report (Figenbaum and Kolbenstvedt 2016). Elements from the two parts of the project are brought together in chapter 4, in an assessment of these PHEVs' potential average environmental impacts over a full year of driving.

2.2 Methods

The vehicles' emissions and energy consumption measurements were conducted in the emission laboratory at VTT in Finland on commission from TØI. The VTT facility consists of a fully equipped exhaust emission laboratory installed in a climatic chamber. A chassis dynamometer creates a driving resistance on the wheels, representing the road conditions, i.e. simulating rolling resistance, aerodynamic drag and dynamic forces. The vehicles were driven in different drive cycles. The exhaust gas measurement system can measure most types of emissions. In this project, the exhaust gravimetric emissions of carbon dioxide (CO_2), nitrogen oxide (NO_X), carbon monoxide (CO), hydrocarbon compounds (HC) and particulates (PM) as well as the total number of particulates (PN), were assessed. The climatic chamber can be cooled to winter temperatures and a temperature of -7°C was used in EMIROAD. The energy recharged back into the vehicles where measured before and after driving. The setup when driving is shown in figure 2.2.

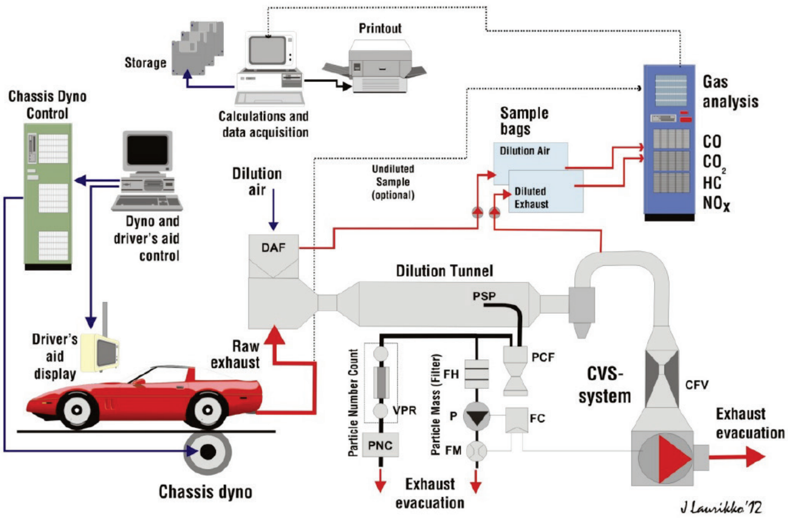

Figure 2.2: VTT Emission laboratory set-up. Drawing by: VTT, J. Laurikko, 2012.

2.3 Test program

A test program was devised to allow maximum testing over a period of two weeks at different ambient temperatures, with different drive modes and drive cycles.

2.3.1 Vehicle configurations

The main characteristics of the two PHEVs tested are presented in table 2.1.

Table 2.1: Vehicle characteristics and performance as stated in the type approval / brochures.

	Vehicle A	Vehicle B
E-mode range	50 km	31 km
CO_2-emission	37 g/km	48 g/km
NO_X-emission	8.9 mg/km	9 mg/km
Fuel consumption	1.6 liter/100 km	2.1 liter/100 km
Calculated fuel energy	14,5 kWh/100 km	18.8 kWh/100 km
Electricity consumption	11.4 kWh/100 km	11.0 kWh/100 km
Battery capacity	8.7 kWh	6.4 kWh
Charge time, 3.6 kW	2 h 15 min	1 h 45 min
Acceleration 0-100 km/h	7.6 seconds	5.9 seconds
Vehicle segment	Compact	Midsized (Norwegian definition)

2.3.2 Test conditions

The test conditions were selected to closely resemble real world traffic, and to make it possible to relate them to the official EU type approval test. The target was to be able to analyze the implication of different ways of driving PHEVs with full or empty batteries in hot (+23°C) and cold (-7°C) climates. A complication is that these vehicles can be used in many different user selectable modes as seen in table 2.2.

Table 2.2: Vehicle user selectable drive modes

Vehicle A	Vehicle B
E-mode (vehicles most electric mode)	Pure E-mode (100% electric)
Battery hold (maintain battery charge)	Battery hold (maintain battery charge)
Battery charge (recharge battery)	Battery charge (recharge battery)
Hybrid Auto (most efficient hybrid mode)	Hybrid Auto (most efficient hybrid mode)
Hybrid Sport mode (maximize power)	Hybrid Sport mode

The vehicles were tested using three different drive cycles and in different drive modes at +23°C and -7°C and with battery State of Charge (SOC) at 100% or 0%. It is thus possible to analyze:

- Implication of drive cycles, i.e. different usage and driving styles
- Implication of the vehicles selectable drive modes
- Implication of cold weather versus warm weather
- Implication of fully charged versus depleted battery

The battery SOC is not known exactly for these vehicles during driving. The vehicles only display the remaining range in E-mode in the on-board display. It is thus difficult to do repetitive testing at intermediate SOC levels.

2.3.3 Driving cycles

Drive cycles that are established in the vehicle testing community were selected to make the test as repetitive and comparable as possible. The speed profiles of the selected drive cycles used in the tests are shown in figures 2.3, 2.4 and 2.5.

The New European Drive Cycle (NEDC) is used for European type approval testing, and the results are used as the vehicles official emission and energy consumption data. These type approval tests follow a specific protocol that allows some preparation of the vehicles. In the EMIROAD project the vehicles were taken directly from the street and tested as they were.

The Helsinki-city cycle represents a typical trip in the city center of Helsinki. The Artemis Urban cycle is commonly used in European test programs to estimate emissions under more realistic real city traffic conditions than the NEDC test.

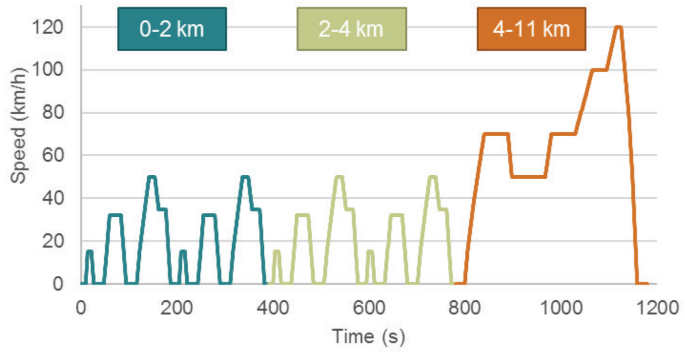

Figure 2.3: Speed profile for the New European Driving Cycle (NEDC) (Hagman, Weber and Amundsen 2015). NEDC is used for type approval of new vehicles in Europe. In the tests, the cycle is split in three intervals with separate gas exhaust gas possibility as shown with different colors.

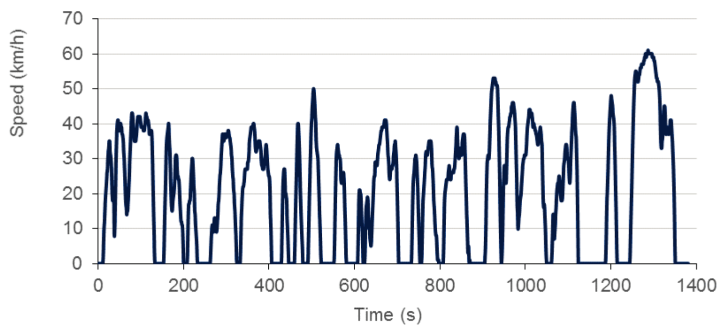

Figure 2.4: Speed profile of the Helsinki-city cycle, typical driving in Helsinki city (Hagman, Weber and Amundsen 2015).

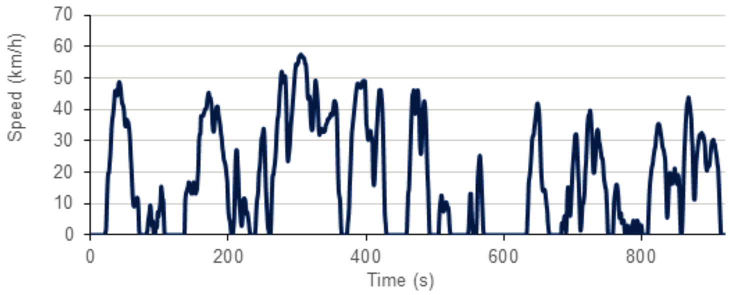

Figure 2.5: Artemis Urban drive cycle, typical city driving (Hagman, Weber and Amundsen 2015).

Table 2.3 presents some essential characteristics of the test cycles.

Table 2.3: Key characteristics of the NEDC, Helsinki-city and Artemis Urban test cycles.

	Length (m)	Duration (s)	Average speed (km/h)	Maximum speed (km/h)	Percentage stops (%)
NEDC	10931	1180	33	120	23
Helsinki-city	7807	1380	20	61	30
Artemis Urban	4470	920	18	58	29

2.3.4 Boundary conditions for energy consumption and CO_2-emission

This report only considers direct tailpipe emissions. Pure electric propulsion does not produce exhaust emissions. Therefore, the CO_2- and local emission for pure electric propulsion is regarded as zero in the measurement program.

For a global estimation of total greenhouse gas emissions of a PHEV, WTW (well-to-wheel) emissions, including emissions from generation, conditioning and transport of the fuel/electricity, should be accounted for. Note that this is the case both for the electricity and the liquid fuel used by the vehicle. The European Emission Trading System for greenhouse gases (EU ETS) will however nullify the effect of these additional emissions (Figenbaum, 2016), under the condition that the EU ETS is effective in capping CO_2-emission from electricity production. Refinery and oil extraction emissions are also part of the EU ETS. A recent review of the effectiveness of the EU ETS (EC, 2015) found it to work as intended. The zero emission assumption for pure electric propulsion in this report is thus not unreasonable.

A full life cycle analysis (LCA) would also include the production of vehicles and components. The production could be within or outside of the EU ETS. An LCA analysis of PHEVs is beyond the scope of this report.

2.3.5 Test matrixes

The test matrix for the two PHEVs are shown in tables 2.4 and 2.5.

In general, all tests with the NEDC test cycle and the Artemis Urban cycle were repeated twice at +23°C and at -7°C, with a filly charged and a fully discharged battery. The Helsinki-city test was only done once at each temperature and only with a fully charged battery.

Vehicle B was less extensively tested than vehicle A, partly due to technical problems, and partly due to lack of time.

Table 2.4: Vehicle A test matrix. As/is tests ran directly after another test with electricity consumption measured as average over both tests.

			+23°C		-7°C	
Drive cycle	Drive mode	SOC	Cold start	Warm start	Cold start	Warm start
NEDC	Electric	100%		1		2
	Hybrid auto	100%	2		2	
	Hybrid auto	As/is		2		2
	Hybrid auto	0%	2	2	2	2
	Battery charge	0%				1
Artemis Urban	Electric	100%		1		1
	Hybrid Auto	100%		2		2
	Hybrid Auto	0%		2		2
	Battery hold	100%			1	
Helsinki-city	Hybrid auto	100%		2		2

Table 2.5: Vehicle B test matrix.

			+23°C		-7°C	
Drive cycle	Drive mode	SOC	Cold start	Warm start	Cold start	Warm start
NEDC	Electric	100%		1		1
	Hybrid auto	100%	2		2	
	Hybrid auto	0%	2		2	
Artemis Urban	Electric	100%		1		
	Hybrid Auto	100%		2		2
	Hybrid Auto	0%		2		2
Helsinki-city	Hybrid auto	100%		2		2

2.4 Comparisons of results

Two types of test result comparisons are done in this report. Results are compared to:

1. the type approval limits and values, to provide a scale of the emissions under conditions deviating from the type approval
2. the results for comparable diesel and gasoline vehicles obtained in other EMIROAD tests, to provide a frame of reference to other technologies.

The type approval is done in the NEDC drive cycle at +23°C. There are no type approval limits defined for driving at -7°C or with other drive cycles. It can thus not be concluded the that the vehicle is not in compliance with the emission standard if the results in this report show that the vehicle emit more than the type approval limits under deviating test conditions, such as tests when it is cold, and in more demanding drive cycles than the NEDC. The target for the testing was rather to find out how the vehicles perform under real driving conditions and the type approval limits and values are used as a scale to compare these results with.

Real Driving Emission testing will be required for new models starting from September 2017. Mobile measurement equipment will be installed on the vehicle and the measurements will be done on normal roads at variable temperatures. Less stringent emission limits will however apply. The lowest normal temperature is +3°C. The emission limits are less stringent for temperatures in the interval -2°C to +3°C (ICCT 2016).

3 Laboratory measurement results

The measurement results are first presented separately for each vehicle, then the results for comparable tests of both vehicles are presented.

Vehicle A was kindly made available to EMIROAD by the Norwegian importer and transported to Finland. Vehicle B was made available by a private person in Finland.

3.1 Vehicle A

Vehicle A is a compact sized plug-in hybrid vehicle with a stated E-mode range of 50 km. According to the type-approval, the vehicle emits 37 g/km CO_2 and consumes 117 Wh/km of electricity and 0.016 liter of gasoline/km. The battery size is 8.7 kWh and the vehicle accelerates 0-100 km/h in 7.6 seconds.

Vehicle A was the first PHEV to be tested in the EMIROAD program, and at the VTT facility. It was therefore put through a large experimental test program. The target was to uncover as much as possible about the characteristics of emissions and energy consumption under different driving conditions, in different drive modes, temperatures and SOC levels.

A sports oriented diesel fueled ICE variant of the same vehicle was selected for comparison, based on it having similar performance and market appeal. It was a 2-liter engine 2013 year-model vehicle, with an automated gear box. The vehicle fulfilled the Euro 5 emission standard.

3.1.1 E-mode, most electric mode

Before the testing commenced it was assumed that the E-mode on PHEVs would enable pure electric driving. Vehicle A however switched on the engine, occasionally in the E-mode when being tested at +23°C, and for long time periods at -7°C. The emission testing equipment was therefore activated to measure the emissions.

The overall results are presented in figure 3.1. The official type approval values of vehicle A and the CO_2-emission of the comparable diesel version of the vehicle, are shown for the same drive modes.

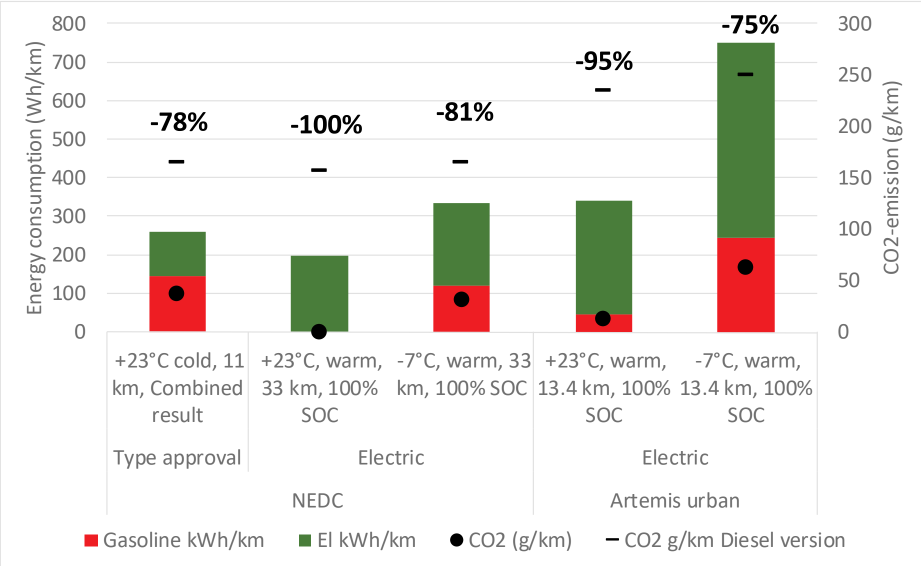

Figure 3.1: Vehicle A, measured E-mode energy consumption (Wh/km) and CO_2-emission (g/km), compared to official type approval values, and EMIROAD measured CO_2-emission of a comparable diesel vehicle (g/km). CO_2-emission reduction versus diesel version is also shown (percentage).

Note that the total driving length of the test cycles and the number of cycles driven are not the same (see tables 2.3 and 3.1). The diesel vehicle was tested one drive cycle, i.e. 11 km and 4.5 km respectively in the NEDC and Artemis Urban cycles, whereas the hybrid vehicle was driven three repetitive runs in these cycles in E-mode. All results are with a warm start.

The first cycle was started with a fully charged battery. The second and third cycles followed directly after the first cycle without recharging the battery between the cycles.

Second by second analysis of the drive modes reveals when and how long the ICE was operative during these tests, as seen by the measured engine speed in figure 3.2 (NEDC +23°C), figure 3.3 (NEDC -7°C) and figure 3.4 (Artemis Urban +23°C and -7°C). The figures illustrate that the ICE is switched on in a non-predictive pattern, sometimes early in a trip, other times late.

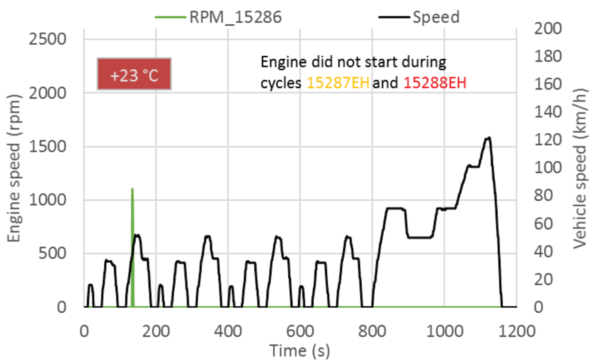

Figure 3.2: Vehicle A; ICE engine speed (RPM_15286: Engine speed in rounds per minute, test nr. 15286) and vehicle speed over three consecutive NEDC-cycles at +23 °C in the E-mode. Engine started and shut off immediately afterwards in the first trip (green line at about 120 seconds). The engine was off in the second and third cycles. The vehicle was started with a fully charged battery and not recharged between the cycles.

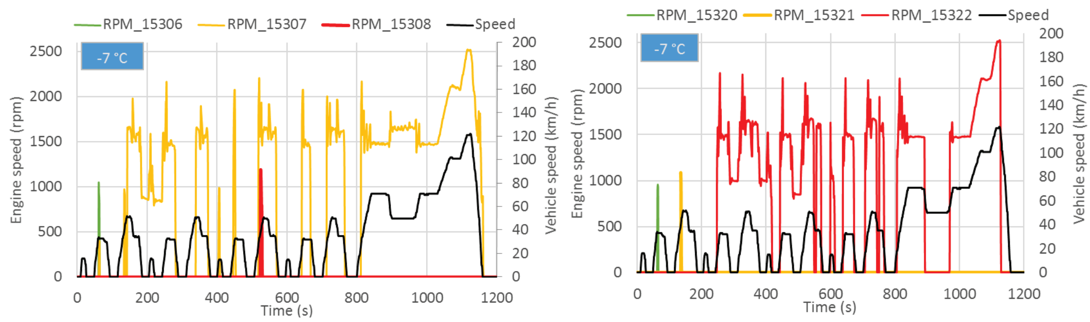

Figure 3.3: Vehicle A; two tests (test 1 left) showing ICE speed in rounds per minute (RPM_15306 etc., numbers refer to different cycles) and vehicle speed over three consecutive NEDC-cycles at -7°C in the E-mode. Engine started and shut of immediately afterwards in the first cycle in both tests (green line). The engine was switched on after about 170 seconds in test 1 in the second cycle, and after 230 seconds in the third cycle in test 2, and in both cases remained running for most of the remaining cycle. In the third cycle of test 1 and the second cycle of test 2, the ICE was briefly switched on. The vehicle was started with a fully charged battery but not charged between cycles.

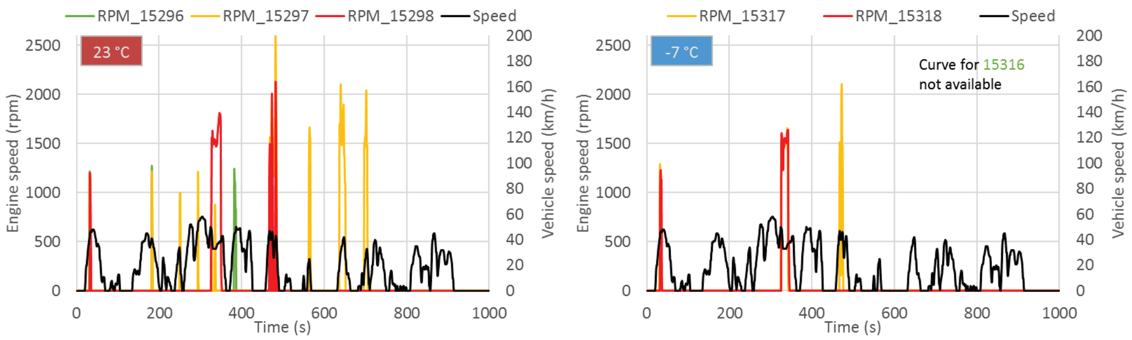

Figure 3.4: Vehicle A; ICE rpm and vehicle speed over three consecutive Artemis Urban-cycles at +23°C and -7°C in the E-mode. The ICE started and ran occasionally for a few seconds in cycles 2 and 3, more often at +23°C than at -7°C. At +23°C the ICE started briefly in the first cycle. The ICE was running most of the time at -7°C in the first cycle (data missing in chart). The vehicle was started with a fully charged battery, but not recharged between cycles.

The average emission of local pollutants is low in this drive mode for all the tests as seen in figure 3.5. The low emissions cause the measurement accuracy of the emission test system to be reduced, and the results are thus less reliable than when emissions are higher. CO-emission was slightly higher than the EU type approval limit of 1.0 g/km (NEDC test), when driven in the Artemis Urban test. All other emissions were much lower than the type approval limits.

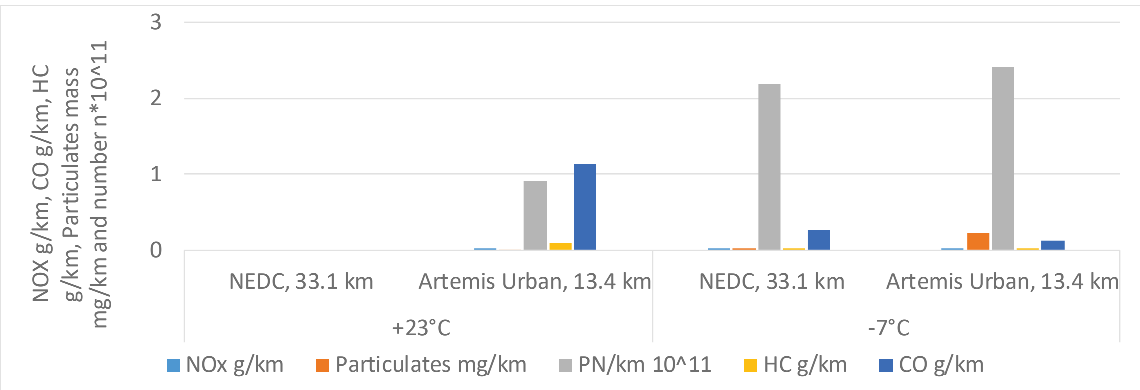

*Figure 3.5. Vehicle A; NO_X, HC, CO emission in g/km and Particulates mass emission in mg/km and particulates number emission in n*10^11.*

3.1.2 Hybrid Auto mode

During these tests the vehicle was driven in the hybrid auto mode. The vehicle also has a sports hybrid mode, but that mode was not tested.

CO_2-emission and energy consumption

The testing started with a complete NEDC cycle with results collected in three bags for exhaust analysis, covering the first 0-2 km, the next 2-4 km, and the last 4-11 km of the cycle. Immediately after that test ended, another NEDC test was done with a warm start. The total driving distance of the complete test was thus 22 km. The electricity consumption was measured as the sum of the cold start and the warm start cycle, i.e. for the total distance of 22 km. 16 NEDC tests were done in total, at ambient temperatures of +23°C and at -7°C, with the battery at 100% SOC and 0% SOC, and with cold and warm start. It should be noted that the official type approval test covers the emission per km over the 11 km NEDC test with a cold start at +23°C.

The Artemis Urban test was done twice at +23°C and at -7°C, respectively, with a battery that had been fully charged, but in between a preconditioning drive using the vehicle's battery hold mode was conducted. The SOC is thus not verified to be 100% at the start of the test as the vehicles ability to maintain the SOC at 100% is not known. The vehicle was also tested at 0% SOC at both temperatures. In the Helsinki-city cycle test the vehicle was tested with a fully charged battery twice at +23°C and at -7°C, respectively, with a preconditioning drive before the test in the battery hold mode.

The average measured energy consumption and CO_2-emissions is shown in figure 3.6. The results are fairly repeatable, within 10% variation for the CO_2-emission and fuel consumption (except for the Artemis Urban test) and within 4% variation for the electricity consumption, when comparing two tests with the same conditions for temperature, SOC and warm/cold start. The variation is larger than when testing ICEV vehicles.

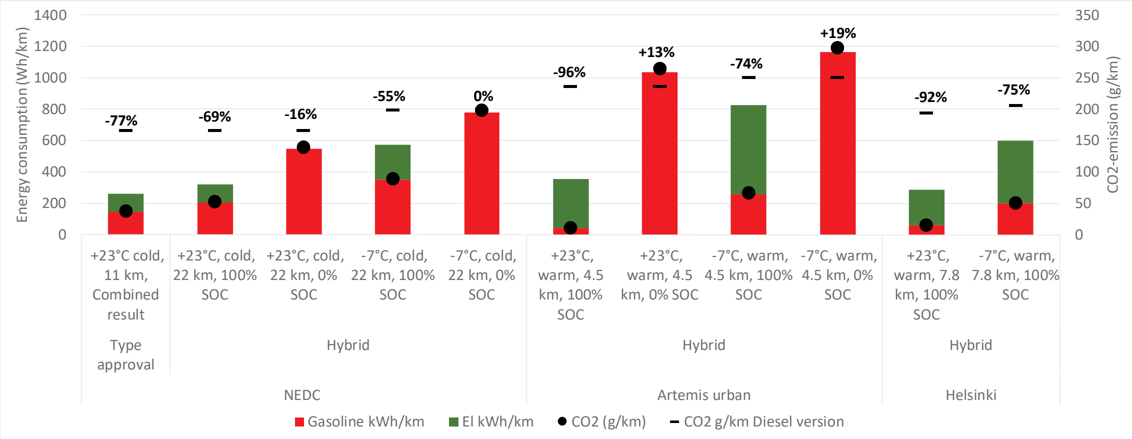

Figure 3.6: Vehicle A; hybrid mode CO_2-emission (g/km) and energy consumption (Wh/km), compared with the official type approval values. CO_2-emission of the most comparable diesel engine version of the vehicle and emission reduction vs. diesel version is also shown.

Note that all drive modes apart from Artemis at 0% SOC produce less CO_2 over the 11 km cycle than the comparable diesel vehicle. The variation between drive modes and temperature is however much larger for Vehicle A than for the diesel vehicle. The CO_2-emission of Vehicle A ranges from 10 g/km to 297 g/km in these tests, whereas the diesel vehicles emission varied between 165 g/km and 250 g/km. The difference lies mainly in the share of electric driving among these tests.

The sub-cycle NEDC test results for CO_2-emission at +23°C and -7°C, and at 100% and 0% SOC, are shown in figure 3.7. The emissions are as expected much higher at -7°C than at +23°C, and at 0% SOC and the first 2 km. The vehicle can drive more or less electric even in the hybrid mode when the vehicle is warm and the power required is moderate, as seen by the 0-4 km warm start tests at +23°C with a fully charged battery (figure 3.7). At higher speeds (4-11 km) and at -7°C the engine is switched on more often.

When the battery is fully discharged, the vehicle strategy could potentially be to first charge the battery somewhat to preserve battery life, before operating as a hybrid vehicle. If this is the case it would partly explain the high emission in this driving condition. A test at an intermediate battery SOC level could potentially have given more clues to explain the 0% SOC behavior.

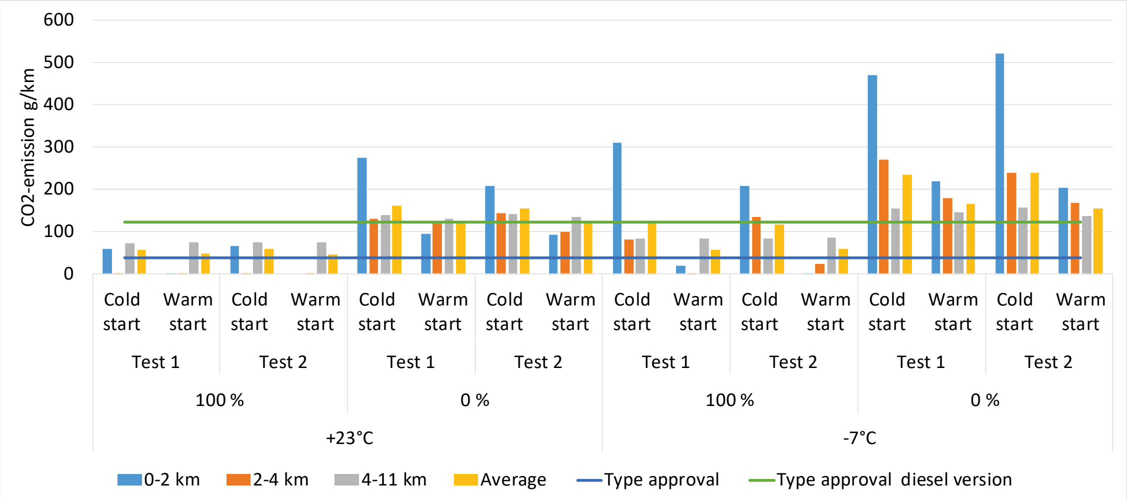

Figure 3.7 Vehicle A; hybrid mode CO_2-emission in g/km of NEDC cycles and sub-cycles at +23°C and -7°C, with cold and warm start and at 100% and 0% SOC. Average = result over full 11 km NEDC cycle. Blue line: Type approval CO_2-emission. Green line: Type approval CO_2-emission of most comparable diesel version.

Emissions of NO_X, HC, CO and particulates

The local pollutant emissions of NO_X, HC, CO and particulates, are shown for the different drive cycles in figure 3.8.

The NO_X-emission is well below the type approval limit value in the cold start NEDC test at 100% SOC, and at +23°C and at -7°C. The Helsinki-city and Artemis Urban drive cycles at +23°C with a fully charged battery also produce low NO_X-emissions. The emission is also low with an empty battery at +23°C, and with a warm start at -7°C with the NEDC cycle. For other drive modes and conditions, the emissions are above the NEDC type approval value. It can be concluded that unfavorable driving conditions in cold climate can lead to excessive NO_X-emissions, whereas lighter loads and higher temperature keep emission below the limit.

The particulate mass emission is low in all drive cycles, apart from the NEDC cycle cold start at -7°C, as seen in figure 3.8. The number of particulates is lower than the 2016 limit value in all conditions, but at -7°C, in several drive cycles and in particular the NEDC, more particles are emitted than the new limit value for type approval from Sept. 2017.

The results show that excessive HC-emissions are linked to demanding driving conditions and cold temperature. Excessive CO-emissions are also linked to cold temperature. The vehicle however has lower NEDC emissions of these components than the type approval limit both at 100% and 0% SOC at an ambient temperature of +23°C.

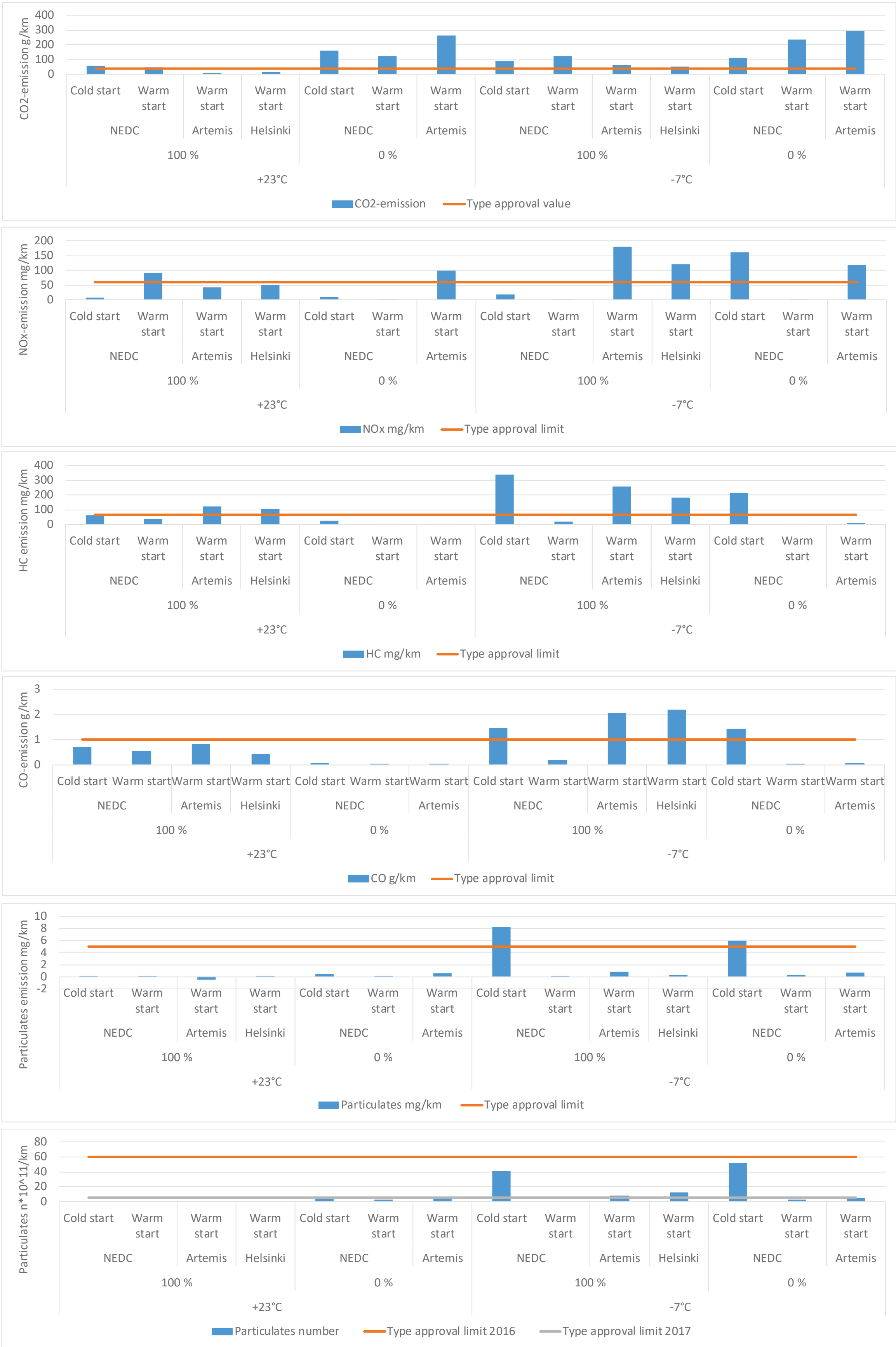

*Figure 3.8: Vehicle A; CO_2, NO_X, HC, CO (g/km) and particulates (mg/km, n*10^11) emissions, per drive cycle at +23°C and -7°C, and 100% and 0% battery SOC. Lines represents type approval values (CO_2) and NEDC type approval limits. Particulate number lines: Existing limit and Sept. 2017 limit.*

Potentially the excessive emissions could be related to a problem with reaching the three-way catalyst light-off temperature. The NEDC drive cycles were therefore analyzed further, splitting the cycles in three distance intervals, 0-2 km, 2-4 km and 4-11 km, as seen in figure 3.9. It is clear that at +23°C ambient temperature, the main reason for excessive NO_X-emissions is high speed driving. In cold temperatures (-7°C) it seems that it is the cold start and the first 2 km of driving that causes the excessive emissions.

The reasons for high emissions with warm starts in the Artemis Urban and Helsinki-city cycles are not obvious. The emissions are low in the NEDC warm start tests for similar battery SOC and temperature conditions.

The main particulate emission in cold climate occurs in the first 2 km of the test cycle. Particulates number emissions follow the pattern of the particulate mass emission.

Figure 3.9 further supports the conclusion that cold starts are the main source of the HC- and CO-emissions.

*Figure 3.9: Vehicle A; CO_2, NO_X, HC, CO (g/km) and particulates (mg/km, n*10^11) emissions, per NEDC sub-cycle and full cycle at +23°C and -7°C, and 100% and 0% battery SOC. Lines represents type approval values (CO_2) and limit values. Particulate number lines: Existing limit and Sept. 2017 limit.*

3.1.3 Battery hold and battery charge modes

The vehicle has two drive modes that can be used to respectively preserve the battery capacity and recharge the battery for later driving in the E-mode, for instance by users planning to drive into a zone where the ICE usage must be minimized for environmental reasons. These drive modes were tested at -7°C ambient temperature and the results thus represents winter driving. The measured energy consumption and CO_2-emission is very high as seen in figure 3.10.

The battery hold mode test started with a fully charged battery but apparently did not sustain the battery charge completely. After the test, 1.27 kWh was recharged into the battery.

The battery charge mode test started with an empty battery. The charge mode uses the IC engine and the generator to produce electricity that is charged into the battery while the vehicle is driving. This electricity can be used later to power the vehicle in E-mode. The measured energy consumption and CO_2-emission will thus cover both the driving in the charge mode and part of the subsequent driving in the E-mode, thus partly explaining the high measured values.

The emission of NO_X was measured to be 200 mg/km, i.e. far above the NEDC type approval value, in the battery charge mode. In the battery hold mode, the emission was measured to be 60 mg/km. For particulates mass and numbers, the result was opposite with 11 mg/km and 104*10^11 in the battery hold mode versus 1.6 mg/km and 6*10^11 in the charge mode.

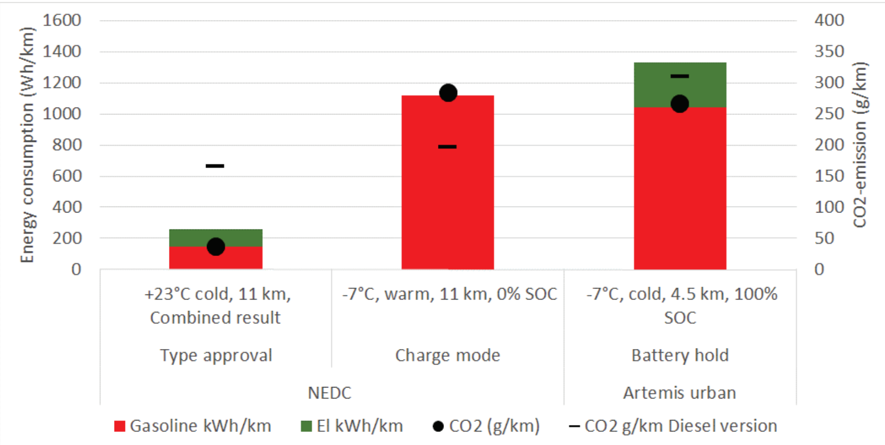

Figure 3.10: Vehicle A; battery hold and battery charge modes energy consumption (Wh/km, gasoline and electricity) and CO_2-emission (g/km), compared with the NEDC official type approval values and the CO_2 emission of the diesel version of the same vehicle.

3.1.4 Overall assessment of vehicle A

The tests of vehicle A were fairly repeatable. The CO_2-emission and energy consumption varied within 10% and electricity consumption within 4% over identical tests containing several drive cycles. Further analysis shows, however, that sometimes the ICE is switched on early during the driving and other times late.

The vehicle does not have a pure electric drive mode. In the electric drive mode, the ICE will start occasionally. In the hybrid mode the vehicle may run partly fully electric, but the ICE is switched on in the more demanding parts of the driving cycle.

The battery hold mode where the battery charge is kept constant, and the battery charge mode where the battery is recharged while driving, are very energy consuming drive modes with high CO_2-emissions. In the latter mode the battery charging will allow driving in the electric mode later in the trip, so the average energy consumption and emission for the entire trip would be lower than the result seems to indicate. Owners could however also potentially charge the vehicle while driving to be able to run it in the sports hybrid mode later in the trip.

The vehicle's CO_2-emission has been compared to that of a similarly powered diesel version of the vehicle. The rationale being that this diesel vehicle would be the likely alternative for a buyer seeking similar vehicle performance. In most drive cycles the emission of the PHEV is much lower than that of the diesel version. Some demanding drive cycles when the battery is fully discharged and in low ambient temperatures may lead to higher emissions for the PHEV than for the diesel version.

The type approval CO_2-emission level seems to be a very optimistic value. It seems only reachable for an optimum PHEV driving pattern with a high share of driving in the E-mode. In favorable driving conditions and starting fully charged, the vehicle can however have 70% lower CO_2-emission than the comparable diesel vehicle.

Cold climate and demanding driving conditions and 0% state of charge of the battery are typical conditions were locally polluting emissions can be excessive, and CO_2-emissions can be even higher than that of similar diesel powered vehicles. Local emissions seem to be low when the ICE is on for prolonged time intervals, thus heating up the catalyst beyond light-off. Local emission values may on the other hand be higher with many starts and stops and infrequent operation of the ICE, because of less efficient catalyst warm-up.

3.2 Vehicle B

Vehicle B is a mid-sized plug-in hybrid vehicle with an E-mode range of 31 km. The vehicle emits 48 g CO_2/km, and consumes 110 Wh/km of electricity and 0.021 liter/km of gasoline, all according to the type approval. The battery size is 6.4 kWh and the vehicle accelerates 0-100 km/h in 5.9 seconds.

Vehicle B was less extensively tested than vehicle A. The focus of the testing was on the hybrid and electric drive modes at different temperatures and in different test cycles. In the hybrid mode, the vehicle was tested with full and empty battery.

Vehicle B's E-mode was a pure electric drive mode. In the hybrid mode, the vehicle apparently selected the most efficient pre-programmed driving pattern. It was thus capable of fulfilling the demands of some of the hybrid mode tests using only the electric motor. The vehicle thus had a high share of pure EV driving in some of the hybrid mode tests.

Vehicle B was compared with earlier EMIROAD emission test results obtained for a diesel version and a gasoline version of the same vehicle. These vehicles as not quite as powerful as the PHEV version that uses both drive systems in the hybrid mode, and thus not equal substitutes when it comes to performance.

3.2.1 E-mode

Vehicle B had a pure electric drive mode. The available power was however severely impacted at -7°C so the vehicle could only follow the NEDC drive cycle 14.5 km, as seen in figure 3.11. The vehicle would then have to be switched to the hybrid drive mode to continue the trip. The test was however interrupted when the vehicle could no longer follow the drive cycle. The on-board vehicle display indicated that the battery SOC then had fallen below 10%. The vehicle could have been forced to continue driving using the ICE but measurement of electrical energy uptake would not have been possible in the chosen setup, so the test was stopped.

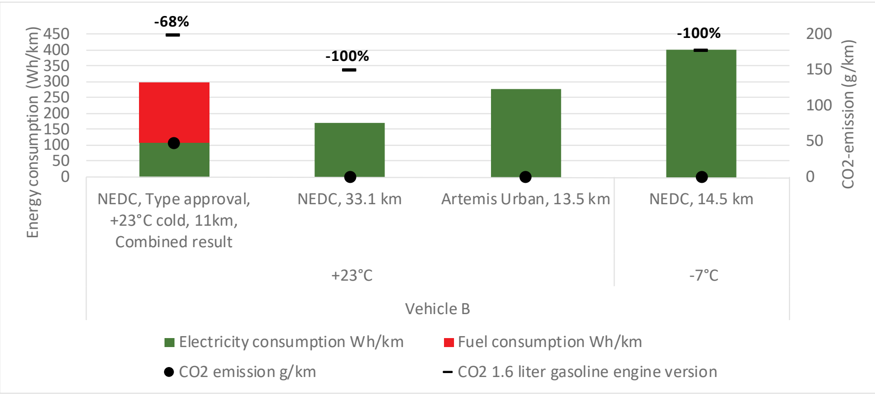

Figure 3.11: Vehicle B; pure electric drive mode, energy consumption (Wh/km) and CO_2-emission (g/km) at +23°C and -7°C, 100% SOC at start of test. Comparison with official NEDC type approval values and CO_2-emission test results of a 1.6-liter gasoline engine version of the vehicle. As the vehicle could do the tests in pure EV mode the emission reduction was 100%.

3.2.2 Hybrid mode

Energy consumption and CO_2-emission

Vehicle B was apparently programmed to run on pure electric power also in the normal hybrid auto mode, whenever possible. Therefore, the NEDC test at +23°C, the Helsinki-city test at +23°C and -7°C, and the Artemis Urban test at -7°C, could be driven with electricity only, when starting the tests with a fully charged battery (100% SOC). For some unknown reason the ICE was switched on during the Artemis cycle at +23°C, but not at -7°C. The ICE was partly on with a CO_2-emission of 82 g/km when driving in the NEDC at -7°C. The CO_2-emission and energy consumption was quite high when the vehicle was started with 0% battery SOC at an ambient temperature of -7°C. The vehicle emitted less than the comparable gasoline engine version of the vehicle in most drive modes where comparable tests were done. The CO_2-emission can however be higher when the battery is empty and the temperature is low, as seen in figure 3.12.

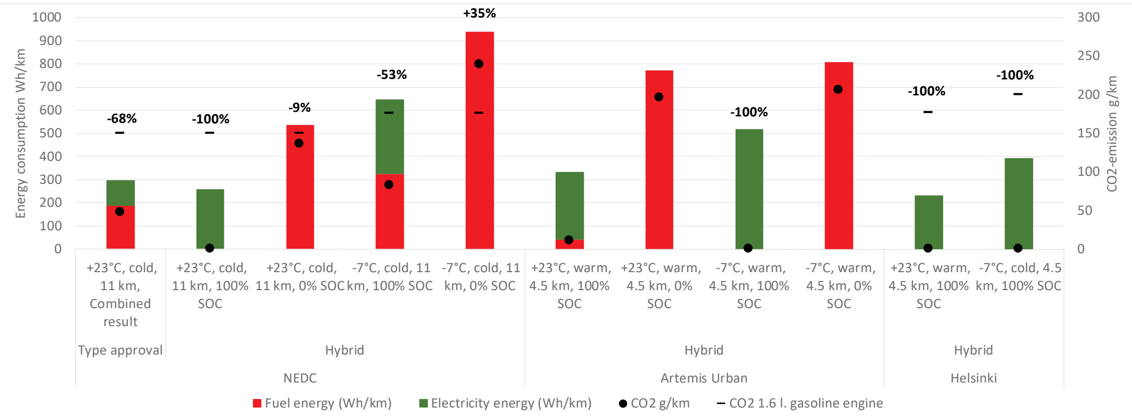

Figure 3.12: Vehicle B; hybrid drive mode. Energy consumption (Wh/km) and CO_2-emission (g/km) at +23°C and -7°C, 100% and 0% SOC at start of test. Comparison with official type approval values and CO_2-emission of 1.6 l gasoline version of the vehicle (g/km). PHEV CO_2-reduction potential (percentage) over gasoline engine version.

Emissions of NO_X, HC, CO and particulates

The NEDC cycle at +23°C, the Helsinki-city cycles at +23°C and -7°C and the Artemis Urban cycle at -7°C, all with 100% battery SOC at start of the tests, could be driven with electricity only, so that no NO_X, particulates, CO or HC were emitted. When driving in high load conditions, with 0% SOC or in cold climate, some of the local emissions were above the NEDC type approval emission limits, as seen in figure 3.13. Driving according to the Artemis driving cycle resulted in high NOx-emissions for Vehicle B, while the other emissions were quite low.

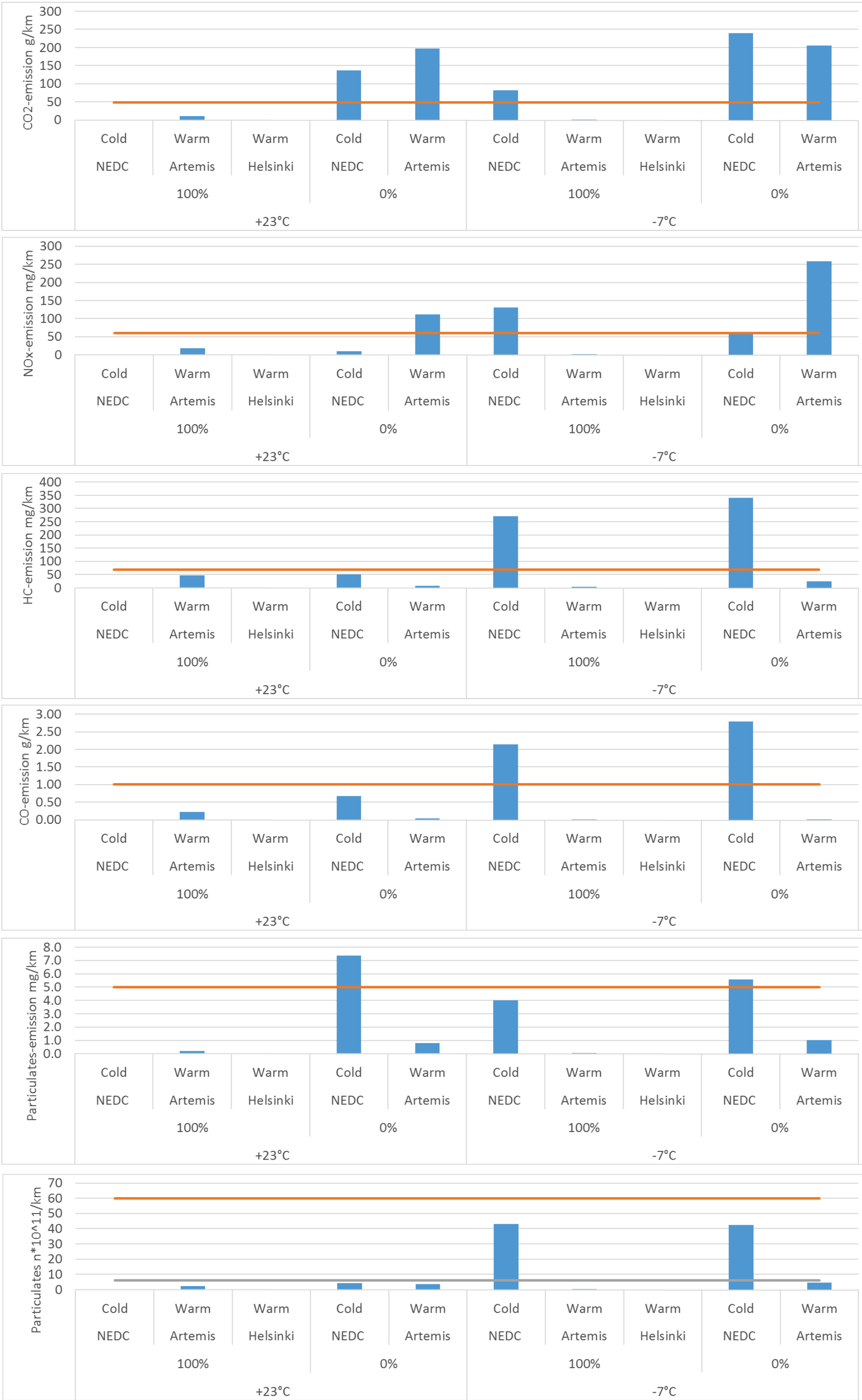

*Figure 3.13: Vehicle B; CO_2-, NO_X-, HC-, CO- and particulates mass emissions in g/km and mg/km, and particulate number emissions in n*10^11, per drive cycle at +23°C and -7°C, and 100% and 0% battery SOC. Lines represents type approval values (CO_2) and limit values. Orange line: CO_2-emission type approval value, other gases and particulates type approval limit. Grey line: Particulate number limit from September 2017.*

3.2.3 Overall assessment of vehicle B

Vehicle B functioned very differently from vehicle A. It was fully capable of driving in pure electric mode both in warm and cold climates. The vehicle's range in E-mode is 31 km according to the type approval, but it was as low as 14.5 km when tested at -7°C in the NEDC. The vehicle SOC was then estimated to be less than 10% by the on-board computer, and the vehicle could no longer follow the drive cycle. If the vehicle had been driven further it would have switched on the ICE and continued in a hybrid drive mode.

When driving in high load conditions, with 0% SOC or in cold climate, some of the local emissions were above the type approval emission limits. CO_2-emission can under heavy load, cold climate or at 0% SOC, be much higher than the NEDC type approval value.

The CO_2-emission level of vehicle B varies much more between drive cycles and temperatures than it does for the comparable 1.6-liter gasoline version of the vehicle.

3.3 Comparison between vehicles

3.3.1 Vehicle drive mode strategies

Table 3.1 gives an overview of the drive modes that were selected by the test driver and how the vehicles operated in the test. Note that the test conditions are not directly comparable in the tests were the vehicles drove different distances.

The results appear favorable for vehicle B, as it can run more in pure electric mode. On longer trips the advantage would be eliminated as vehicle B would have to start the ICE when the battery is empty. Since it has a smaller battery the ICE would be running more on long trips for vehicle B than for vehicle A.

Table 3.1: Summary of actual drive mode operation of vehicles A and B.

Drive mode setting	Temperature	Cycle	Condition	Vehicle A operation	Vehicle B operation
Hybrid, 100% SOC	+23°C	NEDC 11 km	Warm	Partially electric	Pure electric
		NEDC 11-22 km	Cold	Partially electric	Not tested
		Artemis Urban 4.5 km	Warm	Mostly electric	1 test pure electric, 1 mostly
		Helsinki-city 7.8 km	Warm	Mostly electric	Pure electric
	-7°C	NEDC 11 km	Warm	Partially electric	Partially electric
		NEDC 11-22 km	Cold	Partially electric	Not tested
		Artemis Urban 4.5 km	Warm	Partially electric	Pure electric
		Helsinki-city 7.8 km	Warm	Partially electric	Pure electric
Electric, 100% SOC	+23°C	NEDC 33 km	Warm	Pure electric	Pure electric
		Artemis Urban 13.5 km	Warm	Mostly electric	Pure electric
	-7°C	NEDC	Warm	Mostly electric, 33 km	Pure electric, terminated 14.5 km, could not follow cycle
		Artemis Urban 13.5 km	Warm	Partially electric	Not tested

3.3.2 Electric drive modes

Figure 3.14 displays the comparable E-mode test results of the vehicles. It is seen that the energy consumption of Vehicle B is lower than that of Vehicle A in these tests.

Vehicle A had a longer range in E-mode than vehicle B due to a larger battery, and the mixed operation strategy allowing the ICE to assist in high load conditions. When the batteries have been emptied, the vehicles need to switch to the hybrid auto mode with empty battery. That would lead to large emissions and a much higher energy consumption for both vehicles. Vehicle A can thus, depending on the concrete usage pattern, have a lower average CO_2-emission than vehicle B in spite of not being able to run in a "pure" electric mode.

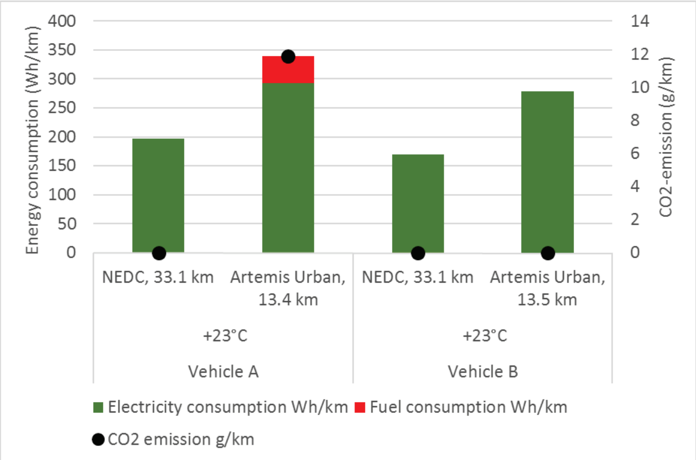

Figure 3.14: Comparison of energy consumption and CO_2-emission of directly comparable electric drive modes for vehicles A and B.

3.3.3 Hybrid mode

Figure 3.15 shows the hybrid mode results that are most comparable between the vehicles. Vehicle A has a much higher energy consumption than Vehicle B in the Artemis test in this drive mode. The same is the case for the Helsinki-city test. These drive cycles have faster accelerations than the NEDC test.

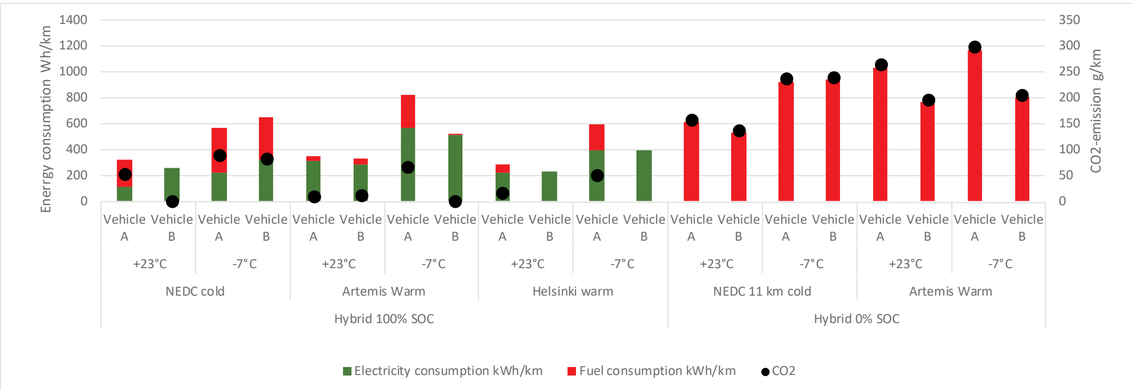

Figure 3.15: Comparison of energy consumption and CO_2-emission of comparable hybrid drive modes of vehicles A and B.

4 Combining tests and usage pattern

In this chapter the measurement results are combined with some examples of user patterns, to generate an estimate for annual average energy consumption and emissions.

4.1 General results from the user survey

Figenbaum and Kolbenstvedt (2016) found that 74% of consumers owning PHEVs charge their vehicles every day, and another 15% do it 3-5 times per week. Charging at work is uncommon as 66% never charge in that location, only 16% do it regularly. In other locations, charging is even rarer. In the calculations done in this chapter it is therefore assumed that PHEVs are typically charged overnight every night, and not charged anywhere else during the day. The typical PHEV is used 15000-16000 km/year and are on average driven about 55% in E-mode (Ibid).

4.2 Vehicle A

The measurements are not directly transferable to average driving over a full year.

Figure 4.1 shows an estimate of the average yearly CO_2-emission of a driving pattern where a user drives 14 km each way to work every day for a total of 230 days, i.e. 6440 km per year. In addition, another 10 km is assumed to be driven locally each day all year round, i.e. 3650 km. Local driving and commuting thus amounts to roughly 10000 km/year. Long distance driving is assumed to make up the difference up to three annual total driving distances of 12000 km, 16000 km and 20000 km. The middle estimate would be about the average value that was found for new PHEVs in the user survey (Figenbaum and Kolbenstvedt 2016). The figure also shows the average emission of the comparable diesel vehicle and the estimated E-mode driving share. The NEDC drive cycle test results were used in the estimation, as most data was collected using that drive cycle. It was assumed that the vehicles for five months per year follow the emissions of the -7°C test and for seven months the +23°C test. E-mode was assumed used until the battery is empty as this is the lowest cost drive mode for the user. The hybrid drive mode was assumed for all driving exceeding users estimated range capability in E-mode. Charging is assumed to only happen overnight, i.e. after a driving day of 14*2+10 km. The range in E-mode for Vehicle A was estimated to be 40 km/day in the summer and 28 km/day in the winter, according to results from the user survey (Figenbaum and Kolbenstvedt 2016). These average range estimates seem potentially feasible if the driving is not too aggressive, based on the results of the E-mode in the laboratory tests. All driving over 10000 km/year was assumed to be in the 0% SOC hybrid drive mode for this example.

The typical average driving length of newer vehicles of 16000 km, results in a CO_2-emission of Vehicle A that is about 46% less than that of the comparable diesel vehicle. If the annual driving distance is less than 16000 km the advantage will be larger. The advantage will be smaller the longer the annual driving distance is over 16000 km. The average NO_X and particulates emissions can be below the type approval limits for this usage pattern over the year, and also for the winter season.

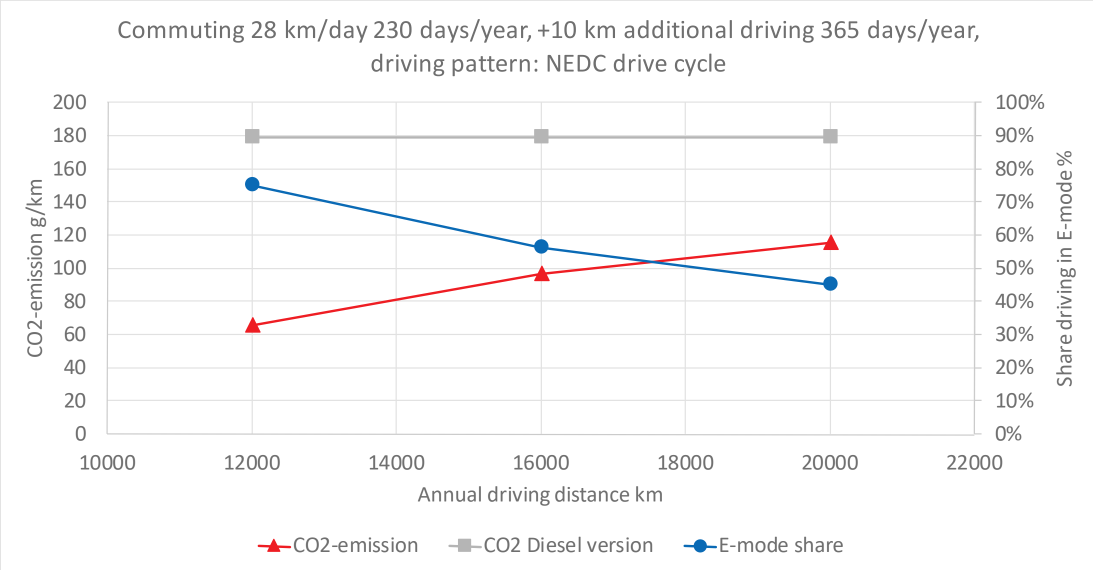

Figure 4.1: Vehicle A; estimated CO_2-emission and E-mode share of driving over the year for a driving pattern consisting of commuting to work 14 km each way, 230 days/year + 10 km additional local driving/day and assuming long distance driving the rest of the trips. E-mode NEDC driving assumed whenever possible. The vehicle was assumed to switch to the 0% SOC NEDC hybrid mode when the battery was empty. Charging overnight assumed. CO_2-emission of comparable diesel vehicle is also shown.

More aggressive driving can lead to less CO_2 benefits. The average NO_X-emissions could potentially increase to levels above the type approval limit values during the winter season, as seen by the higher emissions in the warm start Artemis Urban and Helsinki-city cycles. The emission of the comparable diesel vehicle is however also much larger in these cycles, so the relative CO_2-difference between the PHEV and the diesel vehicle will thus not be significantly impacted as seen in table 4.1. Both vehicles have extremely low particulates emissions. Charging during the day will lead to a higher share of E-mode driving and subsequently larger CO_2- and NO_X-emission reductions for the PHEV vehicle compared with the diesel vehicle.

Table 4.1: Vehicle A and comparable diesel vehicle emission for a composite driving pattern, 16000 km per year average driving distance assumed for PHEVs, same underlying driving pattern assumption as in figure 4.1.

	NEDC cold start/ cautious driving			Artemis urban warm start/aggressive driving***		
	CO_2 g/km	NO_X mg/km	Particulates mg/km	CO_2 g/km	NO_X mg/km	Particulates mg/km
Vehicle A	97	21	<0.8	164	68	<0,4
Diesel vehicle	179	276	<0.2	279	561	<0.6
Reduction	46%	92%*	**	41%	88%*	**

* The diesel vehicle used in the comparison was a Euro 5 EU emission standard 2013 year-model

** The particulates emissions are extremely low and within the measurement equipment accuracy, the differences are not significant

*** Not a realistic average annual driving pattern

The calculation above should be considered to be an example. User profiles are very diversified, as seen in figure 4.2, and will generate a large spread in the potential annual CO_2-emissions. In the user survey (Figenbaum and Kolbenstvedt 2016), Vehicle A was used on average about 15000 km/year which would result in a CO_2-emission reduction of about 50% compared to the diesel vehicle.

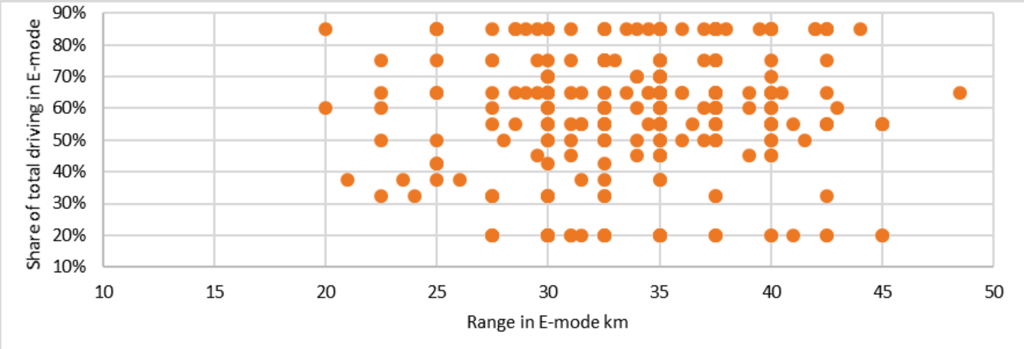

Figure 4.2: Vehicle A; spread of private users average summer and winter estimated range in E-mode, and estimated average share of total driving in E-mode of summer and winter. Source: EMIROAD vehicle user survey March 2016 (adapted from Figenbaum and Kolbenstvedt 2016).

Figure 4.3 shows the estimated cumulative share of private owners that are below a calculated CO_2-emission factor, based on the owners' estimated share of driving in E-mode in the summer and winter (Source: EMIROAD vehicle user survey March 2016, adapted from Figenbaum and Kolbenstvedt 2016) shown in table 4.2.

Table 4.2: Share of private users by estimates of share of total driving in E-mode in the winter versus summer for Vehicle A. Source: EMIROAD vehicle user survey March 2016, adapted from Figenbaum and Kolbenstvedt 2016.

		Users estimate of share of total driving in E-mode in the winter				
		0-40 %	41-50 %	51-60 %	61-70 %	>70 %
Users estimate of share of total driving done in E-mode in the summer	0-40 %	13%	1%	0%	0%	0%
	41-50 %	5%	5%	1%	1%	0%
	51-60 %	3%	6%	7%	2%	1%
	61-70 %	2%	4%	9%	9%	2%
	>70 %	1%	3%	4%	8%	12%

The average CO_2-emission was calculated to be 92 g/km, the median about 86 g/km. This calculation method thus yields a CO_2-reduction of 49% compared to the comparable diesel vehicle. The CO_2-emission in real average traffic-condition is thus about 2.5 times higher than the type approval value. This deviation is much larger than the 42% increase found for 2015-year-model ICEVs by Tietge et al (2016). Data from 965 PHEVs on "Clean car contracts" in the Netherlands, where used to estimate that "company car PHEVs" could be emitting three times as much as the type approval value (IBID). Dutch company car owners may however have smaller incentives to plug-in and charge their PHEVs if the cost of fuel is paid for by the company but the electricity charged at home is not.

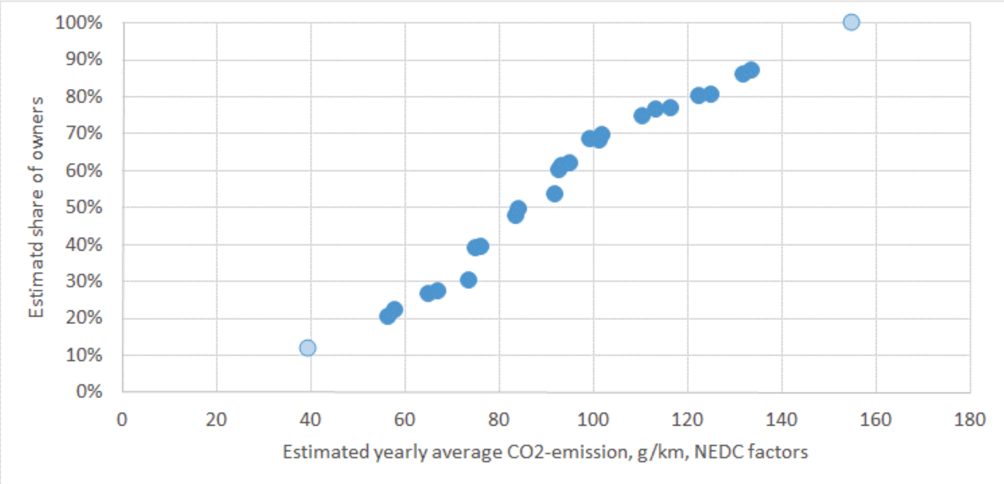

Figure 4.3: Estimated share of owners below a calculated average yearly CO_2-emission factor based on owners' estimates of share of driving in E-mode summer and winter (Source: EMIROAD vehicle user survey March 2016, adapted from Figenbaum and Kolbenstvedt 2016). NEDC test results in E-mode used when calculating the emission for the estimated E-mode share of driving, and 0% SOC hybrid drive mode test results used for all other driving. Results at +23°C was weighted 0.6 and results at -7°C was weighted 0.4 to take into account seasonal differences.

Users estimate a much higher share of E-mode driving (about two-thirds of driven km according to Figenbaum and Kolbenstvedt 2015) when driving to and from work, leading to larger reductions and less local pollution for that trip type than was calculated above. There is a big uncertainty in estimates of E-mode share of driving when they are based on user's own assessment. The two calculation methods nevertheless produced similar results.

The German web site Spritmonitor.de allows users to log fuel consumption of their vehicles. The 49 registered users of the PHEV version (Spritmonitor 2017) of Vehicle A logged an average consumption of 3.96 l/100 km, equivalent to 92 g/km, compared with 6,45 l/100 km and 172 g/km CO_2, for the comparable diesel version, i.e. 46% reduction of CO_2 under German conditions[1]. That results fits well with an annual driving distance of about 16000 km/year in the estimation for Norway.

4.3 Vehicle B

The Method 1 calculation presented for Vehicle A in the previous section was also done for Vehicle B. The users estimated range could however not be taken from the user survey (Figenbaum and Kolbenstvedt, 2016), as there were not enough respondents to produce valid results. An E-mode range of 33 km in the summer and 14 km in the winter was therefore assumed based on the vehicle test results in E-mode.

The estimation result is shown in figure 4.4. When used 16000 km/year in this assumed usage pattern, the average CO_2-emission was estimated to be 118 g/km, 2.5 times higher than the EU NEDC type approval value. The CO_2-emission is 27% less than with the 1.6-liter gasoline version of the vehicle and 36% less compared with a 2.2-liter diesel version. The PHEV version is however a more powerful vehicle so they are not equal substitutes. If the annual driving distance is less than 16000 km the advantage will be larger, while it will

[1]Assuming 2,66 kg CO_2/l diesel, 2,32 kg CO_2/l gasoline.

be smaller the longer the annual driving distance is over 16000 km. User profiles are very diversified and will generate a large spread in the potential annual CO_2 emissions.

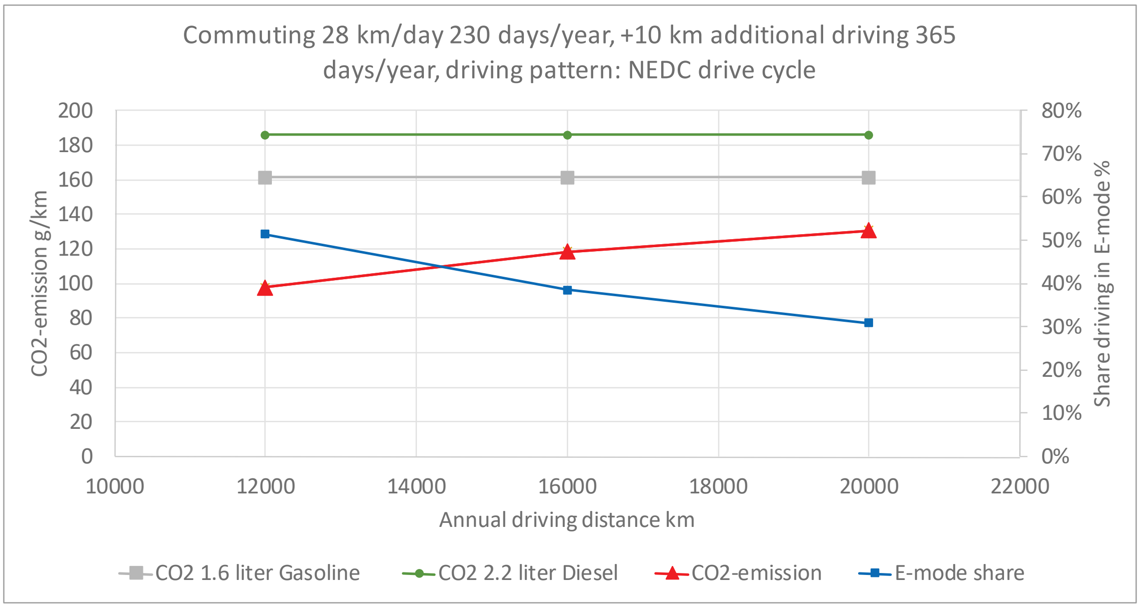

Figure 4.4: Vehicle B; estimated CO_2-emission and E-mode share over the year for driving pattern consisting of commuting to work 14 km each way, 230 days/year + 10 km additional local driving/day + long distance driving the rest of the trips. CO_2-emission of comparable gasoline and diesel vehicles. E-mode NEDC driving assumed whenever possible. The vehicle was assumed to switch to the 0% SOC NEDC hybrid mode when the battery was empty. Charging overnight assumed.

Data could not be retrieved from Spritmonitor.de for this vehicle. The number of registered users were less than 10 and the results would not be valid.

5 Discussion and conclusion

5.1 Discussion of results

PHEVs produce very different amounts of CO_2-emission and local pollutants depending on configuration, manufacturer strategy, user preferences and drive mode selection, driving pattern and driving conditions. The energy consumption and mix between electricity and gasoline varies accordingly.

Some PHEVs are framed as sports vehicles designed to appeal to enthusiasts. Other manufacturers position their vehicles as 4WD capable, as some of the additional cost of the hybridization can be recouped by reduced complexity of a 4WD system. The vehicle performance using the electric motor alone might therefore not be the most important design target for vehicle manufacturers. Some models however seem to be designed in a manner to allow as much pure electric driving as possible.

The most important characteristics of PHEVs is the share of driving that can be accomplished in E-mode. This drive mode is the primary reason for consumers to buy a PHEV rather than a HEV. The larger the share of driving in E-mode, and the higher the share of pure electric driving being allowed, the lower the fuel consumption and CO_2-emission will be on trips within the E-modes range limits. The estimates of these vehicles average CO_2-emission over a year demonstrates however that the ability to drive "pure" electric in the E-mode is not as critical a parameter in achieving low average yearly emissions as the range in E-mode.

The drive modes that the vehicle user can select do not function uniformly among the two tested vehicles. In Vehicle B the electric mode is pure electric, whereas in Vehicle A it can be characterized as being "mostly" electric. The driving in E-mode with Vehicle A is thus supported by the ICE at medium to high loads and under unfavorable climatic conditions. On the other hand, driving in the hybrid mode of Vehicle B was pure electrically in many drive cycles and driving conditions, whereas Vehicle A used the ICE more.

Potentially, the behavior of Vehicle A could be related to the required propulsion power being higher than the battery can deliver, the battery "state of health" requiring it, or to eliminate the highest loads to increase battery life. Yuksel et al (2016) for instance states that a blended mode operation for a PHEV (partly electric, partly ICE supported) can significantly improve battery life ($LiFePO_4$ battery used as an example).

This observed and measured vehicle behavior does not necessary lead to the general conclusion that Vehicle B will produce less CO_2-emissions per year than Vehicle A. This will depend on how the vehicles are used. If the trips are predominantly short with ample charging opportunities, then Vehicle B may be the best option. Vehicle A has a longer range in E-mode and a larger battery, so it will overall be able to do more driving in electric mode than Vehicle B can do, but potentially more spread out over a trip. Overall, Vehicle A is expected to produce less CO_2 over a year of 16000 km of average driving than Vehicle B, due to the longer E-mode range and the larger battery.

Warm start in pure electric mode with 100% SOC is not really possible in the real world unless the vehicle is preheated, or the battery hold mode was used in the preceding part of the trip. The reason is that the vehicle would normally cool down during the recharging of the battery which may take several hours depending on the battery depth of discharge. The same is true of warm starts in the hybrid mode at 100% SOC. If these vehicles are driven in E-mode in the cold and the engine starts after the cabin heated up, the start may be semi-hot, depending on whether the heating system loop includes the engine block of the ICE.

Low temperatures and aggressive driving reduced the range in E-mode and increased the energy consumption in all drive modes and drive cycles tested for both vehicles. The same situation applies also for ICEVs.

Some PHEVs on the market cannot be driven in the E-mode when ambient temperature falls below -10°C. The cold weather tests presented in this report were done at -7°C, so that issue was not encountered in the testing.

Driving in the battery charge and battery hold modes, respectively recharging the battery and preserving the battery SOC, resulted in very high emissions of CO_2 and high energy consumption in Vehicle A. These modes will allow for a later part of the journey to be conducted with electric power, for instance in a zero-emission city zone, or in sports mode, and thus be desirable functions for some users. When the battery is charged in the charge mode, followed by driving in the E-mode, the average energy consumption should be evaluated for the entire trip. If the vehicle does not have a pure electric drive mode, the use of these range preserving modes makes less sense from an emission point of view. These drive modes were not tested in Vehicle B.

<u>Coming back to the hypotheses in chapter 1 it is evident that:</u>

1. Some PHEVs have a pure battery electric drive mode in warm as well as cold climates, others use the ICE to support acceleration when needed in both seasons.
2. Battery range is not quite sufficient for everyday traffic in the winter. One vehicle did not even have a pure electric mode. The other vehicles E-mode would take the average user to work but not back again without charging.
3. Due to the heavier weight of the added battery and the electrical system, the energy consumption in non-electric mode can be higher than for comparable ICEVs and especially for HEVs, under unfavorable conditions.
4. The start and stop of the drive system in hybrid mode can lead to high emissions. The average emission will however likely stay below the type approval value for average users that use the E-mode whenever they can. Aggressive driving in the hybrid mode lead to elevated emissions in the cold and when battery SOC is low.
5. The total energy consumption and CO_2-emissions for these two vehicles can under Norwegian usage patterns and climatic conditions be about 30-50% lower than from comparable ICEVs, while keeping average local emissions below the type approval limits. The spread in CO_2-emission and energy consumption between drive modes and temperatures is however much larger than for ICEVs.
6. The blended electric/ICE operation of Vehicle A in E-mode is not an issue when it comes to reducing CO_2-emission and energy consumption over a year. The range in E-mode is more important. It is likely that the blended mode increase battery life, one of the most crucial parameters for electric vehicle total cost of ownership.

5.2 Conclusion

The testing of these two vehicles demonstrates that PHEVs are a non-uniform category of vehicles. The amount CO_2 and local pollutants these vehicles emit will depend heavily on how the vehicles are designed, and how and where they are used. They are high performance vehicles and care should be taken when identifying vehicles to compare emissions with. The main results can be summed up to the following points:

- The variation in CO_2-emission is huge for these vehicles when driving in different user selectable drive modes, different drive cycles, temperatures and SOC levels. The variation is mainly linked to the share of driving that can be accomplished in E-mode. The variation is much larger than for an ICEV, in particular for CO_2.
- The CO_2 reduction benefit was about 50% for the vehicle with 50 km E-mode range and about 30% for the vehicle with 31 km E-mode range.
- The average yearly estimated CO_2-emission was about 2.5 times higher than the value stated in the type approval official CO_2-emission test.
- Large CO_2-reductions can be achieved with optimum driving patterns, i.e. predominantly local short distance driving, and relatively few long distance trips.
- Less CO_2-reduction will be achieved if drivers have a large share of long distance trips. The benefits could then become marginal compared with HEVs.
- The energy saving percentage will be less than the CO_2-saving indicated, due to electricity consumed being counted as zero-emission in the CO_2-assessment.
- One vehicle did not have a pure E-mode even at low speeds in the cold, but this was not estimated to be critical to overall achievable reduction of annual emissions.
- Some driving conditions caused elevated local emission levels, but average driving in different drive modes leads to average emissions below the emission limit values.

The testing supports a conclusion that the users driving pattern needs to match the characteristics of these vehicles, to reap the maximum benefits in terms of reduced CO_2-emission and less local pollution. The EU NEDC type approval test overestimates the benefits of PHEVs compared with ICEVs, but the CO_2 reduction potential versus ICEVs is nevertheless large. PHEVs thus have promising environmental characteristics, but should ideally be equipped with larger batteries to allow more E-mode driving, which would lead to larger emission reductions compared with ICEVs.

Charging at work or other places during the day can significantly improve the environmental benefits of the current generation of PHEVs, by increasing the E-mode share of the driving over the year.

5.3 Future research

The tests reported in this report were designed to be exploratory, i.e. to provide insights into both expected and unexpected aspects of PHEVs. More testing of different types of vehicles is required to get a better understanding of the diversity of this vehicle category and their emission- and energy usage characteristics, for instance:

- PHEVs should be tested at an interim SOC level, for instance 50%. At 0% SOC the vehicle might not be capable of hybrid operation until a minimum level of SOC has been reached, leading to a higher measured energy consumption in the tests than what could be achievable in real traffic.
- PHEVs ability to drive all electric is a characteristic that needs to be determined prior to initiate testing, to avoid losing emission data. The exact boundaries for when the vehicle exits the E-mode is also an interesting parameter to test further, as well as the total E-mode range.
- PHEVs should be tested over longer distances, for instance 50-100 km, to see how the emission from the vehicle changes when the drive mode is switched from E-mode to Hybrid auto after the battery is emptied. That would also make it easier to compare vehicles capable of some pure electric driving and those that are not.
- PHEVs should also be tested at temperatures below -10°C.

5.4 Error sources

The test proved repeatable for energy consumption and CO_2-emission, despite the variability of drive modes and operation strategies that can be selected with the dual drive systems of these vehicles. The variation between tests was larger than what is typical of ICEVs, but the results nevertheless indicate that the test method itself is repeatable with small error margins. NO_X-emissions and particulates showed larger deviations between tests. However, this was not unexpected, as these emissions will depend on how often the ICE engine is switched on, it's average load and duration of operation, and how these factors influence the efficiency of the exhaust after-treatment system.

The vehicles' total range in E-mode was not tested, although the 33 km NEDC test provides some indication. The tests were designed to provide energy consumption and CO_2-emission data. The electrical energy consumption measured is from the grid, using a kWh measurement device between the wall socket and the vehicle charging cable, and cannot be used to calculate the vehicles expected range in E-mode. There are energy losses between the wall socket and the electricity stored in the battery that would not be accounted for.

To be able to precondition vehicles before testing, the vehicles were for some of the tests driven in the battery hold mode after being fully charged. This method introduces an uncertainty as to the exact state of charge of the battery at the start of these tests.

6 References

BilSweden 2017. Registration data for new vehicles downloaded from www.bilsweden.se.

EC, 2015. Evaluation of the EU ETS directive. European Commission, Directorate-General for Climate-Action, Directorate B – European International Carbon Markets, November 2015. http://ec.europa.eu/clima/policies/ets/revision/docs/review of eu ets en.pdf .

Figenbaum, E. 2016, in press. Perspectives on Norway's supercharged electric vehicle policy. Environmental Innovation and Societal Transitions. http://dx.doi.org/10.1016/j.eist.2016.11.002

Figenbaum, E., Kolbenstvedt, M., Elvebakk, B. 2014. Electric vehicles – environmental, economic and practical aspects. As seen by current and potential users. TØI-report 1329/2016.

Figenbaum, E., Kolbenstvedt, M. 2016. Learning from Norwegian Battery Electric and Plug-in Hybrid Vehicle users. Results from a survey of vehicle owners. TØI report 1492/2016.

Fridstrøm, L., Østli, V. 2016. The vehicle purchase tax as a climate policy instrument. Transportation Research Part A 96 (2017) 168-189.

Hagman, R., Weber, C., Amundsen, A. 2015. Utslipp fra nye kjøretøy – holder de hva de lover? Avgassmålinger Euro 6/VI – status 2015. TØI rapport 1407/2017. Transportøkonomisk institutt.

ICCT 2017. Real-driving emissions test procedure for exhaust gas pollutants emission of cars and light commercial vehicles in Europe. Policy update. The International Council on Clean Transportation. January 2017. http://www.theicct.org/sites/default/files/publications/EU-RDE_policy-update_18012017_vF.pdf

OFVAS 2017. Registration data for new vehicles downloaded from www.ofvas.no.

Spritmonitor 2017. Data extracted 04.01.2017from the www.spritmonitor.de database on fuel consumption.

Tietge, U., Diaz, S., Mock, P., German, J., Bandivadekar, A., Ligterink, N. 2016. From laboratory to road. A 2016 update of official and «real-world» fuel concumption and CO2 values for passenger cars in Europe. White paper. The International Council on Clean Transportation, November 2016. http://www.theicct.org/sites/default/files/publications/ICCT_LaboratoryToRoad_2016.pdf

Yuksel, T., Litster, S. Viswanathan, V., Michalek, J.J. 2016. Plug-in hybrid electric vehicle $LiFePO_4$ battery life implications of thermal management, driving conditions, and regional climate. Journal of Power Sources 338 (2017) 49-64.

Appendix – Detailed test program

Vehicle A

Test #	DAY	Cycle	SOC	Driving Mode	Start	Temp
	DAY1					
15279EH	CAR 5	NEDC	Full	Normal Hybrid	Cold Start	+23°C
15280EH	CAR 5	NEDC	As is	Normal Hybrid	Warm Start	+23°C
	CAR 5	charge				+23°C
	CAR 5	prep + warmup	Full	Batt Hold		+23°C
15281AUH	CAR 5	Artemis Urban	Full	Normal Hybrid	Warm Start	+23°C
	CAR 5	charge				+23°C
	CAR 5	prep + warmup	Full	Batt Hold		+23°C
15282HH	CAR 5	Helsinki City	As is	Normal Hybrid	Warm Start	+23°C
	CAR 5	charge				+23°C
	CAR 5	prep until batt empty		Electric only		+23°C
	DAY2					
15283EH	CAR 5	NEDC	Empty	Normal Hybrid	Cold Start	+23°C
15284EH	CAR 5	NEDC	As is	Normal Hybrid	Warm Start	+23°C
	CAR 5	prep until batt empty		Electric Only		+23°C
15285AUH	CAR 5	Artemis Urban	Empty	Normal Hybrid	Warm Start	+23°C
	CAR 5	charge				+23°C
15286EH	CAR 5	NEDC (1 only)	Full	Electric Only	Warm Start	+23°C
15287EH	CAR 5	NEDC (1 only)	As is	Electric Only	Warm Start	+23°C
15288EH	CAR 5	NEDC (1 only)	As is	Electric Only	Warm Start	+23°C
	CAR 5	charge				
	DAY3					
15289EH	CAR 5	NEDC	Full	Normal Hybrid	Cold Start	+23°C
15290EH	CAR 5	NEDC	As is	Normal Hybrid	Warm Start	+23°C
	CAR 5	charge				+23°C
	CAR 5	prep + warmup	Full	Batt Hold		+23°C
15291AUH	CAR 5	Artemis Urban	Full	Normal Hybrid	Warm Start	+23°C
	CAR 5	charge				+23°C
	CAR 5	prep + warmup	Full	Batt Hold		+23°C
15292HH	CAR 5	Helsinki City	As is	Normal Hybrid	Warm Start	+23°C
	CAR 5	charge				+23°C
	CAR 5	prep until batt empty		Electric only		+23°C
	DAY4					
15293EH	CAR 5	NEDC	Empty	Normal Hybrid	Cold Start	+23°C
15294EH	CAR 5	NEDC	As is	Normal Hybrid	Warm Start	+23°C
	CAR 5	prep until batt empty		Electric Only		+23°C
15295AUH	CAR 5	Artemis Urban	Empty	Normal Hybrid	Warm Start	+23°C
	CAR 5	charge				+23°C
15296AUH	CAR 5	Artemis Urban (1 only)	Full	Electric Only	Warm Start	+23°C
15297AUH	CAR 5	Artemis Urban (1 only)	As is	Electric Only	Warm Start	+23°C
15298AUH	CAR 5	Artemis Urban (1 only)	As is	Electric Only	Warm Start	+23°C
	CAR 5	Charge				+23°C

Test #	DAY	Cycle	SOC	Driving Mode	Start	Temp
	DAY5					
15299EH	CAR 5	NEDC	Full	Normal Hybi	Cold Start	-7°C
15300EH	CAR 5	NEDC	As is	Normal Hybi	Warm Start	-7°C
	CAR 5	charge				-7°C
	CAR 5	prep + warmup	Full	Batt Hold		-7°C
15301AUH	CAR 5	Artemis Urban	Full	Normal Hybi	Warm Start	-7°C
	CAR 5	charge				-7°C
	CAR 5	prep + warmup	Full	Batt Hold		-7°C
15302HH	CAR 5	Helsinki City	As is	Normal Hybi	Warm Start	-7°C
	CAR 5	charge				-7°C
	CAR 5	prep until batt empty		Electric only		-7°C
	DAY6					
15303EH	CAR 5	NEDC	Empty	Normal Hybi	Cold Start	-7°C
15304EH	CAR 5	NEDC	As is	Normal Hybi	Warm Start	-7°C
	CAR 5	prep until batt empty		Electric Only		-7°C
15305AUH	CAR 5	Artemis Urban	Empty	Normal Hybi	Warm Start	-7°C
	CAR 5	charge				-7°C
15306EH	CAR 5	NEDC (1 only)	Full	Electric Only	Warm Start	-7°C
15307EH	CAR 5	NEDC (1 only)	As is	Electric Only	Warm Start	-7°C
15308EH	CAR 5	NEDC (1 only)	As is	Electric Only	Warm Start	-7°C
	CAR 5	charge				
	DAY7					
15309EH	CAR 5	NEDC	Full	Normal Hybi	Cold Start	-7°C
15310EH	CAR 5	NEDC	As is	Normal Hybi	Warm Start	-7°C
	CAR 5	charge				-7°C
	CAR 5	prep + warmup	Full	Batt Hold		-7°C
15311AUH	CAR 5	Artemis Urban	Full	Normal Hybi	Warm Start	-7°C
	CAR 5	charge				-7°C
	CAR 5	prep + warmup	Full	Batt Hold		-7°C
15312HH	CAR 5	Helsinki City	As is	Normal Hybi	Warm Start	-7°C
	CAR 5	charge				-7°C
	CAR 5	prep until batt empty		Electric only		-7°C
	DAY8					
15313EH	CAR 5	NEDC	Empty	Normal Hybi	Cold Start	-7°C
15314EH	CAR 5	NEDC	As is	Normal Hybi	Warm Start	-7°C
	CAR 5	prep until batt empty		Electric Only		-7°C
15315AUH	CAR 5	Artemis Urban	Empty	Normal Hybi	Warm Start	-7°C
	CAR 5	charge				-7°C
15316AUH	CAR 5	Artemis Urban (1 only)	Full	Electric Only	Warm Start	-7°C
15317AUH	CAR 5	Artemis Urban (1 only)	As is	Electric Only	Warm Start	-7°C
15318AUH	CAR 5	Artemis Urban (1 only)	As is	Electric Only	Warm Start	-7°C
	CAR 5	Charge				-7°C
	DAY9					
15319AUH	CAR 5	Artemis Urban	Full	Batt Hold	Cold Start	-7°C
	CAR 5	charge				-7°C
15320EH	CAR 5	NEDC (1 only)	Full	Electric Only	Warm Start	-7°C
15321EH	CAR 5	NEDC (1 only)	As is	Electric Only	Warm Start	-7°C
15322EH	CAR 5	NEDC (1 only)	As is	Electric Only	Warm Start	-7°C
	CAR 5	charge				-7°C
	CAR 5	prep until batt empty				-7°C
15323EH	CAR 5	NEDC	Empty	Charge Mode		-7°C
	CAR 5	charge				-7°C

Vehicle B

Test #	DAY	Cycle	SOC	Driving M	Start	Temp	
	25.10.2016						
16253EBH	M-B	NEDC	Full	Normal Hy	Cold Start	+23°C	no ICE
skipped	~~M-B~~	~~NEDC~~	~~As is~~	~~Normal Hy~~	~~Warm Sta~~	~~+23°C~~	
	~~M-B~~	~~charge~~				+23°C	
	~~M-B~~	~~prep + warmup~~	~~Full~~	~~Batt Hold~~		+23°C	
skipped	~~M-B~~	~~Artemis Urban~~	~~Full~~	~~Normal Hy~~	~~Warm Sta~~	+23°C	
	~~M-B~~	~~charge~~				+23°C	
	~~M-B~~	~~prep + warmup~~	~~Full~~	~~Batt Hold~~		+23°C	
skipped	~~M-B~~	~~Helsinki City~~	~~As is~~	~~Normal Hy~~	~~Warm Sta~~	+23°C	
	~~M-B~~	~~charge~~				+23°C	
	~~M-B~~	~~prep until batt empty~~		~~Electric only~~		+23°C	
	26.10.2016						
16257EBH	M-B	NEDC	Empty	Normal Hy	Cold Start	+23°C	N-R
skipped	~~M-B~~	~~NEDC~~	~~As is~~	~~Normal Hy~~	~~Warm Sta~~	~~+23°C~~	
	M-B	prep until batt empty		Electric Only		+23°C	
16258AUB	M-B	Artemis Urban	Empty	Normal Hy	Warm Sta	+23°C	
	M-B	charge				+23°C	
16259AUB	M-B	Artemis Urban	Full	Normal Hy	Warm Sta	+23°C	
	M-B	charge				+23°C	
16260EBH	M-B	NEDC (1 only)	Full	Electric O	Warm Sta	+23°C	no bag samples
16261EBH	M-B	NEDC (1 only)	As is	Electric O	Warm Sta	+23°C	no bag samples
16262EBH	M-B	NEDC (1 only)	As is	Electric O	Warm Sta	+23°C	no bag samples
	M-B	charge					
	27.10.2016						
16263EBH	M-B	NEDC	Full	Normal Hy	Cold Start	+23°C	no ICE
	M-B	charge				+23°C	
	M-B	prep + warmup	Full	Batt Hold		+23°C	
16264AUB	M-B	Artemis Urban	Full	Normal Hy	Warm Sta	+23°C	some ICE
	M-B	charge				+23°C	
	M-B	prep + warmup	Full	Batt Hold		+23°C	
16265HBH	M-B	Helsinki City	As is	Normal Hy	Warm Sta	+23°C	no ICE
	M-B	charge				+23°C	
	M-B	prep + warmup	Full	Batt Hold		+23°C	
16266HBH	M-B	Helsinki City	As is	Normal Hy	Warm Sta	+23°C	no ICE
	M-B	charge				+23°C	
	M-B	prep until batt empty		Electric only		+23°C	
	28.10.2016						
16267EBH	M-B	NEDC	Empty	Normal Hy	Cold Start	+23°C	N-R
	M-B	prep until batt empty		Electric Only		+23°C	
16268AUB	M-B	Artemis Urban	Empty	Normal Hy	Warm Sta	+23°C	
	M-B	charge				+23°C	
16269AUB	M-B	Artemis Urban	Full	Electric O	Warm Sta	+23°C	
16270AUB	M-B	Artemis Urban	As is	Electric O	Warm Sta	+23°C	
16271AUB	M-B	Artemis Urban	As is	Electric O	Warm Sta	+23°C	
	M-B	Charge				+23°C	
	Batt Hold = Petrol only						

Test #	DAY	Cycle	SOC	Driving Mo	Start	Temp	
	31.10.2016						
16272EBH	M-B	NEDC	Full	Normal Hyb	Cold Start	−7°C	N-R
	M-B	charge				−7°C	
	M-B	prep + warm	Full	Batt Hold		−7°C	
16273AUB	M-B	Artemis Urba	Full	Normal Hyb	Warm Sta	−7°C	
	M-B	charge				−7°C	
	M-B	prep + warm	Full	Batt Hold		−7°C	
16274HBH	M-B	Helsinki City	As is	Normal Hyb	Warm Sta	−7°C	
	M-B	charge				−7°C	
	M-B	prep until batt empty		Electric only		−7°C	
	01.11.2016						
16278EBH	M-B	NEDC	Empty	Normal Hyb	Cold Start	−7°C	N-R
	M-B	prep until batt empty		Electric Only		−7°C	
16279AUB	M-B	Artemis Urba	Empty	Normal Hyb	Warm Sta	−7°C	
	M-B	charge				−7°C	
16280EBH	M-B	NEDC (1 only	Full	Electric Onl	Warm Sta	−7°C	no bag samples
16281EBH	M-B	NEDC (1 only	As is	Electric Onl	Warm Sta	−7°C	no bag samples
SKIPPED	~~M-B~~	~~NEDC (1 only~~	~~As is~~	~~Electric Onl~~	~~Warm Sta~~	~~−7°C~~	battery drained alreay during 16281EBH
	M-B	charge					
	02.11.2016						
16285EBH	M-B	NEDC	Full	Normal Hyb	Cold Start	−7°C	N-R
	M-B	charge				−7°C	
	M-B	prep + warm	Full	Batt Hold		−7°C	
16286AUB	M-B	Artemis Urba	Full	Normal Hyb	Warm Sta	−7°C	
	M-B	charge				−7°C	
	M-B	prep + warm	Full	Batt Hold		−7°C	
16287HBH	M-B	Helsinki City	As is	Normal Hyb	Warm Sta	−7°C	
	M-B	charge				−7°C	
	M-B	prep until batt empty		Electric only		−7°C	
	03.11.2016						
16288EBH	M-B	NEDC	Empty	Normal Hyb	Cold Start	−7°C	N-R
	M-B	prep until batt empty		Electric Only		−7°C	
16289AUB	M-B	Artemis Urba	Empty	Normal Hyb	Warm Sta	−7°C	
SKIPPED	~~M-B~~	~~Artemis Urba~~	~~Full~~	~~Electric Onl~~	~~Warm Sta~~	~~−7°C~~	Had no time, car to be returned
SKIPPED	~~M-B~~	~~Artemis Urba~~	~~As is~~	~~Electric Onl~~	~~Warm Sta~~	~~−7°C~~	Had no time, car to be returned
SKIPPED	~~M-B~~	~~Artemis Urba~~	~~As is~~	~~Electric Onl~~	~~Warm Sta~~	~~−7°C~~	Had no time, car to be returned
	M-B	Charge				−7°C	

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