

Estimating real-world emissions of PHEVs in Norway by combining laboratory measurement with user surveys

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Abstract

The paper presents the results of experimental testing of the exhaust emission and energy consumption of two gasoline plug-in hybrid vehicles in an emission testing laboratory with different drive cycles, drive modes and at summer and winter temperatures. One was a compact vehicle with a type approval electric mode range of 50 km, the other a mid-sized vehicle with an electric mode range of 31 km. Additionally, an online survey of 2065 private PHEV owners investigated the usage pattern of the vehicles. Combining the laboratory tests with the user survey results provided an estimate for the reduction of CO₂-emission of PHEVs in use in Norway. The main conclusion is that the PHEV is a vehicle type that needs to match well with the use pattern to produce low CO₂- and local emissions. The achievable CO₂-emission reduction was proportional to the range in E-mode, i.e. 50 km range resulted in about 50% reduction.

Keywords: PHEV (plug in hybrid vehicle), Emissions, Energy consumption, Usage behavior

1 Introduction

Electromobility is high on the political agenda in Norway. At the end of 2016, Norway had 100000 Battery Electric Vehicles (BEVs) and 30000 Plug in Hybrid Vehicles (PHEVs) on the road and market shares for each of about 15% the last year. Combined, they made up 5% of the total passenger vehicle fleet. The majority of these vehicles are owned by private households.

Most of the national incentives are directed towards BEVs, but PHEVs are also gaining popularity. However, little is known about their real-world impact on the environment in the use phase under Norwegian conditions.

To cover this gap of knowledge, the Norwegian EMIROAD (emissions from road transport vehicles) research program initiated experimental testing of PHEVs emission and energy use under simulated real Norwegian traffic and climatic conditions [1]. The usage pattern of PHEVs was established and compared with the usage pattern of BEVs and Internal Combustion Engine Vehicles (ICEVs), using data from a survey of owners of these three vehicle types.

The paper presents the results of the experimental testing of the exhaust emission and energy consumption of two gasoline plug-in hybrid vehicles in an emission testing laboratory. One, a compact vehicle with an official electric-mode (E-mode) range of 50 km, the other a mid-sized vehicle with an E-mode range of 31 km. The aim of the testing was to uncover the impact of these PHEVs on local pollutants, CO₂-emission and energy use in Norwegian driving conditions.

These laboratory tests were supplemented by information from the user survey. The usage patterns from the survey are combined with the experimental results, to produce estimates of the environmental impact from the use phase of these PHEVs compared to similar ICEV vehicles.

The paper starts with a presentation of the theoretical framework for evaluation of the environmental characteristics of PHEVs in section 2. Section 3 presents the methods used and the characteristics of the vehicles tested. The results are presented in section 4, followed by a discussion of the overall results in section 5, and the conclusion in section 6.

2 Theoretical framework

A 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 batteries for propulsion over typical 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 directly or indirectly.

This duality of power sources and engine/motors introduce flexibility for the user. It also adds complexity for researchers aiming to understand the environmental impacts of PHEVs. The user can select different drive modes where the ICE may be operative to a larger or lesser extent, thus further complicating the picture. Figure 1 shows an example of a PHEV lay-out with an overview of typical user selectable drive modes.

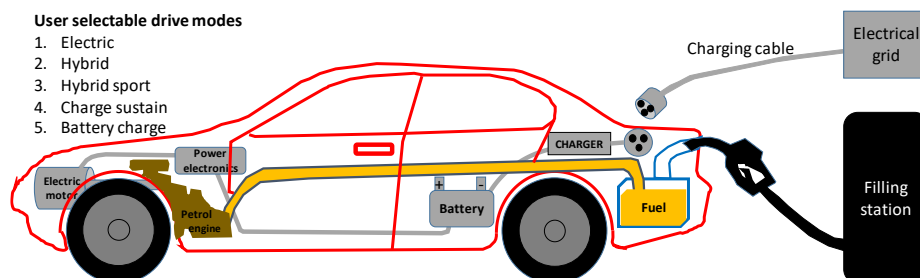


Figure 1: Typical plug-in hybrid vehicle lay-out and user selectable drive modes.

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 only use an Internal Combustion Engine (ICE, gasoline or diesel) for propulsion. It is therefore no longer adequate to measure the energy consumption, the emission of CO₂ 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 pattern of the vehicles and the users selection of drive modes.

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 kilometers. Others maximize the share of driving in the electric drive mode by charging whenever possible.

The purpose of the measurement program of PHEVs 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 tests were carried out at VTT's emission laboratory in Finland in close co-operation with their test engineers. The data cannot be used to estimate the average emissions or energy consumptions of the total fleet of PHEVs on the road, as only two vehicles were tested. The tests were deliberately designed to be exploratory, i.e. to also find the unexpected rather than focusing on the average.

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 climate and driving conditions on energy use, 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 an average round trip to work.
3. The energy consumption in non-electric modes can be higher than for comparable HEVs/ICEVs.
4. Frequent start and stop of the drive system in hybrid mode can lead to high emissions.
5. The annual average energy use and CO₂-emission of PHEVs will be much lower than for ICEVs.
6. A pure E-mode is not necessarily better from a CO₂-reduction perspective than a blended E-mode.

Pure electric propulsion does not produce exhaust emissions. Therefore, the CO₂- and local emission for pure electric propulsion is regarded as zero in the measurement program. The production and distribution of vehicles and fuels are not taken into account in the analysis in this paper. 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 [5], under the condition that the EU ETS is effective in capping CO₂-emissions [6]. A full life-cycle analysis would also take into account vehicle production. Norway does not produce vehicles, and 96% of the electricity is produced from hydro-electric power and 2% from wind power. The zero emission assumption for pure electric propulsion in this report is thus not unreasonable, when the target is to analyze national impacts of PHEVs.

3 Methods

3.1 Measurement program

The test program [1] consisted of two vehicles tested in three different drive modes, at two ambient temperatures and 2-4 drive modes. The characteristics of the two vehicles tested are presented in table 1.

Table 1: Tested vehicles, characteristics

	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)
Model year	2015	2016
Emission regulation	Euro 6	Euro 6
User selectable drive modes	E-mode (vehicles most electric mode) Battery hold (maintain battery charge) Battery charge (recharge battery) Hybrid Auto (most efficient hybrid mode) Hybrid Sport mode (maximize power)	Pure E-mode (100% electric) Battery hold (maintain battery charge) Battery charge (recharge battery) Hybrid Auto (most efficient hybrid mode) Hybrid Sport mode (maximize power)
Comparable ICEV tested in EMIROAD	Diesel	Gasoline (and diesel) variant(s)
Same manufacturer, same base model	2-liter engine, automated gear box 2013 model, Euro 5 Version with closest acceleration performance	1.6-liter gasoline engine, gear box XXXX model Euro 5 Lower performance

The laboratory tests included measurements of energy use, the emission of CO₂ and "local" emissions, i.e. HC, CO, NO_x, and particulates mass and number count. The test cell set up is illustrated in figure 2.

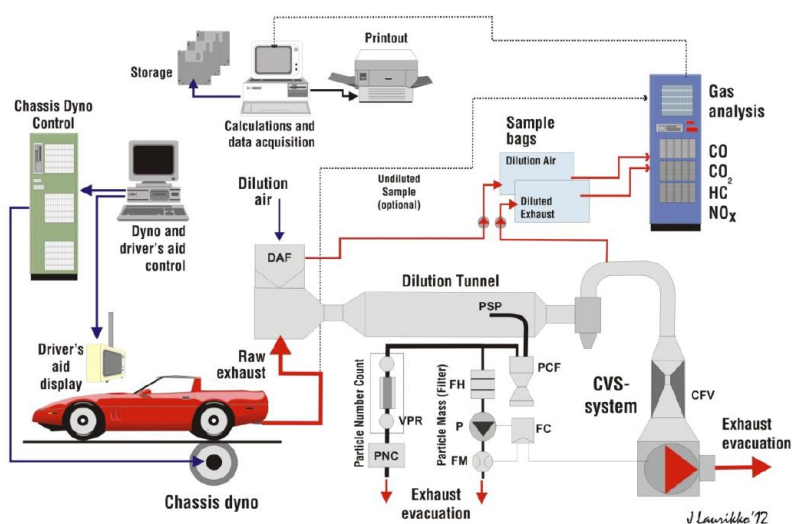


Figure 2: VTT Emission laboratory set-up. Drawing by: VTT, J. Laurikko, 2012.

Three different drive cycles were applied, the NEDC, Artemis Urban and Helsinki city cycles. Table 2 presents some essential characteristics of the test cycles.

Table 2: 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

The test matrices are summarized in tables 3 and 4. The tests included warm and cold starts, driving in different hybrid system drive modes, and at ambient temperatures of +23°C and -7°C. 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

Table 3: Vehicle A test matrix. As/is tests ran directly after another test with electricity consumption measured as average over both tests.

Drive cycle	Drive mode	SOC	+23°C		-7°C	
			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 4: Vehicle B test matrix.

Drive cycle	Drive mode	SOC	+23°C		-7°C	
			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

3.2 User survey

In real traffic, PHEVs will be used part-time in different user selectable drive modes and with different use patterns. A user survey [2] among 2065 private Norwegian PHEV owners, 3111 BEV owners and 2080 ICEV owners, in March 2016, produced user estimates of the real E-mode range in summer and winter, the total annual km driven, the estimated share of driving done in E-mode and their charging behavior (Figenbaum and Kolbenstvedt 2016). These results are used to estimate a representative usage and charging pattern that is combined with the measurements, to provide estimates of how these vehicles contribute to reduced CO₂-emission, less energy use and local pollution over a year of use, compared with an ICEV of similar type.

4 Results

The results are presented separately for both vehicles as only a subset of tests are directly comparable between the two vehicles.

4.1 Vehicle A

Electric drive 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, when being tested at +23°C, and for long time periods at -7°C. The overall results with warm starts and fully charged battery are presented in figure 3. The type approval values of vehicle A and the measured emissions of a comparable diesel version, are also shown. Although the engine starts, the CO₂-emission reduction is large compared with the diesel version of the vehicle.

Emissions of NO_x and particulates were far below the emission limits, whereas the CO emission was slightly above the NEDC limit of 1 g/km when driven in the Artemis Urban test at +23°C (figures not shown here).

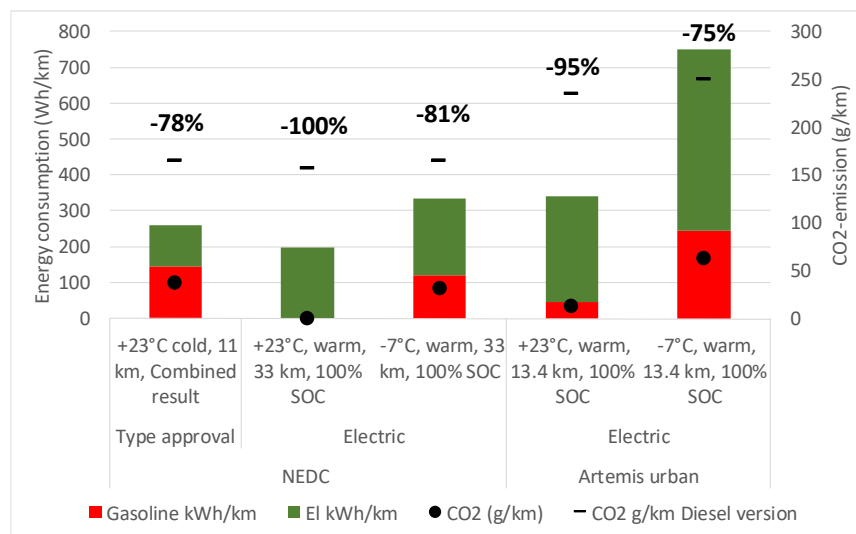


Figure 3: Vehicle A, measured E-mode energy consumption (Wh/km) and CO₂-emission (black dots) in g/km, compared to official type approval values, and EMIROAD measured CO₂-emission of a comparable diesel vehicle (black hyphen). CO₂-emission reduction versus diesel version is also shown (percentage).

The driving length of the test cycles and the number of cycles driven are not the same. The diesel vehicle was tested one drive cycle, i.e. 11 km and 4.5 km, respectively in NEDC and Artemis Urban cycles, whereas the PHEV was driven three repetitive runs. Cold start effects might therefore have a bigger influence on the magnitude of emission values for the diesel vehicle.

Hybrid drive mode

In the hybrid auto mode, the test results are less conclusive. In most cases, the CO₂-emission was below the diesel vehicles emissions. An empty battery combined with high load driving resulted, however, in CO₂-emissions above that of the diesel vehicle. The repeatability of the tests was good, but less than for ICEV vehicles, likely due to the battery state of charge or state of health influencing the start-up conditions for the ICEV.

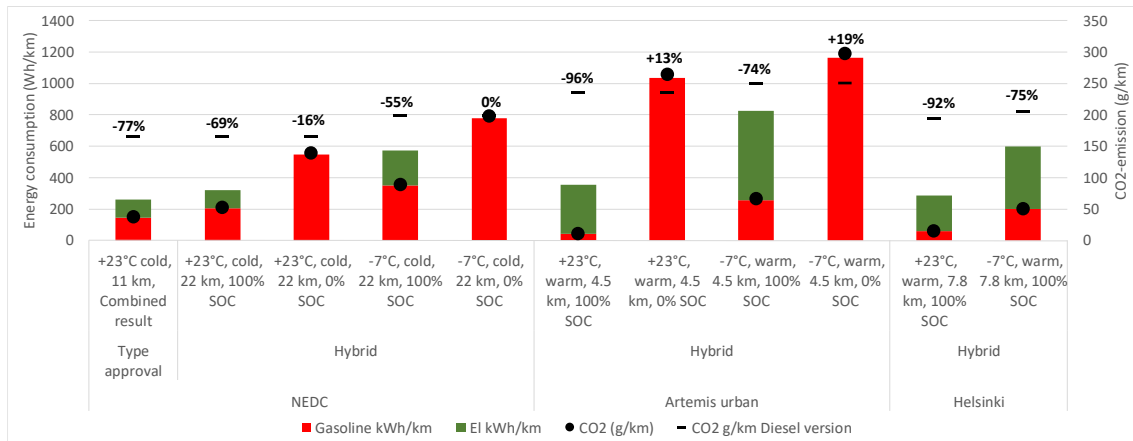


Figure 4: Vehicle A; hybrid mode CO₂-emission (black dots) in g/km and energy consumption (Wh/km), compared with the official type approval values. CO₂-emission (black hyphen) of the most comparable diesel engine version of the vehicle and emission reduction vs. diesel version (percentages) is also shown.

Some drive cycles, particularly high loads and low temperatures led to excessive local pollutants emissions as seen in figure 5. Particulate number emissions followed particulate mass and was below the 2016 limit value, but high above the limit that will be introduced in September 2017 when tested in the cold.

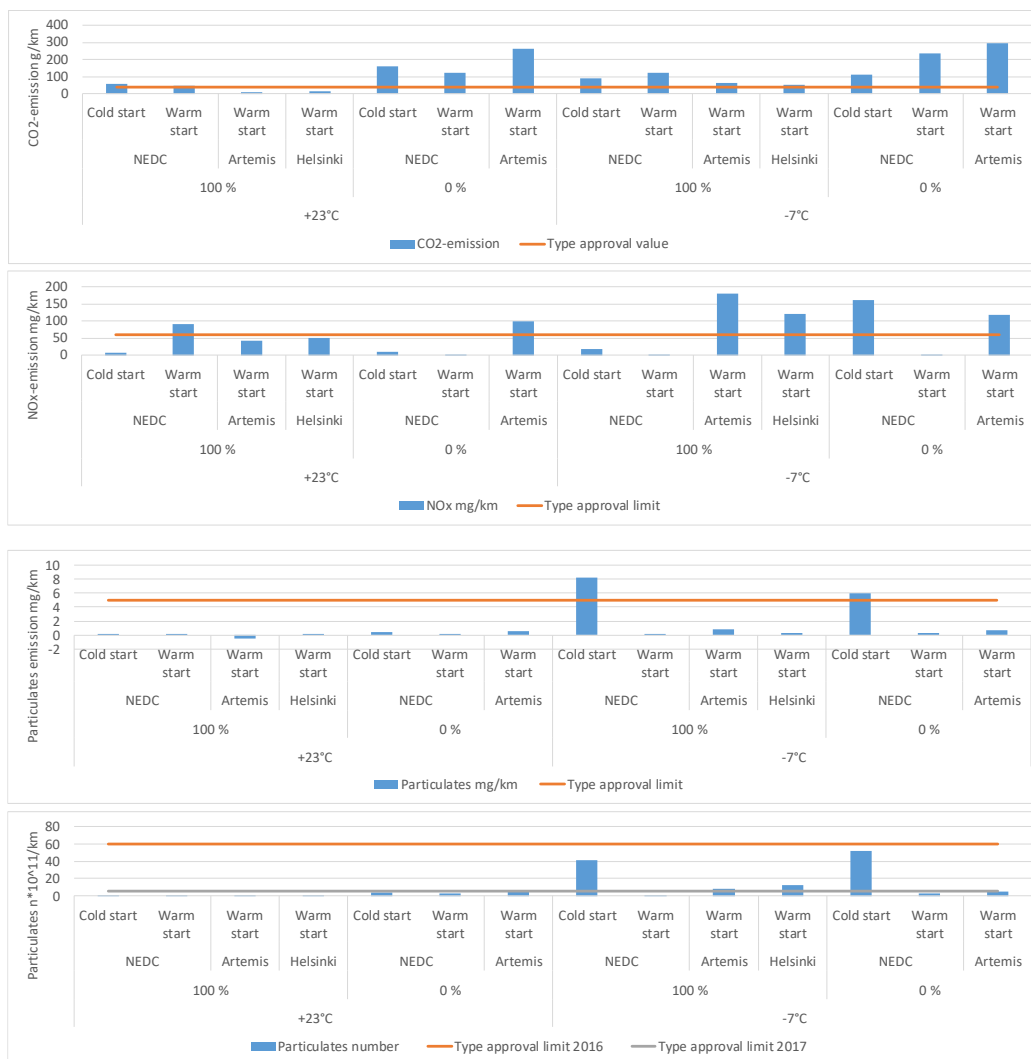


Figure 5: Vehicle A; CO₂ (g/km), NO_x (mg/km) and particulates (mg/km, n·10¹¹) emissions, per drive cycle at +23°C and -7°C, and 100% and 0% battery SOC. Lines represents type approval values (CO₂) and NEDC type approval limits. Grey line is particulates number limit from September 2017.

Other user selectable drive modes

The vehicle had two drive modes that can be used to respectively preserve the battery capacity, and recharge an empty battery for later driving in the E-mode. These drive modes were tested at -7°C ambient temperature and the results thus represents winter driving. The measured energy consumption and CO₂-emission was very high compared with the type approval values, as seen in figure 6.

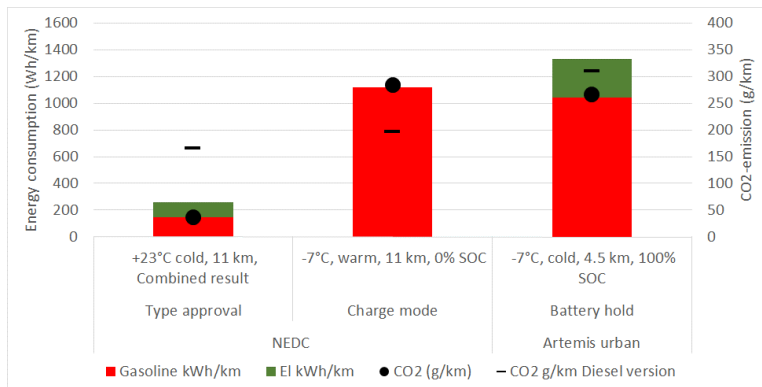


Figure 6: Vehicle A; battery hold and battery charge modes energy consumption (Wh/km, gasoline and electricity) and CO₂-emission (black dots) in (g/km), compared with the NEDC official type approval values and the CO₂ emission (black hyphen) of the diesel version of the same vehicle.

Estimate for yearly average

The average yearly CO₂-emission and energy consumption was calculated using two different approaches.

In method 1, a yearly average simplified driving pattern was constructed. It is assumed that an average user drives 14 km each way to work (from the National Travel Survey 2009) 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. Figure 4.1 shows the estimate of the average yearly CO₂-emission of such a driving pattern.

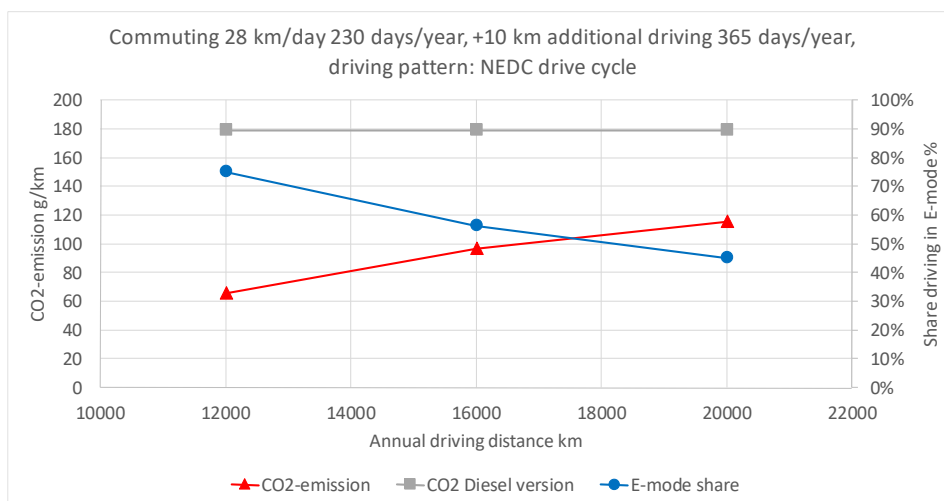


Figure 7: Vehicle A; estimated CO₂-emission and E-mode share of driving over the year for a driving pattern consisting of commuting to work 14 km each way, 230 days/year + 10 km additional local driving/day and assuming long distance driving the rest of the trips. E-mode NEDC driving assumed whenever possible. The vehicle was assumed to switch to the 0% SOC NEDC hybrid mode when the battery was empty. Charging overnight assumed. CO₂-emission of comparable diesel vehicle is also shown.

The other method utilized the users own estimated range in E-mode and estimated share of E-mode driving taken from the user survey. The average CO₂-emission was calculated to be 92 g/km, and the median 86 g/km as seen in figure 8. This calculation method yields a CO₂-reduction of 49% compared to the similar ICEV.

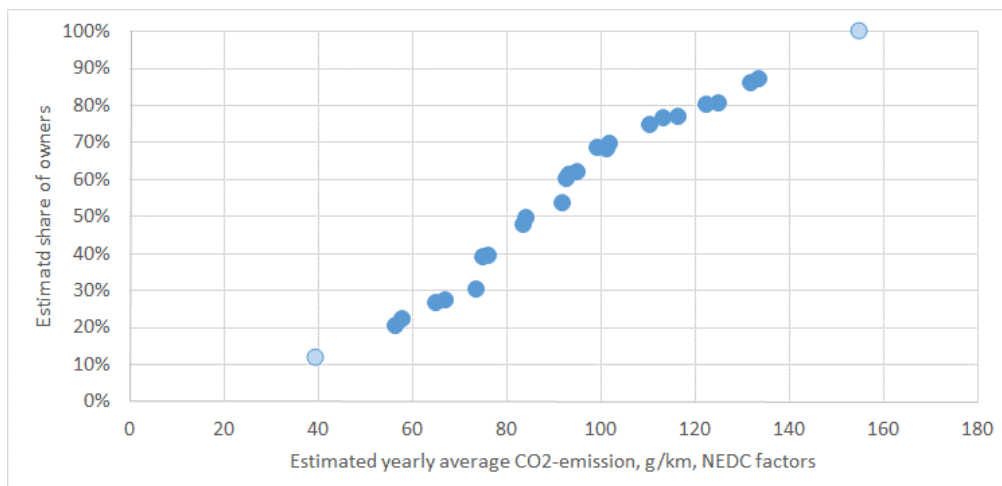


Figure 8: Estimated share of owners below a calculated average yearly CO₂-emission factor based on owners' estimates of share of driving in E-mode summer and winter (Source: EMIROAD vehicle user survey March 2016, adapted from [2]). NEDC test results in E-mode used when calculating the emission for the 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.

There is a big uncertainty estimates of E-mode share of driving when they are based on the user's own assessment. The two calculation methods nevertheless produced similar results. The CO₂-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. [3]. The German web site Spritmonitor.de allows users to log fuel consumption of their vehicles over time. They register km driven (from the odometer) and fuel filled at regular intervals. The 49 registered users of the PHEV version [4] of Vehicle A, achieved a 46% reduction of CO₂ under German conditions¹, compared with users operating the most comparable dieselverson of the same car.

4.2 Vehicle B

Electric drive mode

Vehicle B had a pure electric drive mode. The available power was so severely impacted at -7°C, that the vehicle could only follow the NEDC cycle for 14.5 km before the battery was drained, as seen in figure 9.

¹Assuming 2.66 kg CO₂/l diesel, 2.32 kg CO₂/l gasoline.

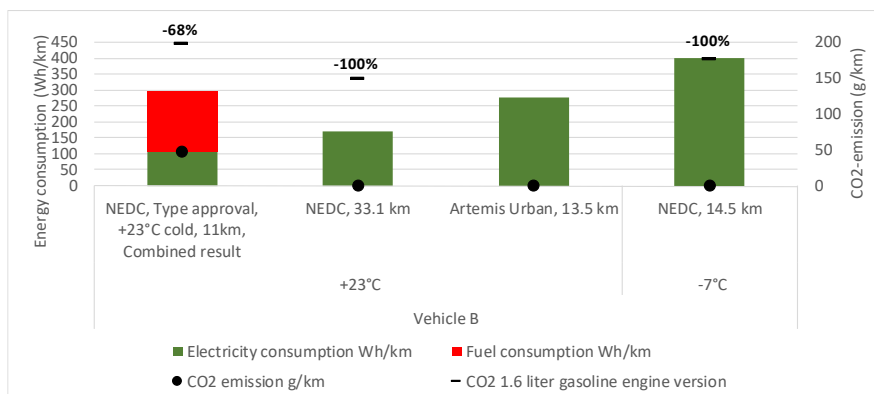


Figure 9: Vehicle B; pure electric drive mode, energy consumption (Wh/km) and CO₂-emission (black dots) in g/km at +23°C and -7°C, 100% SOC at start of test. Comparison with official NEDC type approval values and CO₂-emission (black hyphen) test results of a 1.6-liter gasoline engine version of the vehicle. As the vehicle could do the tests in pure EV mode the emission reduction was 100%.

Hybrid auto mode

Vehicle B was apparently programmed to run only on pure electric power in the 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 alone, when starting with 100% battery 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 CO₂-emission of 82 g/km when driving in the NEDC at -7°C. The CO₂-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 CO₂-emission can however be higher when the battery is empty and the temperature is low, as seen in figure 10.

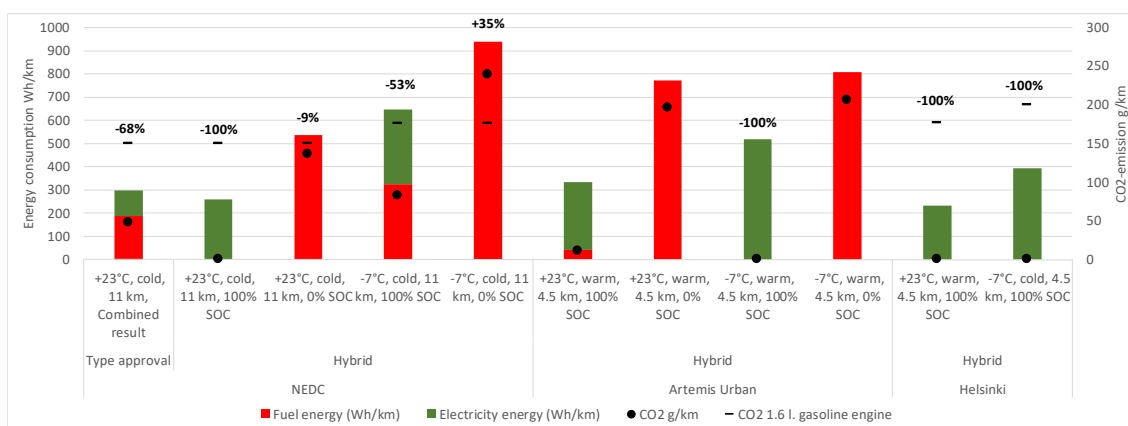


Figure 10: Vehicle B; hybrid drive mode. Energy consumption (Wh/km) and CO₂-emission (black dots) in g/km at +23°C and -7°C, 100% and 0% SOC at start of test. Comparison with official type approval values and CO₂-emission (black hyphen) of 1.6 l gasoline version of the vehicle (g/km). PHEV CO₂-reduction potential (percentage) over gasoline engine version.

The NEDC cycle at +23°C, the Helsinki-city cycles at +23°C and -7°C and the Artemis Urban cycle at -7°C, with 100% battery SOC at the start, could be driven with electricity only, so that no local pollutants or CO₂ were emitted. When driving in high load conditions, with 0% SOC or in cold climate, some of the local

emissions were above the NEDC emission limits, as seen in figure 11. Driving according to the Artemis driving cycle resulted in high NO_x-emissions for Vehicle B, while the other emissions were quite low.

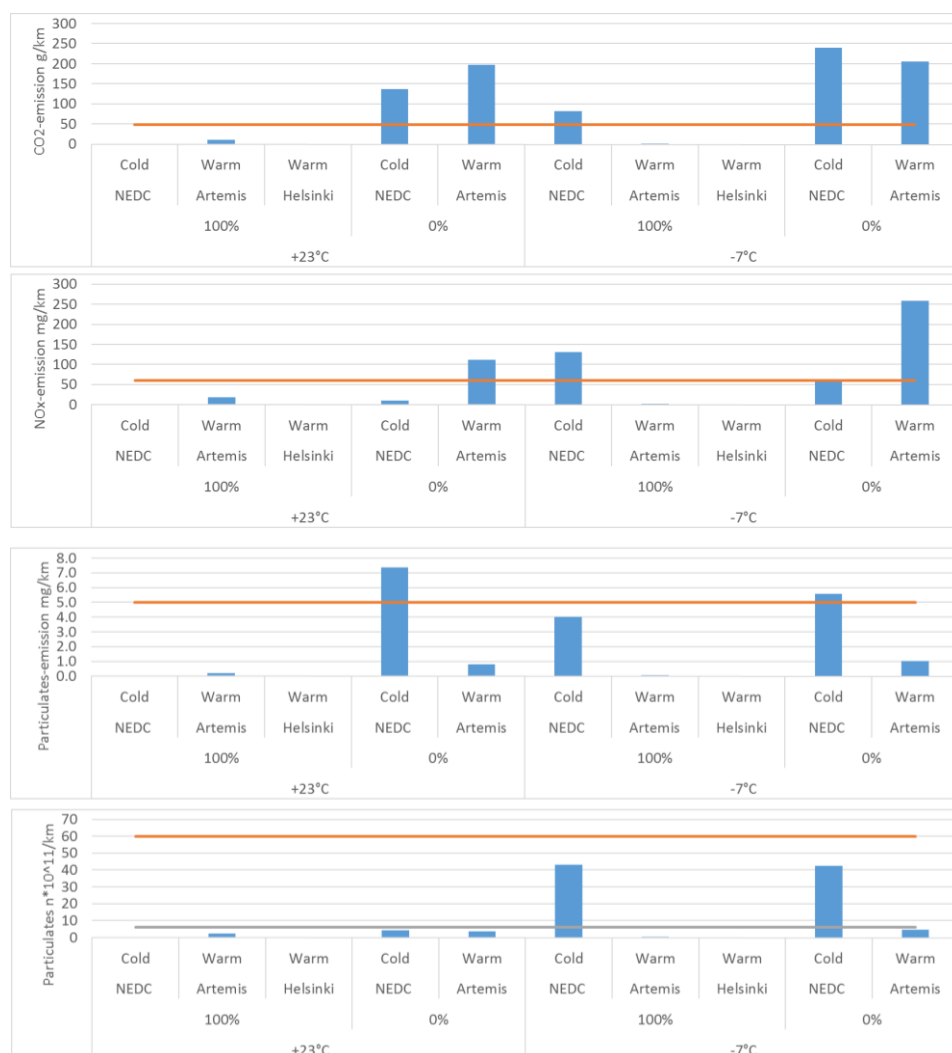


Figure 11: Vehicle B; CO₂, NO_x and particulates mass and number emissions in g/km, mg/km and n·10¹¹, per drive cycle at +23°C and -7°C, and 100% and 0% battery SOC. Lines represents type approval values (CO₂) and limit values. Orange line: CO₂-emission type approval value, other gases and particulates type approval limit. Grey line particulates number limit from September 2017.

Estimate for yearly average

The first calculation method for yearly average of Vehicle A was also used 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 laboratory test results in E-mode.

The estimation result is shown in figure 12. When used 16000 km/year in this assumed usage pattern, the average CO₂-emission was estimated to be 118 g/km, 2.5 times higher than the EU NEDC type approval value. The CO₂-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.

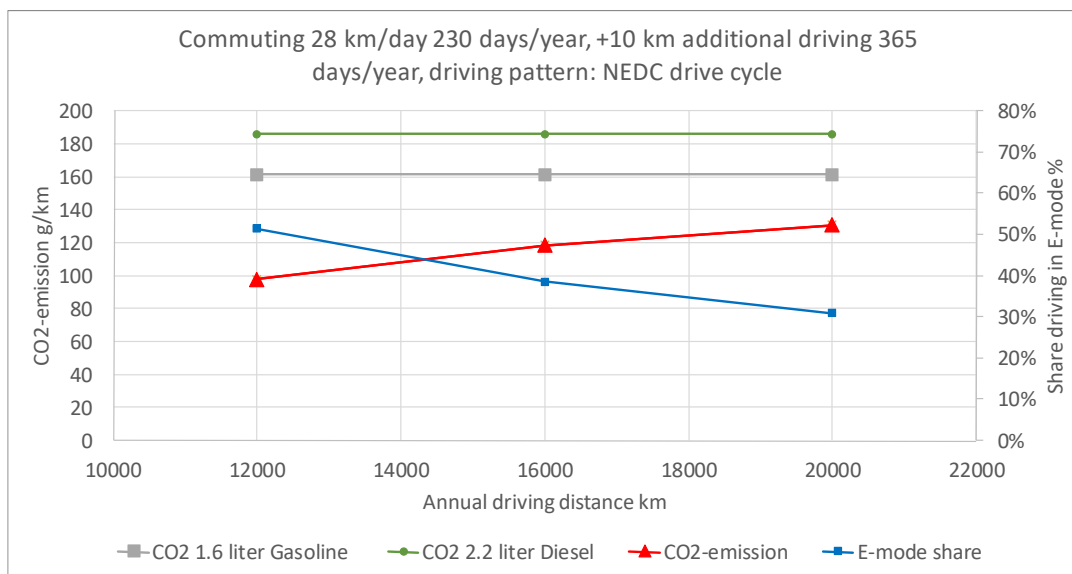


Figure 12: Vehicle B; estimated CO₂-emission and E-mode share over the year for driving pattern consisting of commuting to work 14 km each way, 230 days/year + 10 km additional local driving/day and assuming long distance driving the rest of the trips. CO₂-emission of comparable gasoline and diesel vehicles. E-mode NEDC driving assumed whenever possible, i.e. for trip distances with e-mode range. The vehicle was assumed to switch to the 0% SOC NEDC hybrid mode when the battery was empty. Charging overnight assumed.

5 Discussion

PHEVs produce very different amounts of CO₂-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.

The most important characteristics of PHEVs is the share of driving that can be accomplished in E-mode. This drive mode is assumed to be the primary reason for consumers to buy a PHEV rather than a HEV a PHEV owners in the survey saw electric driving locally as a primary reason to buy a PHEV [2]. The larger the share of driving in E-mode, the lower the fuel consumption and CO₂-emission will be. The estimates of these vehicles' average CO₂-emission over a year demonstrates, however, that it is rather the range in E-mode than the ability to drive purely electric that is critical to achieve low average yearly emissions.

When these vehicles are used for about 15000 km/year [2], the real-world CO₂-emission would be 50% less than the emission from a similar ICEV for the compact vehicle and 30% for the mid-sized vehicle, i.e. proportional to E-mode range. The assumption is that E-mode driving is used for commuting and local driving and the "0% SOC hybrid auto mode" is used for the remaining driving. The driving pattern stated above would lead to average local pollutant emissions below the type approval limits.

Drivers with an aggressive driving style and people driving more on longer distances, i.e. more than 15000 km/year, will see less reduction, and those that drive less or less aggressively will achieve a larger reduction.

In Vehicle B the electric mode is pure electric, whereas in Vehicle A it can be characterized as being "mostly" electric supported by the ICE at medium to high loads and under unfavorable climatic conditions. Driving in the hybrid mode of Vehicle B was done pure electrically in many drive cycles and driving conditions.

This observed and measured vehicle behavior does not necessary lead to the general conclusion that Vehicle B will produce less CO₂-emissions per year than Vehicle A. It 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 CO₂ over a year of 15000 km of average driving than Vehicle B, due to the longer E-mode range and the larger battery.

For both vehicles, low temperatures and aggressive driving reduced the range in E-mode, and increased the energy consumption in all drive modes and drive cycles tested. The same situation applies also for ICEVs. The cold weather tests presented in this report were done at -7°C, so issues with potential E-mode cut-off at low ambient temperatures was not encountered. Vehicles with that type of strategies will produce higher average emissions than estimated in this paper.

Driving in the battery charge and battery hold modes, respectively recharging the battery and preserving the battery SOC, resulted in very high emissions of CO₂ 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.

Coming back to the hypotheses in chapter 1 it is evident that:

1. Some PHEVs have a pure battery electric drive mode in warm as well as cold climates, others not.
2. Battery range is not sufficient to cover average everyday traffic in the winter in Norway.
3. The energy consumption in non-electric modes can be higher than for comparable ICEVs/HEVs.
4. The start and stop of the drive system in hybrid mode can lead to high emissions but the average emission will however be likely to stay below the type approval value.
5. Under Norwegian usage patterns and climatic conditions, the total energy consumption and CO₂-emissions can be about 30-50% lower from these PHEVs than from comparable ICEV
6. The blended electric/ICE operation of Vehicle A in E-mode is not an issue when it comes to reducing CO₂-emission and energy consumption over a year. E-mode range is more significant.

Some PHEVs do not allow electrical operation when temperature falls below -10°C to protect the batteries. Such behaviour could not be detected, since the vehicles were tested at -7°C. The survey only covered privately owned PHEVs. Private users are likely to utilize the PHEVs electric range capability and recharge overnight, to reduce their cost of driving as it is cheaper to operate the vehicle on electricity than gasoline. People using a leased company car with fuel paid for by the company may not have the same incentive [3].

6 Conclusion

The variation in CO₂-emission is huge for these vehicles when driving in different user selectable drive modes, different drive cycles, temperatures and SOC levels. The variation is much larger than for an ICEV, in particular for CO₂. The conclusion is therefore that PHEVs is a vehicle type that needs to match well with the usage pattern to produce low CO₂- and local pollutant emissions. The vehicles range in E-mode is indicative of real-world performance, as longer range leads to a higher share of electric mode driving and less CO₂-emissions, as long as the vehicle is plugged in and charged frequently. The two vehicles produced CO₂-emission reductions proportional to the range in E-mode when considering an average usage pattern. A 50 km type approved NEDC range lead to 50% reduction estimate in real traffic conditions, and a 31 km E-mode range about 30% reduction, assuming daily recharging at home.

Whether the vehicle has a pure electric drive mode or not seems to be less important for the overall result than the range in E-mode. The average yearly estimated CO₂-emission was about 2.5 times higher than the value stated in the type approval official CO₂-emission test. Larger CO₂-reductions can be achieved with optimum driving patterns, i.e. predominantly local short distance driving, and relatively few long distance trips. Less CO₂-reduction (measured in percentage) will be achieved if drivers have a large share of long distance trips. The benefits could then become marginal compared with HEVs as PHEVs are heavier and thus have high energy consumption when used as a HEV than a regular HEV has. This issue becomes even more important when factoring in emission differences in vehicle production.

Policies that can provide users with incentives to charge their vehicle as often as possible should be considered. Enterprises that offer employees company cars should make sure that the vehicles are recharged.

Some specific user selectable drive modes and demanding driving patterns, especially in cold climate, could lead to excessive local pollutant emissions (over type approval limits). On average, these vehicles are expected to produce local emissions below the emission limit values, when they partly drive on electricity.

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.

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References

- [1] E. Figenbaum, C. Weber, *Experimental testing of Plug-in Hybrid Vehicles - CO₂-emission, energy consumption and local pollution*. TOI report 1539/2016, ISBN 978-82-480-1818-6 Electronic version, Institute of Transport Economics, Oslo, Norway, April 2017.
- [2] E. Figenbaum, M. Kolbenstvedt, *Learning from Norwegian Battery Electric and Plug-in Hybrid Vehicle users. Results from a survey of vehicle owners*. TOI report 1492/2016, ISBN 978-82-480-1789-9 (electronic version), Institute of Transport Economics, Oslo, Norway, June 2016.
- [3] 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 consumption 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
- [4] Spritmonitor 2017. Data extracted 04.01.2017 from the www.spritmonitor.de database on fuel consumption.
- [5] 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>
- [6] 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.

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