

## Developing applicable driving cycle for retrofitted Plug-In Hybrid Electric Vehicles (PHEVs): environmental impact assessment

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### Abstract

According to estimates by two market research companies [1], the proportion of hybrid vehicles in world vehicle registrations will increase from about 1.25 percent in 2010 to a maximum of 18 percent in 2020. A recent EURELECTRIC report [2] calls the plug-in hybrid “a logical development of the hybrid vehicle,” and envisions a potential PHEV market share in Europe of 8 to 20 percent by 2030. The global market for PHEVs is estimated to reach 130,000 vehicles by 2015 [3]. In light of this trend, standardization is needed. The primary objective of standardization is to lower development and production costs and ensure consistent quality, while at the same time satisfying all the demands of practical vehicle operation [4]. Adequate standards for measuring the performance or fuel consumption as well as the emission measurement standards do satisfy customer demand for comparable figures between hybrid models and conventional vehicles. The main objective of this paper is to provide a new adapted type approval test procedure for homologation purposes to better reflect the real environmental benefits of this type of vehicles. The driving cycle is based on the New European Driving Cycle. The environmental assessment together with the new Ecoscores [5] of retrofitted large family cars and SUV's are evaluated.

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*Keywords: car, emissions, PHEV (plug in hybrid electric vehicle), range, standardization*

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### 1 Introduction

In the search for alternative fuels, hybrid vehicles can contribute to reduce airborne emissions in the road-traffic sector. Hybrid technology is an opportunity to bridge the time lapse that will occur before future propulsion systems. The fuel-saving effect of hybrid vehicles, however, depends heavily on their operating conditions. The biggest reduction in fuel consumption is always obtained in city traffic and on short journeys.

There are several degrees of hybridization: depending on technical complexity, different levels of fuel economy can be realized. For example, the adoption of an automatic start-stop system, can reduce fuel consumption in certain operating conditions with only a limited degree of expense. Further potential can be found in the use of a starter generator as a means of boosting the power from the internal combustion engine [6] (mild hybrid). These two alternatives are likely to be of interest mainly to operators of vehicle fleets on delivery work.

Full hybrid vehicles should permit purely electric operation over short distances. In addition, the combination of ICE engine and electric motor means the former is run, whenever possible in the most favourable operating zone in terms of fuel consumption and exhaust emissions. Further savings can thus be made on fuel, but with a high level of technical complexity, which must be offset financially against the possible fuel savings.

The term Plug-In Hybrid refers to a further trend in hybrid vehicle development. These vehicles are equipped with an exceptionally high-performance battery which can be recharged directly from an off-board electric power supply, that's why the term "plug-in" is used. They are also called "range extender" or "grid-dependent" hybrids. The aim of this development is for specific journeys, for instance to and from work, to be performed purely by means of electric propulsion. The internal combustion engine is required only to recharge the batteries in exceptional cases (for longer trips for example). These Plug-In Hybrid Electric Vehicles (PHEVs) can be charged from the grid late at night, at what in many places are lower nighttime rates, making the cost of transportation energy only a fraction of what one pays now for gasoline or diesel fuel.

In order to assess the environmental impact of this operation mode, the plug-in electricity supply for the Belgian situation is assessed.

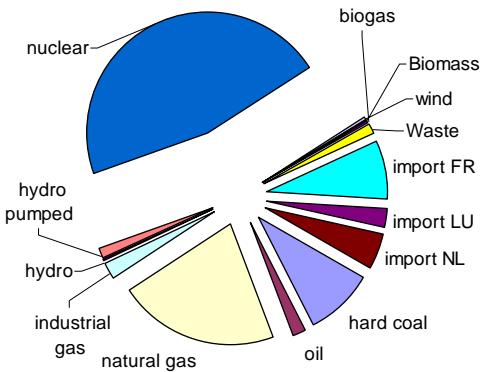


Figure 1: Electricity supply mix for Belgium, adapted from EcoInvent 2007 [7]

The electricity production mix in Belgium is mainly generated by nuclear power, natural gas, petroleum crude oil, coal, water, wind, cogeneration with biomass and waste [8] (Fig.1). These indirect emissions will decrease as older less efficient plants are replaced by cleaner more efficient plants and the share of renewable electrical energy production increases in the future. As a summary, the different described hybrid vehicle systems and functions are displayed in Figure 2. It gives a good view of the relationship between the operation voltage and power of the electric motor.

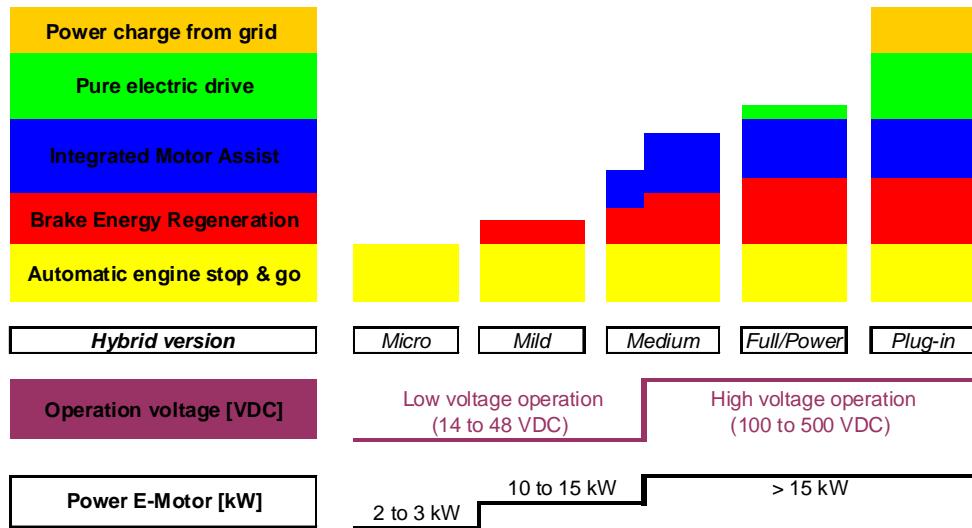


Figure 2: Overview of the hybridization vehicle systems and functions

## 2 Requirements retrofit PHEV conversion module

Today there are only retrofit plug-in conversion kits on the US market. The Toyota Prius from model year 2004 to 2009 can be retrofitted to a PHEV to extend the all electric driving range (AER).

The Hymotion L5 Plug-in Conversion Module is a rechargeable Nanophosphate™ Lithium-ion battery that uses regular grid power to recharge, providing the user with ~5kWh of rechargeable energy storage at full capacity. Once the L5 module is depleted, the vehicle reverts to the normal drive cycle of a stock Toyota Prius. In this way a retrofitted plug-in hybrid saves more energy and produces less pollution than standard hybrids on the road today. Also a charger, hardware for battery box, electrical connections, battery box fan with AC power supply and air



Figure 3: The A123 Hymotion™ L5 Plug-in Conversion Module for a Prius [9]

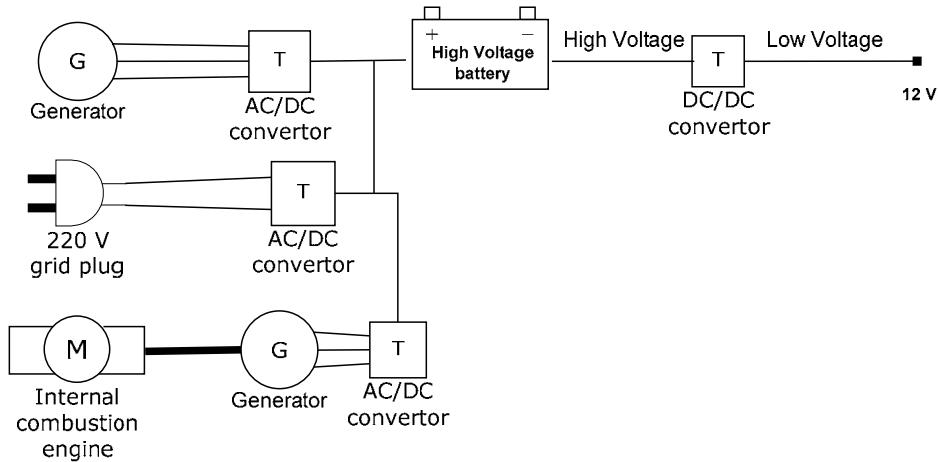


Figure 4: Overview of the power electronic in a PHEV

are included in the upgrade kit. The schematic model of the needed electric components for a PHEV is summarised in Figure 4.

The battery charger converts the 220V alternating current voltage from the house grid plug into a direct current voltage for loading the high voltage battery. At the system level, the module contains a Battery Management System (BMS) that monitors the voltage of each cell in the pack as well as the temperature of the individual battery modules. This information is fed into the electronics controller which automatically terminates charge or discharge in the event that any safety limits are exceeded. The Hymotion conversion kit has 2 CAN Bus ports, one connected to the stock Prius battery, one to the rest of the Prius. This allows it to command and modify certain messages from the stock battery to the Prius, while relaying all other messages.

In the absence of established PHEV certification procedures, the California Air Resources Board (CARB), outlined a path for conditional approval for selling retrofit PHEV modules to customers in California. Therefore each US retrofit module need to be intensively tested and certified in compliance with all relevant Federal safety and emissions standards, including NHTSA and FMVSS vehicle safety standards.

### 3 Requirements of a retrofit PHEV battery

Because of the larger pure electric range the large retrofit high voltage battery need to have a much higher energy content compared with other hybrid vehicles. There is also an important difference in the level of discharge: full-hybrid vehicles use a maximum discharge range from 25% of the total battery energy to enlarge the possible amount of charge cycles. On the other hand, a Plug-In Hybrid Vehicle uses the full discharge range of the battery. At lower speeds and shorter commuting distances, a retrofitted Plug-in hybrid can purely run on the large plug-in capable battery pack thus not using any fossil fuel while still having the ability to travel its full gasoline only range when the large battery packs SoC (State of Charge) has been depleted.

The following table shows an overview over the relevant battery technologies for electric vehicles. For plug-in Hybrids with their higher requirements on both energy density and power density Lithium batteries seem to be appropriate.

Table 1: Overview battery technologies for electric vehicles [10]

| Battery type | Specific energy [Wh/kg] | Specific power [W/kg] | Life Cycle | Efficiency [%]          |
|--------------|-------------------------|-----------------------|------------|-------------------------|
| Lead-acid    | 25-30                   | 80-300                | 600-1000   | 82,5                    |
| NiCd         | 50-60                   | 200-500               | 1500-2000  | 72,5                    |
| NiMH         | 60-70                   | 200-1500              | 1500-2000  | 70                      |
| NaNiCl       | 125                     | 100-160               | 600-1000   | 92 minus heating losses |
| Li-thium     | 60-150                  | 80-2000               | >1000      | 90                      |

In order to design an appropriate PHEV it's necessary to estimate the typical driving trip patterns and distances.

Based on the Belgian statistical figures of the Federal public Office [11] the average daily covered private trip distance per person is not more than 40 km. These data are also compared with specific survey data collected from the "ESTIMATE"-project [12] to calculate the normal needs. This travel behaviour survey

shows that within Belgium 95 % of the respondents cover less than 58 km per day with their car. A plug-in hybrid that could travel this range on electric power alone would thus satisfy most people's requirements while potentially freeing them from their reliance on petroleum-based fuel. In this study a retrofit PHEV that can run 60 km purely on electricity, will be able to run 100% of his urban kilometres only on the electrical motor is assumed. The assumed relationship between the all electric range (AER) and the share of full electric drive in the urban drive cycle is depicted in the following table.

Table 2: Assumed relationship between electric share of urban drive and AER for retrofit PHEV

| Share urban electric drive | AER retrofit PHEV | Retrofit type |
|----------------------------|-------------------|---------------|
| 25%                        | 15 km             | PHEV15        |
| 50%                        | 30 km             | PHEV30        |
| 75%                        | 45 km             | PHEV45        |
| 100%                       | 60 km             | PHEV60        |

The needed extra amount of rechargeable energy storage of the battery can be calculated with the following formula:

$$ES_{AER} = \frac{AER * EC}{1000} \quad (1)$$

With:

ES<sub>AER</sub>: Rechargeable energy storage in [kWh]

AER: All electric range in [km]

EC: Electric consumption in [Wh/km]

The weight of the battery is depending on her specific energy, following the following formula:

$$Weight_{bat} = \frac{ES_{AER} * 1000}{Specific\ energy} \quad (2)$$

With:

Weight<sub>bat</sub>: Weight of retrofit battery in [kg]

ES<sub>AER</sub>: Rechargeable energy storage in [kWh]

Specific energy: Energy of battery in [Wh/kg]

## 4 Calculation method Ecoscore for retrofitted PHEV's

### 4.1 Procedure emission testing cycle

Within the type approval procedure the New European Driving Cycle (NEDC) is used [13,14].

This is a driving cycle consisting of four repeated ECE-15 driving cycles (Figure 5) and an Extra-Urban driving cycle, or EUDC (Figure 6). The NEDC is supposed to represent the typical use of a car in Europe, and is used to assess the emission levels of car.

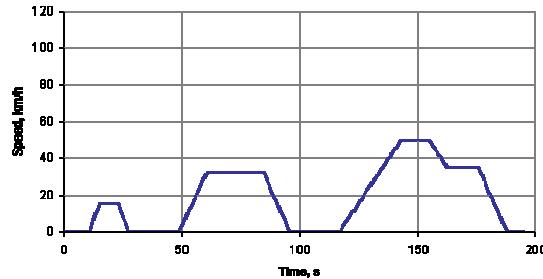


Figure 5: Time-speed data points ECE 15 Cycle

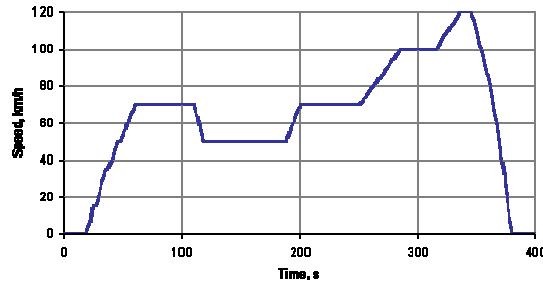


Figure 6: Time-speed data points EUDC Cycle

Table 3 shows a summary of the parameters for both the ECE and EUDC cycles.

Table 3: Characteristics Unit ECE 15 and EUDC  
(Adapted from [www.dieselnet.com](http://www.dieselnet.com))

| Characteristics | Unit | ECE 15             | EUDC  |
|-----------------|------|--------------------|-------|
| Distance        | km   | 4×1,013=4,052      | 6,955 |
| Duration        | s    | 4×195=780          | 400   |
| Average Speed   | km/h | 18,7 (with idling) | 62,6  |
| Maximum Speed   | km/h | 50                 | 120   |
| Cycle share     | %    | 36,8               | 63,2  |

The standardized NEDC fuel consumption value can be calculated as a weighted average of the urban and extra urban consumption value:

$$FC_{NEDC} = 36,8\% FC_{Urban} + 63,2\% FC_{Extra-Urban} \quad (3)$$

With in this formula:

FC<sub>NEDC</sub>: the norm fuel consumption in litre per 100 km (petrol, LPG or diesel) or in Wh per 100 km (electric grid power)

FC<sub>Urban</sub>: the fuel consumption in litre per 100 km or in Wh per 100 km during ECE driving cycle

FC<sub>Extra-Urban</sub>: the fuel consumption in litre per 100 km or in Wh per 100 km during EUDC driving cycle

## 4.2 Assumptions for the retrofit PHEV

A methodology to assess the emissions of vehicles converted to plug-in hybrids is proposed in this section, in order to assess the emissions and fuel consumption and to calculate the Ecoscore of these vehicles.

For the extra urban EUDC-driving cycle the homologated extra urban fuel consumption value of the hybrid vehicle from the homologation file is taken into account, since we assume that the extra urban part will not be driven in electric mode. For the urban part the all electric range is taken into account.

In this way, the new consumption value for retrofitted PHEV's can be calculated according to the following equations:

$$FC_{phev\_i} = (1 - i) * 36,8\% HC_{urban} + 63,2\% HC_{extra-urban} \quad (4)$$

$$EC_{phev\_i} = i * 36,8\% EC \quad (5)$$

With in these equations:

FC<sub>phev i</sub>: the fuel consumption in litre per 100 km in the case of petrol, LPG or diesel;

EC<sub>phev i</sub>: the electricity consumption in Wh per 100 km in the case of electric grid power;

EC: the pure electric consumption in Wh per 100 km from the electric grid power plug;

HC: the extra-urban fuel consumption in litre per 100 km in hybrid mode;

i: specific factor depending on all electric range (AER) coming from the retrofit battery:

- Where i equals to 0 for HEV;
- Where i equals to 0,25 for PHEV15;
- Where i equals to 0,5 for PHEV30;
- Where i equals to 0,75 for PHEV45;
- Where i equals to 1 for PHEV60.

### 4.3 Consumption calculation of AER

Since the PHEV is not yet homologated for the market, assumptions on energy consumption have to be made.

For the urban driving cycle the electric grid consumption (including the battery charging efficiency of 90 %), is for a retrofitted PHEV in charge-depleting operating mode is calculated by the following formula (6):

$$C = 80 + 80/M \quad (6)$$

with:

C: specific consumption value in [Wh / Ton km]

M: mass of the vehicle in [Ton]

This equation is based on several real road measurements performed by CITELEC [15]. The empirical formulae can be validated by the results of Argonne National Laboratory [16] according to the following relation between Electric consumption versus Vehicle mass:

$$Y = 0,19537 * X - 87,8426 \quad (7)$$

With:

Y: Electric consumption in [kWh/mile]

X: Vehicle mass in [kg]

The relationship between both empirical formulae are displayed in Figure 7.

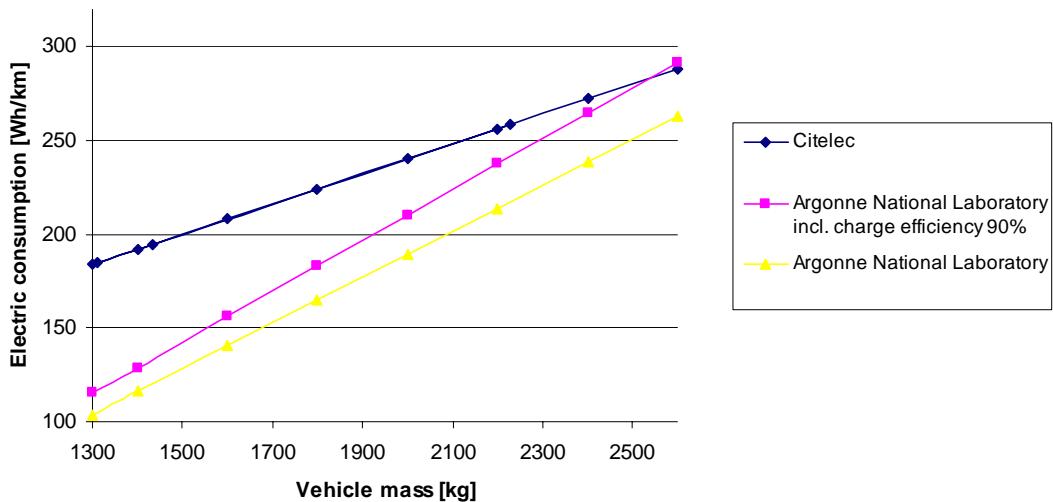


Figure 7: Electric consumption versus Vehicle mass: source comparison empirical results

Until 2500 kg vehicle mass the empirical formula of CITELEC gives the highest consumption values. Hence, the values of this worst case scenario will be further used in the model.

The results of the electrical consumption calculation for the urban ECE-cycle are shown in

Table 4 and 5. For both models a PHEV with plug-in capability and sufficient battery capacity to provide respectively 15, 30, 45 and 60 kilometres of all-electric range on the urban driving cycle are considered.

Table 4: Electric economy calculation for PHEV retrofit Prius

|  | Toyota Prius<br>retrofitted PHEV 15 km | Toyota Prius<br>retrofitted PHEV 30 km | Toyota Prius<br>retrofitted PHEV 45 km | Toyota Prius<br>retrofitted PHEV 60 km |
|--|--|--|--|--|
| Mass HEV [kg]                          | 1310                                   | 1310                                   | 1310                                   | 1310                                   |
| Mass Retrofit Plug-in [kg]             | 41                                     | 61                                     | 92                                     | 122                                    |
| Total mass [kg]                        | 1351                                   | 1371                                   | 1402                                   | 1432                                   |
| Electric consumption<br>[Wh/km]        | 188                                    | 190                                    | 192                                    | 195                                    |
| Energy storage<br>retrofit module[kWh] | 3                                      | 6                                      | 9                                      | 12                                     |

Table 5: Electric economy calculation for PHEV retrofit Lexus RX400h

|  | Lexus RX 400h<br>retrofitted PHEV 15 km | Lexus RX 400h<br>retrofitted PHEV 30 km | Lexus RX 400h<br>retrofitted PHEV 45 km | Lexus RX 400h<br>retrofitted PHEV 60 km |
|--|---|---|---|---|
| Mass HEV [kg]                          | 2000                                    | 2000                                    | 2000                                    | 2000                                    |
| Mass Retrofit Plug-in [kg]             | 75                                      | 114                                     | 170                                     | 227                                     |
| Total mass [kg]                        | 2075                                    | 2114                                    | 2170                                    | 2227                                    |
| Electric consumption<br>[Wh/km]        | 246                                     | 249                                     | 254                                     | 258                                     |
| Energy storage<br>retrofit module[kWh] | 4                                       | 7                                       | 11                                      | 15                                      |

#### 4.4 WTW emissions PHEV's

For the Toyota Prius and the Lexus RX 400h this model was simulated in order to obtain the total environmental impact and the appropriate Ecoscore [5]. Other representative big family cars and Sport utility vehicles with conventional drivelines and fuels are added to compare the relative impact.

In Table 6 and table 7 we notice that for the large family car category, the retrofitted plug-in Prius PHEV 60 km can reduce smog-forming gases by 26% and greenhouse gases by 21% (WTW) when compared to the standard Prius. In Table 8 the calculated Well-to-tank grid Belgium electricity production emissions for the considered PHEV's are displayed.

Table 6: Consumption values and Well-to-wheel GHG emissions

| Car model                   | Consumption |        | Green house gases |        |        |                  |        |        |                 |        |        |
|-----------------------------|-------------|--------|-------------------|--------|--------|------------------|--------|--------|-----------------|--------|--------|
|                             | Electric    | Fuel   | CO <sub>2</sub>   |        |        | N <sub>2</sub> O |        |        | CH <sub>4</sub> |        |        |
| Unit                        | [Wh/km]     | [l/km] | [g/km]            | [g/km] | [g/km] | [g/km]           | [g/km] | [g/km] | [g/km]          | [g/km] | [g/km] |
| Emission type               |             |        | WTT               | TTW    | WTW    | WTT              | TTW    | WTW    | WTT             | TTW    | WTW    |
| <b>Large family cars</b>    |             |        |                   |        |        |                  |        |        |                 |        |        |
| Volvo S40 1.8 Petrol        | 0           | 7,3    | 37                | 174    | 211    | 0,0005           | 0,0050 | 0,0055 | 0,1174          | 0,0200 | 0,1374 |
| VolvoS40 2.0 Diesel 100 kW  | 0           | 5,8    | 22                | 153    | 175    | 0,0004           | 0,0080 | 0,0084 | 0,0895          | 0,0100 | 0,0995 |
| Volvo S40 2.0D FAP          | 0           | 5,8    | 22                | 154    | 176    | 0,0004           | 0,0080 | 0,0084 | 0,0895          | 0,0100 | 0,0995 |
| Volvo S40 1.8 LPG           | 0           | 9,2    | 34                | 153    | 187    | 0,0005           | 0,0050 | 0,0055 | 0,1127          | 0,0200 | 0,1327 |
| Prius 1.5VVT-I HYBRID       | 0           | 4,3    | 22                | 104    | 126    | 0,0003           | 0,0050 | 0,0053 | 0,0692          | 0,0200 | 0,0892 |
| Prius 1.5VVT-I PHEV 60      | 71,8        | 2,7    | 34                | 66     | 99     | 0,0003           | 0,0032 | 0,0035 | 0,0440          | 0,0126 | 0,0566 |
| Prius 1.5VVT-I PHEV 45      | 53,8        | 3,1    | 31                | 75     | 106    | 0,0003           | 0,0036 | 0,0039 | 0,0503          | 0,0145 | 0,0648 |
| Prius 1.5VVT-I PHEV 30      | 35,9        | 3,5    | 28                | 85     | 112    | 0,0003           | 0,0041 | 0,0044 | 0,0566          | 0,0163 | 0,0729 |
| Prius 1.5VVT-I PHEV 15      | 17,9        | 3,9    | 25                | 94     | 119    | 0,0003           | 0,0045 | 0,0049 | 0,0629          | 0,0182 | 0,0810 |
| <b>SUV's</b>                |             |        |                   |        |        |                  |        |        |                 |        |        |
| Mercedes-Benz ML 350        | 0           | 11,1   | 56                | 266    | 322    | 0,0008           | 0,0050 | 0,0058 | 0,1786          | 0,0200 | 0,1986 |
| Mercedes-Benz ML 320CDI     | 0           | 9,3    | 35                | 245    | 280    | 0,0006           | 0,0080 | 0,0086 | 0,1436          | 0,0100 | 0,1536 |
| Mercedes-Benz ML 320CDI FAP | 0           | 9,1    | 34                | 241    | 275    | 0,0006           | 0,0080 | 0,0086 | 0,1405          | 0,0100 | 0,1505 |
| Mercedes-Benz ML 350 LPG    | 0           | 14,1   | 52                | 234    | 286    | 0,0007           | 0,0050 | 0,0057 | 0,1727          | 0,0200 | 0,1927 |
| Lexus RX 400H               | 0           | 8,1    | 41                | 192    | 233    | 0,0006           | 0,0050 | 0,0056 | 0,1303          | 0,0200 | 0,1503 |
| Lexus RX 400 PHEV 60        | 94,9        | 4,8    | 51                | 121    | 172    | 0,0005           | 0,0032 | 0,0037 | 0,0776          | 0,0126 | 0,0902 |
| Lexus RX 400 PHEV 45        | 71,2        | 5,5    | 47                | 139    | 186    | 0,0005           | 0,0036 | 0,0041 | 0,0888          | 0,0145 | 0,1033 |
| Lexus RX 400 PHEV 30        | 47,5        | 6,2    | 44                | 157    | 201    | 0,0005           | 0,0041 | 0,0046 | 0,0999          | 0,0163 | 0,1163 |
| Lexus RX 400 PHEV 15        | 23,7        | 6,9    | 41                | 174    | 216    | 0,0005           | 0,0045 | 0,0051 | 0,1111          | 0,0182 | 0,1293 |

Table 7: Well-to-wheel air-quality and sound emissions

| Car model                | Air quality |        |        |        |        |        |        |        |        |        |        |        |                 |        | Sound   |    |
|--------------------------|-------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|-----------------|--------|---------|----|
|                          | NMHC        |        |        | CO     |        |        | PM10   |        |        | NOx    |        |        | SO <sub>2</sub> |        |         |    |
| Unit                     | [g/km]      | [g/km] | [g/km] | [g/km] | [g/km] | [g/km] | [g/km] | [g/km] | [g/km] | [g/km] | [g/km] | [g/km] | [g/km]          | [g/km] | [dB(A)] |    |
| Emission type            | WTT         | TTW    | WTW    | WTT    | TTW    | WTW    | WTT    | TTW    | WTW    | WTT    | TTW    | WTW    | WTT             | TTW    | TTW     |    |
| <b>Large family cars</b> |             |        |        |        |        |        |        |        |        |        |        |        |                 |        |         |    |
| Volvo S40 1.8 Petrol     | 0,070       | 0,052  | 0,122  | 0,047  | 0      | 0,047  | 0,026  | 0      | 0,026  | 0,117  | 0,022  | 0,139  | 0,329           | 0,005  | 0,334   | 71 |
| Volvo S40 2.0 Diesel     | 0,058       | 0,031  | 0,089  | 0,042  | 0,500  | 0,542  | 0,017  | 0,022  | 0,039  | 0,081  | 0,245  | 0,326  | 0,208           | 0,005  | 0,213   | 74 |
| Volvo S40 2.0D FAP       | 0,058       | 0,015  | 0,073  | 0,042  | 0      | 0,042  | 0,017  | 0,002  | 0,019  | 0,081  | 0,159  | 0,240  | 0,208           | 0,005  | 0,213   | 74 |
| Volvo S40 1.8 LPG        | 0,064       | 0,052  | 0,116  | 0,044  | 0      | 0,044  | 0,021  | 0      | 0,021  | 0,097  | 0,022  | 0,119  | 0,251           | 0,002  | 0,253   | 71 |
| Prius HEV                | 0,042       | 0,020  | 0,062  | 0,028  | 0,180  | 0,208  | 0,015  | 0      | 0,015  | 0,069  | 0,010  | 0,079  | 0,194           | 0,003  | 0,197   | 69 |
| Prius PHEV 60            | 0,029       | 0,013  | 0,042  | 0,020  | 0,114  | 0,133  | 0,013  | 0      | 0,013  | 0,072  | 0,006  | 0,078  | 0,150           | 0,002  | 0,152   | 67 |
| Prius PHEV 45            | 0,032       | 0,014  | 0,047  | 0,022  | 0,130  | 0,152  | 0,013  | 0      | 0,013  | 0,071  | 0,007  | 0,078  | 0,161           | 0,002  | 0,163   | 68 |
| Prius PHEV 30            | 0,035       | 0,016  | 0,052  | 0,024  | 0,147  | 0,171  | 0,014  | 0      | 0,014  | 0,071  | 0,008  | 0,079  | 0,172           | 0,003  | 0,175   | 68 |
| Prius PHEV 15            | 0,038       | 0,018  | 0,057  | 0,026  | 0,163  | 0,189  | 0,015  | 0      | 0,015  | 0,070  | 0,009  | 0,079  | 0,183           | 0,003  | 0,186   | 69 |
| <b>SUV's</b>             |             |        |        |        |        |        |        |        |        |        |        |        |                 |        |         |    |
| M-B ML 350               | 0,107       | 0,023  | 0,130  | 0,071  | 0,260  | 0,331  | 0,039  | 0      | 0,039  | 0,179  | 0,011  | 0,190  | 0,500           | 0,008  | 0,508   | 75 |
| M-B ML 320CDI            | 0,093       | 0,020  | 0,113  | 0,067  | 0,450  | 0,517  | 0,027  | 0,029  | 0,056  | 0,130  | 0,316  | 0,446  | 0,334           | 0,008  | 0,342   | 72 |
| M-B ML 320CDI FAP        | 0,091       | 0,020  | 0,111  | 0,065  | 0,450  | 0,515  | 0,026  | 0,003  | 0,029  | 0,127  | 0,316  | 0,443  | 0,327           | 0,008  | 0,334   | 72 |
| M-B ML 350 LPG           | 0,097       | 0,023  | 0,120  | 0,068  | 0,260  | 0,328  | 0,032  | 0      | 0,032  | 0,148  | 0,011  | 0,159  | 0,385           | 0,002  | 0,388   | 75 |
| Lexus RX 400H            | 0,078       | 0,030  | 0,108  | 0,052  | 0,300  | 0,352  | 0,029  | 0      | 0,029  | 0,130  | 0      | 0,130  | 0,365           | 0,006  | 0,371   | 71 |
| Lexus RX 400 PHEV 60     | 0,051       | 0,019  | 0,070  | 0,034  | 0,190  | 0,223  | 0,021  | 0      | 0,021  | 0,114  | 0      | 0,114  | 0,253           | 0,004  | 0,257   | 69 |
| Lexus RX 400 PHEV 45     | 0,056       | 0,022  | 0,078  | 0,038  | 0,217  | 0,255  | 0,022  | 0      | 0,022  | 0,116  | 0      | 0,116  | 0,275           | 0,004  | 0,280   | 70 |
| Lexus RX 400 PHEV 30     | 0,062       | 0,024  | 0,086  | 0,041  | 0,245  | 0,286  | 0,024  | 0      | 0,024  | 0,118  | 0      | 0,118  | 0,298           | 0,005  | 0,303   | 70 |
| Lexus RX 400 PHEV 15     | 0,068       | 0,027  | 0,095  | 0,045  | 0,272  | 0,318  | 0,025  | 0      | 0,025  | 0,120  | 0      | 0,120  | 0,320           | 0,006  | 0,326   | 71 |

Table 8: Well-to-tank grid electricity production emissions

| Grid Electricity Consumption | CO <sub>2</sub> | N <sub>2</sub> O | CH <sub>4</sub> | NMHC  | CO    | PM    | NOx   | SO <sub>2</sub> |
|------------------------------|-----------------|------------------|-----------------|-------|-------|-------|-------|-----------------|
|                              | WTT             | WTT              | WTT             | WTT   | WTT   | WTT   | WTT   | WTT             |
| Prius 1.5VVT-I PHEV 60       | 19,927          | 0,0001           | 0,0003          | 0,003 | 0,002 | 0,003 | 0,028 | 0,028           |
| Prius 1.5VVT-I PHEV 45       | 14,945          | 0,0001           | 0,0002          | 0,002 | 0,002 | 0,002 | 0,021 | 0,021           |
| Prius 1.5VVT-I PHEV 30       | 9,963           | 0,0001           | 0,0001          | 0,002 | 0,001 | 0,002 | 0,014 | 0,014           |
| Prius 1.5VVT-I PHEV 15       | 4,982           | 0,0000           | 0,0001          | 0,001 | 0,001 | 0,001 | 0,007 | 0,007           |
| Lexus RX 400 PHEV 60         | 26,364          | 0,0001           | 0,0003          | 0,004 | 0,003 | 0,004 | 0,037 | 0,037           |
| Lexus RX 400 PHEV 45         | 19,773          | 0,0001           | 0,0003          | 0,003 | 0,002 | 0,003 | 0,028 | 0,028           |
| Lexus RX 400 PHEV 30         | 13,182          | 0,0001           | 0,0002          | 0,002 | 0,001 | 0,002 | 0,019 | 0,018           |
| Lexus RX 400 PHEV 15         | 6,591           | 0,0000           | 0,0001          | 0,001 | 0,001 | 0,001 | 0,009 | 0,009           |

The above tables 6, 7 and 8 show that for the SUV category, a retrofitted plug-in PHEV 60 km version of the Lexus RX 400h reduces greenhouse gases by 26% and smog-forming gases by 30% relative to the Lexus RX 400h, and respectively by 47% and 54% when compared to a conventional SUV like the Mercedes ML 350. The maximum fuel usage cut of approximately 40% from HEV to PHEV60 is conform with the statement of AESAC in 2007 [17].

Figure 9 illustrates the total impact (TI) per passenger, split up per damage category, for each

of the large family vehicles listed in the previous tables. This figure allows the comparison of the different damage categories for the reference vehicles within the specific vehicle category. The drive of the NEDC-cycle with a plug-in hybrid vehicle PHEV 60 km is characterised by the lowest impact on the global warming, human health, ecosystem and sound pollution.

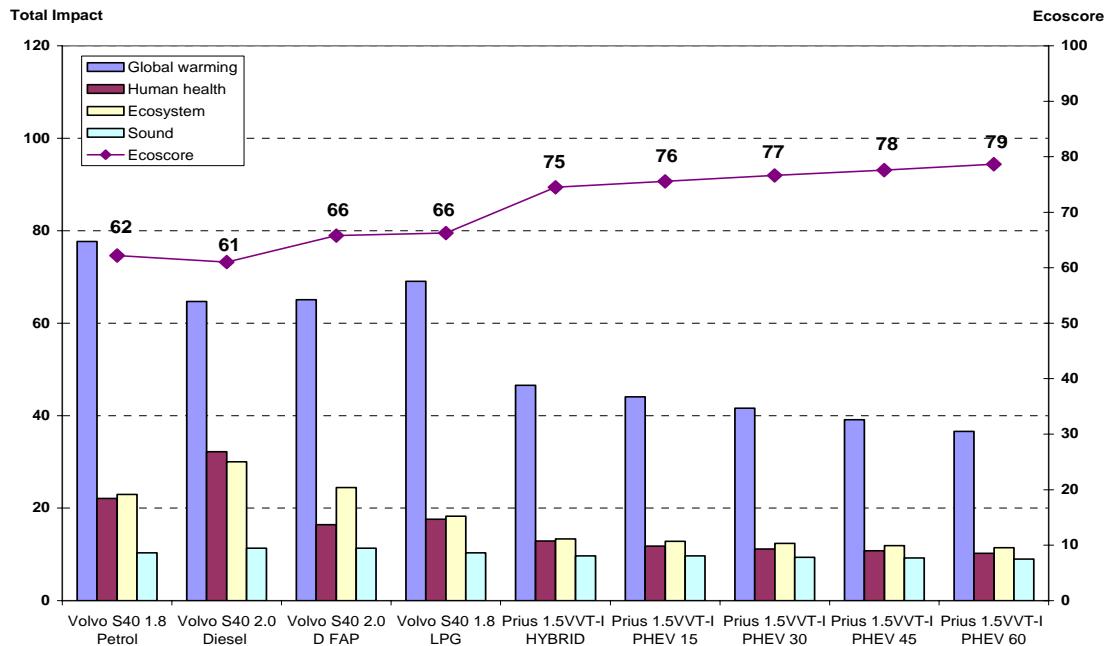


Figure 8: Total impacts and Ecoscores of large family cars

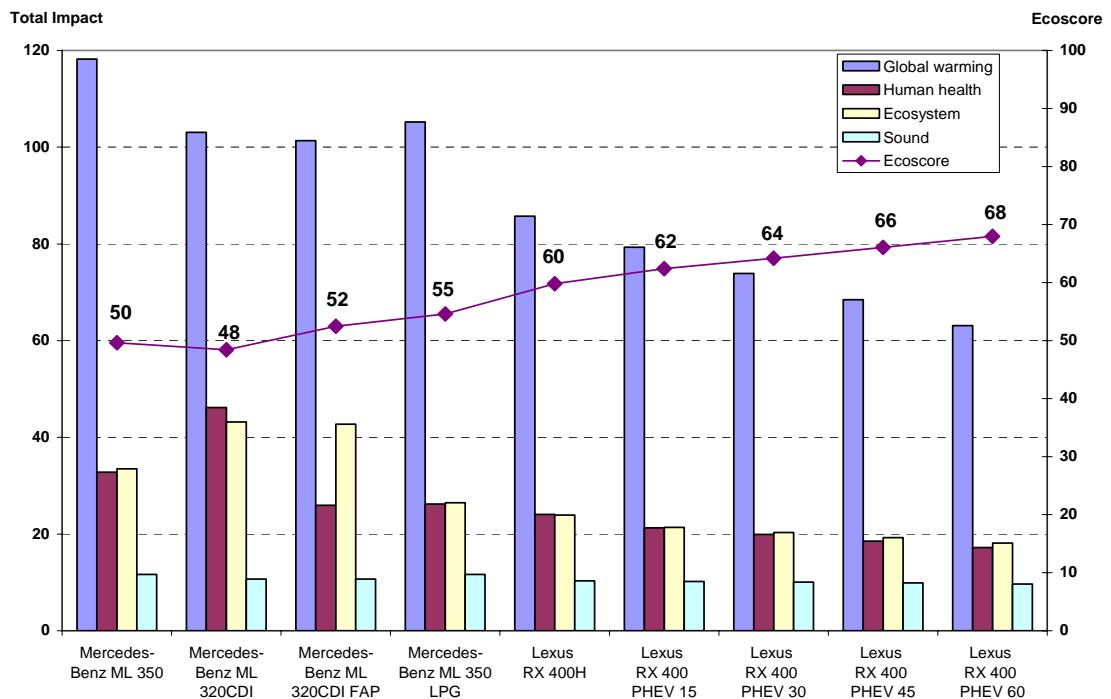


Figure 9: Total impacts and Ecoscores of SUV's

Figure 10 illustrates the total impact (TI), split up per damage category, for each of the considered SUV vehicles. This figure allows the comparison of the different damage categories for the reference vehicles within the SUV category. Hybrid and plug-in hybrid passenger transport technologies also show a lower level of noise pollution than the most recent conventional technologies. The retrofitted plug-in hybrid Lexus RX 400h PHEV 60 km has the lowest impact on each damage category. Also the appropriate Ecoscores are displayed in the same figure. The retrofitted Prius PHEV60 has the highest Ecoscore.

## 5 Sensitivity analysis for the specific energy value of the retrofit PHEV battery

In order to analyse the robustness of the considered models, the impact on the choice of

the specific energy value of the battery is assessed. In table 9 and 10 the impact on the requirements due to the choice of the minimum value of 60 Wh/kg and the maximum value of 150 Wh/kg for the Lithium battery are displayed. A lower specific energy value will have a negative impact on the weight of the battery and the vehicle consumption. For the Prius the weight increase is so small that it has no influence on the needed amount of energy storage in kWh. For the Lexus RX400h only 1 kWh more energy storage is needed for the PHEV30, PHEV45 and the PHEV60.

Both minimum and maximum ranges of the specific energy values give for all the retrofitted Prius and the Lexus RX400h models no changes in the Ecoscore and the CO<sub>2</sub> TTW emission values (without decimal places).

Table 9: Impact specific energy range of retrofit battery PHEV for large family cars

|   | Toyota Prius<br>retrofitted PHEV 15 km | Toyota Prius<br>retrofitted PHEV 30 km | Toyota Prius<br>retrofitted PHEV 45 km | Toyota Prius<br>retrofitted PHEV 60 km |
|---|--|--|--|--|
| Energy storage<br>retrofit module[kWh]                        | 3                                      | 6                                      | 9                                      | 12                                     |
| Mass HEV [kg]   | 1310                                   | 1310                                   | 1310                                   | 1310                                   |
| Weight charger+hardware pack                                  | 22                                     | 22                                     | 22                                     | 22                                     |
| Weight retrofit Lithium battery<br>with 60 Wh/kg energy [kg]  | 47                                     | 95                                     | 144                                    | 195                                    |
| Weight retrofit Lithium battery<br>with 150 Wh/kg energy [kg] | 19                                     | 38                                     | 58                                     | 78                                     |
| Total mass with 60 Wh/kg [kg]                                 | 1379                                   | 1427                                   | 1476                                   | 1527                                   |
| Total mass with 150 Wh/kg [kg]                                | 1351                                   | 1370                                   | 1390                                   | 1410                                   |
| Electric consumption<br>with 60 Wh/kg battery [Wh/km]         | 190                                    | 194                                    | 198                                    | 202                                    |
| Electric consumption<br>with 150 Wh/kg battery [Wh/km]        | 188                                    | 190                                    | 191                                    | 193                                    |

Table 10: Impact specific energy range of retrofit battery PHEV for SUV's

|   | Lexus RX 400h<br>retrofitted PHEV 15 km | Lexus RX 400h<br>retrofitted PHEV 30 km | Lexus RX 400h<br>retrofitted PHEV 45 km | Lexus RX 400h<br>retrofitted PHEV 60 km |
|---|---|---|---|---|
| Energy storage<br>retrofit module[kWh]                        | 4                                       | 7                                       | 11                                      | 15                                      |
| Mass HEV [kg]   | 2000                                    | 2000                                    | 2000                                    | 2000                                    |
| Weight charger+hardware pack                                  | 50                                      | 50                                      | 50                                      | 50                                      |
| Weight retrofit Lithium battery<br>with 60 Wh/kg energy [kg]  | 61                                      | 125                                     | 190                                     | 258                                     |
| Weight retrofit Lithium battery<br>with 150 Wh/kg energy [kg] | 25                                      | 50                                      | 76                                      | 103                                     |
| Total mass with 60 Wh/kg [kg]                                 | 2111                                    | 2175                                    | 2240                                    | 2308                                    |
| Total mass with 150 Wh/kg [kg]                                | 2075                                    | 2100                                    | 2126                                    | 2153                                    |
| Electric consumption<br>with 60 Wh/kg battery [Wh/km]         | 249                                     | 254                                     | 259                                     | 265                                     |
| Electric consumption<br>with 150 Wh/kg battery [Wh/km]        | 246                                     | 248                                     | 250                                     | 252                                     |

## 6 Conclusions

Basically, Plug-In Hybrid Electric Vehicles (PHEVs) use the same technology as the standard hybrids on the road, but have a larger battery pack that can be recharged by plugging into a standard home electrical outlet. A key reason for exploring PHEV technology is its ability to achieve significant fossil fuel consumption reduction benefits. As the blend of electricity generation progresses towards greener generation sources, such as solar and wind, the environmental benefits of plug-in hybrids will continue to grow.

Type approval should be based on a driving cycle that corresponds more closely to real circumstances driving conditions. A new applicable test method of fuel consumption and exhaust emissions for retrofitted externally chargeable HEVs is developed to better reflect the environmental advantages of this type of vehicles.

An applicable model was developed to calculate the Ecoscore for all possible retrofit PHEV's. The mean assumption is that a HEV retrofitted with an extra battery capacity providing 60 pure electric kilometres is sufficient to run completely the four ECE urban drive cycles of the NEDC test cycle.

A retrofitted PHEV that can run only 45 pure electric kilometres will only run the three ECE-cycles in charge-depleting mode. The electric consumption value is calculated with an

empirical formulae from several road measurements performed by CITELEC. The rest of the test cycle, the fourth ECE cycle and the extra urban driving cycle (EUDC) will then be ran in the standard hybrid mode.

The retrofitted PHEV that can run only 30 pure electric kilometres will only run the first two ECE-cycles in charge-depleting mode, the rest will be ran in the standard hybrid mode.

The retrofitted PHEV that can run only 15 pure electric kilometres will only run the first ECE-cycle in charge-depleting mode, the rest will be ran in the standard hybrid mode.

For these four retrofit PHEV's the influence on the environmental impact and their Ecoscore was investigated.

Calculations of the environmental impact show that within a chosen category the drive of the NEDC-cycle with a plug-in hybrid vehicle with an extra battery capacity providing 60 pure electric kilometres is characterised by the lowest impact on the global warming, human health, ecosystem and sound pollution.

For both considered retrofitted plug-in large family and SUV vehicles the Tank-To-Wheel CO<sub>2</sub> emissions drop from 9 % for the PHEV15 to 37 % for the PHEV60.

For considered retrofitted plug-in large family vehicles the Ecoscore increases up to 4 points compared to their standard hybrid version. For considered retrofitted plug-in SUV vehicles the Ecoscore increases up to 8 points compared to their standard hybrid version.

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