THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

BRIEFING

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Too low to be true? How to measure fuel consumption and CO_2 emissions of plug-in hybrid vehicles, today and in the future

The global market for electric vehicles is growing rapidly. In January 2017, cumulative global sales of electric vehicles reached the second million milestone.[1] Plug-in hybrid electric vehicles (PHEVs[2]) play a particularly important role given their relatively high market share – accounting for 13 % of all new passenger cars in Norway and 5 % in the Netherlands in 2016, for example.[3]

From the perspective of vehicle manufacturers, type-approval authorities, and consumers, PHEVs provide a specific challenge: They use two different energy sources, fuel and electricity, and the relative shares between these two energy types strongly depend on how the vehicle is driven and recharged in practice. Therefore, it is no surprise that some consumers struggle to understand why the fuel consumption values advertised for their PHEVs are so much lower and the advertised electric range is so much higher than what they experience in everyday driving.

1 Lutsey, N. (2017). The rise of electric vehicles: The second million. Retrieved from http://www.theicct.org/blogs/staff/second-million-electric-vehicles

2 Note that in some regulations, a PHEV is referred to as an off-vehicle charging hybrid electric vehicle (OVC-HEV)

3 Senzeybek, M., Tietge, U., & Mock, P. (2017). CO_2 emissions from new passenger cars in the EU: Car manufacturers' performance in 2016. Retrieved from http://www.theicct.org/co2-emissions-new-PV-EU-OEM-performance-2016

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This document first outlines the current procedure for the determination of fuel consumption, carbon dioxide (CO_2) emissions,[4] electric energy consumption, and electric range, specifically for PHEVs in Europe; this current procedure is described in the United Nations Economic Commission for Europe (UN-ECE) Regulation R101.[5] It then highlights the most relevant changes expected with the introduction of the new Worldwide Harmonized Light Vehicles Test Procedure (WLTP), which will come into effect in the European Union (EU) in September 2017. Finally, key differences between the EU and U.S. test procedures for PHEVs are briefly discussed.

A PHEV CAN DRIVE IN TWO OPERATING MODES

If the battery of a PHEV is fully charged, the vehicle will mainly drive using the electric charge – except if the desired speed and/or acceleration forces the internal combustion engine (ICE) to assist. Because this operating mode depletes the battery, it is referred to as a *charge-depleting (CD) mode* (in UN-ECE R101, this is indicated as “Condition A”).

When the battery is (almost) depleted, the PHEV will mainly use the ICE for driving. The battery can still be used for more conventional hybrid vehicle operation (e.g., for storing energy from regenerative braking), but it will generally remain at about the same charge level. Therefore, this is referred to as the *charge-sustaining (CS) mode* (in UN-ECE R101, this is indicated as “Condition B”).

There is no discrete point in time when the vehicle decides to transition from CD to CS mode, but the test procedure provides for a calculation to estimate that point. The PHEV test procedure measures separate fuel and electricity consumption values for both of these operation modes and combines them into one weighted average fuel consumption for the final test result.

TESTING IN CD MODE

For the R101 test procedure, as it is currently applied in Europe, the vehicle is preconditioned by first discharging the battery in a defined manner to the battery’s minimum state of charge (SOC) level (SOC is an indicator where the battery is between empty and full). It is then soaked in a climate-controlled area at a temperature between 20°C and 30°C while the battery is being fully charged overnight.

The next day, the vehicle is tested over one complete cycle in the New European Driving Cycle (NEDC; Figure 1).[6] The fuel consumption in CD mode is defined as the fuel consumption measured during that test (indicated as C_1, in liters per 100 kilometers). The battery is then fully recharged. The electrical energy required during that recharging process (defined as e_1) is divided by the distance driven during the NEDC test to arrive at the electric energy consumption for the CD mode (E_1, in Wh/km).

4 Since CO_2 is directly proportional to fuel consumption, the reader may substitute CO_2 for fuel consumption.

5 The current test procedure is described in Paragraphs 3 and 4 of Annex 8 in United Nations Economic Commission for Europe (UN-ECE) Regulation R101. UN-ECE R101 is available at https://www.unece.org/trans/main/wp29/wp29regs101-120.html

6 This test is referred to here as “Option 1”. There is a second option, “Option 2”, under which the vehicle is tested over repeated NEDC test cycles until the battery is depleted. For simplification, we focus only on Option 1 in this briefing paper.

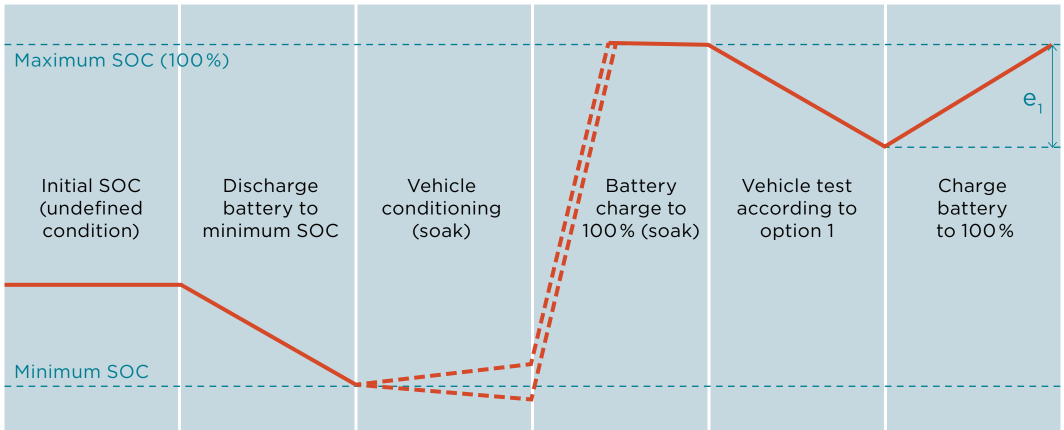

Figure 1: Schematic overview of the CD mode test procedure for Option 1 (one NEDC test cycle).

TESTING IN CS MODE

Following optional conditioning of the vehicle, the battery is first discharged to a minimum SOC level, and the vehicle is soaked in a climate-controlled area between 20°C and 30°C (Figure 2). The vehicle is then tested over one NEDC test cycle. After the test, the battery is charged until it reaches the maximum SOC, and the electricity required during this charging process is measured (defined as e_2, in Wh). In a next step, the battery is discharged until it reaches its minimum SOC and is then recharged until it reaches its maximum SOC. The electricity required for this final charging process is also measured (e_3, in Wh). This last step allows determination of the net battery charge from minimum to maximum SOC.

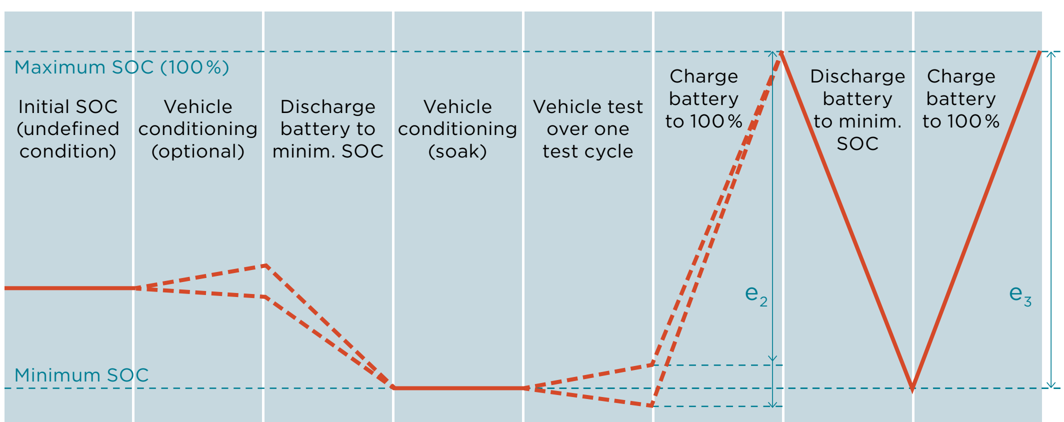

Figure 2: Schematic overview of the CS mode test procedure.

Fuel consumption in CS mode (defined as C_2 in liters per 100 kilometers) is calculated from the measured fuel consumption during the test cycle, divided by the distance driven. The net electric energy consumed over the test cycle (e_4, in Wh) is calculated by subtracting e_2 from e_3. Finally, that net electric energy (e_4) is divided by the distance driven during the test to deliver the electric energy consumption, E_4 (in Wh/km), for the CS mode.

A specific issue with respect to PHEV testing in CS mode is the fact that a vehicle driving in CS mode may have a fluctuating SOC. If the battery is discharged during the test (see the lower line in the fifth stage of Figure 3), because the vehicle drives at least partly using its electric motor, the electric energy consumption (E_4) is higher and the fuel consumption is lower. On the other hand, if the battery charge increases during the test (the upper line in the fifth stage of Figure 3), because the ICE directs energy back into the battery, the energy consumption (E_4) is lower and the fuel consumption is higher. The overall energy demand for driving the vehicle over the test cycle is the same in both situations. Hence, there is a trade-off between electric energy and fuel consumption. To avoid this dependency affecting the test results, it would be possible to mathematically correct for the differences in SOC during the CS test mode. However, such a correction is not part of the current PHEV test procedure.

DETERMINING ELECTRIC VEHICLE RANGE

The electric range (D_e) of a PHEV is determined by driving consecutive NEDC cycles until the vehicle is no longer able to meet the target speed of 50 km/h by driving on electricity or until the vehicle indicates that the battery has reached its minimum SOC. Only those parts of the cycles during which the ICE is not running are counted as the electric range.[7] The electric range, D_e, is the total distance driven during the test, minus the parts that were excluded for the reasons indicated above.

COMBINING THE TEST RESULTS FOR CD AND CS MODE

The last step is to calculate a weighted fuel consumption result, C, according to the following formula:

$$C = \frac{D_e \cdot C_1 + D_{av} \cdot C_2}{D_e + D_{av}}$$

Where:
C = fuel consumption in liters per 100 kilometers,
C_1 = fuel consumption in liters per 100 kilometers in CD mode,
C_2 = fuel consumption in liters per 100 kilometers in CS mode,
D_e = electric range of the vehicle, and
D_{av} = 25 km (average distance driven in CS mode, assumed by UN-ECE R101).

The electric energy consumption for CD and CS mode is calculated by dividing e_1 or e_4, respectively, by the total distance driven in kilometers during the tests. The weighted average energy consumption, E, is calculated analogous to the formula above.

7 In addition, decelerations at vehicle speeds above the speed at which the ICE was previously started and where it normally would be expected to operate are excluded.

As can be seen from the denominator of the formula above, the weighted fuel consumption and CO_2 emissions of a PHEV are strongly affected by the electric range of the vehicle. For a vehicle with an electric range of only 25 km – and no fuel consumption in CD mode – the weighted fuel consumption is effectively half of the CS fuel consumption. With an electric range of 75 km, the weighted fuel consumption is reduced to one fourth of that under CS conditions. Table 1 illustrates this relationship, using the CO_2 emissions of the vehicle as the metric.

Table 1: Relationship between electric range and CO_2 emission levels of a PHEV using the NEDC test method.

Electric range	0 km	25 km	50 km	75 km
Weighted CO_2	200 g/km	100 g/km	67 g/km	50 g/km

Most PHEVs currently for sale in Europe offer an electric range of around 50 km, according to NEDC test conditions. When comparing the NEDC CO_2 level of these PHEVs to the corresponding conventional gasoline version vehicles, it is about 70% lower. Table 2 highlights three examples.

Table 2: Exemplary PHEV and corresponding gasoline version vehicles with NEDC electric range and CO_2 emission level.[8]

VW Golf (gasoline)	0 km e-range 121 g/km	**VW Golf GTE (PHEV)**	50 km e-range 36 g/km
Porsche Panamera (gasoline)	0 km e-range 177 g/km	**Porsche Panamera (PHEV)**	51 km e-range 56 g/km
Mitsubishi Outlander (gasoline)	0 km e-range 149 g/km	**Mitsubishi Outlander (PHEV)**	54 km e-range 41 g/km

In the real world, the CO_2 emission level of a PHEV strongly depends on the driving behavior of the customer and ambient temperature, as well as the recharging behavior (timing and duration). The NEDC, in that it is not a demanding test cycle and hence not representative of real-world driving, results in rather optimistic estimates of energy consumption as well as PHEV electric range. This explains why customers might be disappointed by the PHEV electric range and fuel consumption figures as advertised by the vehicle manufacturer.

8 Data sources: Vehicle manufacturers' websites. Values given are for a specific vehicle model version that was considered to be the closest comparison possible.

TRANSITIONING TO THE NEW WLTP: WHAT WILL CHANGE?

As of September 2017, the new WLTP test procedure will become mandatory in the EU.[9] WLTP will introduce the following key changes, with respect to the current regulation UN-ECE R101:

» The NEDC test cycle is replaced by the WLTC, which is more representative of average driving behavior, more dynamic, and has a higher maximum speed.[10] As a result of this more realistic driving profile, it may be expected that the electric range as well as the fuel consumption for PHEV in WLTP will be closer to what is observed by vehicle owners in everyday driving conditions. The electric range is expected to be reduced by approximately 25% with respect to the NEDC-based range.[11]

» The WLTC is subdivided into four phases: low, medium, high, and extra-high vehicle speed, which can be regarded as typical driving for an urban, rural, 100-km/h limit, and 130-km/h limit motorway, respectively. Fuel and electrical energy consumption are determined for each of these phases and aggregated according to the phase's specific utility factor (see next bullet point) into one combined average. The electric range of the vehicle is also specified for each of the four phases.

» The weighting factor of 25 km for the current NEDC CS test is arbitrary. In reality, it depends on the electric range of the vehicle: If a vehicle has a high electric range, it likely will be driven mostly in CD mode. If a vehicle has a low electric range, it likely will be driven more in CS mode. WLTP introduces a variable weighting factor (referred to as the utility factor) that more accurately describes the ratio of driving in CD and CS mode as a function of the electric range and that is based on available driving data[12] (Figure 3).

9 See Annex 8 of the most recent version of the regulatory text (GTR 15) for details. It can be found as document No. ECE/TRANS/WP.29/GRPE/2017/7 at http://www.unece.org/trans/main/wp29/wp29wgs/wp29grpe/grpedoc_2017.html

10 Mock, P. *et al.* (2014). The WLTP: How a new test procedure for cars will affect fuel consumption values in the EU, (International Council on Clean Transportation: Berlin, 2014), http://www.theicct.org/wltp-how-new-test-procedure-cars-will-affect-fuel-consumption-values-eu

11 Lima, P. (2016). WLTP and electric cars. Retrieved from http://pushevs.com/2016/10/13/wltp-electric-cars

12 The utility factor highly depends on how a PHEV is driven in practice. For that reason, utility factors are defined differently in Europe, Japan, and the United States. The recharging behavior of the driver also influences the utility factor, but due to a lack of data, this influence was not considered in the current WLTP version; however, it is expected to be addressed in future revisions of the utility factors.

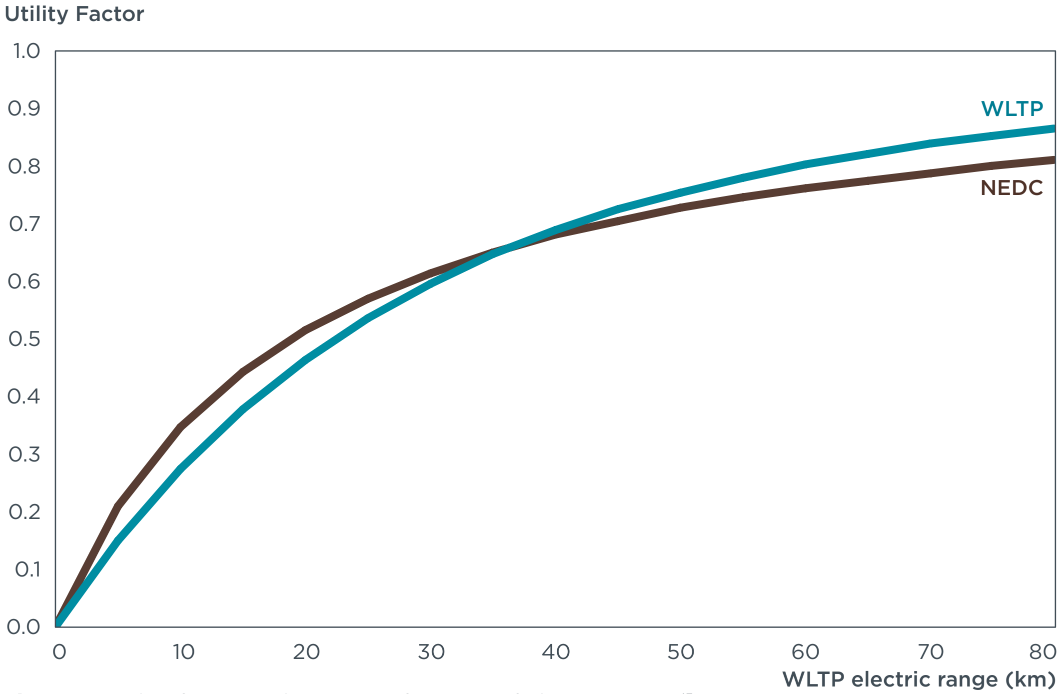

Figure 3: Utility factor in the EU as a function of electric range.[13]

- In WLTP, there will be just one defined test method for the CD mode test, instead of two different options (as is currently the case; see Footnote 6), which can lead to slightly different results. The vehicle will be driven until the battery has reached the SOC level at which it continues in CS mode. Fuel and electric energy consumption are averaged over the total number of complete cycles. Electric range is determined from the same CD mode test.
- In contrast to the NEDC test procedure, the CS mode test results are corrected toward a zero energy change of the battery to avoid any trade-off between the CS fuel and electric energy consumption.
- Instead of having different test procedures for range determination, fuel consumption, and electric energy consumption in the NEDC test procedure, WLTP combines these into one CD mode test.
- Range determination is differentiated into:
  - All electric range (AER, the range that can be driven until the first ICE start),
  - Actual charge-depleting range (R_{CDA}, the total range in charge-depleting mode),
  - Charge-depleting cycle range (R_{CDC}, the total range up to and including the transition cycle), and
  - Equivalent all electric range (EAER, the part of the R_{CDA} range that can be attributed to the use of the electric energy from the battery).[14]

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13 The NEDC line (corrected for an anticipated difference in electrical range under WLTP) shows the current weighting, based on a fixed distance of 25 km of driving in CS mode. For PHEVs with an electric range up to approximately 40 km, the reported fuel consumption in WLTP will be higher. For more details, see the technical report of WLTP, document No. GRPE-72-02-Rev.1 at https://www.unece.org/trans/main/wp29/wp29wgs/wp29grpe/grpeinf72.html

14 Although the test cycles are different between WTLP and Regulation R101 (NEDC), the R_{CDA} is the equivalent of the OVC-HEV range, D_{OVC}, and EAER is comparable – but not equal – to the electric range, D_e. R_{CDC} is used only for calculation purposes.

» In addition, results for the AER and EAER are also determined for the so-called WLTP city test cycle, which effectively is the combination of the low and medium phases of the WLTC. These results are added primarily information for consumers, to show what the performance of the vehicle is under urban conditions.

» WLTP uses an interpolation family approach for CO_2, fuel and electric energy consumption, AER (if a linearity criterion is fulfilled), and EAER. Effectively this means that for every vehicle family member, depending on its actual mass, aerodynamic resistance, and rolling resistance, dedicated values for these parameters will be calculated by interpolation between the vehicles of the family that have the highest and lowest energy consumption over the test cycle.

DETERMINING PHEV FUEL AND ELECTRIC ENERGY CONSUMPTION IN WLTP

After the vehicle has been preconditioned by driving at least one WLTC cycle, the battery is charged to the maximum SOC level while the vehicle is soaked in a climate-controlled area at 23°C (Figure 4). The vehicle is tested over multiple WLTC test cycles, until the test break-off criterion is reached, that is, the net energy change of the battery from the start to the end of the test cycle is less than 4% of the cycle energy at the wheels. The cycle in which this criterion is fulfilled is referred to as the *confirmation cycle* (n+1), whereas, in the previous cycle, the transition from CD to CS operation is considered to have taken place; hence, it is called the *transition cycle* (n). After a maximum of 120 minutes, the battery is recharged to the maximum SOC level to determine the charge energy, E_{AC}.

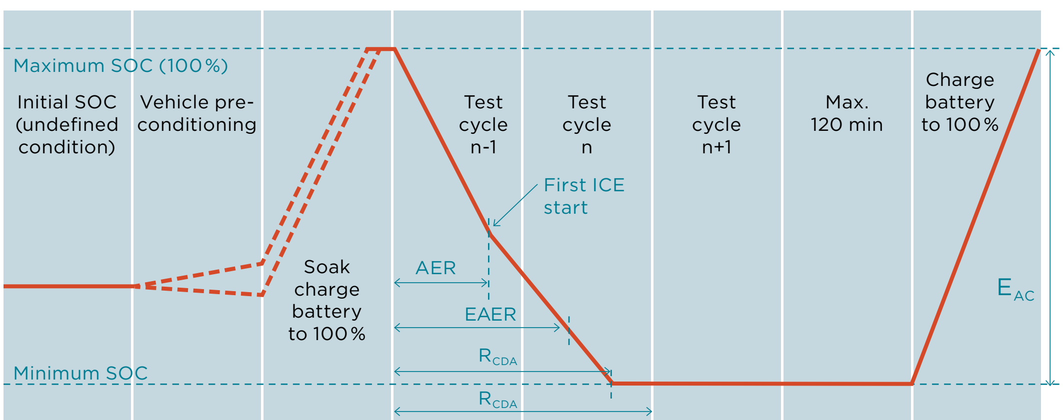

Figure 4: Schematic overview of CD mode test procedure in WLTP.

Calculation of the average weighted fuel consumption, C, in WLTP is done according to the following formula:

$$C = UF \cdot C_1 + (1 - UF) \cdot C_2$$

Where:

C = weighted fuel consumption in liters per 100 kilometers;
C_1 = fuel consumption in liters per 100 kilometers in CD mode;
C_2 = fuel consumption in liters per 100 kilometer in CS mode; and
UF = utility factor as a function of the electric range R_{CDC}, defined as the distance driven up to and including the transition cycle.

The energy consumption, EC (in Wh/km), follows from dividing the recharged energy, E_{AC}, by the equivalent all-electric range, EAER.

$$EC = \frac{E_{AC}}{EAER}$$

The EAER is determined by taking the total driven distance up to and including the transition cycle, n, and subtracting the parts during which the combustion engine was in operation. Calculation of this engine operation share is based on comparing the CO_2 mass emissions for the CS cycle with the average emissions during the cycles driven in CD mode, as follows:

$$EAER = \left(\frac{M_{CO2,CS} - M_{CO2,CD,avg}}{M_{CO2,CS}} \right) \times R_{CDC}$$

Where:

R_{CDC} = the CD range up to and including the transition cycle n (in km),
$M_{CO2,CS}$ = the CS CO_2 mass emission (in g/km), and
$M_{CO2,CD,avg}$ = the arithmetic average CO_2 mass emission of the CD test (in g/km).

The actual CD range, R_{CDA} (in km), is calculated by summing the distances driven up until the cycle preceding the transition cycle, and performing a CO_2-based linear interpolation during the transition cycle to establish the transition point from CD to CS mode, as follows:

$$R_{CDA} = \sum_{c=1}^{n-1} d_c + \left(\frac{M_{CO2,CS} - M_{CO2,n,cycle}}{M_{CO2,CS} - M_{CO2,CD,avg,n-1}} \right) \times d_n$$

Where:
$M_{CO2,\ CS}$ = the CS CO_2 mass emission (in g/km);
$M_{CO2,n,cycle}$ = the CO_2 mass emission during the transition cycle, n (in g/km);
$M_{CO2,CD,avg,\ n-1}$ = the arithmetic average CO_2 mass emission of the CD test from the beginning up to and including test cycle, n–1 (in g/km);
d_c = the distance driven during test cycle, c, of the CD test (in km); and
d_n = the distance driven during transition cycle, n, of the CD test (in km).

COMPARING PHEV FUEL AND ELECTRIC ENERGY CONSUMPTION TESTING IN THE EU VS. U.S.

The concept for testing PHEV in the U.S. is, to a large extent, similar to the WLTP procedure.[15] However, there are some significant differences in the testing details and the calculation of results, notably:

- » Fuel efficiency and range determination are based on two test cycles instead of one: The city cycle (Urban Dynamometer Driving Schedule [UDDS]) and the highway cycle (Highway Fuel Economy Test Driving Schedule [HWFET]).
- » The fractional utility factors used to weigh the CD and CS results have different values, reflecting the driving conditions for the average U.S. fleet.
- » The final CD range, R_{CDA}, is calculated by weighing the city and highway cycles by a factor of 0.55 and 0.45, respectively.
- » No EAER is calculated – only the AER and actual charge-depleting range, R_{CDA}.
- » The end-of-test criterion for the CD test, to establish whether the vehicle has entered into CS mode, is defined differently.
- » The details on preconditioning of the vehicle (e.g., soak temperature) are defined differently.

For consumer information purposes, all fuel economy figures in the U.S. are corrected to better reflect the real-life fuel economy. The corrected values are used for a labeling system on fuel economy and is presented on new vehicles on a window sticker. The fuel economy label adjustments are a function, in part, of fuel consumption, with larger adjustments applied to vehicles with lower fuel consumption. The adjustment is capped at 30%. Thus, due to their low fuel consumption, for most PHEVs, the correction is made by multiplying city/highway fuel economy and range values by 0.7 and dividing city/highway energy consumption and CO_2 values by 0.7.

A direct comparison of PHEV in the EU and U.S. is difficult, because technical characteristics of the same vehicle model might be different in both markets. Nevertheless, a rough comparison is feasible for some models, for example, the Porsche Cayenne PHEV with 3.0L engine displacement, available both in Europe and the United States. The electric range of this vehicle, according to NEDC, is given in the EU as 38 km, whereas in the U.S. it is 20 miles (~32 km) before real-world adjustment and only 14 miles (~22.5 km) after real-world adjustment (i.e., on the U.S. consumer information label). Similarly, the combined tailpipe CO_2 value for electric and combustion engine driving is only 79 g/km in the EU but is 258 g/miles (~160 g/km) on the U.S. label. In the case of the BMW i3 (94 Ah) Range Extender, the electric range in NEDC is 240 km, whereas in the U.S. it is shown as 139 miles (~223 km) before real-world adjustment and 97 miles (~156 km) on the consumer information label. The combined tailpipe CO_2 figure in the EU is 13 g/km, whereas it is 29 g/mile (~18 g/km) on the U.S. label.[16]

15 U.S. Environmental Protection Agency (EPA) testing follows SAE recommended practice J1711 for PHEV testing and applies EPA 40 CFR part 600 for the fuel efficiency standards.

16 Sources: http://www.fueleconomy.gov and manufacturers' websites

CONCLUSION

The electric driving range of a PHEV strongly influences the fuel consumption and CO_2 emission values that are used for the official reporting as well as for communication to consumers. In the current vehicle testing procedure, following the guidelines in UN-ECE R101, the electric range of PHEV tends to be estimated in a rather optimistic way. In the real world, the CO_2 emission level of a PHEV strongly depends on factors such as the driving distance, consumer behavior, ambient temperature, and recharging behavior. Beginning in September 2017, as part of the new WLTP test procedure, a utility factor is introduced that is expected to better reflect the real-world energy consumption and electric range of PHEVs. Nevertheless, even under the WLTP, official and real-world values for PHEV will continue to strongly deviate for some customers. In the future, the specific driving behavior of individual customers could be taken into account for estimating fuel consumption and CO_2 emission values that more accurately reflect the everyday driving experience and that allow for a fairer comparison between individual vehicle types.