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Energy efficiency evaluation of a Plug-in Hybrid Vehicle under European procedure, Worldwide harmonized procedure and actual use

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Abstract

This paper describes a two-fold approach carried out in collaboration between IFPEN and the French ADEME with the aim to evaluate a Plug-in Hybrid vehicle according to its conditions of use. The vehicle considered, an Opel *Ampera*, has been widely tested on a chassis dyno and simulated using IFPEN LMS.IMAGINE.Lab AMESim® platform. The software principles and its validation on different specific cases, thanks to experimental results, are described. The PHEV simulation tool is used to evaluate the influence of two European standard procedures and the influence of their parameters on the weighed CO_2 emission.

Keywords: PHEV , Simulation, Energy consumption, GHG emissions, Standard procedures

1 Introduction

Plug-in hybrid vehicles (PHEVs) offer the opportunity to be operated with zero tailpipe emissions (ZEV) on a variable part of their use together with the possibility to shift vehicle energy consumption from fossil energies to other primary sources owing to the electricity vector. PHEVs generally operate under two different situations, i) in charge depleting (CD), where the vehicle can be operated in full electric operation (behaving then as an EV) or in blended operation (the internal combustion engine (ICE) is needed for dynamic purposes) or ii) in charge sustaining (CS) where the IC. engine is used to maintain battery State of Charge (SOC). These two operations can be combined in numerous ways according to the vehicle drivetrain characteristics, to the vehicle type of use, to the distance driven between battery charges and to the energy management.

As a consequence the evaluation and forecast of PHEVs true capabilities in Green House Gas (GHG) emissions and local nuisances reduction in a day to day basis become very complex.

With the aim to get a better understanding of PHEVs potential, IFPEN, with the support of the French Environment & Energy Management Agency (ADEME), has set up a research program associating experimental analysis together with system simulation of PHEVs In the frame of this program two cost shared projects, CONSOVEx and SIMULVEx have been carried out (see chap. 2). The paper will present and discuss results obtained for different types of use of the vehicle, according to the Normalized European Test Procedure (R101) and to the new

Worldwide harmonized Light vehicles Test Procedures (WLTP). In this last case, the weighting between the CD and CS operations of the drivetrain will also be taken into account through statistics expressed by a ratio called Utility Factor (UF). The UF represent the fraction of the distance covered in charge depleting (electric modes for our PHEV case) to the total distance covered between 2 charges (see 7.1.2).

2 Projects CONSOVEx and SIMULVEx

The aim of these two cost-shared programs is to evaluate energy consumption of EVs and GHG emissions of PHEVs according to their conditions of use, i.e. :

- Driving schedules and auxiliaries use for EVs ;
- Driving schedules, procedures and distance between charge for PHEVs.

Due to the high number of cases to be considered and to the high cost of experiments, the two programs included both experimental and simulation phases. The experimental phases were carried out on IFP Group chassis dyno with the purpose to generate data for system analysis and comprehension together with software validation. Once validated, the software will enable to fully investigate the drivetrain behaviour in order to set up the already described energy and GHG analysis but also to prepare the next generation of drivetrains using optimized components, architectures and control.
The EVs analysis case has already been presented in [Badin 2013], this paper will detail the case of PHEVs through the illustration of the Opel *Ampera*.

3 Vehicle tests

The tests were carried out on IFPEN chassis dyno with an Opel *Ampera* purchased on purpose for the project, the test procedure included:

- Various standardized and actual use cycles performed in both CD and CS conditions, with ICE cold and hot;
- Steady speeds, performed in both CD and CS conditions;
- European R101, US SAEJ1711 and new WLTP procedures.

Data recording on the vehicle have been performed through a set of sensors (current, voltage, temperature, ICE in-cylinder pressure…), through the CAN network using a dedicated software and through the CVS gas analyser.
As far as energy consumption is concerned, we recorded grid electric consumption values in CD operation varying between 163 to 215 Wh/km, which is slightly under the bandwidth of consumption announced by GM, based on a customer fleet survey (resp. in the order of magnitude of 180 to 230 Wh/km, taking into account the influence of auxiliaries in actual use) [Laba 2013]. In CS condition, the recorded values ranges from 4.5 to 6.5 L/100 km (expressed at zero high power battery ΔSOC), again slightly under the GM fleet survey range (resp. close to 5.4 to 7.2 L/100 km).

As far as All Electric Range (AER) is concerned, the recorded values for the different driving schedules lie between 50 to 80 km, which is close to the bandwidth announced by GM (40 to 80 km). The AER recorded according to the European procedure is 76 km (see chap. 7.1) which is slightly under (8%) the official value of 83 km for this specific type of use.

The energy consumption and CO_2 emission of the vehicle according to the R101 procedure have also been characterised. The obtained weighed value is 40 g/km, which is more than 40% above the official value of 27 g/km. Some elements regarding the procedure and the calculation of the weighed value (influence of battery SOC variation and AER) are detailed in chapter 7.1 and indicate that an emission of 31 g/km could be reached (15% more than the official value, keeping in mind that our chassis dyno setting may be different from the one implemented in the official procedure).

We also investigated the vehicle dynamic performances with a battery at a high SOC (CD operation in electric modes) and at a low SOC (CS operation). As illustrated in Figure 1, it appears that the vehicle speed is slightly lower at the beginning in CS operation due to the ICE delay in providing high power, but the time to reach 100 km/h is nearly the same in both configurations. This confirms that the *Ampera* offers full dynamic performances, both in electric and hybrid modes, and could be considered as a ‘*no compromise*’ PHEV.

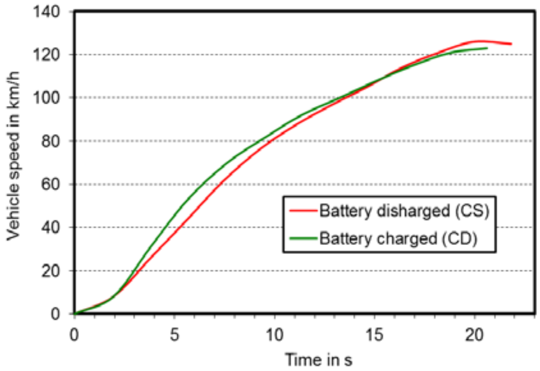

Figure 1: Vehicle wide opened throttle accelerations in CS and CD operations

Remark : These tests have been chained on a single road section but without any specific control (slope, wind…) and then do not necessarily represent the vehicle characteristics.

The knowledge of the ICE Mean Effective Pressure (MEP) and the knowledge of the ICE Fuel Consumption map (see Chap. 4.1.3) enabled us to determine the FMEP values. Then, through our measurements, we were able to determine the ICE torque and working area, as illustrated in Figure 2 and 3, using the GM provided fuel consumption map at the background.

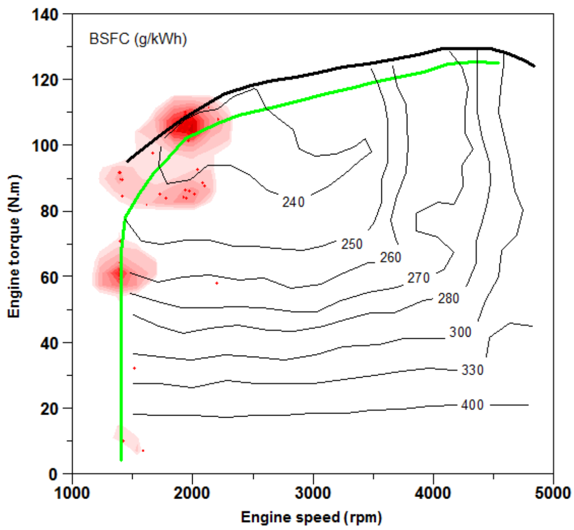

Figure 2: ICE working area (urban driving schedule)

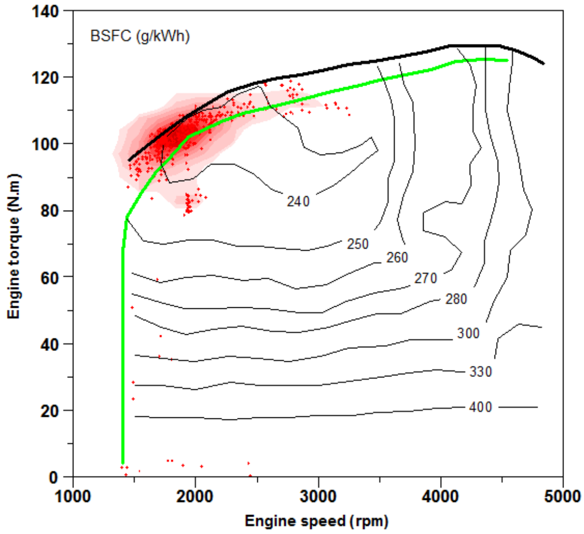

Figure 3: ICE working area (extra urban driving schedule)

These two figures illustrate one of the most important feature of hybridisation which is to maintain the ICE as close as possible to its best efficiency working area whatever the vehicle use conditions are (the ICE may not be operated exactly on its best efficiency curve because generally a global optimization on the entire drivetrain efficiency is performed and also because of thermal or component working envelope constraints).

For the chassis dyno setting we used road load values issued from the EPA website (inertia 1700 kg, F_0 115.9 N, F_1 -0.009 N/(km/h) and F_2 0.002 N/(km/h)².

4 Vehicle simulation

The Opel *Ampera* simulator has been designed on the LMS.IMAGINE.Lab AMESim® platform, thanks to the different specific libraries available with this software [Dabadie 2005], [Menegazzi 2006] (see Figure 4). Such software is a precious tool to carry out drivetrain sizing and energy consumption evaluation of innovative drivetrains [Marc 2010], [Da Costa 2012], [Rousseau 2012].

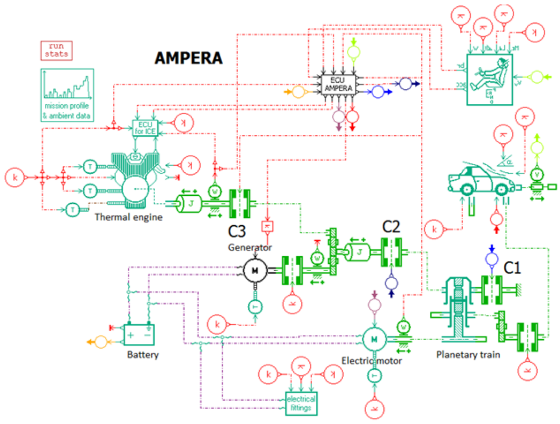

Figure 4 : Amesim sketch of the Opel *Ampera* simulator

The powertrain architecture powering the Opel *Ampera* vehicle consists in an output split, planetary-based system [Miller 2011]. Three clutches (C1, C2, C3 on Figure 4) allow connecting or disconnecting the internal combustion engine and the generator. Both electric machines can actually work in motoring and generating mode.

Four operating modes are allowed with this powertrain:

1. Electric mode with one electric motor;
2. Electric mode with two electric motors;
3. Hybrid mode in range extender configuration. The engine and generator are connected and produce electric power. The main electric motor alone propels the wheels;
4. Hybrid mode in power split configuration. In this mode, the three machines are all connected together with a variable speed ratio that depends on the generator speed.

The main characteristics of the *Ampera* components are the following:

- ICE : 1,4 L and 63 kW (130 N.m at 4800 rpm),
- Main electric motor (motor B): 111 kW peak and 370 N.m, Generator (motor A): 54 kW peak and 182 N.m,
- Battery: energy 16 kWh nominal, peak power 115 kW, observed SOC range 65%, nominal voltage 360V.

4.1 Component modelling

4.1.1 Electric machines

In this system modelling approach, electric machines are essentially described through efficiency maps obtained using an IFPEN in-house software (EMTool) [Le Berr 2012]. EMTool offers the capability to size and to characterize EM from basic requirements (maximum power and torque, maximum motor speed, input voltage). The efficiency map of the main electric motor is reported in Figure 5.

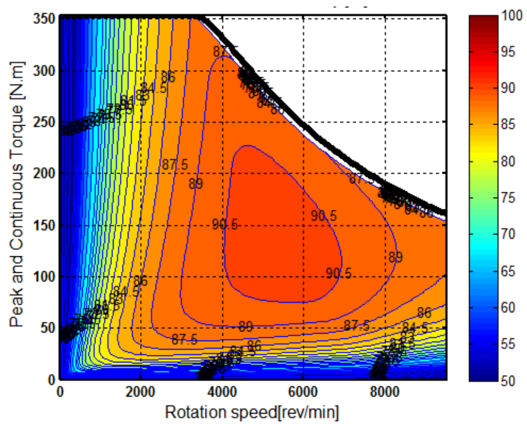

Figure 5: Efficiency map of the electric motor and inverter (%)

4.1.2 Battery

The battery model implemented in Amesim is based on a simple circuit model composed of a voltage source and a resistance, both functions of the battery state of charge (SOC). From the main characteristics of the battery (chemistry, P/E ratio…), the Open Circuit Voltage (OCV) and the internal resistance are obtained using an IFPEN in-house software [Petit 2014]. Due to the lack of battery data a final adjustment is made to fit with the experimental results. Figure 6 shows the OCV in function of the SOC for the fitted and raw results.

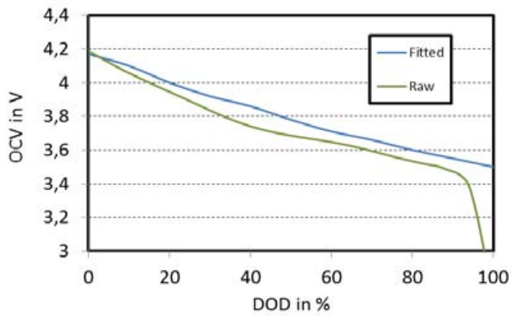

Figure 6: Battery cell OCV in V used for simulation

4.1.3 IC. Engine

ICE model is also based on efficiency map as presented in Figure 7. The fuel consumption data are issue from GM publication [Grebe 2011].

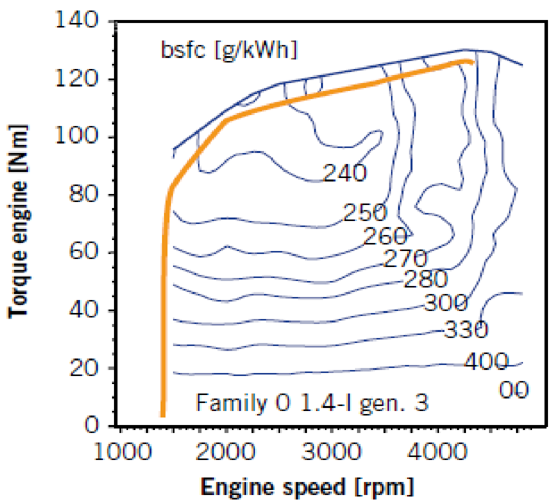

Figure 7: Specific fuel consumption lines of the EcoTec engine with its Optimal Operation Line

Fuel overconsumption due to low temperature conditions during the cold start is taken into account in the model by a combination of a thermal model of the IC engine able to compute water and oil temperature and an analytical friction law function of oil temperature.

4.2 Energy management and control

A dedicated ECU component has been developed for the Opel *Ampera* simulator. The energy management strategy is based on literature and in-house activities [Falières 2011]. Conditions for switching between the 4 standard modes have been slightly optimised to better fit with the results recorded on the chassis dyno. For instance, the electric modes repartition function according to vehicle speed and wheel torque is presented on Figure 8.

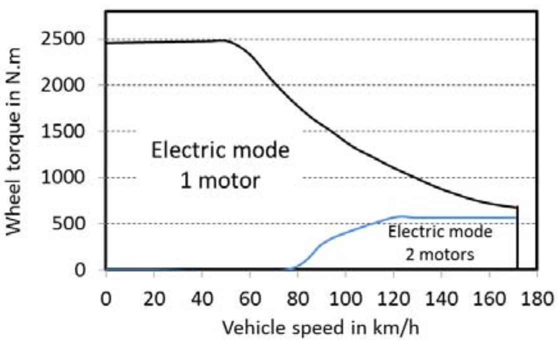

Figure 8: Modes of operation in electric-only driving

For cold start, few adaptations are made, such as:

- Decrease of the minimum SOC threshold value triggering the thermal engine start ;
- Limitation of the power produced by the ICE at the beginning of a cold start, (reduction of about 70%). During this particular running phase, ICE fuel consumption is also increased.

5 Simulator validation

5.1 Methodology

Different driving cycles have been simulated to calibrate the strategy and evaluate the missing data. These parameters have been identified on constant velocity tests, NEDC and different actual use driving schedules [André 2004], both performed on the chassis dyno in depleting and sustaining cases (see chap. 3). The simulator validation has been performed on a set of other standard and actual driving cycles covering a wide type of use (from jammed urban to motorway) to compare the simulation results to test results.

5.2 Instantaneous data comparison

One of the most important data to be scrutinized is the behaviour of the battery. The comparisons between measurements and simulation results for the high power battery voltage and intensity during a highway type cycle are shown in Figure 9. This cycle is performed in depleting mode, initial battery SOC being close to 86%.

Voltage difference between measurement and simulation never exceeds 3V (less than 1 % of 370 nominal voltage). Current simulation result is also very close to the measurement with a maximum error on current peaks less than 6 %. These results show that powertrain dynamic behaviour is well represented in the model.

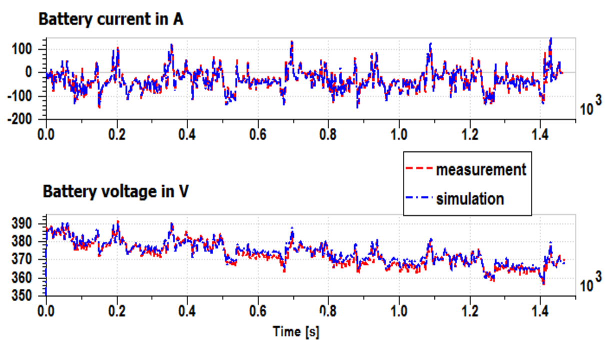

Figure 9: High power battery current and voltage comparison

5.3 Energy consumption and AER

Another important step in the validation process is the vehicle energy consumption, for this PHEV case it means:

- Electrical consumption in depleting operations. For our set of driving schedules our model accuracy lies between -4 to +4% of the energy delivered by the battery. As a consequence the all electric range will be evaluated with a good accuracy, as illustrated in table 1;

Table 1 : Evaluation of All-electric Range (km)

Cycle	Measure	Simulation
NEDC	75.5	75
UDDS	80.5	78
HFEDS	75.5	77.5
US06	51.5	53

- Fuel consumption in charge sustaining operations. For this validation a great care has been taken on the battery SOC behaviour, to make sure that initial and final values in the simulation matched those of the chassis dyno tests. Provided that this condition is respected, for our set of driving conditions, including warm and cold start cases, our model accuracy lies between -5 to +2% of the fuel consumption.

The high variability of the selected driving condition cases for the simulator validation process enables us to consider that the powertrain model is accurate, notably in terms of efficiency of the different components together with fuel and electricity consumptions.

5.4 Drivetrain implemented modes comparison

The last set of comparisons performed concern the drivetrain mode repartition during cycles. An example is shown in Figure 10, for the WLTC (with cold start), in charge sustaining operation case.

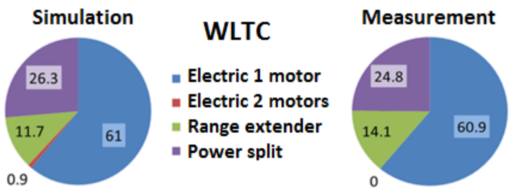

Figure 10: Drivetrain operating modes percentage of time spent comparison in charge sustaining case (%)

It appears that the mode repartition obtained from the simulation is reasonably similar to the test measurement, showing a relevant modelling of the powertrain strategy and mode management. It has to be noticed than there was no test information available on the state of the three clutches. Therefore the test mode repartition is obtained indirectly, assuming hypotheses which can result in small uncertainties.

6 Powersplit drivetrain behaviour in actual use

6.1 Drivetrain modes

Thanks to the previously presented simulator, a study with the aim to analyse the powersplit drivetrain behaviour is performed on a large set of driving cycles. This study has been performed on both CD et CS operations.

In CD operation, simulations are carried out with a maximum initial battery state of charge (85% for our case). Figure 11 presents the percentage of time spent in each of the two electric modes for our set of driving cycles (organized according to increasing mean vehicle speed from left to right).

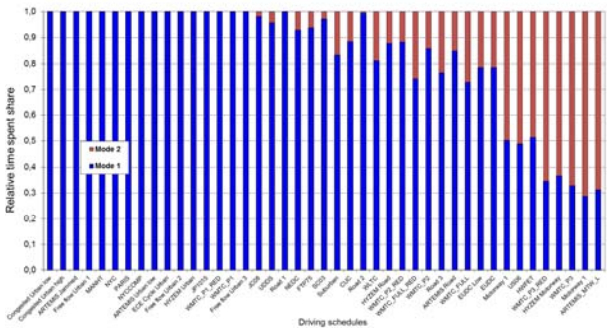

Figure 11: Percentage of time spent in each mode in charge depleting for various driving schedules

The full electric mode implement one or two electric machines with the aim to select the most efficient combination of modes and motors input speeds able to satisfy the required axle torque and speed at each moment. One could note the appearance of the mode 2 for high speed cycles and its predominance for the fastest.

Our simulation results appears to be consistent with the operation of the drivetrain reported by GM [Miller 2011] for a set of driving schedules, as illustrated in table 2.

Table 2: Comparison in percentage of time spent in each mode with GM data in charge depleting (%)

GM distribution comparison		Simulation	GM data
UDDS (EPA urban)	Mode 1 EV	96	93
	Mode 2 EV	4	7
HWFET (EPA motorway)	Mode 1 EV	51	49
	Mode 2 EV	49	51
US06	Mode 1 EV	49	58
	Mode 2 EV	51	42

For the CS operation, simulations are carried out using a low initial state of charge corresponding to the SOC threshold for engine activation (ECU) observed during the tests phase. Figure 12 illustrates the percentage of time spent in the four drivetrain modes for the different driving cycles (organized with an increasing mean vehicle speed from left to right).

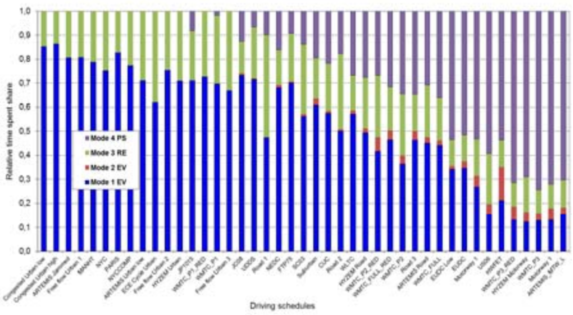

Figure 12: Percentage of time spent in each mode in charge sustaining (iso SOC evaluation) for various driving schedules

The low battery SOC requires the use of the ICE even for the low speed cycles where the most efficient mode is the series one. As fast as the driving schedule speed increases we can notice a progressive appearance of the power split mode, this one becomes predominant for the fastest cycles. One could notice a very limited appearance of the electric mode 2 for the fastest cycles.

As for the depleting case, a comparison with GM data is given in table 3. Data appears to be consistent with however some discrepancies in modes 2 and 3 on the 2 last driving schedules.

Table 3: Comparison in percentage of time spent in each mode with GM data in charge sustaining (%)

GM distribution comparison		Simulation	GM data
UDDS (EPA urban)	Mode 1 EV	73	71
	Mode 2 EV	0	3
	Mode 3 RE	20	20
	Mode 4 PS	7	6
HWFET (EPA motorway)	Mode 1 EV	14	11
	Mode 2 EV	4	25
	Mode 3 RE	13	6
	Mode 4 PS	69	58
US06	Mode 1 EV	34	21
	Mode 2 EV	14	5
	Mode 3 RE	4	16
	Mode 4 PS	49	58

It appears that the energy management and control simulation of this complex drivetrain through relatively basic laws reproduces quite well the vehicle behavior for different conditions of use (some of the parameters such as vehicle rolling resistance and battery behavior in the GM data being not necessarily identical).

6.2 All Electric Range

Our simulation model enables us to forecast the vehicle electric range on a set of driving schedules besides the standard European procedure. Figure 13 illustrates the electric range evaluations according to vehicle average speed. The curve shape appears to be similar with those of electric vehicles, as already discussed in our EVS27 paper [Badin 2013], i.e.:

- The range is limited for the lower speeds due to the influence of auxiliaries energy consumption;
- The range is limited at high speeds due to the increase in vehicle losses;
- The maximum range (corresponding to the minimum energy consumption) is obtained for speeds between 20 to 60 km/h;
- The average speed is not the only descriptor of the vehicle energy consumption and all electric range. As already discussed for the EV cases, the vehicle accelerations, which could be considered as representative of a 'driver aggressiveness' will also impact the vehicle consumption and all electric range [Badin 2013].

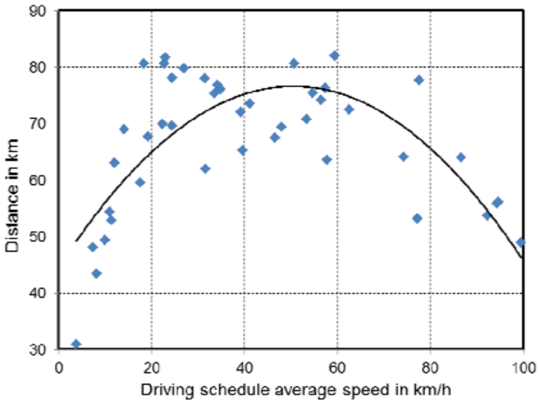

Figure 13: All electric range variations for various driving schedules.

One could note that our AER evaluation is consistent with the recorded data on the vehicle for various driving schedules (see table 1).

7 Drivetrain evaluation according to various standard procedures

The simulator is an interesting tool to evaluate the impact of procedure specificities on the results obtained. In this objective the following section will discuss about the influence of the new worldwide harmonized procedure (WLTP) compared to the already existing European Regulation 101 for the PHEV case.

7.1 Regulation 101 procedure

7.1.1 Description of the procedure

For plug-in hybrid vehicles, the Regulation 101 of the UNECE (United Nation Economic Commission for Europe) has to be applied. This procedure consists of three sequences, A, B and C which are briefly summarized hereafter.

Sequence A (Depleting) is composed of:

- Conditioning: the energy storage (battery) is set to its maximum state of charge (homologated process),
- Test: the vehicle runs one NEDC then is recharged,
- Measurements: fuel consumption, pollutant emissions, grid electric energy consumed and distance driven are collected.

Sequence B (Sustaining) is composed of:

- Conditioning: the energy storage (battery) is set to its minimum state of charge (homologated process);
- Test: the vehicle runs one NEDC then is recharged;
- Measurements: fuel consumption, pollutant emissions, grid electric energy consumed and distance driven are collected.

Sequence C (All Electric Range) is composed of:

- Conditioning: the energy storage (battery) is set to its maximum state of charge (homologated process);
- Test: the vehicle runs NEDCs in electric mode until it is not able to meet the target curve up to 50km/h or when the ICE starts up;
- Measurements: the distance driven is collected, it is the electric range.

In the European procedure, the PHEVs fuel consumption, CO_2 emissions at vehicle level and electric consumption are calculated as weighted value using the following formula (which is here expressed for the fuel consumption case).

$$M = \frac{D_e . \frac{m_A}{D_A} + 25 . \frac{m_B}{D_B}}{D_e + 25}$$

equation 1

With D_e the electric range,

D_A the actual driven distance for test A,

D_B the actual driven distance for test B,

m_A the fuel consumption for test A,

m_B the fuel consumption for test B.

Regarding this formulation some remarks may be made, i.e.:

- The fuel consumption during test A may be null if the vehicle is able to cover the entire driving schedule without the use of the ICE (enough power from the electric drivetrain and enough energy in the battery allowed ΔSOC);
- The value of 25 km is assumed to represent the average distance covered in CS mode prior to the next battery charge.

For the vehicle considered in this paper it appears that the test A has been completed in all electric mode (m_A = 0) leading to a simplification in the equation 1. The 25 km constant will enable us to calculate the ratio of the charge depleting distance to the distance covered between 2 charges (known as Utility Factor - UF). For our vehicle, considering the recorded AER of 76 km, the corresponding UF will be 0.75.

7.1.2 Influence of parameters variations on the results of the evaluation procedure

In the sequence B of the European procedure, the test is performed with a battery pack discharged to its minimum allowed value, but the SOC variation during the test is not controlled. Yet, on such a PHEV with a large amount of possible battery energy swing (65% of 16 kWh) on a quite short distance driven (NEDC represents 11 km) the effect on fuel consumption in the CS conditions may be high. Indeed our evaluation highlights the fact that a value of +1% of the battery ΔSOC (recharge) during the NEDC procedure will lead to an increase of 8% of the ICE running time and consequently an increase of 10% in fuel consumption and CO_2 emission. This increase will be accompanied by a decrease in electric consumption, indicating a displacement of the vehicle energy shift from electricity toward petroleum.
For the PHEV case, it appears that the CO_2 emission is the only criteria considered in the calculation of the purchase incentive. Considering the French case, the purchase incentive (‘bonus’) will be 6300 € in 2015 for CO_2 emissions lower than 20 g/km and 4000 € for CO_2 emissions lower than 50 g/km.

For the vehicle tested in the Lab., the weighted CO_2 emission calculated according to the procedure is 40 g/km (see chap. 3) but it happened that during our test B the battery has been charged with a ΔSOC of 1,9%. Corrected thanks to the above mentioned factor, the CO_2 emission corresponding to a zero ΔSOC would be 33 g/km, according to the 76 km AER we recorded. If we now consider the official value of 83 km, equation 1 will lead to a weighted value of 31 g/km. These considerations illustrate the sensitivity of the published results to the experimental data for the existing European procedure.

Another factor which appears in the equation 1, and has an influence on the result is the 25 km distance supposed to be covered in CS mode prior to the next following charge. Figure 14 highlights the influence of this parameter on the Utility Factor and as consequence on the weighted CO_2 values, which can be significantly affected.

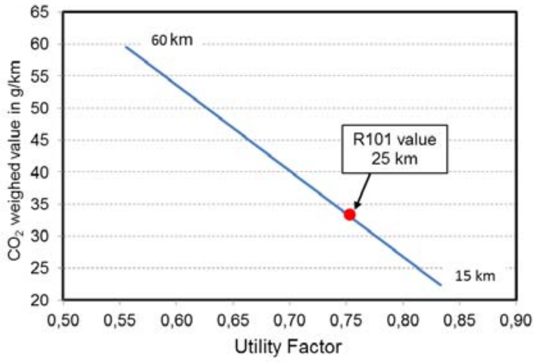

Figure 14: Variation of the CO_2 weighted emission according to the average distance covered in CS (expressed in UF) for our PHEV case

7.2 Worldwide harmonized procedure

7.2.1 Description of the procedure

A proposal for a new Worldwide harmonized Light vehicles Test Procedure (WLTP) has been submitted to the World Forum for Harmonization of Vehicle Regulations (WP.29) by Working Party on Pollution and Energy (GRPE). For the case of plug-in hybrid vehicles the WLTP consists on one test covering both the depleting and sustaining operations. As illustrated in figure 15, the initial state of charge is set to its maximum, then the chosen set of driving schedules is repeated until the battery reaches its minimum allowed SOC and finally a whole cycle is performed in sustaining operation (final green phase in figure 15).

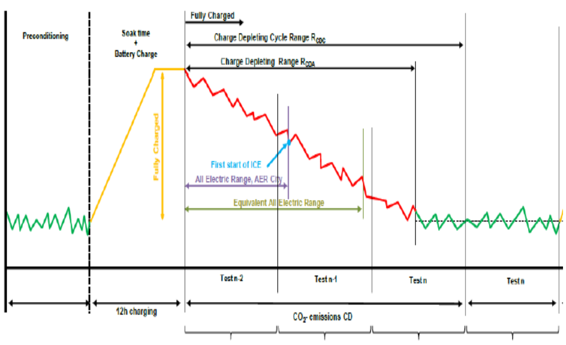

Figure 15: WLTC procedure principle

The speed profile of the 4 phases (low, medium, high and extra high) driving schedule to be repeated corresponds to a class 3 vehicle (P > 34 W/kg). As compared to the already existing European driving patterns (Urban and Extra urban), the drivetrain operating envelope appears to be larger (Figure 16).

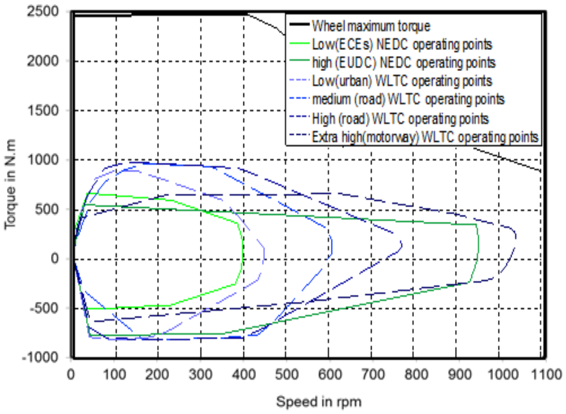

Figure 16: NEDC and WLTC operating points

Indeed, the new WLT cycle present a larger range of vehicle operating points than the NEDC. The new driving schedule appears to be a more dynamic and then more power demanding cycle than the NEDC. Moreover NEDC operating areas show very low density (mainly due to the driving cycle steady speed shape) whereas WLTC low to high speed operating areas are consistent.

During the test, at the end of each cycle the driven distance, the fuel consumed, the CO_2 emissions and the battery charge are recorded. The official CO_2 emission value, at the vehicle level, is calculated as a weighted value involving depleting and sustaining operations through the following formula:

$$CO_{2,weighted} = \sum_{j=1}^{k} \left(UF_j * CO_{2,CD,j}\right) + \left(1 - \sum_{j=1}^{k} UF_j\right) * CO_{2,CS}$$

Equation 2

With k the number of phases driven during the CD operation,

$CO_{2,CD,j}$ the CO_2 emission on j^{th} charge depleting (CD)cycle (red phase in Figure 15),

$CO_{2,CS}$ the CO_2 emission on full charge sustaining (CS) cycle,

UF_j the j^{th} utility factor.

As already stated, the UF represent the fraction of the distance covered in charge depleting (electric modes for our PHEV case) to the total distance covered between 2 charges. The Utility Factor, enabling to combine the CD and CS values, is based on driving behaviour statistical analysis carried out in different countries or continent (ex the US DOT National Highway Transportation 2001 Survey, reference for US procedure's UF). The WLT Procedure states that each participating country will have to develop its own UFs. Currently Utility Factors are available for US, EU and Japan regions. For the EU case, the development of revised UF, to have more representativeness, was still going on in 2014. We considered in our calculation the UF data available in mid-2014 [Eder 2014]. For a comparison purpose, we also considered the US UF involved in the J1711 procedure. The 2 considered UF are illustrated in Figure 17.

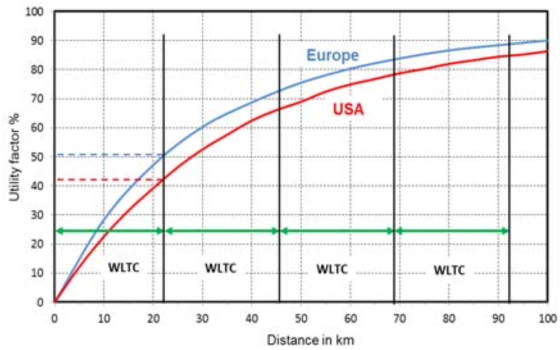

Figure 17: Travel distance statistics

7.2.2 Results calculation

To express the weighted CO_2 emission of our PHEV we implemented the 3 following methods:

1. European R101 procedure;
2. European R101 procedure but using the specific WLT cycles;
3. New WLT procedure with the European UF presented in Figure 17.

The CO_2 results of these 3 simulations are presented in Figure 18.

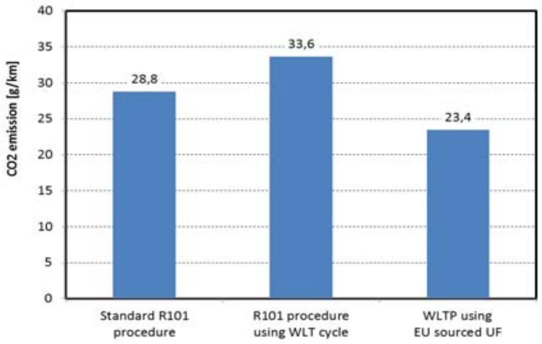

Figure 18: Influence of driving cycle and procedure

For case 1, the obtained value of 28.8 g/km is very close to the official value of 27 g/km obtained on the Opel vehicle, following the same standard procedure.

For case 2, keeping the same procedure but using the new WLT cycle, the weighted emission is 33.6 g/km, an increase of 20 % on the case 1. The increase of the weighted value highlight the influence of the WLT driving pattern, which appears to be more power (and energy) demanding, as already stated. According to equation 1 this will have 2 concomitant consequences, an increase in the CO_2 emission appearing in the numerator and a decrease in the AER appearing in the denominator (from 75 km with the NEDC to 67.5 km with the WLTC).

The case 3, implementing the WLTP with the 2014 European suggested UF appears to be much more favourable to our PHEV, regarding the CO_2 emission with a significantly low value of 23.4 g/km.

7.2.3 Influence of parameters variations on the results

Once the WLT procedure is adopted, it is interesting to forecast the influence of the Utility Factor on the CO_2 weighted values. Figure 19 compares the values obtained with the WLT procedure for the 2 UF presented in Figure 17.

One could note that, due to higher daily distances driven is the US, their UF is lower (see Figure 17) and consequently the weighed CO_2 value is closer to the CS conditions, leading to an overvalued result by 23%.

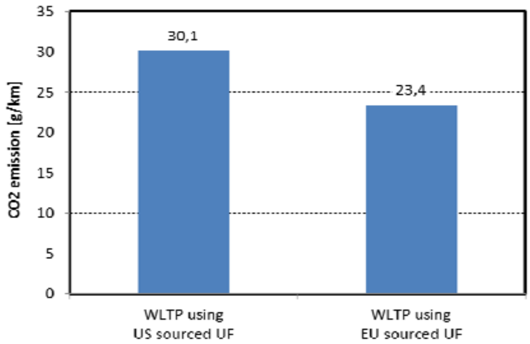

Figure 19: Influence of utility factors

These results highlight the particular influence of the daily distance driven (or the distance between charge) for the PHEV case, and the way it is taken into account in the new procedure.

8 Conclusion and perspectives

We have described in this paper the analysis of a Plug-in Hybrid Vehicle behaviour according to its usage, which has been illustrated through the real case of the Opel *Ampera*.
As far as the methodology is concerned, the project highlighted the importance of the two-fold approach we carried out: experimental tests on chassis dyno together with system simulation.
The tests are necessary to get an understanding on the vehicle behaviour, to generate the results and the data needed for the simulation purpose and to validate the software tool; however these tests are very expensive and time consuming.
The simulation is necessary, firstly to get a very precise understanding of the vehicle drivetrain and all the components behaviour for various types of use. Secondly, the simulation, once validated, is a precious tool to quickly evaluate the very large number of cases which appear, as far as PHEVs are concerned (components, drivetrain architecture, energy management, vehicle type of use, daily mission, standard evaluation procedure…).
We also highlighted the fact that the simulation has to be carried out on a system level but relies on specific in-house built tools dedicated to components sizing and data generation (EMTool for electric machines, dedicated tools for batteries sizing and optimized energy management).
The software validation indicates that the drivetrain operating modes are well reproduced and that the error in the energy flow in the drivetrain do not exceed -/+4%.

The evaluation of PHEVs fuel, electricity consumption and CO_2 emission at vehicle level is very complex because the result has to be expressed as a weighted value computed with data corresponding to charge depleting and charge sustaining operations. The weighting can be done through a constant value (25 km assumed CS operation in the R101 procedure) or through a set of ratios between CD and total distances between charges (Utility Factor – UF).

Our simulation tool has enabled us to forecast the influence of different standard procedures hypothesis on the results.

We considered the standard procedure with the existing European R101, the R101 using new WLT driving cycle and the new WLTP. The results show that the new WLTP, with the available mid-2014 European UF, lead to the minimum value of 23.4 g of CO_2/km, as compared to 28.8 given by the R101 procedure (23% decrease). The influence of the driving pattern, for the same procedure, has also been established with an increase of 20% (from 28.8 to 33.6 g/km) moving from the European cycle to the WLT one.

Finally, we established the influence of the Utility Factor for the same WLT procedure. Indeed, moving from the mid-2014 European UF to the US one, we noticed an increase of 28% in the CO_2 emission value. This increase is due to the lower UF values for the US, involving then more CS operation in the weighted value.

These results highlight the influence of the procedure and the influence of the procedure parameters on PHEVs CO_2 emissions.

IFPEN developed simulation tool will be very useful in the future to evaluate the influence of the new UF that may be proposed by the working parties. It will also be an interesting tool to evaluate PHEVs behaviour in actual use (CO_2 emission, electricity consumption, AER, component actual use conditions…). Coupled with the IFPEN developed Life Cycle Analysis (LCA) tools, our result will also enable to forecast the PHEVs contribution to GHG reduction on a global basis (vehicle and involved energy paths for fuel and electricity).

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