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Fuel Consumption Potential of Different Plug-in Hybrid Vehicle Architectures in the European and American Contexts

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Abstract

Plugin Hybrid Electric Vehicles (PHEVs) have demonstrated the potential to provide significant fuel displacement across a wide range of driving cycles. Companies and research organizations are involved in numerous research activities related to PHEVs. One of the current unknown is the impact of driving conditions and standard test procedure on the true benefits of PHEVs from a worldwide perspective. To address this issue, Argonne National Laboratory (ANL) and IFP Energies nouvelles (IFPEN) have partnered under the IEA Annex XV task to evaluate the market specificities between Europe and U.S. Four different PHEV powertrain configurations with four All Electric Range will be analyzed under different standards (i.e., NEDC, UDDS, HWFET) and real world drive cycles (i.e. ARTEMIS…). The impact of different driving behavior for Europe and the US market will be analyzed through component sizing, fuel consumption benefits as well as Green House Gases (GHGs) considering the electricity production mix. The study will provide insight on how PHEVs can be designed to support worldwide market introduction of a limited number of vehicle options to maximize market penetration.

Keywords: Hybrid Electric Vehicles (HEV), Plug-In Hybrid Electric Vehicles (PHEV), Extended-Range Electric Vehicles (EREV), Environmental Impacts, International Collaboration

1 Introduction

National authorities all over the world have defined more stringent CO2 standards to decrease the overall fuel consumption of light duty vehicles. Figure 1 compares the normalized CO2 emissions from different countries up to 2020.

In response to these constraints, car manufacturers and suppliers have developed numerous technologies to enhance vehicle drivetrain efficiency or shift a part of the energy consumption from fossil fuels to other primary energies (i.e., electricity, hydrogen…). Among the existing panel of possible solutions, hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) constitute one of the most promising solution with dozens of HEV models already in production and some recently unveiled for PHEVs.

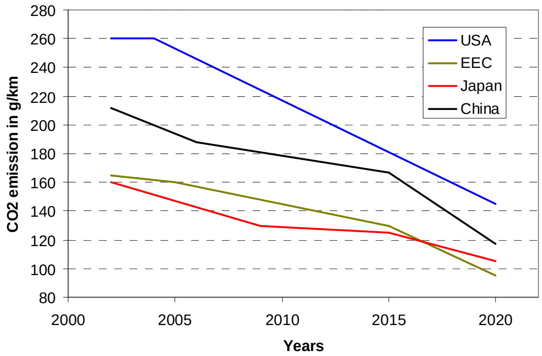

Figure 1: Comparative evolution of CO_2 emissions targets in different countries, from [1]

Understanding the real potential of such drivetrains is a complex task as it depends on a high number of parameters, including:

- Vehicle hybrid drivetrain architecture and functionalities (all electric range, plug in capabilities...);
- Vehicle class (compact, sedan, SUV, 4WD...) and dynamic performances;
- Vehicle usage (urban, extra urban, motorway, combined, type of standard procedures);
- For PHEVs, the electricity mix considered for the battery charge from the mains;
- Type of drivetrain components implemented
- Type of vehicle energy management implemented.

In order to clarify the potential of HEVs and PHEVs both in Europe and in the US, ANL and IFPEN have collaborated to develop a specific methodology to precisely establish the fuel consumption and GHG emission potential of different HEV and PHEVs. For this purpose, the same vehicle body in white with similar drivetrain components technologies have been considered. The vehicles have been simulated through different American and European driving patterns. For the case of PHEVs, standard procedures such as US J1711 and EEC Regulation 101 have been considered.

This paper presents and discusses the results obtained for a large number of configurations simulated in both Laboratories.

2 Methodology

2.1 Tools

Since the study was performed under a collaboration of two different laboratories, two simulation tools were used.

IFPEN used an in-house simulator developed under the LMS.IMAGINE.Lab AMESim® platform with components available in the IFP-Drive library [2]. This simulator is working under co-simulation with Simulink® for control algorithm. The models used for this study are steady-state efficiency depending on operating points, should it be for internal combustion engines, electric motors or transmissions and power electronics. The control is based on an online Equivalent Consumption Minimization Strategy (ECMS) principle. Although this approach leads to a higher computation time, it reduces the calibration process and fitted this study addressing several vehicles.

ANL used in-house developed software Autonomie, which is a MATLAB-based software environment and framework for automotive control-system design, simulation, and analysis [3]. The tool is designed for rapid and easy integration of models with varying levels of detail (low to high fidelity) and abstraction (from subsystems to systems and entire architectures), as well as processes (calibration, validation, etc.). Developed by Argonne in collaboration with General Motors, Autonomie was designed to assess the fuel consumption and cost of advanced powertrain technologies. Autonomie has been validated for several powertrain configurations and vehicle classes using Argonne's Advanced Powertrain Research Facility (APRF) vehicle test data [4],[5],[6].

Before starting the study, IFPEN and ANL ran simulations on several reference vehicles, to ensure consistency between AMESim and Autonomie.

In previous studies [7], ANL already compared the instantaneous optimal control algorithm with the reference rules-based control to show the effect of different control strategies, and provided similar fuel economy results while properly managing the battery SOC. Thus we had to make sure the models gave consistent results.

Figure 2 and Figure 3 compare the behaviour of AMESim and Autonomie on the NEDC cycle, for the parallel HEV vehicle. AMESim generally tends to use higher gears, as it's based on fuel consumption minimization, whereas Autonomie integrates driveability constraints on the control calibration. Table 1 shows that the overall fuel consumption results are similar between both tools.

Table 1: Comparison of levels of fuel consumption between AMESim and Autonomie

Vehicle		Conventional [L/100km]	Parallel HEV [L/100km]
NEDC	Autonomie	5.75	3.52
	AMESim	5.64	3.51
Artemis Urban	Autonomie	8.42	3.97
	AMESim	8.27	3.74
Artemis Road	Autonomie	4.88	3.75
	AMESim	4.78	3.67
Artemis Highway	Autonomie	6.44	5.93
	AMESim	6.3	6.1
UDDS	Autonomie	5.56	3.52
	AMESim	5.51	3.6
HWFET	Autonomie	4.2	4.13
	AMESim	4.16	4.18

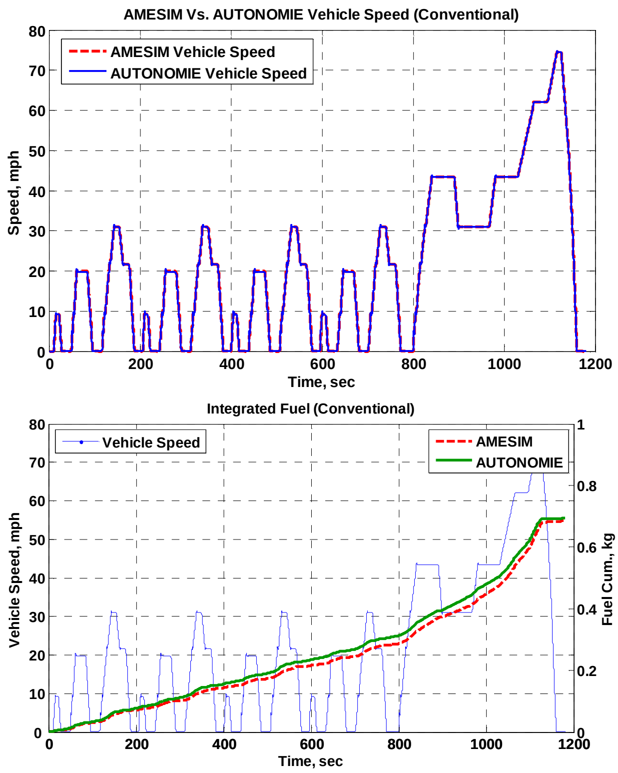

Figure 2: Comparison Result between AMESim and Autonomie for Conventional Vehicle

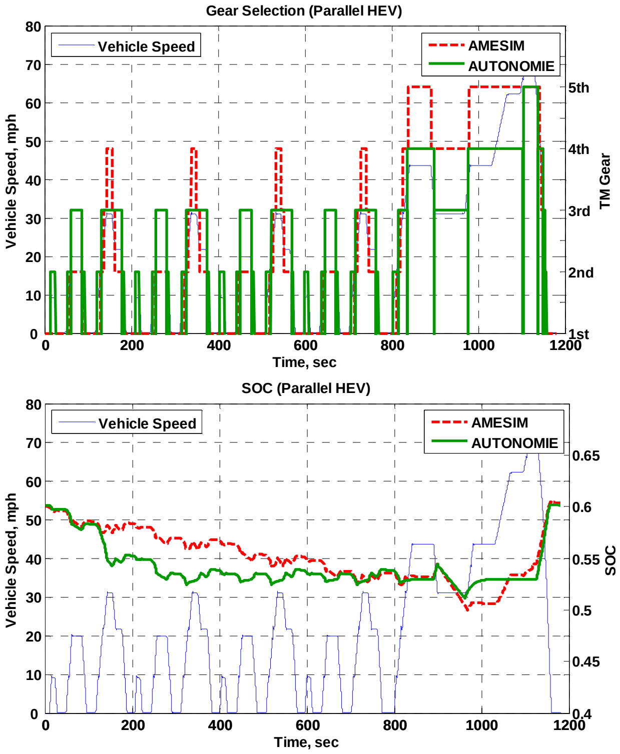

Figure 3: Comparison Result between AMESim and Autonomie for Parallel HEV

2.2 Component data

Internal Combustion Engine (ICE)

IFPEN and ANL used in-house measured efficiency of an 1800cc spark ignition engine developed at IFPEN, equipped with VVT at intake and exhaust camshafts, direct-injection and turbocharger. The results from the test beds have been used to generate maximum Brake Mean Effective Pressure (BMEP) and Brake Specific Fuel Consumption (BSFC) of both the turbocharged and the naturally aspirated versions of the engine.

At this step of the study, the BSFC associated to an engine technology is considered as depending on the engine speed, BMEP, but not on its displacement. At the same time, the maximum BMEP does not depend on the engine's displacement. Finally, ANL provided an estimation of the engine's weight, depending on its maximum torque and maximum speed.

Electric Machine

An IFPEN in-house software (EMTool) was used to develop the efficiency maps of the different electric machines (EM). EMTool offers the capability to size and to characterize EM from basic requirements (maximum power and torque, maximum motor speed, input voltage). This tool is based on analytical models allowing to design an electric motor that meets the required specifications [8],[9],[10]. Electromagnetic parameters are then calculated from the geometry and are associated to quasi-static control strategy to evaluate electric motor performances and efficiency [10],[11]. A complete efficiency map can be then determined and integrated in the vehicle simulator. To validate the relevance of the results given by the EMTool, a comparison with an experimental efficiency map of the Toyota Prius II electric motor [12] is presented from Figure 4 to Figure 6 with the repartition of the error between simulation and experimental results on the whole operating conditions. Efficiency maps have a mean difference of 5% and a maximum of 17% in highly saturated regimes (saturation phenomena are not taken into account in EMTool for the moment). The EMTool is also able to calculate the mass and the volume of the different parts of the electric machine.

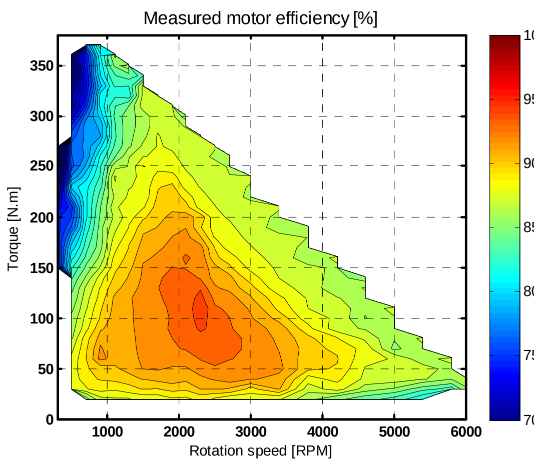

Figure 4: Efficiency map of the Toyota PRIUS II electric motor (experimental data from Oak Ridge laboratory)

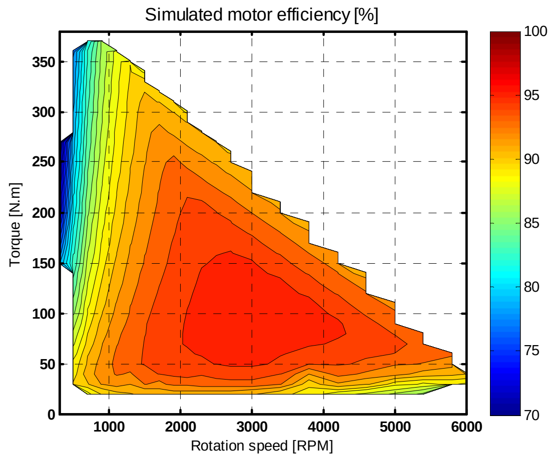

Figure 5: Efficiency map of the Toyota PRIUS II electric motor (simulation results coming from the EMTool)

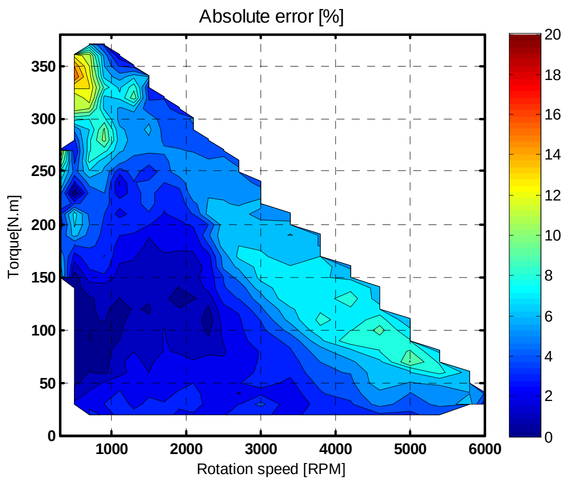

Figure 6: Absolute error map between experimental results and simulation results

Battery

Batteries were the only energy storage systems used in this study, on the assumption that ultra-capacitors alone could not provide sufficient available energy for the electric drive applications considered. We also considered that coupling ultra-capacitors with batteries would be cost-prohibitive and that Li-ion battery life would be significantly improved in the short term, making the combination ineffective.

The batteries used in the study as the reference have been provided by Argonne, Idaho National Laboratory, and major battery suppliers. A scaling algorithm developed by Argonne's battery experts is used for the high-energy cases [13]. The battery electrode materials are $LiMn_2O_4$ and $Li_4Ti_5O_{12}$, which provide a cell area-specific impedance of about 40% of that of the commonly available lithium-ion batteries.

2.3 Drivetrain Architectures Considered

For this paper, several powertrain architectures have been compared, depicting the actual trend in conventional and hybrid vehicles:

- Conventional 5 speed vehicle, with both automatic and manual gearbox
- Pre-transmission parallel HEV and PHEV's. Parallel PHEV's were also evaluated in a "mild-hybrid" version, with lower battery and electric motor power. This version does not respect the all-electric performance criteria but aims at limiting costs.
- Input-split HEV and PHEV (Toyota HSD-like transmission)
- Output-split PHEV (GM Volt-like transmission)
- Series hybrid
- Battery electric vehicle (BEV, no internal combustion engine), 150km range

The different configurations, as shown in Figure 7, have been simulated for different component power and energy. All electric ranges of 15, 30, 50 and 70 km were considered.

The selection of the single-mode power-split hybrid and the parallel hybrid was based on the current sales volume of both Toyota and Ford hybrid vehicles.

The series engine configuration selected is the simplest one and has been used by many companies. For this option, the electric-range extended vehicles (E-REV) powertrain used in the GM Volt [14] offers significant advantages, especially during high-vehicle-speed operations. Since the Volt uses a series-output split powertrain architecture, which provides benefits over the series architecture that typically has been considered for use in EREVs, it has been compared in this study.

Both simulation tools were used to simulate the conventional vehicles to ensure that the baseline vehicles provided similar fuel consumption. Autonomie was used to simulate the power split configurations (both input split and power split) as well as the battery electric vehicles. AMESim was used to simulate the pre-transmission and the series configurations.

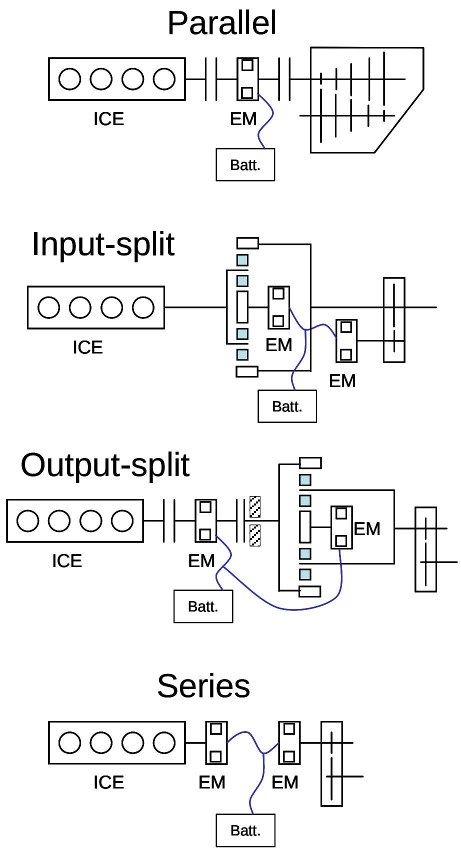

Figure 7: Hybrid powertrain architectures considered

2.4 Component Sizing

To properly evaluate the benefits of different powertrain configurations, one needs to ensure that their Vehicle Technical Specifications are comparable. All the vehicles have been sized to meet the same requirements:

- Initial vehicle movement (IVM) to 100kph in 9 sec +/−0.1 sec with ICE + electric power,
- Maximum grade of 5% at 110kph at gross vehicle weight (GVW) with ICE power only,
- Maximum vehicle speed >150kph with ICE power only, and
- All electric Range (AER) on UDDS (for US) or Artemis Urban (for Europe)

The only requirement that is different from one architecture to the other is the acceleration capability in all-electric mode :

- Energy recovery on urban cycles for HEV's and mild-hybrid parallels.

- Urban capability (based on UDDS in the US and Artemis Urban for Europe) for parallel and power-split PHEV's.
- Highway capability (based on US06 in the US and Artemis Highway for Europe) for output-split.
- Maximum performance available in all-electric mode for the series.

As detailed previously, the component's characteristics are determined by the constraints. The main vehicle characteristics used in this study are summarized in Table 2.

Several automated sizing algorithms were developed to provide a fair comparison between technologies. These algorithms are specific to the powertrain (i.e., conventional, power-split, series-split, electric) and the application (i.e., HEV, PHEV).

Table2: Specification of the compact-size sedan

Body and chassis mass	800 kg	*Frontal area*	2.18 m²
Drag coefficient	0.3	*Wheel radius*	0.317 m
Final drive ratio	Conv. AU : 4.44 Conv. MT : 4.29 Parallel HEV&PHEV : 4.29 Split HEV&PHEV : 4.059 Series PHEV : 11.36 GM Voltec : 3.02 BEV : 4.44		
Gear ratio	Conv. AU : 2.67, 1.53, 1.02, 0.72, 0.53 Conv. MT : 3.14, 1.87, 1.24, 0.95, 0.73 Parallel HEV&PHEV : 3.14, 1.87, 1.24, 0.95, 0.73 Split HEV&PHEV : 2.6 (Zr/Zs) Series PHEV: - GM Voltec : 2.24 (Zr/Zs) BEV : 1.86, 1		

2.5 Drive Cycles and Evaluation Procedures

This study aimed at evaluating results on US and EEC standard procedures, as well as real world driving cycles. The US standard test procedure for plug-in electric vehicle can be found in [15] while the EEC standard test procedure is described in [16]. For this study, we considered that all the European vehicles had a "Zero-emission" functionality: as long as the energy storage has enough energy, the user can decide to enter this mode and disable the ICE start. This functionality can be useful to limit emissions in city centres, and has also an impact on the evaluation of energy consumption on the EEC standard procedure.

Three daily missions were built in this study, using the Artemis cycles [17]. The objective is to represent daily trips outer to inner city and inner to outer city, for different distances:

- Mission Profile 1: Artemis Road – Artemis Urban – Artemis Road trip, 39,4km length.
- Mission Profile 2: Artemis Road - Artemis Road – Artemis Urban – Artemis Road - Artemis Road trip, 73.8km length. These two trips have been proposed by N. Marc in [18].
- Mission Profile 3: Artemis Highway – Artemis Road – Artemis Urban – Artemis Road – Artemis Highway trip, 98.5km length.

3 Results

3.1 Sizing Results

Figure 8 shows the main component sizes for the PHEV50 when sized on the UDDS US drive cycle. One notices that the pre-transmission requires the smaller combined power of all electrified vehicles. The ability to follow a specific drive trace in electric only mode leads the output split configuration to have a large electric machine, similarly to the series. The series configuration, where the wheels are only powered from the electrical energy, shows the highest total power, about twice as high as for the pre-transmission parallel.

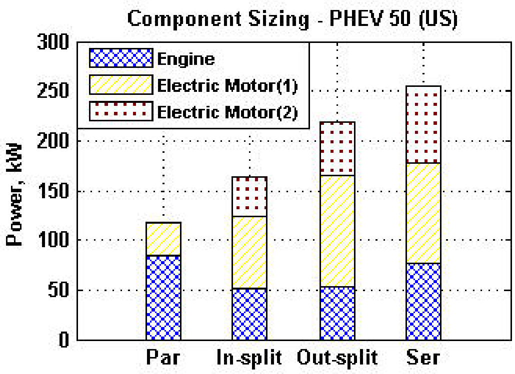

Figure 8: Sizing results for 50km AER US vehicles

Further analysis shows that the component sizes are not significantly influenced by the drive cycle selected to size the energy storage and the electric machines. For example, despite the fact that the UDDS was selected for the US and the Artemis Urban for Europe, the main electric machine power for the input split PHEV15 varies from 69.4 kW for Europe to 68.8 kW for the US. All the component sizes are available in the Appendix.

3.2 Charge-Sustaining Fuel Consumption Results

Figure 9 and Figure 10 show the fuel consumption ratio, in charge-sustaining mode, compared to the reference conventional vehicle for both European and US drive cycles. UL1 cycle has also been simulated [19]. It's a speed profile representing city center with traffic jam (mean speed is 3,8km/h).

As one notices, most of the electric drive powertrain considered lead to fuel consumption reduction. The exception is for the highway drive cycles (Artemis Highway and HWFET) where the pure series configuration shows a higher fuel consumption than for the reference conventional vehicle, due to high powertrain losses. The opposite tendency can be observed in the UL1 cycle, where the series architecture offers a better efficiency. As expected, the drive cycles with the lowest average vehicle speed (Artemis Urban and UL1) leads to the greatest fuel savings with a ratio lower than 0.4 (resp. 0.2).

Most of the powertrain configurations however achieve similar fuel consumption ratio. Higher energy storage systems show higher fuel consumption in charge-sustaining mode, due to higher vehicle weight.

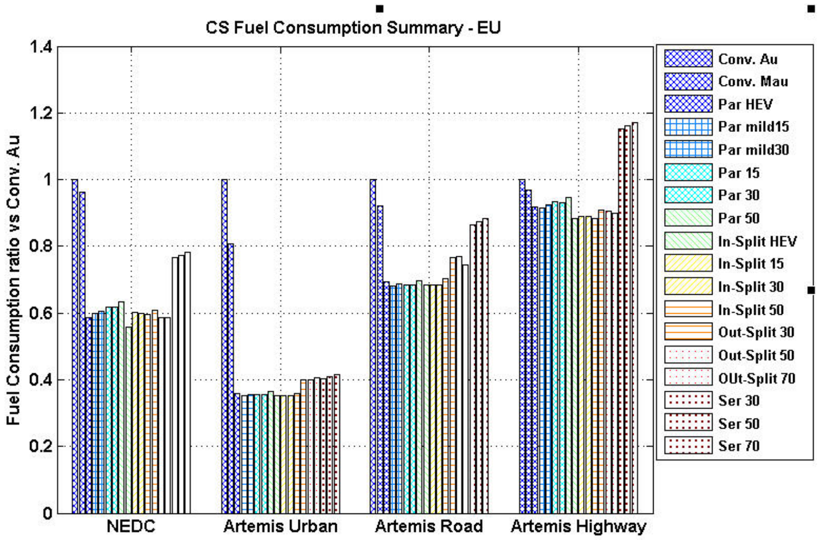

Figure 9: Charge-Sustaining fuel consumption ratio results – European vehicles

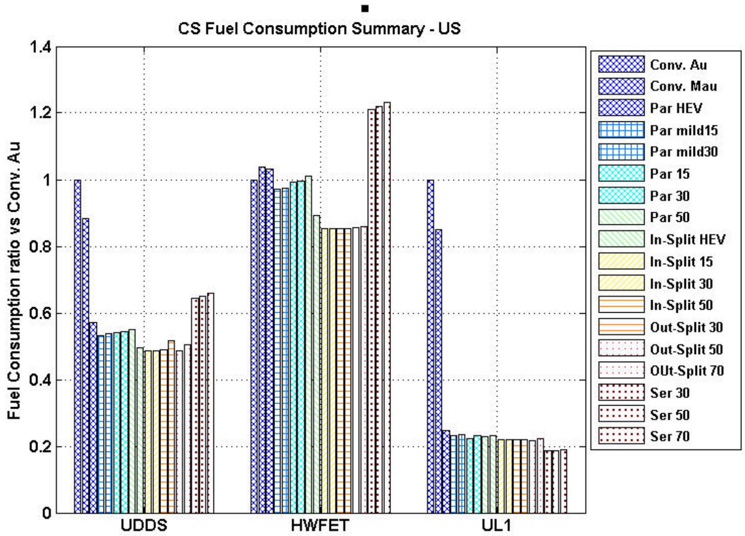

Figure 10: Charge-Sustaining fuel consumption ratio results – US vehicles

3.3 Results on US and EEC standard procedures

Figure 11 shows the fuel and electrical consumption for the different electric drive vehicles considered. Since the standard procedures do not provide a single energy value, both consumptions have been plotted on different axis. The powertrain configurations the closest to the origin show the highest overall efficiencies. To properly analyse the results, special attention has been focused on obtaining similar charge depleting distance across powertrains with the same AER value (i.e. similar energy management strategies during charge depleting were used across powertrains).

The input split HEV and PHEV configurations consistently demonstrate the highest powertrain efficiencies regardless of the standard driving cycles considered. The output split and the pre-transmission configurations provide close results. The series configuration, however, demonstrate significantly higher losses than any other configuration.

In addition, for the same electrical consumption, the fuel consumptions achieved on the US drive cycle are consistently higher than the ones achieved for the European drive cycle.

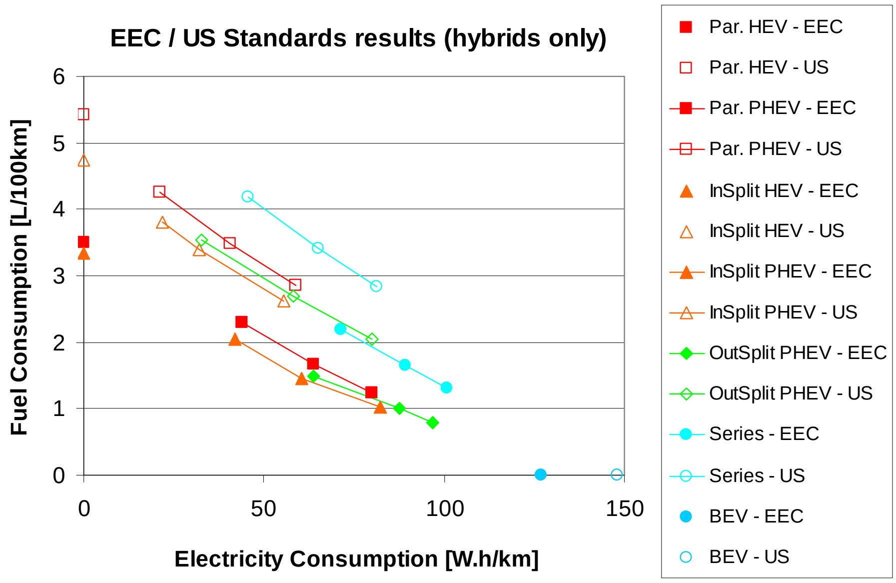

Figure 11: Fuel and electricity consumption results on EEC and US standards for electric drive vehicles

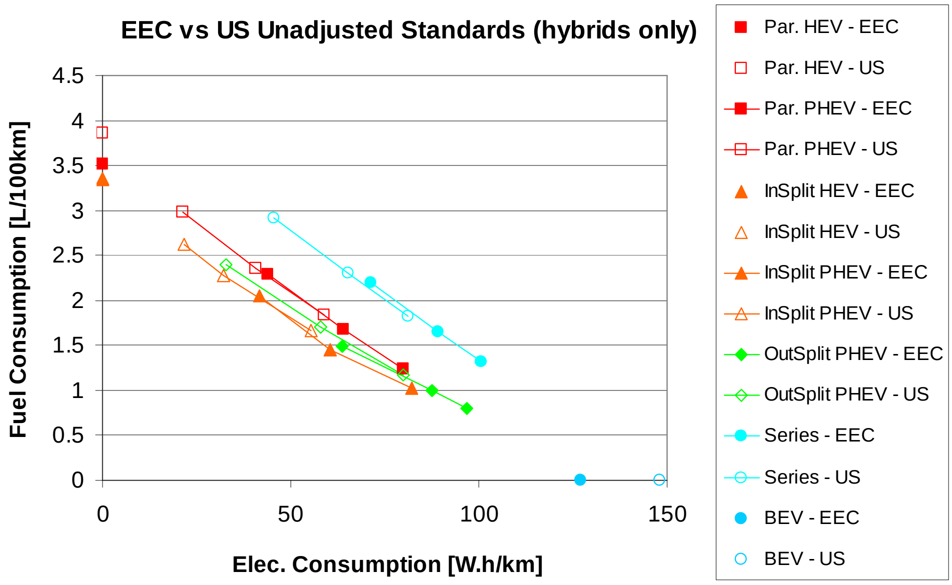

Figure 12: : Fuel and electricity consumption results on EEC standards and US before fuel adjustment

Detailed analysis of the results proved that this difference mainly comes from several factors including:

- Fuel consumption is adjusted on the US cycles, while it is not on the EEC ones. It is the main reason why, for a same level of electricity consumption, fuel consumption is higher on the US norm. As Figure 12 shows, comparing EEC results to US results without using the adjustment factor results in a similar fuel/electricity consumption trade-off, even if the driving patterns are different.
- The utility factor usage in the US versus the EEC norm. The former aims at being an image of the average usage of a car overall the population in the country, while the second one represents a usage where each customer would buy a vehicle with an AER slightly lower (25km) than his daily trip. It explains why the electricity/fuel consumption trade-off goes to more electricity on the EEC norm with higher electric energy content.

This difference should be taken into account when comparing worldwide regulations (cf. Figure 1).

3.4 Results on Actual Use Daily Missions

As discussed earlier, several daily missions have been developed to represent the fuel displacement potential of each powertrain configurations under different driving conditions. In that case, no utility factor or weighting is applied.

Figure 12, Figure 13 and Figure 14 respectively show the consumption for different mission profiles. One notice that the consumption values significantly vary based on the type of trip (city in mission 1 to extra urban in mission 2 and highway in mission3) compared to the standard drive cycle. For example, the input split HEV achieves 4.75 l/100km on the US standard and 3.34 l/100km on the NEDC while it varies from 3.6 to 5 l/100km.

In the majority of cases, for an equivalent amount of electrical energy, the PHEV configurations also lead to higher fuel consumption when simulating real world drive cycles.

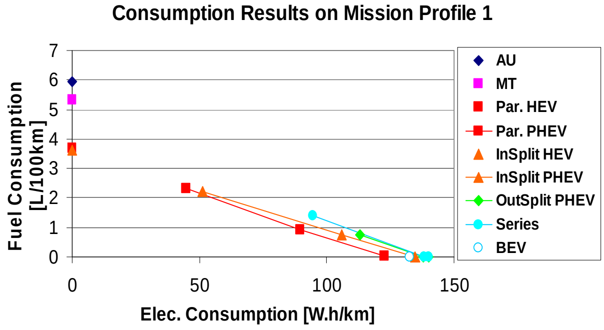

Figure 13: Fuel and electricity consumption results on Mission Profile 1

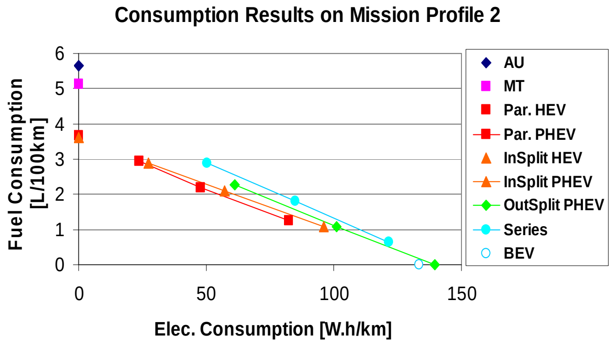

Figure 14: Fuel and electricity consumption results on Mission Profile 2

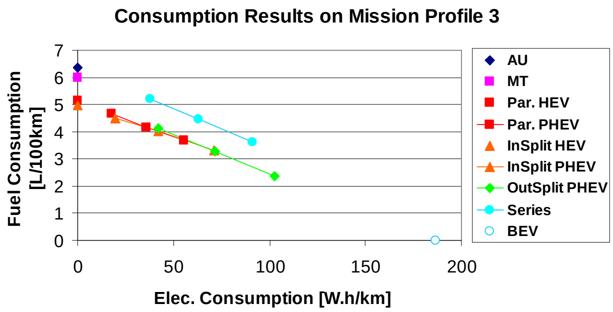

Figure 15: Fuel and electricity consumption results on Mission Profile 3

Figure 15, Figure 16 and Figure 17 respectively show the CO_2 emissions for each powertrain on different mission profile. For each vehicle, three different Well-to-Wheel (WTW) values are provided based on three different assumptions on the CO2 emissions related to electricity production: 100, 450 and 650 gCO_2/kW.h. The former one corresponds to countries with high nuclear energy content, while the last one corresponds to a country using mainly fossil fuel plants.
The results indicate that in the 650gCO_2/kW.h scenario, plug-in vehicle are not an effective solution to significantly decrease global CO_2

emissions. In the 450gCO_2/kW.h scenario, plug-in vehicle show lower WTW emissions on urban and extra-urban usage. The 100gCO_2/kW.h scenario is the only one showing much lower emissions on all the driving patterns, but the required energy system storage capacity has to be higher on highway usage to show CO_2 emission reduction.

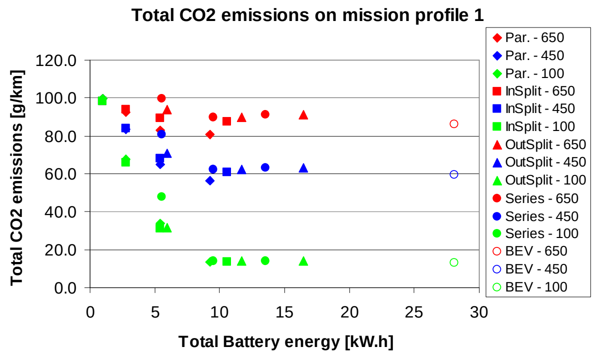

Figure 16: Total Well-to-Wheel CO2 emissions on Mission profile 1, across architecture, battery sizing and electricity Well-to-Tank CO2 emissions

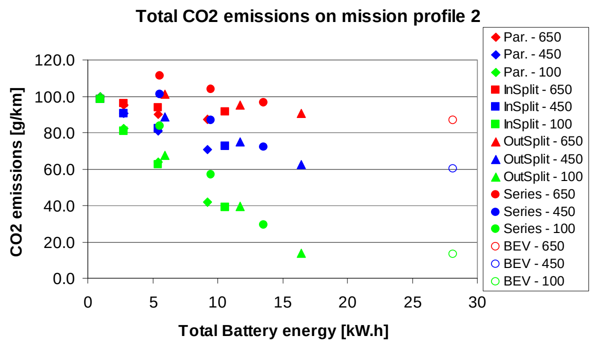

Figure 17: Total Well-to-Wheel CO2 emissions on Mission profile 2, across architecture, battery sizing and electricity Well-to-Tank CO2 emissions

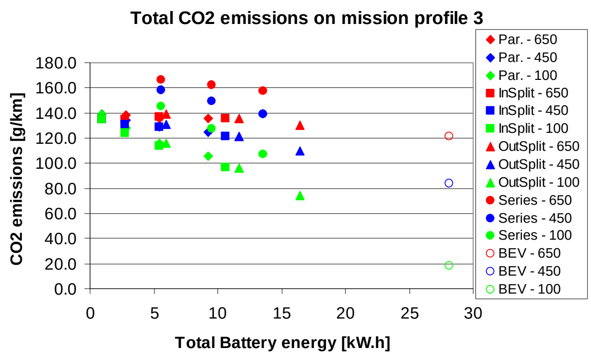

Figure 18: Total Well-to-Wheel CO2 emissions on Mission profile 3, across architecture, battery sizing and electricity Well-to-Tank CO2 emissions

4 Conclusion

Several electric drive vehicle configurations were simulated both under standard driving conditions and real world drive cycles in the US and in Europe.

When sized to meet the same vehicle technical specifications and all electric range, the component power and energy were similar for the US (UDDS cycle) and Europe (Artemis urban). As a result, the same component sizes could provide similar results. Since the fuel consumption reduction of HEVs are higher for the NEDC drive cycle than for the US Combined drive cycle, it is natural to think that the difference of technology benefit for each standard would lead manufacturer to different technology solutions.

In addition, the NEDC drive cycle provides lower fuel consumption values than the US standard, which should be carefully taken into account when comparing fuel consumption standards worldwide.

When comparing powertrain configurations, the input split offers the highest efficiency and the series the lowest, which is consistent with the current technologies in the market. Parallel and output split configurations, which are being introduced in the market, also offer significant fuel displacement.

Future studies will include the impact of component optimum sizes and technology benefits focusing on the new worldwide drive cycle compared to current standard and different mission profiles.

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References

[1] The International Council for Clean Transportation, *Global Comparison of Light-Duty Vehicle Fuel Economy/GHG Emissions Standards*, August 2011

[2] P. Menegazzi, P. Aubret, F. Badin, R. Trigui, C. Marchand, *An Advanced Simulation Tool for the Consumption, Emissions, and Performance Analysis of Conventional and Hybrid Vehicles*, FISITA paper - F2006P115, 2006

[3] S. Halbach, P. Sharer, S. Pagerit, C. Folkerts, and A. Rousseau, Model Architecture, Methods, and Interfaces for Efficient Math-Based Design and Simulation of Automotive Control Systems, SAE 2010-01-0241, SAE World Congress, Detroit, 2010

[4] A. Rousseau, P. Sharer, S. Pagerit, and M. Duoba, *Integrating Data, Performing Quality Assurance, and Validating the Vehicle Model for the 2004 Prius Using PSAT*, SAE paper 2006-01-0667, SAE World Congress, Detroit, 2006

[5] Q. Cao, S. Pagerit, R. Carlson, and A. Rousseau, *PHEV hymotion Prius model validation and control improvements*, 23rd International Electric Vehicle Symposium (EVS23), Anaheim, CA, 2007

[6] N. Kim, R. Carlson, F. Jehlik, and A. Rousseau, *Tahoe HEV Model Development in PSAT*, SAE paper 2009-01-1307, SAE World Congress, Detroit, 2009

[7] N. Kim, and A. Rousseau, *Instantaneous Optimal Control for Hybrid Electrical Vehicle*, SAE 2011-01-0873, SAE World Congress, Detroit, 2011

[8] M. O. Thurston, *Handbook of Electric Motors*, second edition, Ohio State University, 2004

[9] T.J.E. Miller, Brushless Permanent-Magnet and Reluctance Motor Drives, Clarendon Press, Oxford, 1989

[10] J. Pyrhonen, T. Jokinen, V. Hrabovcova, *Design of Rotating Electrical Machines*, John Wiley & Sons, Ltd. ISBN: 978-0-470-69516-6, 2008

[11] C. Hwang, S.M. Chang, C.T. Pan, T.Y. Chang, *Estimation of parameters of interior permanent magnet synchronous motors*, J. Magn.Magn. Mater. 600–603, 2002

[12] R. H. Staunton, C. W. Ayers, L. D. Marlino, J. N. Chiasson, T. A. Burress, *Evaluation of the 2004 Toyota Prius Hybrid Electric Drive System*, UT-Battelle, LLC, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 2006

[13] P. Nelson, K. Amine, A. Rousseau, and H. Yomoto, *Advanced Lithium-Ion Batteries for Plug-in Hybrid-Electric Vehicles*. Presented at the 23rd International Electric Vehicle Symposium, 23rd International Electric Vehicle Symposium (EVS23), Anaheim, CA, 2007

[14] M. Miller, A. Holmes, B. Conlon, and P. Savagian, *The GM 'Voltec' 4ET50 Multi-mode Electric Transaxle*, SAE 2011-01-0887, SAE World Congress, Detroit, 2011

[15] Hybrid-EV Committee, *Recommended Practice for Measuring the Exhaust Emissions and Fuel Economy of Hybrid-Electric Vehicles, Including Plug-in Hybrid Vehicles*, SAE 2010-06-08, SAE World Congress (http://standards.sae.org/j1711_201006/), 2010

[16] UNECE Vehicle Regulations - 1958 Agreement, Regulation No. 84, http://www.unece.org/trans/main/wp29/wp29regs81-100.html

[17] M. Andre, *The ARTEMIS European driving cycles for measuring car pollutant emissions, Science of the Total Environment*, Vol. 334-335, p. 73-84, 2004

[18] N. Marc, E. Prada, A. Sciarretta, S. Anwer, F. Vangraefschepe, F. Badin, A. Charlet, P. Higelin, *Sizing and fuel consumption evaluation methodology for hybrid light duty vehicles*, EVS 25 Shenzen, China, 2010

[19] J.P. Krauser, *Méthodologie statistique pour l'étude des cinématiques et des consommations des véhicules légers, INRETS LEN*, Université des Sciences et des Techniques du Languedoc, ISBN: 2-85782-251-0, INRETS Bron, France, 1989

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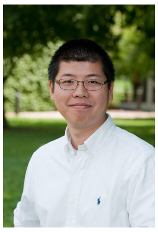

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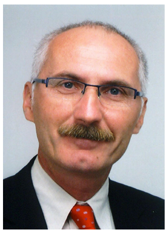

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Appendix

Vehicle Component Sizes

Sizing Results		Conv.		Parallel Hybrid						Input split Hybrid				Output split Hybrid			Series Hybrid			BEV
				HEV	Plug-in					HEV	Plug-in			Plug-in			Plug-in			
		Auto.	Man.		Mild 15	Mild 30	AER 15	AER 30	AER 50		AER 15	AER 30	AER 50	AER 30	AER 50	AER 70	AER 30	AER 50	AER 70	AER 150
Europe	Vehicle Mass [kg]	1220	1219	1271	1292	1313	1319	1342	1371	1348	1320	1340	1375	1412	1440	1466	1541	1573	1614	1361
	ICE power [kW]	105.9	104.5	80.2	80.2	82.2	78.2	82.2	84.2	57.3	50.3	50.7	51.4	51.5	51.8	52.8	76	77	78	
	El. machine 1 power [kW]			25	25	25	34	34	34	67.9	69.4	70.3	72.1	104.2	103	94.3	99	101	103	98.4
	El. machine 2 power [kW]									35	34.6	34.9	35.3	51.5	51.8	52.8	76	77	78	
	Battery power [kW]			30	30	30	42	42	42	48.9	59.8	60.5	62.2	100.5	102.2	100.5	130	130	135	104.9
	Battery energy [kW.h]			0.97	2.79	5.43	2.79	5.43	9.25	0.97	2.77	5.44	10.6	5.94	11.71	16.44	5.54	9.5	13.56	28.1
US	Vehicle Mass [kg]	1220	1219	1278	1288	1311	1317	1338	1364	1329	1316	1330	1353	1438	1461	1488	1541	1570	1610	1368
	ICE power [kW]	105.9	104.5	80.2	80.2	82.2	78.2	82.2	84.2	85.5	50.2	50.5	50.9	51.9	52.7	54.3	76	77	78	
	El. machine 1 power [kW]			25	25	25	34	34	34	58.4	68.8	69.9	71	110.2	113	116.2	99	101	103	109.2
	El. machine 2 power [kW]									48.5	34.6	34.8	35.1	51.9	52.7	54.3	76	77	78	
	Battery power [kW]			30	30	30	42	42	42	25.6	59.4	60.2	61.1	141.3	144.8	148.8	130	130	135	132.9
	Battery energy [kW.h]			0.97	2.49	5.21	2.49	5.21	8.32	0.97	2.6	4.97	8.43	5.25	9.15	12.99	5.54	9.13	13.03	27.6

Fuel and Electric Consumption Results on Standard Drive Cycles

CS Fuel consumption Results		Conv.		Parallel						Input split				Output split			Series			BEV
				HEV	Plug-in					HEV	Plug-in			Plug-in			Plug-in			AER 150
		Auto.	Man.		Mild 15	Mild 30	AER 15	AER 30	AER 50		AER 15	AER 30	AER 50	AER 30	AER 50	AER 70	AER 30	AER 50	AER 70	
Europe	NEDC	5.98	5.75	3.51	3.59	3.61	3.69	3.69	3.78	3.34	3.6	3.58	3.56	3.63	3.5	3.51	4.58	4.62	4.68	
	Artemis Urban	10.4	8.42	3.74	3.66	3.71	3.7	3.69	3.79	3.66	3.67	3.66	3.74	4.16	4.17	4.23	4.21	4.27	4.34	
	Artemis Road	5.3	4.88	3.67	3.61	3.65	3.63	3.63	3.7	3.62	3.62	3.63	3.73	4.07	4.08	3.95	4.58	4.63	4.68	
	Artemis Highway	6.65	6.44	6.1	6.09	6.14	6.2	6.19	6.29	5.87	5.91	5.91	5.87	6.05	6.02	5.98	7.67	7.72	7.79	
	UL1	29.1	24.8	7.16	6.96	7.04	6.51	6.5	6.68	6.78	6.44	6.4	6.41	6.56	6.15	6.2	5.41	5.47	5.53	
US	UDDS	6.3	5.56	3.6	3.35	3.38	3.41	3.42	3.46	3.12	3.07	3.06	3.08	3.25	3.07	3.18	4.06	4.1	4.16	
	HWFET	4.05	4.2	4.18	3.93	3.95	4.02	4.03	4.09	3.62	3.45	3.45	3.46	3.46	3.47	3.48	4.9	4.94	4.99	
	UL1	29.1	24.8	7.16	6.78	6.84	6.51	6.76	6.67	6.78	6.42	6.38	6.4	6.4	6.31	6.45	5.41	5.46	5.53	

CD Fuel consumption [L/100km]		Conv.		Parallel						Input split				Output split			Series			BEV
				HEV	Plug-in					HEV	Plug-in			Plug-in			Plug-in			AER 150
		Auto.	Man.		Mild 15	Mild 30	AER 15	AER 30	AER 50		AER 15	AER 30	AER 50	AER 30	AER 50	AER 70	AER 30	AER 50	AER 70	
Europe	NEDC				0.12	0.13	0	0	0		0	0	0	0	0	0	0	0	0	
	Artemis Urban				0.01	0.02	0	0	0		0	0	0	0	0	0	0	0	0	
	Artemis Road				0.06	0.21	0.07	0.04	0.05		0	0	0	0	0	0	0	0	0	
	Artemis Highway				1.08	1.11	0.31	0.31	0.36		0.56	0.96	1.04	0	0.04	0.03	0	0	0	
	UL1				0	0	0	0	0		0	0	0	0	0	0	0	0	0	
US	UDDS				0.02	0.04	0	0	0		0	0	0	0	0	0	0	0	0	
	HWFET				0	0	0	0	0		0.49	0	0	0	0	0	0	0	0	
	UL1				0	0	0	0	0		0	0	0	0	0	0	0	0	0	

CD Electricity consumption [W.h/km]		Conv.		Parallel						Input split				Output split			Series			BEV
				HEV	Plug-in					HEV	Plug-in			Plug-in			Plug-in			AER 150
		Auto.	Man.		Mild 15	Mild 30	AER 15	AER 30	AER 50		AER 15	AER 30	AER 50	AER 30	AER 50	AER 70	AER 30	AER 50	AER 70	
Europe	NEDC				114	115	116	117	119		97.7	102	115	109	123	125	137	139	140	127
	Artemis Urban				114	116	117	120	128		128	129	131	144	146	150	124	125	127	119
	Artemis Road				120	113	122	118	122		133	135	135	137	137	139	139	140	142	134
	Artemis Highway				188	188	205	205	208		213	217	205	221	219	219	240	242	245	223
	UL1				141	142	141	141	143		152	153	155	177	179	183	152	154	156	247
US	UDDS				103	104	105	105	106		109	110	111	112	117	117	120	121	123	120
	HWFET				117	118	119	119	120		107	125	126	126	127	127	149	150	151	127
	UL1				141	142	141	142	143		152	152	154	178	180	181	152	154	156	240

CD range [km]		Conv.		Parallel						Input split				Output split			Series			BEV
				HEV	Plug-in					HEV	Plug-in			Plug-in			Plug-in			AER 150
		Auto.	Man.		Mild 15	Mild 30	AER 15	AER 30	AER 50		AER 15	AER 30	AER 50	AER 30	AER 50	AER 70	AER 30	AER 50	AER 70	
Europe	NEDC				15.5	30.6	15.2	30.1	51.1		18.8	36.5	61.6	35.6	62.1	85.6	27.1	44.9	64	146
	Artemis Urban				15.5	30.4	15.1	29.4	47.5		15.2	30.5	49	28.3	47.5	66	29.9	49.9	70.5	150
	Artemis Road				14.7	31.2	14.4	29.8	49.8		15.1	31.3	52.8	32.9	54.9	77.2	26.7	44.6	63.1	137
	Artemis Highway				9.4	18.7	8.6	17.2	26.2		9.07	19.2	34.1	18.7	32.1	45.1	15.5	25.6	36.6	82.8
	UL1				12.5	24.8	12.5	24.8	42.5		11.5	23	38.2	23.2	39	54.2	24.4	38.9	55.2	68.6
US	UDDS				15.2	32.5	14.9	32	51.5		14.1	28.4	48.4	30	50	70	30.9	49.6	70	150
	HWFET				13.3	28.5	13.1	28.3	45.3		13.1	25	41.9	26.8	47.5	66.6	24.9	40	57	146
	UL1				11.1	23.8	11.1	23.8	38.1		9.2	17.4	28.6	17.7	29.6	40.6	24.4	39.3	57.5	70.7

PHEV standard procedures results		Conv.		Parallel						Input split				Output split			Series			BEV
				HEV	Plug-in					HEV	Plug-in			Plug-in			Plug-in			AER 150
		Auto.	Man.		Mild 15	Mild 30	AER 15	AER 30	AER 50		AER 15	AER 30	AER 50	AER 30	AER 50	AER 70	AER 30	AER 50	AER 70	
Europe	Fuel [L/100km]	5.98	5.75	3.51	2.26	1.69	2.29	1.67	1.24	3.34	2.06	1.46	1.03	1.5	1	0.79	2.2	1.65	1.31	0
	Electricity [W.h/km]	0	0	0	43.6	63.3	43.9	63.9	79.9	0	41.9	60.5	82.1	63.8	87.5	96.8	71.3	89.3	101	127
	F.C. gain [%]	0	3.85	41.3	62.2	71.7	61.6	72	79.2	44.1	65.6	75.7	82.8	75	83.2	86.7	63.2	72.4	78	100
US	Fuel [L/100km] - adjusted	7.18	6.76	5.43	4.17	3.43	4.26	3.48	2.85	4.75	3.81	3.4	2.63	3.54	2.7	2.04	4.18	3.41	2.83	0
	Electricity [W.h/km]	0	0	0	21.3	40.7	21.3	40.7	58.9	0	21.7	32.2	55.5	32.8	58	79.9	45.6	65.2	81.2	148
	F.C. gain [%]	0.0	5.8	24.4	41.9	52.2	40.7	51.5	60.3	33.8	46.9	52.6	63.4	50.7	62.4	71.6	41.8	52.5	60.6	100.0
	Fuel [L/100km] - unadjusted	5.3	4.95	3.86	2.91	2.31	2.98	2.35	1.84	3.35	2.62	2.28	1.66	2.4	1.71	1.17	2.92	2.3	1.82	0
	Electricity [W.h/km]- unadjusted	0	0	0	21.3	40.7	21.3	40.7	58.9	0	21.7	32.2	55.5	32.8	58	79.9	45.6	65.2	81.2	148