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Comparison of Energy consumption and costs of different HEVs and PHEVs in European and American context

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Abstract

This paper will analyse on the one hand the potential of Plug in Hybrid Electric Vehicles (PHEVs) to significantly reduce fuel consumption and displace it toward various primary energies thanks to the electricity sector. On the other hand the total cost of ownership (TCO) of two different PHEV architectures will be compared to a conventional vehicle and a HEV without external charging.

The vehicles energy consumptions have been calculated using simulation softwares at Argonne National Lab and IFP Energies nouvelles.

The TCO analysis carried out by DLR and Argonne National Lab includes the vehicle initial price together with the maintenance, energy consumptions and other costs during their life.

The impact of driving behaviour variations between Europe and the US will be addressed in the paper through its influence on component sizing and fuel consumption benefits.

Keywords: Hybrid electric vehicles - Energy Efficiency - Costs

1 Introduction

Car manufacturers and components suppliers have been facing these years very stringent constraints in the development of their vehicles, mainly:

- The decrease of the Green House Gases (GHG) emitted by the vehicles (mainly the CO_2) with very severe targets fixed by numerous countries around the world ;
- The decrease of local harmful effects such as atmospheric pollutants or noise which are recognized as being a major problem in large urban centers. The ultimate goal being here the vehicle with zero local emissions (ZEV) which will require an electric drive ;
- The decrease of fossil fuel consumption which will require the use of new fuels, such as

electricity, to transfer more transportation energy consumption towards other more sustainable primary energies such as renewables ;

- The need for the vehicle to have an environmental and energy footprint as limited as possible on its entire life cycle (from its construction to its recycling phases);
- The need for the vehicle to have an economic balance over its entire life (purchase, energy(ies) consumption(s) , maintenance, resale, recycling) close to, or better than the conventional ones to ensure its significant penetration in the market.

In response to these constraints, industrialists have developed numerous solutions; among the existing panel of technologies, we will address in this paper three of many possible hybrid (HEV) and plug-in hybrid (PHEV) drivetrains.

Understanding the real potential of such drivetrains is a very complex task as it will depend on a high number of parameters, the main ones being:

- The vehicle hybrid drivetrain architecture and functionalities (all electric range, plug in capabilities...);
- The vehicle body type (compact, sedan, SUV, 4WD...) and dynamic performances;
- The vehicle type of use (urban, extra urban, motorway, combined, type of standard regulatory procedures);
- For the specific case of the PHEVs, the electricity mix used for the battery charge from the mains;
- The type of drivetrain components implemented (conventional or advanced technologies);
- The type of powertrain configuration (combination of components, including sizing) and energy management strategy implemented;

With the aim to assess the energy consumption potential and the economic balance of HEVs and PHEVs, Argonne National Lab (ANL) in the US, the German Aerospace Center (DLR) in Germany and IFP Energies nouvelles (IFPEN) in France have collaborated to develop a specific methodology. The methodology and obtained results are detailed in [1] and [2] for a panel of drivetrain architectures with different choices for the All electric Range (AER).

The present paper details the methodology used to evaluate the vehicles, their drivetrain and type of use with standard procedures and actual use driving cycles. Cross-national perspectives and results obtained in energy and costs for a selected subset of those cases are presented and discussed in the paper.

2 Methodology

The first question is whether recent advances in battery technology based on lithium-ion chemistries will allow HEV and particularly PHEV powertrains, produced at reasonably high volume (100,000 units in this paper) to compete with a reference conventional gasoline vehicle (CV). If so, can electrified powertrains of these types universally compete with the CV, or are they only competitive under certain patterns of customer use? Do current average prices for gasoline and electricity paid by consumers in Europe and the U.S. give reason to believe that government encouragement of the development of these powertrains will ultimately lead to market success? However, for the next decade, this is a primary question. If the answer is that there do appear to be market segments where such powertrains could compete, development and refinement over the years will determine whether they become very common, or only contribute in a small way to energy security and GHG reduction in the participating nations. If there is evidence here that PHEVs can compete, then the many more powertrain combination and permutations possible than examined here ref [1] deserve detailed evaluation against the portfolio of competing options such as direct injection turbocharged diesel and gasoline fuelled engines and pure electric vehicles.

2.1 Tools

For the vehicle components sizing and energy consumptions evaluations ANL and IFPEN used their own tools i.e. MATLB-based software Autonomie for ANL and LMS.IMAGINE.Lab AMESim® for IFPEN. Before starting the study a crosscheck of the 2 softwares on a reference vehicle has been carried out it order to ensure consistency between Autonomie and AMESim. Details are provided in [1].
For the TCO analysis, ANL BatPAC and DLR in house tools have been used, details are provided in [2].

2.2 Vehicle characteristics

The type of vehicle considered is a compact size sedan (C segment) with a body in white mass of 800 kg, a frontal area of 2,18 m^2, a C_d coefficient of 0,3, and a C_{rr1} coefficient of 0,006.

2.3 Drivetrains architectures

For this paper, the following powertrain architectures have been taken into account for comparison (see fig 1) :

- Conventional 5 speed vehicle, with an automatic gearbox ;
- Pre-transmission parallel HEV ;
- Input-split PHEV (Toyota HSD-like transmission). For this architecture an AER of 30 km has been considered ;
- Series hybrid, for this architecture, an AER of 70 km has been considered.

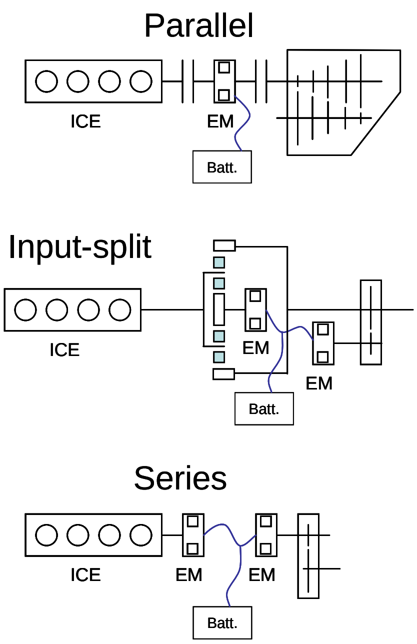

Figure 1: Hybrid powertrain architectures considered

2.4 Drivetrains components sizing

Components sizing have been carried out according to the following design limits based on assumptions about consumer demand for a typical vehicle:

- Dynamic performances, from 0 to 100km/h in 9 sec +/−0.1 sec using both engine and electric machine. This exceeds the performance of many commercial HEVs;
- Maximum grade of 5% at 110km/h at gross vehicle weight with engine power only;
- Maximum vehicle speed >150km/h with engine power only. This exceeds the performance of commercial electric vehicles;
- Rated all electric Range (AER) for the input split (IS) type architecture has been developed using the UDDS driving schedule for the US and the Artemis Urban driving schedule for Europe. This is a limited all electric capability which is less than available in commercial electric vehicles, but is adequate for city centres worldwide due to the Artemis Urban driving schedule requirement. Such configuration may be called *Urban capable* PHEV [3]. Although the Artemis Urban cycle dominated component sizing choices, the supplemental tests for UDDS capability assured that the input split PHEV could obtain regulatory credit in California. The IS PHEV example in this paper is required to have 30 km of rated AER
- For the specific case of the series architecture, the all electric charge depleting (CD) mode provides a capability for the vehicle to meet all other performance requirements (acceleration, grade and maximum speed) using only battery power. The series PHEV example in this paper is required to have 70 km of rated (and actual) AER. In this case the term AER is literally always correct; however, for the input split there are some circumstances (example: Artemis Motorway cycle) where the CD phase of operation will use the engine momentarily in blended mode.

The components sizing for the different cases considered is indicated in Table 1. The requirements imposed result in very large increases in both battery pack power (kW) and energy storage capability (kWh) as one transitions from HEV to IS PHEV30 to series PHEV70. As one goes through these steps, the power to energy (P/E) ratios for the battery packs decrease, as illustrated in Table 1, this will have an influence on the cost evaluation presented in section 2.6.

Tab 1 : Vehicle components sizing

			Conventional	Parallel Hybrid	Input split Hybrid	Series Hybrid
			Automatic	HEV	PHEV 30	PHEV 70
Europe	Vehicle Mass	kg	1220	1271	1340	1614
	ICE power	kW	105,9	80,2	50,7	78
	El. machine 1 power	kW		25	70,3	103
	El. machine 2 power	kW			34,9	78
	Battery power	kW		30	60,5	135
	Battery energy	kWh		0,97	5,44	13,56
	Battery P/E ratio	h^{-1}		31	11	10
US	Vehicle Mass	kg	1220	1278	1330	1610
	ICE power	kW	105,9	80,2	50,5	78
	El. machine 1 power	kW		25	69,9	103
	El. machine 2 power	kW			34,8	78
	Battery power	kW		30	60,2	135
	Battery energy	kWh		0,97	4,97	13,03
	Battery P/E ratio	h^{-1}		31	12	10

2.5 Vehicle types of mission considered

Different situations have been considered to evaluate energy consumptions and operating costs of the vehicles, according to the driving schedules used and to the procedure implemented.

2.5.1 Driving schedules

As far as driving schedule is concerned, there are two types of driving cycle evaluation that have been conducted: **Standard procedure** certification test cycles that have been used since the 1970s, and **actual use related procedure** which implement cycles resulting from on-road testing that has taken place more recently (see Annex 1). Within the full complement of simulations conducted for vehicles characterized by both IFP Energies nouvelles and Argonne National Laboratory, the on-road cycles used in this paper include a very low speed jammed urban case for the US (UL1), and three Artemis test cycles developed in the European research program on evaluation of on-road driving ARTEMIS (Urban type, Road and Motorway types) [4]. The standard procedure certification test cycles include the NEDC for the European case and UDDS and HWFET for the U.S. case. These standard procedure cycles are used for official ratings of compliance with fuel economy and GHG regulations. However, as a result of recognition that consumer experience was not well represented by rough adjustments of these cycles, studies in the U.S. led to a decision to develop a new set of test cycles that are now being used to construct an improved consumer information sticker placed on new cars [5]. One of the driving cycles that led to those U.S. revisions (LA92, also called the California Unified Cycle) was an update for California driving developed in 1992. Annex 1 shows that it is similar to the Artemis Urban cycle with respect to acceleration and deceleration rates, but stop time is much less and average speed higher. Consumer information presented to the U.S. consumer for highway (or motorway) driving now relies almost exclusively on the US06 Highway cycle, which is similar to the Artemis Motorway cycle in most respects.

2.5.2 Procedures

For the **Standard procedures**, two cases were considered, i.e. :

- **For the US regulatory certification case**, we implemented the SAE J1711 procedure, more information in [6] : The simulation on the UDDS cycle is started with a battery at 100 % State of Charge (SOC) to simulate the Full Charge Test (FCT) and implement the Charge Depleting (CD) behaviour. The calculation is stopped when the simulated vehicle has reached its Charge Sustaining (CS) operation mode (the battery SOC difference over one cycle being close to 0). The Charge Depleting Range (CDR) together with the two fuel consumptions characteristic of a PHEV may then be assessed, i.e. the charge depleting consumption FC_{dep} and the sustaining one FC_{sus} (expressed in gallons per mile - gpm). One could note that for certain types of PHEVs (urban capable and E-REVs) the UDDS FC_{dep} is nil. The aggregation of the two fuel consumptions (FC_{glob}) may then be computed thanks to the Utility Factor (UF) established by the US Department of Transportation [7] and which accounts for the fraction of driven miles expected in CD according to the CDR (see Figure2), using the following equation *(1)* :

$$FC_{glob}\ (gpm) = FC_{dep}.UF + (1-UF).FC_{sus}$$

The same equation may be used to compute the electricity consumption of the PHEV.

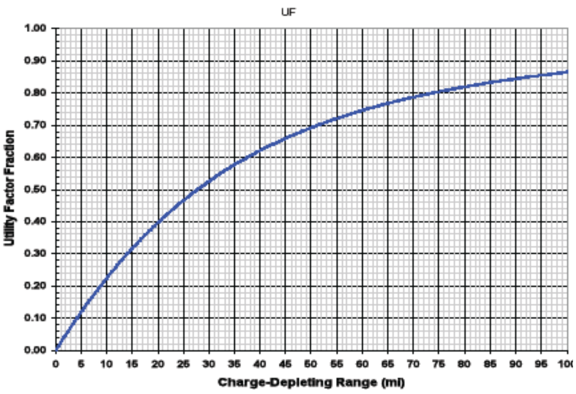

Figure 2: Utility factor according to AER (from US DOT survey 2001)

- **For the EU regulatory certification case**, the ECE R101 procedure has been implemented, see details in [8] : The first step is the evaluation of the vehicle's All Electric Range (AER). The simulation is run using the NEDC driving schedule, with the vehicle in electric mode and with a fully charged battery. The AER is obtained when the SOC reaches its minimum (the procedure allows the vehicle not to follow the cycle for speeds above 50 km/h though this has not been necessary for our cases). Once this has been done, the procedure itself consists of two phases, in the first (A), the simulation of the NEDC cycle is carried out in hybrid mode with the battery again fully charged to evaluate the Fuel Consumption (FC_A in L/100 km) and the Electricity Consumed from the grid to recharge the battery at the end of the cycle (EC_A in Wh/km) in Charge Depleting condition. The value of FC_A may be nil if the engine is not started during the NEDC procedure (the speed tolerance indicated above being respected). In the 2nd phase (B), the calculation is run again on the NEDC cycle but with a fully discharged battery to evaluate the Fuel Consumption (FC_B) and the Electricity Consumed from the grid to recharge the battery (EC_B). The equivalent fuel consumption of the PHEV may then be computed thanks to the following equation :

$$FC_{glob}\ (L/100\ km) = (AER.FC_A + 25.FC_B) / (AER + 25) \qquad (2)$$

One could note that the evaluation of the fraction of distance covered in CD mode is taken into account through the distance of 25 km that would have been covered by the vehicle after its AER and prior to its battery charge from the grid. The same equation may be used to compute the electricity consumption of the PHEV.

For the **Actual use related procedure**. While regulatory compliance is one very important evaluation measure for the simulated vehicles, the actual on-road consumption determines how much fuel cost they will experience. A long standing problem has been that the standard certification cycles predicted lower fuel consumption than consumers experienced. The primary reason for this problem for CVs has been the much more rapid rates of acceleration in on-road driving than is used in the standard certification cycles (see Annex 1). Another is extreme temperature operations, both cold and hot. On a percentage basis, climate control increases electricity consumption more than gasoline ICE consumption. On-road climatic energy consumption increases are neglected in the TCO portion of this analysis, and for the non-adjusted standard test procedures.
This inconsistency between certification cycle predictions and on-road experience has led to repeated revisions of consumer information estimates (window label estimates) in the U.S. [9].
In Europe a set of real-world driving cycles has been developed in the ARTEMIS project, under the financial support of the European Commission. The aim of the ARTEMIS project was to enable a better understanding of the actual vehicle pollutant emissions through the integration of a large

amount of European measurements into the real world cycles generation procedure [4]. For this paper, to estimate on-road fuel economy, we use three Artemis cycles to simulate fuel and electricity consumption estimates both for the European and U.S. examples. The similarity of the Artemis cycles to U.S. on-road driving conditions illustrated by the U.S. LA92 and US06 cycles has been discussed and illustrated (see Annex 1).

DLR has demonstrated that there is a strong statistical correlation between measured daily driving and the consumer's estimated annual driving in Germany (see Figure 3). Z. Lin, [10] has demonstrated a strong statistical correlation between daily driving of vehicles used for work and the consumer's estimated annual driving in the U.S. Both DLR and Argonne analysts have studied national transportation surveys and documented that the average speed for vehicles increases with both length of trip and daily distance driven (see Figure 4) [11].

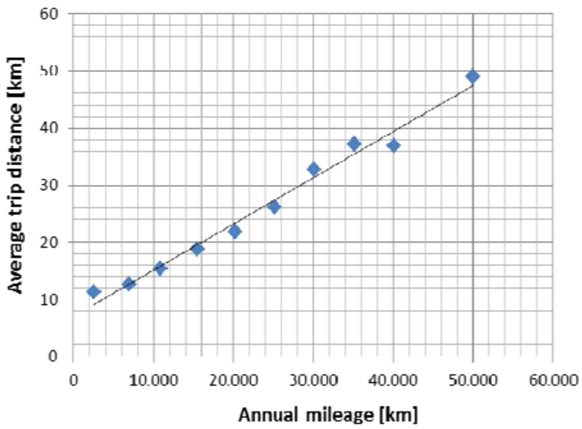

Figure 3: Statistical correlation between annual mileage and average trip distance in Germany (DLR analysis based on MiD 2008 data)

Comparison of the DLR and Argonne results on typical driving patterns per vehicle show that average speeds and annual distances are significantly higher in the U.S. than in Germany, which shows up in our total cost of ownership estimates. Methods of predicting appropriate fuel consumption per km developed by DLR and Argonne are similar in linking average speed to the mix of driving cycles used to construct the estimated fuel consumption.

The driving schedules for the U.S. and European cases have been constructed using pairs of Artemis cycles, weighted in distance shares to create a match to the desired speed for the daily driving distance chosen.

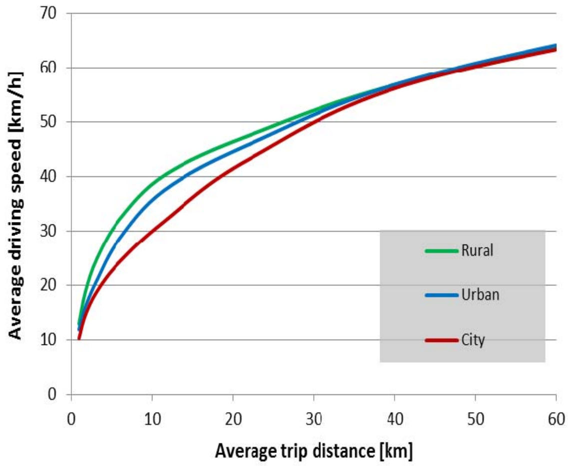

Figure 4 : Average driving speed in Germany as a function of average trip distance and place of residence (DLR analysis based on MiD 2008 data)

The U.S. cases assume 293 days of operation with 285 days of charging at the dwelling and other locations such as work, such that on average 1.25 charges per day are achieved. For the German case an average of 1 charge per day has been considered.

The number of days of charging does not change with daily and annual distance in the U.S. and German cases, so the share of km driven electrically declines as daily distance increases. This means that the CS fuel consumption becomes more important as daily and annual distance rise.

For the U.S. and German yearly covered distances, we have considered the nominal case of respectively 18000 km and 14000 km, together with a short distance case (resp. 6500 and 7000 km) and a longer case (resp 32500 and 20000 km). The overall average speed in the U.S. is faster and the two higher annual distance cases for the U.S. are greater.

2.6 Costs evaluation

The costs evaluation have been conducted in Dollars for the U.S. case and in Euros for the German case, the comparisons being carried out considering the CV case as a reference in both countries. An annual discount rate of 5% has been assumed for the TCO assessment. For a more detailed description of the DLR cost model which has been applied to analyse the cost competitiveness of different powertrain options in the German context see [12].

The main hypotheses considered in the method are detailed hereafter.

Energy costs :
For the U.S. case, the cost of gasoline is assumed to be $0,92 per liter, corresponding to a recent annual value [13]. For electricity 12 dollar cents per kWh is assumed. The cost of charging is assumed to be the same in all locations and is equal to the current U.S. residential average, which is higher than commercial and industrial rates [13]. "Off-peak" rates are not assumed. Sales taxes of 7 percent are assumed in the U.S. [14].
For the German case, the cost of gasoline reflects the general European situation with a higher value of 1,60 €/L and for electricity also a higher value of 0,27 €/kWh is used.

Vehicle holding period

For the U.S. case, a quite long period of 10 years has been considered, under these conditions, the resale value of the vehicle has been considered as negligible and then has not been taken into account. For the German situation a shorter holding period of 4 years has been retained, leading to the evaluation of an expected resale value which enables the calculation of the first owner's net fixed cost and therefore total cost of ownership and average cost per km.

Battery cost evaluation
The sizing procedure for the different cases considered led to a wide range of P/E ratios, values decreasing with the energy contained in the pack. Although the costs per kWh of capacity drop sharply in this same ordering, it is nevertheless true that batteries remain expensive. Battery pack cost has a significant effect on the difference in cost across the powertrains.
Battery pack costs for Europe and the U.S. are determined by different cost models used by DLR and Argonne. The DLR model is proprietary and not publicly available. The Argonne model, BatPAC, is publicly available [15]. Three different li-ion battery chemistries are assumed in the cost estimates. For the European case, the parallel HEV uses NCA while the two PHEVs use NMC. In the U.S. all three of the cost estimates are based on LMO, which BatPAC estimates to be less expensive than NCA and two NMC chemistries. For the series PHEV70 the U.S. estimates of costs, mass and volume of the packs with LMO and NMC441-G chemistry in the model are very close, and depend on the assumed maximum electrode thickness allowed by the manufacturing process. With the Argonne assumptions, the costs of LMO for a series PHEV70 are a bit lower than for both NMC chemistries. The relative attractiveness of NMC chemistries increases as pack energy to power ratio rises, which is the case as one goes from HEV to IS PHEV30 to series PHEV70.

Other costs
The method also account for other operating costs including maintenance and repair cost, vehicle tax, general inspection which have been gathered under the item Other costs.

Incentives
Our TCO analysis does not account for any incentives, subsidies or CO_2 penalties (as it is the case in the U.S. or in France).

3 Results

3.1 Energy consumption evaluation

Table 2 provides the fuel, and PHEV's electricity consumption for the 4 drivetrains considered, obtained on the standard procedures. If we compare the drivetrains architectures, we may note that in both cases the HEV performs better than the CV with 40% less in EEC case and 27% in the U.S. case non adjusted. For the PHEVs cases it appears that the fuel consumption may be significantly decreased, from 65% to 80% (non adjusted) with a transfer to electricity.
If we compare results from EEC and U.S. procedures, it appears that US unadjusted values are close to those of EEC, even if the driving patterns are different. Table 2 also provides U.S. adjusted values, which are increased to take into account the real world driving conditions (different type of cycles, use of auxiliaries such as A/C…). These values appear to be significantly higher than those of the European test procedure. These comparisons are easier for the CV and HEV cases, for the PHEV cases the electric consumption has also to be taken into account.

If, the standard tests present the advantage to generate comparable figures for each procedure, irrespective of the vehicle types, it should be noted that the values obtained are then relative to the procedures and do not cover real cases, especially if the CD to CS range ratio is considered ; more realistic cases will be presented in the cost analysis hereafter.

Annex 2 and 3 provide the simulated fuel and/or electricity consumption in CS and CD operation for the four selected powertrains. These results will be used in the next section in order to evaluate the energy(ies) consumption(s), and cost(s) for the different hypotheses considered.
A noteworthy prediction is that the parallel HEV has higher fuel consumption than the CV in the

HWFET, but lower fuel consumption than the CV in the Artemis Motorway cycle. This implies that a parallel HEV will be inappropriately penalized by the U.S. standard certification measures and will fail to win appropriate credit for its on-road fuel consumption reduction in real world highway driving. This possibility deserves further investigation and verification.

For charge sustaining operation, the NEDC favours the parallel HEV over the IS-PHEV30, while the UDDS and HWFET tests favour the IS-PHEV30 over the parallel HEV (Annex 2). European Artemis on-road cycle simulations favour the IS-PHEV30. In fact, the only result where the HEV is favoured is the NEDC. This difference, which should be further investigated, could contribute to inconsistent priorities in the EU and U.S.

Table 2 : Gasoline and electricity consumption for standard European and US test procedures

		Conventional	Parallel	Input split	Series
		Auto.	HEV	PHEV 30	PHEV 70
Europe	Fuel [L/100km]	5,98	3,51	1,46	1,31
	CO2 (g/km)	140	82	34	31
	Electricity [W.h/km]	0	0	60,5	101,0
US adjusted	Fuel [L/100km]	7,18	5,43	3,4	2,83
	Electricity [W.h/km]	0	0	32,2	81,2
US non adjusted	Fuel [L/100km]	5,3	3,86	2,28	1,82
	Electricity [W.h/km]	0	0	32,2	81,2

3.2 Costs evaluation

Annex 4 to 6 provide the total cost of ownership results for the different cases considered. Figures 5 and 6 illustrate the details of the costs. An important fact to be highlighted is the effect of the distance covered, due to the 10 year holding period the US c$/km figures are lower than 4 year holding period German ones and are therefore well beyond the Euro to Dollar exchange rate. Another fact to be noted is the magnitude of the initial vehicle costs in the TCO. U.S. maintenance cost estimates only account for scheduled maintenance, and do not cover all components. The DLR estimates include component failure in addition to scheduled maintenance.

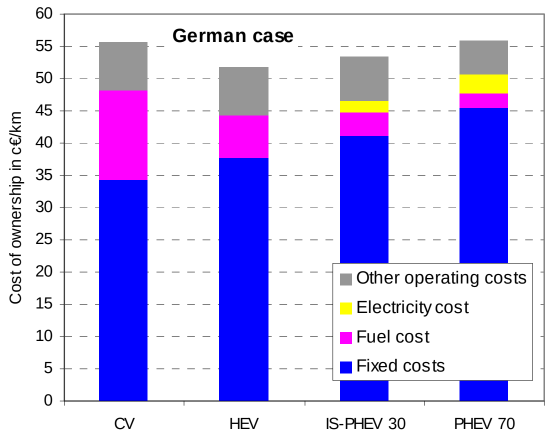

Figure 5 : Details of the German case

(4 years, 14000 km/yr)

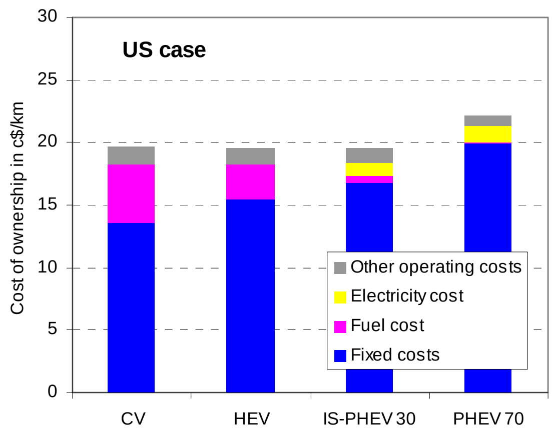

Figure 6 : Details of the US case (10 years, 18000 km/yr)

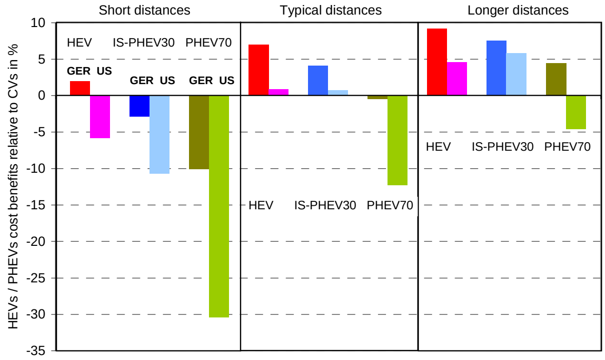

Figure 7 : Benefit in TCO according to drivetrain and distance considered

Figure 7 summarize the benefits in TCO according to the different cases :

- As far as architecture is concerned, it appears that the series PHEV70 consistently has the highest total cost of ownership (TCO), always exceeding the cost of the CV, excepted one case for the longer distance in Germany. Although the large battery pack of the series PHEV70 allows it to drive all electrically for many km per day and realize the greatest substitution of electricity for gasoline, it is simply too expensive. The parallel HEV is most often (but not always) the lowest TCO option, but the IS-PHEV30 is often nearly as inexpensive and has lower TCO than the CV in the U.S. and in Europe for the two longer annual distances. The TCO of the parallel HEV and IS-PHEV30 are always less than the series PHEV70. The IS-PHEV30 is particularly efficient in CS mode in the two highway driving cycles, so higher shares of CS highway driving improve its TCO relative to the parallel HEV;
- As far as distance covered is concerned, it appears that all hybrid technologies need long distances to highlight lower TCO than the CV, this trend increases with the size of the battery;
- As far as country is considered, it appears that higher retail gasoline prices in Germany leads to better values in TCO than in the US when distances are the same, but U.S. vehicles are driven further on average, which increases the benefit of the HEV and IS-PHEV30. The high retail price of gasoline in Germany are primarily a result of much higher taxes than in the U.S.

4 Elements of conclusion

This paper present the results in energy consumption(s) and cost evaluations for different vehicle drivetrain configurations and types of use (standard procedures and actual types of use).

The vehicle drivetrain components have been sized to meet the same program of demand. Their all electric ranges have been expressed for the UDDS cycle in the U.S. and for the ARTEMIS urban cycle for Europe. For a large amount of cases the component sizes for the U.S. and European cases appeared to be very similar.

As far as energy consumption is concerned, it appears that the benefits for the HEVs are higher for the European standard procedure than for the U.S. standard procedure, this may lead to different choices for vehicles manufacturers.

Moreover, the results highlighted the fact that European standard procedure was leading to lower energy consumption values than U.S. adjusted ones and comparable to those of non-adjusted standard methods. This has to be taken into account when comparing fuel consumption standards on a worldwide basis.

As far as drivetrain technologies are concerned, the results indicated that a significant gain could be obtained on fuel consumption with the HEV on the standard procedures (24 to 40%) and in urban conditions. Our evaluations also confirmed that these percentage fuel benefits where lower in extra-urban use with even a unfavourable case under HWFET conditions. For the PHEV cases, an even more important gas consumption decrease could be obtained on the driving cycles thanks to a transfer to electricity. However, for the PHEVs cases these gains will be dependant on the distance covered between two charges of the battery.

As far as costs evaluation is concerned, results are consistent with the findings of Propfe [2], Redelbach [12] and Santini [16] with respect to the prediction that greater than average amounts of annual driving favour the HEV and modest range PHEV relative to the CV. This suggests that comparisons such as that by Kristien, Koen and Johan [17], which consider the diesel CV as well as gasoline CV are necessary. It is the diesel CV that is driven more than average. The findings that a long range series PHEV designed with the electric drive power of an all-electric vehicle is not financially competitive with shorter range IS-PHEVs is consistent with a prior U.S.-based analysis by Moawad et al [18], for on-road driving in a medium sized U.S. city.

Some further developments of the methodology presented in this paper will be accessed in the future with different hypotheses concerning the TCO evaluation or the introduction of the electricity mix for the PHEV cases, in order to calculate their overall Green House Gas balance.

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Annex 1 Selected driving cycle attributes, for on-road and standard certification cycles

Cycle Info	Origin	Mean speed	Stop time	Time at cruise	Time accel-erating	Time decel-erating	Max accel-eration	Mean accel-eration	Max. decel-eration	Mean decel-eration	Top speed
		kph	%	%	%	%	m/s^2	m/s^2	m/s^2	m/s^2	kph
Actual use Cycles											
UL1	EU	3,8	34,8	4,9	28,3	31,9	1,86	0,24	-2,47	-0,48	14,6
Artemis Urban	EU	17,4	28,2	4,3	35,1	32,5	2,86	0,73	-3,14	-0,79	57,4
LA92	US	39,4	16,2	11,4	38,2	34,1	3,08	0,67	-3,93	-0,75	107,6
Artemis Road	EU	60,0	2,4	17,0	41,0	39,7	2,36	0,48	-4,08	-0,50	110,9
US06 Highway	US	96,8	3,0	8,4	48,5	40,1	3,07	0,34	-3,07	-0,41	127,8
Artemis Highway	EU	99,0	1,5	25,0	40,0	33,5	1,92	0,43	-3,36	-0,51	149,6
Certification Cycles											
UDDS	US	31,3	18,9	6,8	39,7	34,7	1,48	0,5	-1,48	-0,58	90,8
NEDC	EU	33,4	24,8	38,5	20,9	15,8	1,07	0,59	-1,43	-0,79	119,4
HWFET	US	77,3	0,5	16,6	44,2	38,7	1,43	0,19	-1,48	-0,22	95,9

Annex 2 : Gasoline consumption in charge sustaining on various drive cycles

		Conventional	Parallel	Input split	Series
		Auto.	HEV	PHEV 30	PHEV 70
Europe	UL1	29,1	7,16	6,4	5,53
	Artemis Urban	10,4	3,74	3,66	4,34
	NEDC	6	3,51	3,58	4,68
	Artemis Road	5,3	3,67	3,63	4,68
	Artemis Highway	6,65	6,1	5,91	7,79
US	UL1	29,1	7,16	6,38	5,53
	UDDS	6,3	3,6	3,06	4,16
	HWFET	4,05	4,18	3,45	4,99

Annex 3 : Gasoline, electricity consumption, CD range and time to depletion for the PHEVs in charge depleting on various drive cycles

		CD Fuel consumption [L/100km]		CD Electricity consumption [W.h/km]		CD range [km]		Time to depletion [h : mn]	
		Input split	Series	Input split	Series	Input split	Series	Input split	Series
		PHEV 30	PHEV 70	PHEV 30	PHEV 70	PHEV 30	PHEV 70	PHEV 30	PHEV 70
Europe	UL1	0	0	153	156	23,0	55,2	6:02	14:31
	Artemis Urban	0	0	129	127	30,5	70,5	1:45	4:03
	NEDC	0	0	102	140	36,5	64,0	1:05	1:54
	Artemis Road	0	0	135	142	31,3	63,1	0:31	1:03
	Artemis Highway	0,96	0	217	245	19,2	36,6	0:11	0:22
US	UL1	0	0	152	156	17,4	57,5	4:33	15:07
	UDDS	0	0	110	123	28,4	70,0	0:54	2:14
	HWFET	0	0	125	151	25,0	57,0	0:19	0:44

Annex 4 : Total cost of ownership estimates for EU and U.S. cases (short distances cases)

		German Case (4 yr, 7000 km/yr)					US Case (10 yr, 6550 km/yr)			
		CV	**HEV**	**IS-PHEV 30**	**PHEV 70**		**CV**	**HEV**	**IS-PHEV 30**	**PHEV 70**
Purchase cost	€	28 343	31 012	33 910	37 401	$	24 628	28 097	30 501	36 227
Expected resale value	€	10 069	11 019	12 050	13 293	$	0	0	0	0
Fuel cost	€	3 924	1 804	810	453	$	3 631	1 817	49	61
Electricity cost	€			605	866	$			822	842
Maintenance & repair	€	1 884	1 976	1 793	1 366	$	381	381	336	213
Other costs	€	425	181	147	178	$	0	0	0	0
Total of fixed cost	€	18 274	19 993	21 859	24 108	$	24 628	28 097	30 501	36 227
Total of operating cost	€	6 232	3 961	3 354	2 863	$	4 011	2 197	1 207	1 117
Total Cost of Ownership	€	24 506	23 954	25 213	26 971	$	28 639	30 295	31 708	37 344
Fixed costs	c€/km	65,3	71,4	78,1	86,1	c$/km	37,6	42,9	46,5	55,3
Operating costs	c€/km	22,3	14,1	12,0	10,2	c$/km	6,1	3,4	1,8	1,7
Fuel costs	c€/km	14,0	6,4	2,9	1,6	c$/km	5,5	2,8	0,1	0,1
Electricity costs	c€/km			2,2	3,1	c$/km			1,3	1,3
Other operating costs	c€/km	8,2	7,7	6,9	5,5	c$/km	0,6	0,6	0,5	0,3
Total Cost of Ownership	c€/km	87,5	85,6	90,0	96,3	c$/km	43,7	46,2	48,4	57,0
HEVs cost benefit	%		2,3	-2,9	-10,1	%		-5,8	-10,7	-30,4
Share CD-Mode (electric)	% in dist			57	79	% in dist			97	97
Share CS-Mode	% in dist			43	21	% in dist			3	3

Annex 5 : Total cost of ownership estimates for EU and U.S. cases (typical distances cases)

		German Case (4 yr, 14000 km/yr)					US Case (10 yr, 18000 km/yr)			
		CV	**HEV**	**IS-PHEV 30**	**PHEV 70**		**CV**	**HEV**	**IS-PHEV 30**	**PHEV 70**
Purchase cost	€	28 343	31 012	33 910	37 401	$	24 628	28 097	30 501	36 227
Expected resale value	€	9 064	9 919	10 848	11 966	$	0	0	0	0
Fuel cost	€	7 652	3 731	1 990	1 258	$	8 537	5 016	1 007	135
Electricity cost	€			1 064	1 655	$			1 886	2 392
Maintenance & repair	€	3 768	3 953	3 585	2 732	$	2 606	2 346	2 100	1 415
Other costs	€	425	181	147	178	$	0	0	0	0
Total of fixed cost	€	19 279	21 093	23 062	25 435	$	24 628	28 097	30 501	36 227
Total of operating cost	€	11 845	7 865	6 787	5 822	$	11 143	7 362	4 993	3 942
Total Cost of Ownership	€	31 123	28 958	29 849	31 257	$	35 772	35 459	35 494	40 169
Fixed cost	c€/km	34,4	37,7	41,2	45,4	c$/km	13,6	15,5	16,8	19,9
Operating cost	c€/km	21,2	14,0	12,1	10,4	c$/km	6,1	4,1	2,7	2,2
Fuel costs	c€/km	13,7	6,7	3,6	2,2	c$/km	4,7	2,8	0,6	0,1
Electricity costs	c€/km			1,9	3,0	c$/km			1,0	1,3
Other operating costs	c€/km	7,5	7,4	6,7	5,2	c$/km	1,4	1,3	1,2	0,8
Total Cost of Ownership	c€/km	55,6	51,7	53,3	55,8	c$/km	19,7	19,5	19,5	22,1
HEVs cost benefit	%		7,0	4,1	-0,4	%		0,9	0,8	-12,3
Share CD-Mode	% in dist			49	72	% in dist			80	97
Share CS-Mode	% in dist			51	28	% in dist			20	3

Annex 6 : Total cost of ownership estimates for EU and U.S. cases (long distances cases)

		German Case (4 yr, 20000 km/yr)					US Case (10 yr, 32500 km/yr)			
		CV	**HEV**	**IS-PHEV 30**	**PHEV 70**		**CV**	**HEV**	**IS-PHEV 30**	**PHEV 70**
Purchase cost	€	28 343	31 012	33 910	37 401	$	24 628	28 097	30 501	36 227
Expected resale value	€	8 203	8 977	9 817	10 829	$	0	0	0	0
Fuel cost	€	10 741	5 450	3 136	2 103	$	13 917	8 961	5 127	2 634
Electricity cost	€			1 419	2 305	$			1 782	3 418
Maintenance & repair	€	5 383	5 646	5 122	3 903	$	5 171	4 647	3 761	3 431
Other cost	€	425	181	147	178	$	0	0	0	0
Total of fixed cost	€	20 140	22 036	24 093	26 572	$	24 628	28 097	30 501	36 227
Total of operating cost	€	16 549	11 277	9 824	8 489	$	19 087	13 608	10 671	9 484
Total Cost of Ownership	€	36 689	33 313	33 917	35 061		43 716	41 705	41 172	45 711
Fixed cost	c€/km	25,2	27,5	30,1	33,2	c$/km	7,6	8,6	9,4	11,1
Operating cost	c€/km	20,7	14,1	12,3	10,6	c$/km	5,9	4,2	3,3	2,9
Fuel costs	c€/km	13,4	6,8	3,9	2,6	c$/km	4,3	2,8	1,6	0,8
Electricity costs	c€/km			1,8	2,9	c$/km			0,5	1,1
Other operating costs	c€/km	7,3	7,3	6,6	5,1	c$/km	1,6	1,4	1,2	1,1
Total Cost of Ownership	c€/km	45,9	41,6	42,4	43,8	c$/km	13,4	12,8	12,7	14,1
HEVs cost benefit	%		9,2	7,6	4,4	%		4,6	5,8	-4,6
Share CD-Mode (electric)	% in dist			44	68	% in dist			42	77
Share CS-Mode	% in dist			56	32	% in dist			58	23

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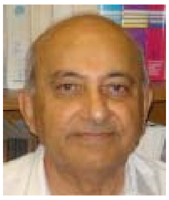

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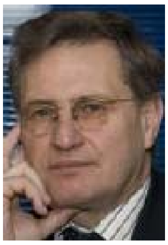

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