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Electric and hydrogen consumption analysis in plug-in road vehicles

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Abstract
The main goal of the present study is to analyze some of the capabilities and behavior of two types of *plug-in* cars: battery electric and hydrogen fuel cell hybrid electric, facing different driving styles, different road gradients, different occupation rates, different electrical loads, and different battery's initial state of charge. In order to do that, four vehicles with different power/weight (kW/kg) ratio (0.044 to 0.150) were simulated in the *software* ADVISOR, which gives predictions of energy consumption, and behavior of vehicle's power train components (including energy regeneration) along specified driving cycles. The required energy, electricity and/or hydrogen, to overcome the specified driving schedules, allowed to estimate fuel life cycle's CO_2 emissions and primary energy.

A vehicle with higher power/weight ratio (kW/kg) demonstrated to be less affected in operation and in variation of the energy consumption, facing the different case studies, however may have higher consumptions in some cases. The autonomy, besides depending on the fuel consumption, is directly associated with the type and capacity (kWh) of the chosen battery, plus the stored hydrogen (if fuel cell vehicles are considered, PHEV-FC). The PHEV-FC showed to have higher autonomy than the battery vehicles, but higher energy consumption which is extremely dependent on the type and ratio of energy used, hydrogen or electricity.

An aggressive driving style, higher road gradient and increase of weight, required more energy and power to the vehicle and presented consumption increases near to 77%, 621%, 19% respectively. Higher electrical load and battery's initial state of charge, didn't affect directly vehicle's dynamic. The first one drained energy directly from the battery plus demanded a fraction of its power, with energy consumption maximum increasing near 71%. The second one restricted the autonomy without influence directly the energy consumption per kilometer, except for the PHEV-FC with energy consumption increasing near 28% (due to the higher fraction of hydrogen used).

In order to have a different and nearer realistic viewpoint the obtained values for these plug-in vehicles, were also compared to the results of a conventional HEV and ICEV, both gasoline vehicles.

Keywords: Alternative propulsion system, Electrical autonomy, Electrical and hydrogen consumption plug-in vehicles, Road vehicle simulator.

Abbreviations: AER - All Electric Autonomy, BEV - Battery Electric Vehicle, CD - Charge Depleting, CS - Charge Sustaining, CO_2 - Carbon Dioxide, EU - European Union, FCV - Fuel Cell Vehicle, FA - Acceleration Factor, H_2 - Hydrogen, HEV - Hybrid Electric Vehicle, HVAC - Heating Ventilating and

Air Conditioning , ICEV - Internal Combustion Engine Vehicle, Li ion – Lithium ions, NG - Natural Gas, NiMh - Nickel-Metal Hydrate, PHEV-FC - Plug-in Hybrid Fuel Cell Electric Vehicle, SI - Spark Ignition, SOC - Battery´s State of Charge.

1. Introduction

The transport sector contributes for the high energy consumption, and it is estimated that at world level it can raise to approximately 90% between the year 2000 and 2030[1].

One of the current main concerns on the energy sector is the high dependency of crude oil. The extraction, processing, transportation, and combustion of oil derivatives, damage the environment and causes acute impacts on the fauna and flora. Besides that, most of world countries are economically sensitive to crude oil market.

It has not yet been able to use other kind of technology aside from the internal combustion engine, and that is independent from any fossil fuel. The efficiency of the internal combustion engine has increased so as the quality of the fuels. New kinds of energy and propulsion systems are being studied, however there's nothing yet capable to completely rival and substitute this 100 year old technology that is the combustion engine. The needing of sustainable mobility in our society claims the world to choose another technology for the transport sector, towards the decreasing of crude oil dependency and associated environmental and economical issues.

Currently with the aim of replacing the conventional combustion engine vehicle (ICEV), there are vehicles whose engine power is fully electric. Within the range of those electric vehicles there are battery electric vehicles (BEV), and fuel cell electric vehicles (FCV). Additionally the FCV can be a plug-in vehicle (PHEV-FC), offering the opportunity to recharge their batteries directly from the electric grid.

A PHEV differs from a pure electric vehicle (BEV) because it uses other energy sources besides electricity plus the battery usually has a lower capacity. A PHEV differs from a conventional hybrid vehicle (HEV) due to its higher battery capacity, the existence of a appropriate electrical outlet (‘‘plug”) to recharge the batteries from the electric grid, and due to the different battery state of charge (SOC) management strategy.

PHEV design has been studied since the 1970s by researchers [2] mainly at University of California Davis (UCDavis). Since the 1990s, the Hybrid Electric Vehicle Working Group (WG) convened by the Electric Power Research Institute (EPRI), has been active in plug-in research by comparing vehicles fuel consumption and emissions in a Well-to-Wheels perspective (fuel life-cycle), as well as customer preferences and analysing the operating costs [3]. The US National Renewable Energy Laboratory has also been active in modelling PHEV [4], component sizing [5] and fuel economy calculation [6]. The MIT’s Laboratory for Energy and the Environment is also concerned with comparing vehicle technologies in terms of fuel and vehicle life-cycle [7]. Recently, the UCDavis plug-in Hybrid Electric Vehicle Research Centre has been very active in analysing the consumer behaviour on using PHEVs [8]. At IDMEC/IST a research team on Transports, Energy and Environment is studding PHEV full life cycle, including materials cradle-to-grave life cycle and fuel production-distribution-storage life cycle, for several fuel pathways such as gasoline, diesel, hydrogen, electricity, and biofuels [9].The same research team has a on-board laboratory to monitor driver behaviour, fuel consumption and tailpipe emissions from such vehicles [10]. However, the influence of driver behaviour, road grade, cargo, air conditioning use and initial battery state of charge has not been fully addressed.

Therefore it is important to compare energy requirements and global level emissions of these vehicles, in order to evaluate the advantage of their choice in the future. This study has the main goal to analyze a few of most important capabilities and behaviour of BEV and PHEV-FC road vehicles facing the driving style, road gradient, occupancy rate, electrical load, and battery's initial state of charge. This study covers pure electric and plug-in hybrid fuel cell vehicles.

2. Technology

Here it will be presented some of the basic concepts of the studied vehicles power train operation. In Figure 1 is schemed the energy flow of an ICEV, BEV and PHEV-FC vehicle. The first one uses chemical energy from a combustion reaction with the efficiency near the 15% for the thermodynamic Otto cycle, but let us assume an optimistic 30% value, given by ADVISOR. However, the electric motor present in the other kinds of vehicles (BEV and PHEV-FC) have a near of 70% up maximum efficiency (ADVISOR values). Of course this value depends of the operating conditions of the motor and also, adding this efficiency there is the battery's efficiency values. The battery's efficiency decreases with higher electric currents, lower values for the state of charge, and lower temperatures. The possibility of regeneration of energy in decelerations or breakings, the stop of the consumption of energy when the vehicle stops (idle), and the higher operating efficiency makes the electric motor a theoretically better efficient substitute for the internal combustion engine. The introduction of a fuel cell (PHEV-FC) adds some advantages, such as the autonomy increasing of the vehicle and extra power if needed. The main disadvantage is that the use of hydrogen energy raises the energy consumption. When considering the fuel cell losses (ADVISOR gives 40% for minimum losses) it's easy to see that this king of energy is substantially less efficient than the energy already stored in the battery.

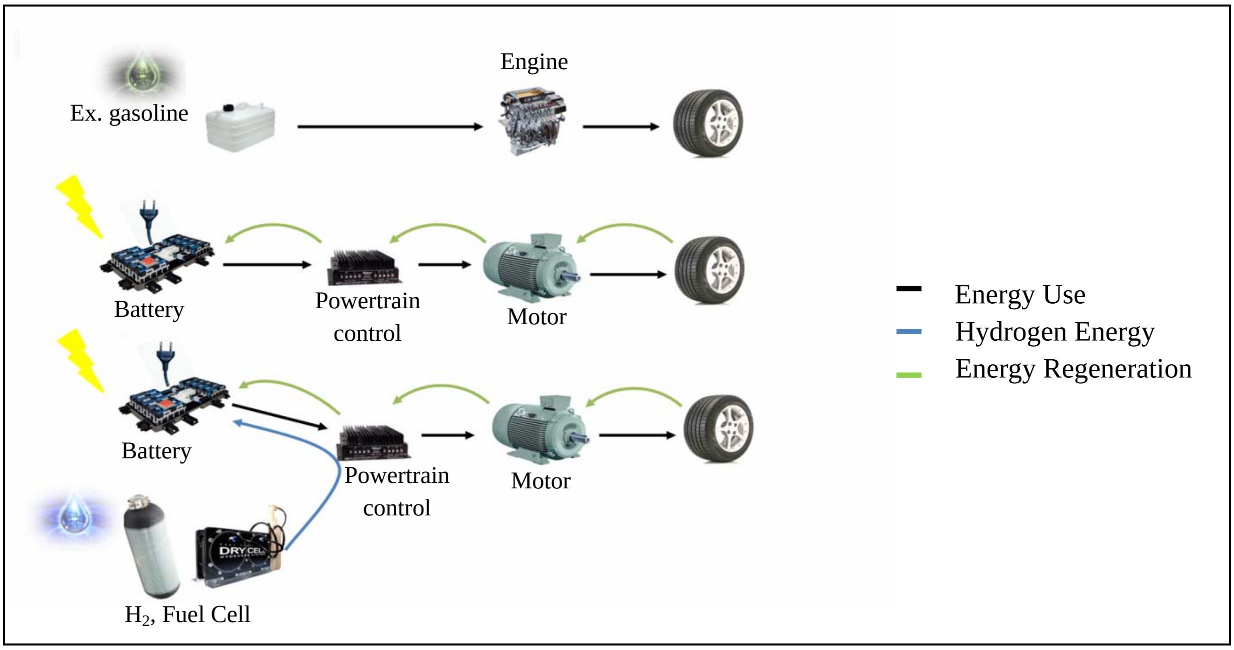


Figure 1. Comparative scheme between an internal combustion engine vehicle (ICEV), a plug-in battery electric vehicle (BEV), and a plug-in fuel cell electric vehicle (PHEV). The diferent energy flows, energy use, hydrogen energy, regenerated energy

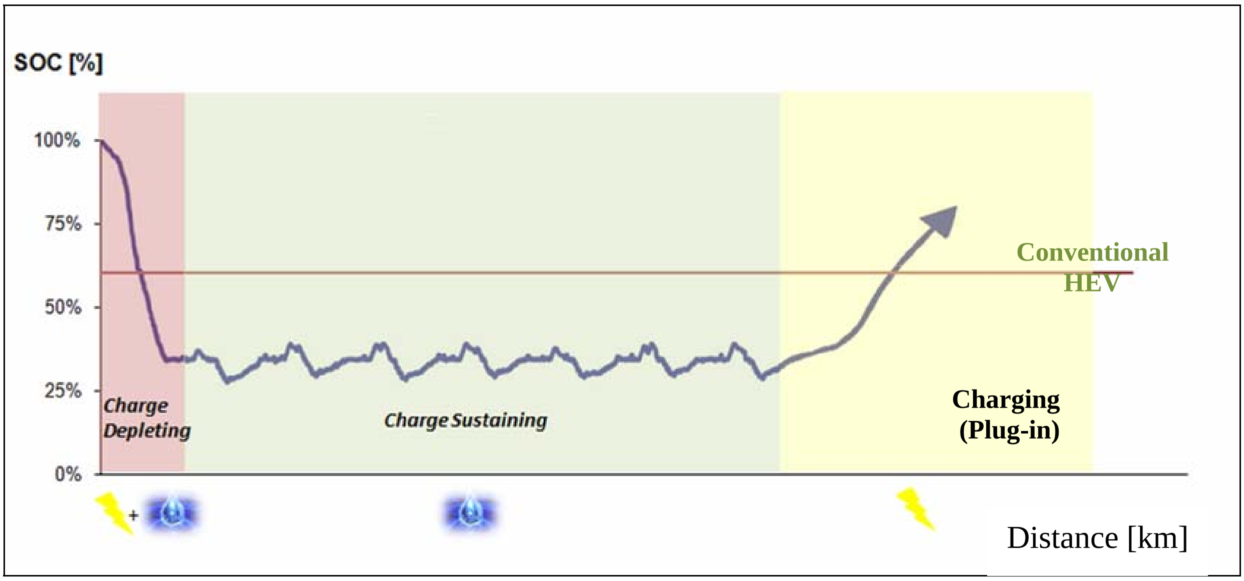


Figure 2. Battery´s state of charge (*SOC*) of a plug-in electric vehicle with fuel cell. Three diferent zones: *Charge Depleting* (red), *Charge Sustaining* (green), and plug-in charging (yelow)

Most HEVs use the battery pack in a charge sustaining mode (maintaining their SOC nearly constant discharging and charging from the vehicle engine and the regenerative braking system) while PHEVs can operate in either charge depleting (CD, similar to BEV vehicles) or charge sustaining mode (CS), as it can be seen in Figure 2. PHEVs and, more specifically PHEV-FCs are designed to use a CD mode discharging the battery till it reaches a minimum SOC (30–45% depending on battery and power train configuration), and a CS mode after this occurrence, in similarity to the conventional hybrids sustaining strategy. The distance travelled before the designed minimum SOC is reached can be one measure of the all electric range (AER), despite the Fuel Cell being used occasionally to help the propulsion. However some authors define it as the distance till the Fuel Cell is turned on for the first time.

3. Methodology

The initial step was selecting the vehicles for this study, BEV and PHEV-FC light-duty vehicles. Table 1 presents the selected vehicles specifications. For a better understanding of the meaning of the obtained results, conventional vehicles such as an HEV and an ICEV, both with gasoline engines, were simulated too, and their specifications are presented in Table 2.

Table 1. Plug-in light-duty vehicles selected

		PHEV-FC*	BEV		
Based Model		Vehicle A	Vehicle B	Vehicle C	Vehicle D
Maximum Speed [km/h]		156	150.1	131	157.9
Weight [kg]		1588	1235	1465	1080
Traction Electric Motor	Type**, Nominal Power	AC, 120 kW	AC, 185 kW	AC, 150 kW	PM, 47 kW
	Torque [N.m]@ rpm / maximum Speed [rpm]	421,2@0-2500 / 15000	650@0-2500 / 15000	220@0-5000 / 11500	249@0-1500 / 9000
Battery Characteristics (Li ion)		8 kWh, 352 V, CS = 30%	55.5 kWh, 363 V	35.5kWh, 384 V	16.05 kWh, 331 V
Fuel Cell (PEM)	Nominal Power , H_2 Storage	80 kW, 4 kg, (10000 psi)	--	--	--
Traction Power/Weight [kW/kg]		0.076	0.150	0.102	0.044

*plug-in series hybrid with hydrogen fuel cell

**PMDC: Permanent Magnet electric motor. AC: Induction Alternate Current electric motor

Table 2. Conventional light-duty vehicles selected

		Gasoline HEV*	Conventional Gasoline ICEV
Based Model		Vehicle E	Vehicle F
Maximum Speed [km/h]		163.2	163
Weight [kg]		1282	1249
Traction Electric Motor	Type**, Nominal Power	PM, 40 kW	--
	Torque [N.m]@ rpm / maximum Speed [rpm]	400@0-1000/ 15000	--
Generator		19kW	--
Battery Characteristics (NiMh)		1.85 kWh, 308 V, CS = 50 %	--
SI Engine	Nominal Power	57 kW	63 kW
	Torque [N.m]@ rpm / maximum Speed [rpm]	115@4000/5000	145@2000/5500
Gasoline Storage [l]		45	47
Traction Power/Weight [kW/kg]		0.031	0.050

*plug-in parallel hybrid with gasoline combustion engine

**PMDC: Permanent Magnet electric motor. AC: Induction Alternate Current electric motor

The driving cycle/route chosen (Table 3) was a typical daily route between the town Cascais and the city Lisbon. The data from this route were measured by GPS (GPS map 76CSx - Precision (point measurement, position, speed, altitude, direction): 1pt/sec, 10m, 0.05m/s, +/- 10feet, +/- 5º.), and like the vehicles specifications, introduced in the software ADVISOR.
With the vehicles and the driving cycles introduced in the software ADVISOR, the next step is the simulation of the different case studies. To simulate the different driving styles, it was introduced an acceleration factor (FA). This value modifies the original driving cycle's accelerations (Table 4 and Figure 3) and tries to simulate the driver's aggressiveness. This simulation was made with constant 0% road grade, in order to avoid the interference of road degree influences in this case study. The acceleration factor of 200% gives the assurance that the vehicles are on their maximum power capacities.

Table 3. Driving cycle, Cascais to Lisbon, 34.2km (Cascais-Lisboa)

		Speed		Acceleration		Deceleration		Up Grade		Down Grade	
Time [s]	Idle Time [s]	Max. [km/h]	Average [km/h]	Max. [m/s^2]	Average [m/s^2]	Max. [m/s^2]	Average [m/s^2]	Max. [%]	Average [%]	Max. [%]	Average [%]
2705	357	115	45.5	3.89	0.69	-7.69	-0.68	11.5	2.5	15.5	3.2

Table 4. Influence of FA in the driving cycle (0% road grade)

Cascais Lisboa	Acceleration Factor %	-30	-20	-10	0	20	200
	Average Speed [km/h]	44.02	44.56	45.07	45.50	46.25	49.58
	Average Acceleration [m/s^2]	0.43	0.45	0.47	0.69	0.71	2.13
	Average Deceleration [m/s^2]	-0.53	-0.53	-0.52	-0.68	-0.50	-1.11
	Time [s]	2796	2762	2731	2705	2661	2482

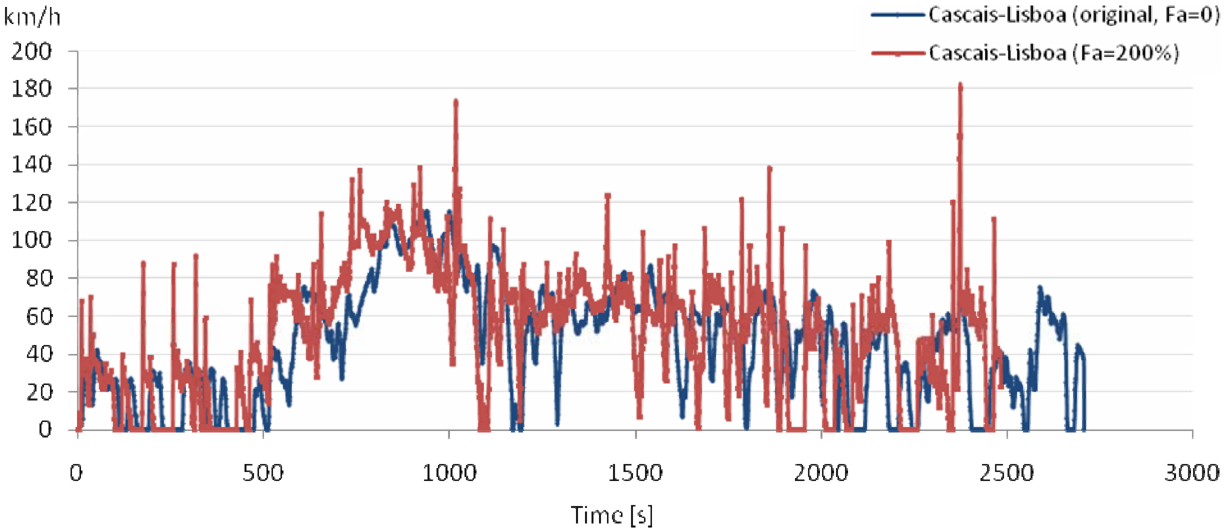


Figure 3. Cascais-Lisboa original driving cycle/route (blue), and the modified cycle, FA=200%, (red)

For the road gradient case study, the vehicles were simulated on the same Cascais-Lisboa driving cycle but with constant road grade along the entire route. The chosen values for the road grade were the maximum down grade of the original cycle, 0%, 50% of the maximum grade of the original cycle, the maximum grade, and 150% of the maximum grade of the original cycle. Those values correspond respectively to -15.5%, 0%, 5.75%, 11.5%, 17.25%.The vehicle's cargo weight case study simulates the vehicle in the original driving cycle each simulation with different values of weight, corresponding to the different number of passengers. For these vehicles the maximum number of passengers is four. So, the weight values used for the simulations were: 70kg, 140kg, 210kg, 280kg.The fourth case study is the influence of the electrical load of the accessories, specifically the HVAC system. It was made two simulations for each vehicle in the original driving cycle, with the HVAC system off (corresponding to 784W [11] of electrical load), and with the HVAC system on (5235W [12] of electrical load).The last case study was the influence of the initial state of charge (SOC) of the battery, at the beginning of the vehicles trip. Preferably the initial SOC should be 100%; however what would be the influence on vehicle's consumption if the initial SOC is only at 75%, 50%, or even 25%. For this case study it must be remembered that the PHEV-FC vehicle (vehicle A) has the charge sustaining level at 30%. The charge sustaining level is a SOC level that when achieved, the fuel cell starts and tries to maintain the SOC level above that value, giving more power when needed and energy to the battery.

The resulting data from ADVISOR, allowed to determinate consumption factor, Lgeq/100km (Lgeq, liters of gasoline equivalent) the vehicles autonomy (kilometers), the energy spent, and some of the vehicle's components behavior. Relying vehicle's energy consumption it was possible to determinate the CO_2 emission factor (g/km), based on the energy's life cycle Well-to-tank (Table 5).

Table 5. Gasoline, electricity and hydrogen´s life cycle, well-to-tank, primary energy and CO_2 emission factors[13]

	Gasoline	Electricity	Hydrogen		
			NG Reforming	Electrolysis (wind energy)	Electrolysis (EU combined grid electricity)
Energy MJ/MJ	0.14	1.87	0.72	0.79	4.22
CO_2 g/MJ	12.5	129.8	88.2	9.1	237

Unlike the BEVs or the PHEV-FCs, the conventional vehicles used to compare the results, the HEV and the ICEV both have CO_2 emissions due to the combustion of gasoline in their engines. Then adding the Well-to-tank emissions factor, it was used 2.31 $kgCO_2/L_{burned\ gasoline}$.

4. Results and discussion

The energy consumption of the vehicles is given in equivalent liters of gasoline, thus allowing to compare the consumption of BEV´s (electricity) and PHEV-FC´s (electricity and hydrogen) similarly, as well as conventional vehicles (gasoline).

Figure 4 shows the difference between the charge sustaining level (orange) electric autonomy (25 km in original route) and the real instant when the fuel cell has started (yellow, corresponding to 5 km in original route).

For each vehicle there are two kinds of simulation in every case study: *1 cycle* and *autonomy*. The first one, *1 Cycle*, simulates the vehicle running once only in the driving cycle. The second one, *autonomy*, simulates the vehicle running in the driving cycle constantly, till all energy in the vehicle ends up (battery, hydrogen for PHEV-FC´s, or gasoline for HEV and ICEV). However to better compare the influence of each case study and vehicles, the results of Figure 5 are given in percentage of increasing (or decreasing) of energy consumption factor Lgeq/100km, in *1 cycle* simulation (a 34.2 km journey, which is a near typical commuting distance). The absolute values for the results can be seen in Table 6, 7.

For BEV´s, *1 Cycle* and *autonomy* are usually similar. However for the PHEV-FC´s (Vehicle A) the *1 Cycle* simulations have usually lower values for the consumption. This is due to the fraction of hydrogen used in the trip. For *1 Cycle* a smaller fraction of H_2 is used than in *autonomy*, because these vehicles have additionally to the fuel cell, some energy stored in the battery (charged firstly in plug-in, electricity). The fuel cell only starts to delivery energy if the SOC level of the battery reaches the CS level (for vehicle A, 30% of SOC), or if extra power is needed. In addition to that, the energy obtained by hydrogen (fuel cell), is subjected to more losses than pure electricity in the battery (the fuel cell have approximately 60% of nominal efficiency in ADVISOR), therefore the bigger the fraction of the use of energy from hydrogen, lower is the powertrain efficiency and higher is the overall energy consumption. Due to the use of hydrogen and for the same reason explained, the vehicle A usually has higher values for the energy consumption than BEV´s.

In PHEV-FC´s vehicles the electric autonomy can have different meanings. As said before, the fuel cell should start only when CS is reached in order to maintain the SOC level. Till the fuel cell starts the battery is continuously discharging (CD mode). However when extra power is needed, the vehicle controller starts the fuel cell earlier.

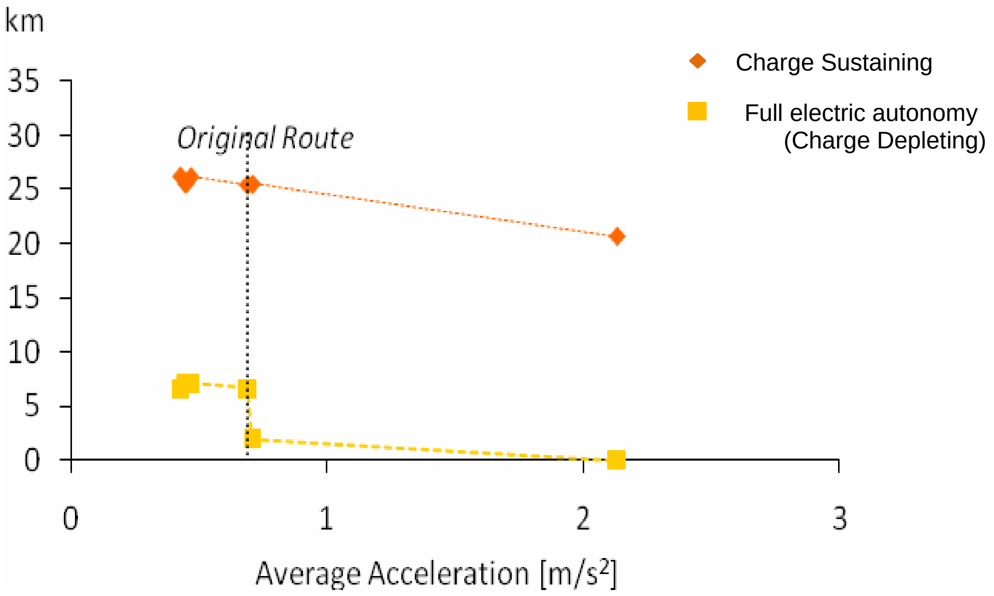


Figure 4. Electric autonomy of the PHEV-FC

4.1 Driving style

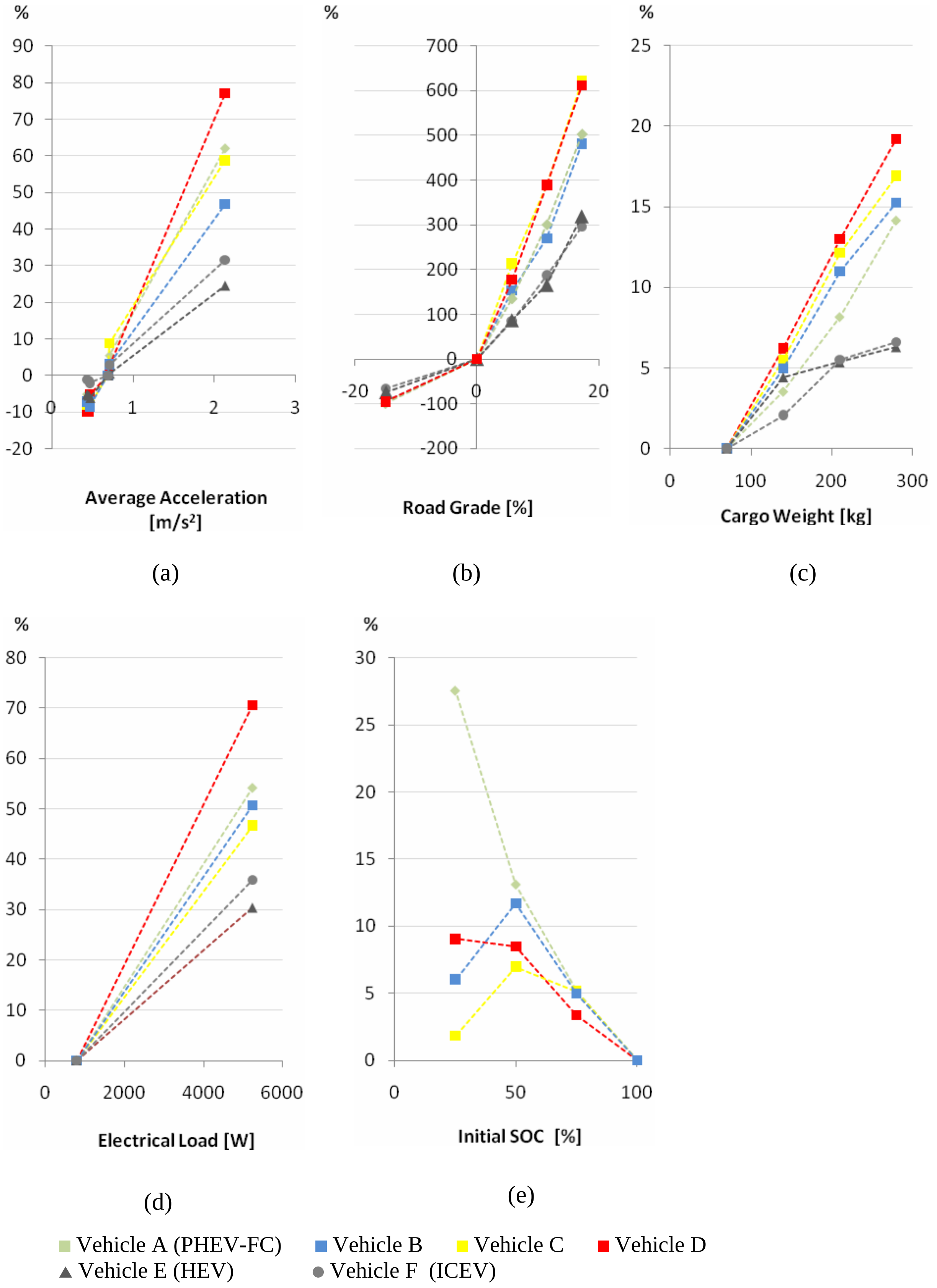
A more aggressive driving style, inducing particularly higher values for the acceleration, requires more power to the vehicle due to the higher torque (and sometimes more rotation speed) needed to meet the minimum requirements of the driving cycle leading to a higher energy consumption. As it can be seen in Figure 5a, a more aggressive driving style increases significantly the energy consumption of the vehicle, and consequently decreases the autonomy (Figure 6a and Table 8).

The autonomy is not only dependent of the energy consumption, the battery's type and energy capacity (kWh) are the main constrains of BEV´s autonomy values, so, the higher is the battery energy capacity, higher is the vehicle's autonomy. The autonomy of vehicle A (PHEV-FC) is higher than the BEV´s, due to the second source of energy stored as hydrogen. In terms of energy consumption the vehicle A differentiates from the BEVs, with higher energy consumption due to fuel cell associated losses.

The power/weight (kW/kg) rate which is very important in most of case studies affecting directly the vehicle performance. More specifically, the lower the power/weight (kW/kg) rate of the vehicle signifies that the vehicle has less power to move his own weight. In addition to that, more power is needed to overcome inertia in more sudden or higher accelerations. In Figure 7 are presented the operation points (torque, motor speed, and efficiency) of the different electric motors. For the original driving cycle accelerations requirements, vehicle D, with the lowest power/weight ratio, achieves higher motor efficiencies than the other vehicles. As it can be read in Table 5, this vehicle has the lowest absolute energy consumption. The vehicles with higher power/weight ratio have a larger range of available torque and speed. So, when higher accelerations are required (and such as power) the roles are inverted, and the vehicles with higher power/weight ratio achieve higher efficiencies. Plus, besides achieving lower energy consumptions than the ones of vehicle D, the less is the variation on the consumption. In Figure 5 is easily seen that the vehicles with the lower power/weight ratio have higher increases in energy consumption.

In Figure 5 both Vehicle E and Vehicle F (respectively HEV and ICEV) have the lowest consumption increases in all case studies. However, both of these vehicles have the highest energy consumption of all vehicles. Comparing a few values (for FA=0), the ICEV (Vehicle F) has 111% more, and the HEV (Vehicle E) 53% more than the consumption of Vehicle A (PHEV-FC) which is the most energy consuming plug-in, with 36% more consumption than Vehicle B (highest consuming of the BEVs). When the average acceleration increases to the maximum (FA=200%) despite the lower consumption variations for the conventional vehicles, the same relation for the absolute values maintains, the ICEV

(Vehicle F) has 71% more, and the HEV (Vehicle E) 17% more than the consumption of Vehicle A (PHEV-FC), which in turn has 50% more consumption than Vehicle B (highest consuming of the BEVs).



(a) (b) (c)

(d) (e)

Figure 5. Energy consumption variation, *Cascais-Lisboa* driving cycle (34.2km): (a) average acceleration, (b) road grade, (c) cargo weight, (d) accessories electrical load, (e) initial SOC

Table 6. Results: energy consumption, 1 Cycle and autonomy,[Lgeq/100km] for plug-in vehicles (A, B, C, D) and conventional vehicles (E, F)

		Energy consumption. 1 Cycle and autonomy.[Lgeq/100km]							
		Vehicle A		Vehicle B		Vehicle C		Vehicle D	
		1 Cycle	Aut	1 Cycle	Aut.	1 Cycle	Aut.	1 Cycle	Aut.
Average Acceleration [m/s^2]	0.43	3.80	4.37	2.74	2.91	1.73	2.62	1.73	1.73
	0.45	3.79	4.34	2.74	2.90	1.73	2.62	1.73	1.73
	0.47	3.78	4.34	2.70	2.93	1.82	2.65	1.82	1.82
	0.69	**4.00**	**4.54**	**2.95**	**3.16**	**1.92**	**2.88**	**1.92**	**1.92**
	0.71	4.22	4.74	3.04	3.24	1.97	3.08	1.97	1.97
	2.13	6.48	6.83	4.33	4.21	3.40	4.43	3.40	3.40
Road Grade [%]	-15	0.06	0.00	0.18	0.18	0.09	0.12	0.09	0.09
	0	**4.00**	**4.54**	**2.95**	**3.16**	**1.93**	**2.74**	**1.93**	**1.93**
	5.75	9.41	9.93	7.48	10.50	--	8.59	--	--
	11.5	16.02	16.71	10.90	10.97	--	13.40	--	--
	17.25	24.09	24.26	17.15	21.03	--	19.76	--	--
Cargo Weight [kg]	**70**	**3.67**	**4.30**	**2.82**	**3.07**	**1.77**	**2.86**	**1.77**	**1.77**
	140	3.80	4.43	2.96	3.20	1.88	2.99	1.88	1.88
	210	3.97	4.58	3.13	3.33	2.00	3.14	2.00	2.00
	280	4.19	4.68	3.25	3.42	2.11	3.26	2.11	2.11
Accessory Electrical Load [W]	**784**	**3.67**	**4.30**	**2.82**	**3.07**	**1.77**	**2.86**	**1.77**	**1.77**
	5235	5.66	6.24	4.25	4.52	3.02	4.54	3.02	3.02
Initial SOC [%]	**100**	**3.67**	**4.30**	**2.82**	**3.07**	**1.77**	**2.86**	**1.77**	**1.77**
	75	3.86	4.33	2.96	3.08	1.83	2.89	1.83	1.83
	50	4.15	4.33	3.15	3.08	1.92	2.87	1.92	1.92
	25	4.68	4.37	2.99	2.93	1.93	2.80	1.93	1.93

		Vehicle E		Vehicle F	
		1 Cycle	Aut	1 Cycle	Aut.
Average Acceleration [m/s^2]	0.43	5.78	5.93	8.33	8.25
	0.45	5.76	5.92	8.32	8.22
	0.47	5.72	5.89	8.26	8.32
	0.69	***6.10***	***6.28***	***8.43***	***8.36***
	0.71	6.13	6.30	8.68	8.62
	2.13	7.60	7.83	11.09	11.00
Road Grade [%]	-15	1.57	1.24	2.82	2.76
	0	6.10	***6.28***	***8.32***	***8.22***
	5.75	11.41	12.79	15.47	15.40
	11.5	16.21	19.37	*23.88*	*23.81*
	17.25	25.61	34.18	32.94	32.85
Cargo Weight [kg]	**70**	***6.28***	***6.36***	***8.19***	***8.18***
	140	6.55	6.57	8.36	8.39
	210	6.61	6.67	8.64	8.60
	280	6.67	6.80	*8.73*	*8.68*
Accessory Electrical Load [W]	**784**	***6.28***	***6.36***	***8.19***	***8.18***
	5235	8.19	8.46	11.13	11.16

Table 7. Results: variation of energy consumption relatively to original route (marked with bold), 1 Cycle and autonomy,[%], for plug-in vehicles (A, B, C, D) and conventional vehicles (E, F)

		Energy consumption variation. 1 Cycle and autonomy.[%]							
		Vehicle A		Vehicle B		Vehicle C		Vehicle D	
		1 Cycle	Aut	1 Cycle	Aut.	1 Cycle	Aut.	1 Cycle	Aut.
Average Acceleration [m/s^2]	0.43	-5.00	-3.74	-7.12	-7.91	-8.03	-9.03	-9.90	-6.22
	0.45	-5.25	-4.41	-7.12	-8.23	-7.66	-9.03	-9.90	-6.22
	0.47	-5.50	-4.41	-8.47	-7.28	-8.03	-7.99	-5.21	-5.70
	0.69	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
	0.71	5.50	4.41	3.05	2.53	8.76	6.94	2.60	6.22
	2.13	62.00	50.44	46.78	33.23	58.76	53.82	77.08	87.05
Road Grade [%]	-15	-98.50	-100.0	-93.90	-94.30	-95.83	-95.62	-95.34	-95.31
	0	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
	5.75	135.25	118.72	153.56	232.28	179.17	213.50	--	177.08
	11.5	300.50	268.06	269.49	247.15	--	389.05	--	389.06
	17.25	502.25	434.36	481.36	565.51	--	621.17	--	611.46
Cargo Weight [kg]	**70**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
	140	3.54	3.02	4.96	4.23	5.51	4.55	6.21	5.73
	210	8.17	6.51	10.99	8.47	12.13	9.79	12.99	11.46
	280	14.17	8.84	15.25	11.40	16.91	13.99	19.21	14.06
Accessory Electrical Load [W]	**784**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
	5235	54.22	45.12	50.71	47.23	46.69	58.74	70.62	56.77
Initial SOC [%]	**100**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
	75	5.18	0.70	4.96	0.33	5.15	1.05	3.39	0.03
	50	13.08	0.70	11.70	0.33	6.99	0.35	8.47	0.52
	25	27.52	1.63	6.03	-4.56	1.84	-2.10	9.04	0.52

		Vehicle E		Vehicle F	
		1 Cycle	Aut	1 Cycle	Aut
Average Acceleration [m/s^2]	0.43	-5.23	-5.46	-1.18	-1.33
	0.45	-5.51	-5.76	-1.31	-1.65
	0.47	-6.21	-6.16	-2.04	-0.45
	0.69	**0.00**	**0.00**	**0.00**	**0.00**
	0.71	0.44	0.40	2.94	3.10
	2.13	24.57	24.69	31.55	31.57
Road Grade [%]	-15	-74.22	-80.23	-66.08	-66.42
	0	**0.00**	**0.00**	**0.00**	**0.00**
	5.75	87.07	103.72	85.97	87.23
	11.5	165.81	208.45	187.15	189.49
	17.25	319.89	444.22	296.05	299.49
Cargo Weight [kg]	**70**	**0.00**	**0.00**	**0.00**	**0.00**
	140	4.43	3.30	2.06	2.58
	210	5.36	4.85	5.52	5.17
	280	6.30	6.96	6.62	6.15
Accessory Electrical Load [W]	**784**	**0.00**	**0.00**	**0.00**	**0.00**
	5235	30.41	32.99	35.90	36.42

4.2 Road gradient

When the road gradient is positive, it is required more torque (and consequently more power) to the vehicle leading to more energy consumption. The weight of the vehicle has also major importance in this case study. The heavier the vehicle is, greater the force must be produced by the electric motor on the rise. Vehicles with lower torque/weight ratio present higher increases in the energy consumption (Figure 5b). Like the power/weight ratio, situation explained behind, the operating points of the motor and associated motor efficiency are very responsible for the difference of the increasing in the energy consumption. On the other hand, vehicles that have lower values for this ratio are easier to be hampered in their performance. This case can be seen for vehicle C and vehicle D that couldn´t complete the driving cycles for road grades above 11.5% and 5.75% respectively. For these road grades their energy consumption was so high that the autonomy became lower than the driving cycle distance. Therefore the values in the Figure 5b are concerned to the autonomy mode for these vehicles.

On the other hand, when the road grade is negative the energy consumption is very low. In this case, there is a down force, due to the gravitational force, that is solitary with the movement, reducing the power that is needed from the motor to move the vehicle. The energy needed is mostly to meet the velocity and acceleration requirements in the right timing. Because the downgrade promotes the movement to the vehicle the autonomy for negative road grade is difficult to represent (Figure 6b).

As it happened in the earlier case study the conventional vehicles (HEV and ICEV) besides having the smallest variations in their energy consumption, they have again the highest consumption absolute values.

For the extreme case of the up grade simulation the ICEV (Vehicle F) has 37% more, and the HEV (Vehicle E) 6% more than the energy consumption of Vehicle A (PHEV-FC), which in turn has 41% more consumption than Vehicle B (highest values of the BEVs).

4.3 Cargo weight

The cargo weight will not have increases as sudden as the earlier case studies. The weight force vector of the vehicle in a flat road has a perpendicular direction to the direction of the movement, and so, in a perfect system the weight doesn’t realize work. Therefore, in 0% road grade of the driving cycle, the weight will not influence sorely the energy consumption. Thus the weight influence will be mostly felt, not along all the driving cycle, but sporadically in road grade (positive or negative) situations. In positive road grades the weight will cause the increasing of power requirement (and even a few on 0% of road grade due to acceleration requirements in order to overcome the inertial force), and as it can be seen on Figure 5c, it requires more energy along the drive cycle. Like the other case studies the autonomy (Figure 6c) decreases with higher energy requirements at the same time the more energy capacity of the battery the higher is the autonomy.

Once more Vehicle C and D (lowest power/weight and torque/weight ratios) are the vehicles that suffer the largest variations in their energy consumption (however having the lowest values for the consumption). When comparing with the conventional vehicles the plug-in vehicles present the same position than the case studies behind regarding the variation and the absolute values of the consumption. When the vehicles transport four occupants the Vehicle F (ICEV) and Vehicle E (HEV) have respectively 108% and 59% more than the energy consumption of Vehicle A (PHEV-FC), that has 29% more consumption than Vehicle B (most consuming BEV).

4.4 Electrical load

In this case study there were made two kinds of simulation for each vehicle: with the HVAC system off, and with HVAC system on. The more accessories are on, more energy and power will be required to the battery. The battery has to be able to deliver the required power, and naturally, delivering more energy to all systems in the vehicle (not to forget the traction motor). It will discharge sooner, and consequently the vehicle will consume more energy.

The lower the capacity and the power available of the battery, more likely the vehicle is undergoing variations in consumption and autonomy. As it can be seen in Figure 5d, the increasing of the electrical load, causes the increasing of the vehicle's energy consumption and the decreasing of the autonomy (Figure 6d) with the greatest variations for the Vehicle D.

In this case study, as the battery's power is highly required, there is the risk of the efficiency decrease, and consequently influence even more the energy consumption.

For the vehicle A (PHEV-FC), the more sudden discharging of the battery promotes the fuel cell to start sooner, and consequently the raising of the overall energy consumption, presenting 30% more consumption in original cycle (HVAC system off) then the Vehicle B, and 33% with HVAC system on. Again comparing with the conventional vehicles, plug-ins continue to have less energy consumption values besides their higher increases. The ICEV has 123%, and the HEV 71% more consumption than the Vehicle A in original cycle, and when the HVAC system is on these conventional vehicles have respectively 97% and 44% more consumption than the PHEV-FC.

4.5 Initial state of charge of battery

The initial state of charge of the battery will not influence directly the consumption (Figure 5e). However, since the battery has less energy stored, is clear that the autonomy is directly affected (Figure 6e). Some variations on vehicle's energy consumption are attributed to the different distances traveled (and different fractions of the driving cycle) associated to different autonomies (Figure 6). For instance, the energy consumption of vehicle D is quite different from the others PEV´s for 25% of initial SOC. In fact, vehicle D was the only one not to complete the driving cycle in this case. Meaning that this vehicle may not had encountered the same driving cycle requirements than others that completed the driving cycle, presenting very different values for the expected consumption.

The PHEV-FC (vehicle A) is a peculiar case. If the initial SOC is at 25%, the fuel cell will start immediately (because 25% is lower than the value stipulated for the charge sustaining mode) with the goal to rise and maintain the SOC at the charge sustaining level, 30%. Therefore, the fraction of hydrogen used along the driving cycle is 100%, in other words, there is no time of the driving cycle that the vehicle only uses electricity (charge depleting mode). On the other hand, when initial SOC is higher than 30%, till the 30% SOC level is reached the fuel cell will not start and no hydrogen will be consumed (unless extra power is needed). As said before, the higher the fraction of hydrogen is used, against the fraction of a fully electric operation (charge depleting), higher will be the energy consumption. Therefore, the lower the initial SOC, higher is the energy consumption (for PHEV-FC´s), and consequently lower is the autonomy.

In some cases the operation of the vehicle can be lightly impaired because, the power that the battery is able to deliver decreases with decreasing of SOC (especially when below near 30%).

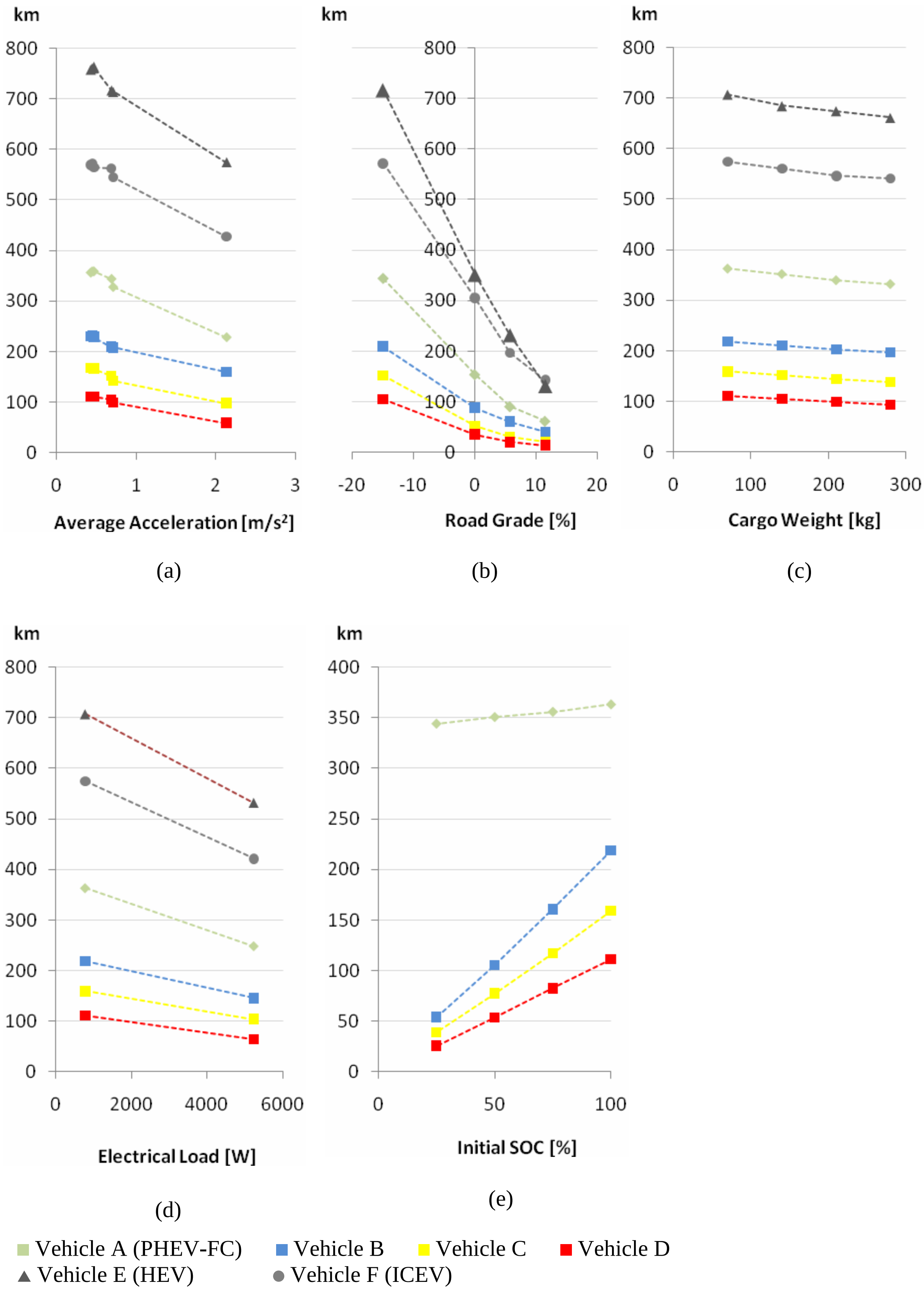
4.6 CO_2 emissions

The CO_2 emissions are from two sources of energy (at fuel life cycle level), production and transportation of electricity, and production and transportation of hydrogen (and the same for the gasoline for the conventional vehicles). In battery electric vehicles only electricity is used, but in plug-in fuel cell vehicles, both electricity and hydrogen are used.

The CO_2 emissions are directly associated to the energy spent. The more energy is spent, greater are the emissions. Not only the quantity of the energy used is important but the quality has a major role in the pollutant emissions. In Figure 8 can be easily distinguished the lower values of the CO_2 emissions for the BEVs than the conventional vehicles. And comparing the conventional vehicles, the HEV (Vehicle E) presents fewer emissions than the ICEV (Vehicle F). In the original cycle, he ICEV has 94% more CO_2 emissions per kilometer than Vehicle B (with the highest values for the BEVs), and the HEV has 49% more. The values for the emissions for the Vehicle A (PHEV-FC) are highly dependent of the source of the energy used. In 1 cycle (Figure 8a) it is clear that the fraction of the hydrogen used is much smaller than that used in autonomy (Figure 8b). The more hydrogen is spent, like the energy consumption, the emissions will rise abruptly.

If hydrogen is obtained by electrolysis with energy from the EU electric grid the resulted emissions will became greater than the conventional gasoline vehicles in g/km of autonomy, near 42% higher. If only 1 cycle is performed, these CO_2 emissions will be lower because less hydrogen is used, and in this case the same less than the ICEV emissions but 14% higher than the HEV.

In Figure 9 can be seen the increases of the CO_2 emissions facing the different case studies, and in Table 9 their absolute resulting values (Table 10 refers to the increases of Figure 9). In Figure 9 is easy to see that the relations between the vehicles are very similar to the relations in the energy consumption with the exception of the Vehicle A due to the hydrogen's different sources.



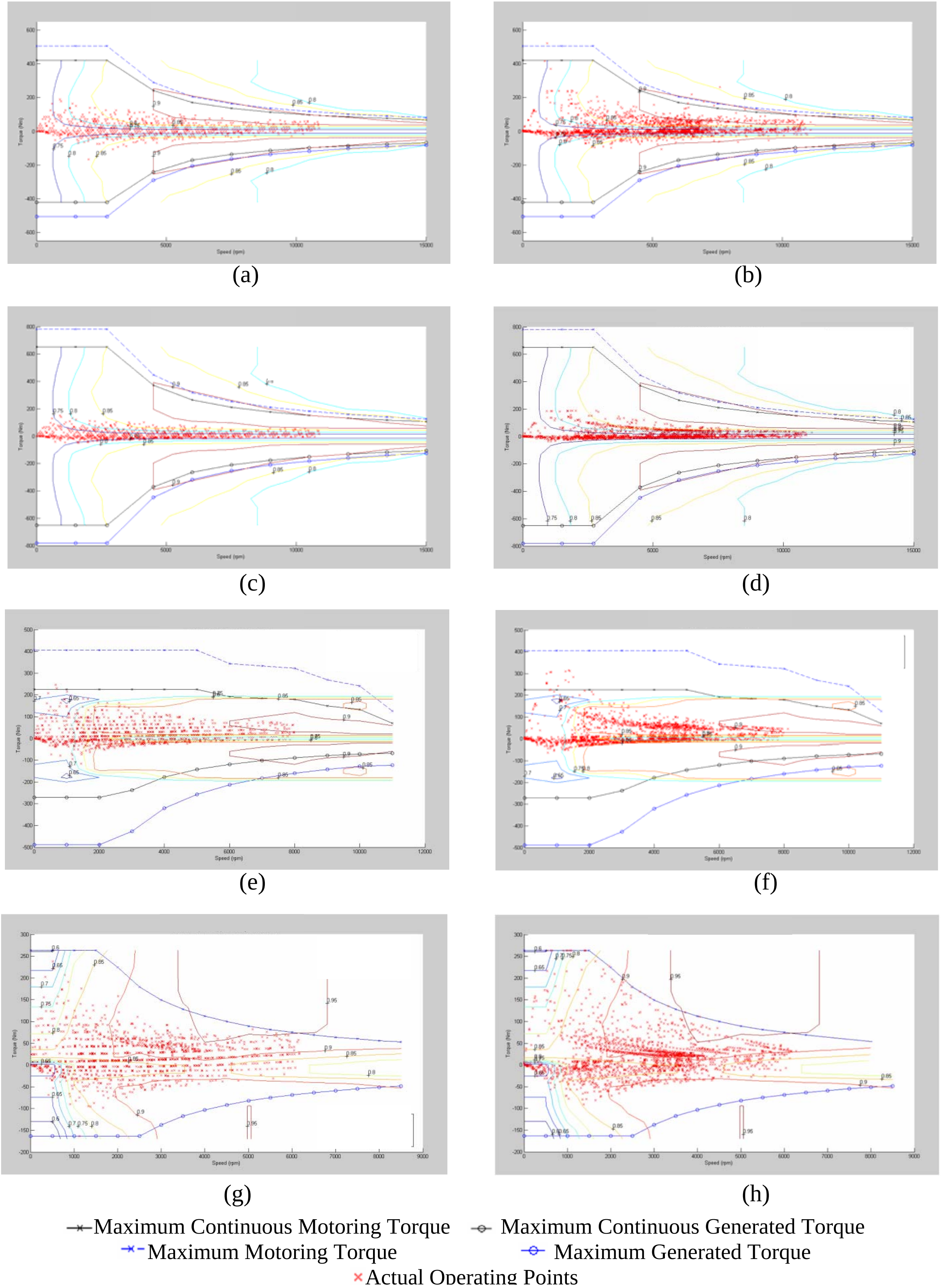
(a) (b) (c)

(d) (e)

Figure 6. Autonomy in kilometres, *Cascais-Lisboa* driving cycle: (a) average acceleration, (b) road grade, (c) cargo weight, (d) accessories electrical load, (e) initial SOC

Table 8. Results: variation of energy consumption relatively to original route (marked with bold), 1 cycle and autonomy,[%], for plug-in vehicles (A, B, C, D) and conventional vehicles (E, F)

		Vehicle A	Vehicle B	Vehicle C	Vehicle D	Vehicle E	Vehicle F
		km (EV+H_2)	km (EV)	km (EV)	km (EV)	km	km
Average Acceleration [m/s^2]	0.43	356.63	230.65	168.01	111.35	758.24	569.66
	0.45	358.84	231.68	168.04	111.49	760.68	571.52
	0.47	359.04	229.17	166.68	111.03	763.92	564.65
	0.69	344.10	209.44	152.27	105.28	716.84	562.09
	0.71	327.92	207.87	142.67	99.12	713.99	545.21
	2.13	228.15	160.30	97.93	58.97	574.90	427.21
Road Grade [%]	-15	--	--	--	--	--	--
	0	344.10	209.44	152.27	105.28	716.56	571.52
	5.75	154.35	88.18	52.42	35.78	351.73	305.25
	11.5	91.31	60.83	31.48	20.29	232.31	197.42
	17.25	62.48	41.23	21.36	13.96	131.67	143.06
Cargo Weight [kg]	70	363.11	219.03	159.25	111.19	707.55	574.50
	140	352.37	210.55	151.97	104.92	684.93	560.03
	210	340.16	202.52	144.19	99.73	674.83	546.26
	280	332.46	197.53	138.74	94.01	661.52	541.23
Accessory Electrical Load [W]	784	363.11	219.03	159.25	111.19	707.55	574.50
	5235	247.56	145.87	104.25	63.92	532.01	421.11
Initial SOC [%]	100	363.11	219.03	159.25	111.19		
	75	355.85	160.86	117.12	82.59		
	50	350.73	105.30	77.48	53.73		
	25	344.24	54.04	39.24	25.82		

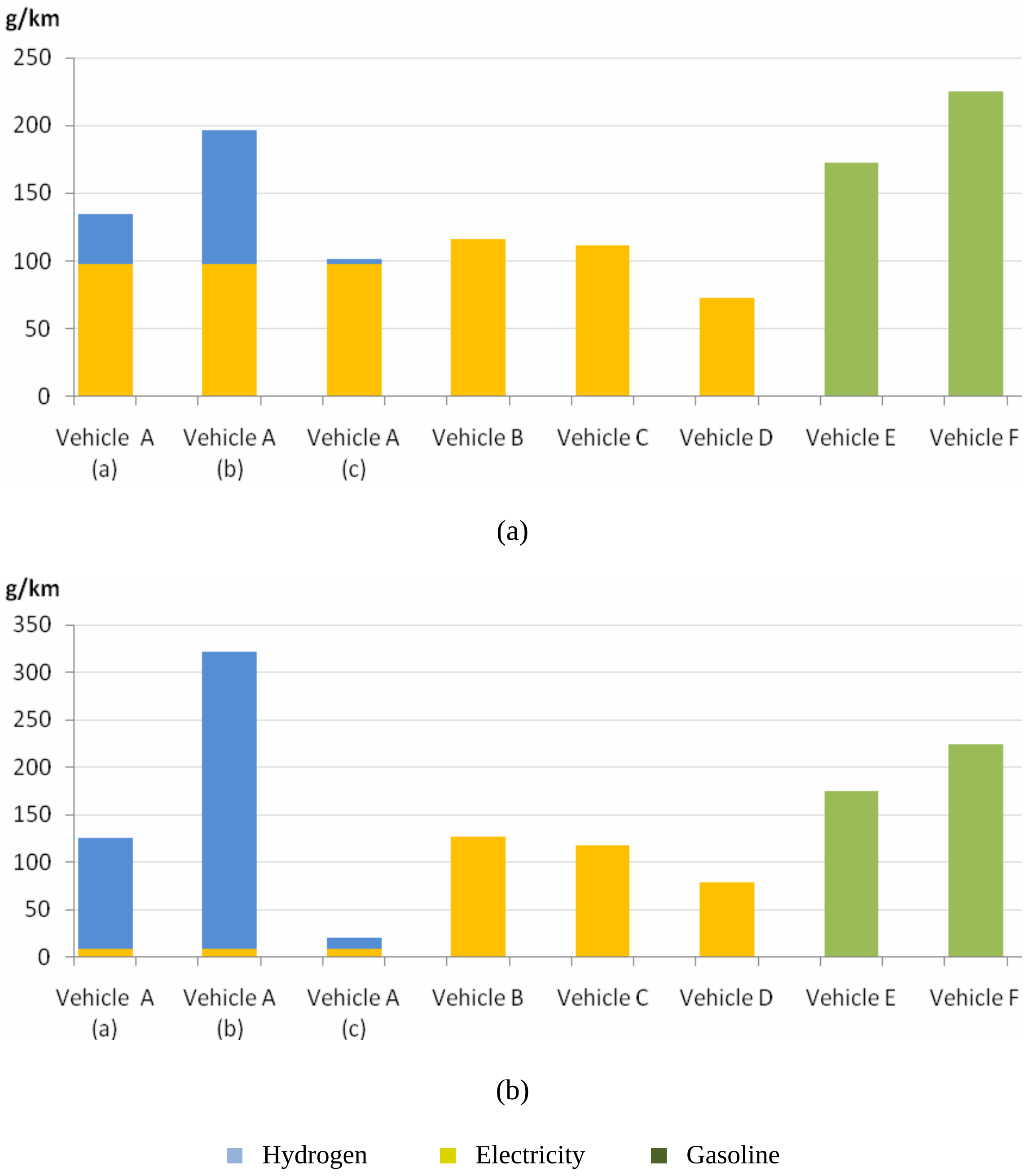

(a) (b)

(c) (d)

(e) (f)

(g) (h)

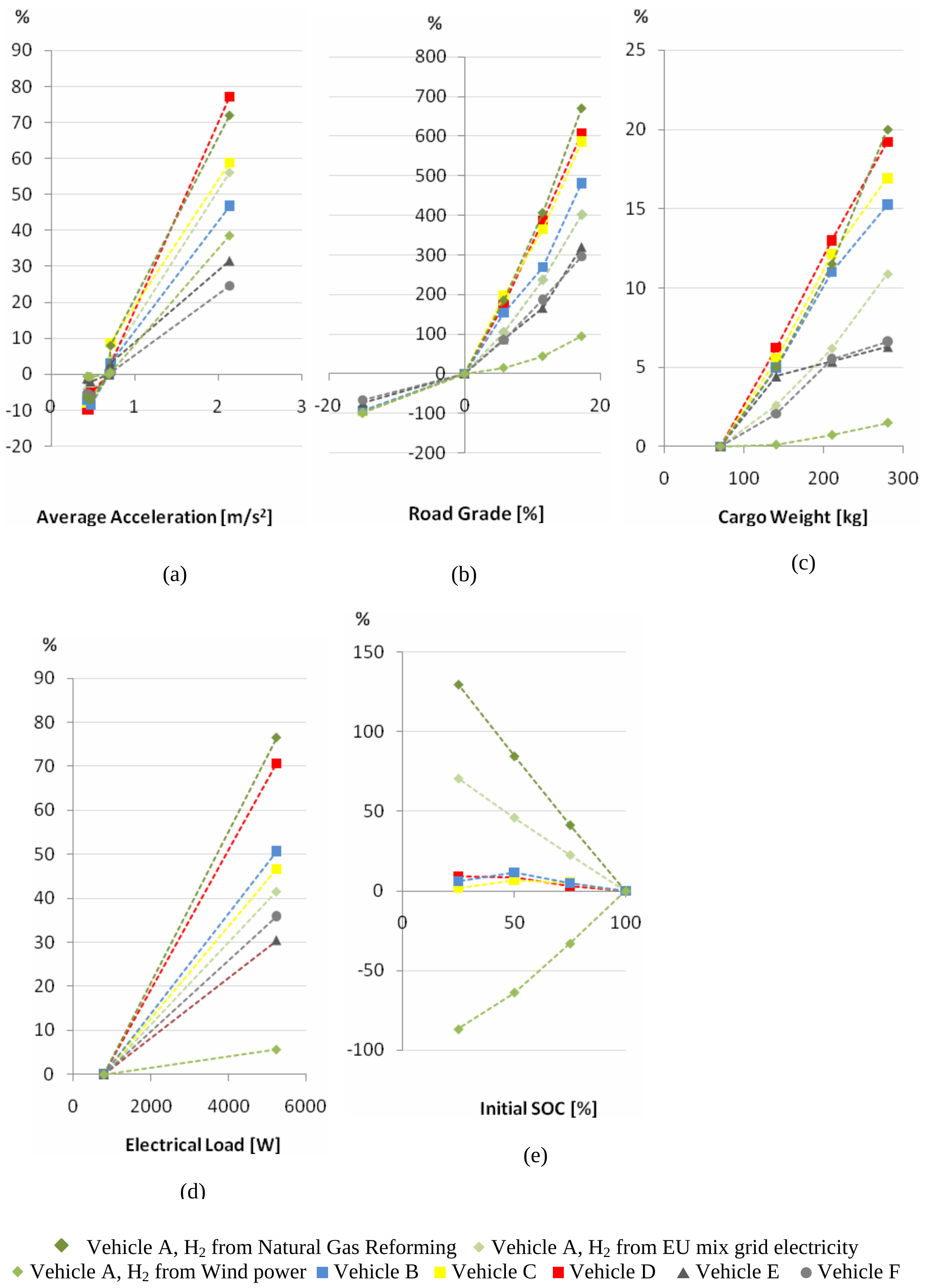
Figure 7. Motor controler operation points (torque [N.m], speed [rpm], efficiency), *Cascais-Lisboa* driving cycle: (a) vehicle A, 0.69m/s^2 average acceleration, (b) vehicle A, 2.13m/s^2 ave. accel., (c) vehicle B, 0.69m/s^2 ave. accel., (d) vehicle B, 2.13m/s^2 ave. accel., (e) vehicle C, 0.69m/s^2 ave. accel., (f) vehicle C, 2.13m/s^2 ave. accel, (g) vehicle D, 0.69m/s^2 ave. accel, (h) vehicle D, 2.13m/s^2 ave. accel



(a)

(b)

Figure 8. CO_2 emissions factor from the simulation in *1 cycle* (a) and in *autonomy* (b) mode, of the original driving cycle, *Cascais-Lisboa* driving cycle (34.2km); in consideration to the energy life cycle well-to-tank. (a) hydrogen production from natural gas reforming, (b) EU mix. grid electricity to electrolysis, (c) wind power to electrolysis



(a) (b) (c)

(d) (e)

Figure 9. CO_2 emission factor variation [%], *Cascais-Lisboa* driving cycle (34.2km): (a) average acceleration, (b) road grade, (c) cargo weight, (d) accessories electrical load, (e) initial SOC

Table 9. CO_2 emissions factor from the simulation in *1 cycle* and in *autonomy* mode, of the original driving cycle, *Cascais-Lisboa* driving cycle (34.2km). (a) hydrogen production from natural gas reforming, (b) EU mix. grid electricity to electrolysis, (c) wind power to electrolysis

		CO_2 emissions factor . 1 Cycle and autonomy.[g/km]							
		Vehicle A (a)		Vehicle A (b)		Vehicle A (c)		Vehicle B	
		1 Cycle	Aut	1 Cycle	Aut.	1 Cycle	Aut.	1 Cycle	Aut.
Average Acceleration $[m/s^2]$	0.43	138.22	124.90	206.75	325.18	101.79	18.44	112.69	119.68
	0.45	137.99	124.18	206.25	323.22	101.71	18.37	112.69	119.27
	0.47	137.68	124.25	205.37	323.18	101.69	18.50	111.05	120.51
	0.69	**144.06**	**129.99**	**221.32**	**337.56**	**102.42**	**19.65**	**121.33**	**129.97**
	0.71	150.07	135.61	238.84	353.42	102.88	19.82	125.03	133.26
	2.13	224.80	195.35	380.62	508.39	141.98	28.94	178.09	173.15
Road Grade [%]	-15	2.49	0.00	2.49	0.00	2.49	0.00	7.40	7.40
	0	**144.06**	**129.99**	**221.32**	**337.56**	**102.42**	**19.65**	**121.33**	**129.97**
	5.75	296.10	281.89	630.97	744.62	118.08	35.91	307.64	431.85
	11.5	485.79	473.37	1121.35	1255.58	147.94	57.56	448.30	451.18
	17.25	722.62	685.14	1706.58	1828.33	199.56	77.44	705.36	864.94
Cargo Weight [kg]	**70**	**134.62**	**123.09**	**196.77**	**319.79**	**101.57**	**18.53**	**115.98**	**126.26**
	140	138.11	126.65	206.63	329.35	101.68	18.90	121.74	131.61
	210	142.95	130.97	219.44	340.94	102.30	19.36	128.73	136.96
	280	149.26	133.84	236.15	348.68	103.07	19.64	133.67	140.66
Accessory Electrical Load [W]	**784**	**134.62**	**123.09**	**196.77**	**319.79**	**101.57**	**18.53**	**115.98**	**126.26**
	5235	190.62	177.70	347.25	466.21	107.35	24.33	174.80	185.90
Initial SOC [%]	**100**	**134.62**	**123.09**	**196.77**	**319.53**	**101.57**	**18.53**	**115.98**	**126.26**
	75	164.80	123.06	277.88	323.77	68.13	16.36	121.74	126.68
	50	196.44	122.48	362.89	326.13	37.00	14.23	129.56	126.68
	25	229.42	122.98	451.50	330.46	13.58	12.68	122.97	120.51
		Vehicle C		Vehicle D		Vehicle E		Vehicle F	
		1 Cycle	Aut	1 Cycle	Aut.	1 Cycle	Aut	1 Cycle	Aut
Average Acceleration $[m/s^2]$	0.43	103.64	107.76	71.15	74.44	158.80	163.03	228.78	226.64
	0.45	104.06	107.76	71.15	74.44	158.34	162.50	228.48	225.90
	0.47	103.64	108.99	74.85	74.85	157.16	161.82	226.78	228.65
	0.69	**112.69**	**118.45**	**78.97**	**79.38**	**167.57**	**172.44**	**231.51**	**229.69**
	0.71	122.56	126.68	81.02	84.31	168.31	173.13	238.31	236.81
	2.13	178.91	182.20	139.84	148.47	208.74	215.02	304.57	302.22
Road Grade [%]	-15	4.94	4.94	3.70	3.70	43.20	34.11	77.50	75.85
	0	**112.69**	**118.45**	**78.97**	**79.38**	**167.57**	**172.51**	**228.48**	**225.90**
	5.75	330.67	353.30	--	218.80	313.46	351.44	424.91	422.96
	11.5	--	551.12	--	386.20	445.41	532.12	656.08	653.98
	17.25	--	812.70	--	561.82	703.59	938.85	904.88	902.46
Cargo Weight [kg]	**70**	**111.87**	**117.63**	**72.80**	**78.97**	**172.43**	**174.71**	**224.95**	**224.73**
	140	118.04	122.97	77.32	83.49	180.07	180.48	229.58	230.54
	210	125.44	129.14	82.26	88.02	181.68	183.18	237.36	236.35
	280	130.79	134.08	86.78	90.07	183.29	186.87	239.84	238.55
Accessory Electrical Load [W]	**784**	**111.87**	**117.63**	**72.80**	**78.97**	**172.51**	**174.71**	**224.95**	**224.73**
	5235	164.10	186.72	124.21	123.80	224.98	232.35	305.71	306.59
Initial SOC [%]	**100**	**111.87**	**117.63**	**72.80**	**78.97**				
	75	117.63	118.86	75.27	78.97				
	50	119.68	118.04	78.97	79.38				
	25	113.93	115.16	79.38	79.38				

Table 10. CO_2 emissions factor variation from the simulation in *1 cycle* (a) and in *autonomy* (b) mode, of the original driving cycle, *Cascais-Lisboa* driving cycle (34.2km). (a) hydrogen production from natural gas reforming, (b) EU mix. grid electricity to electrolysis, (c) wind power to electrolysis

		CO_2 emissions factor variation . 1 Cycle and autonomy.[%]							
		Vehicle A (a)		Vehicle A (b)		Vehicle A (c)		Vehicle B	
		1 Cycle	Aut	1 Cycle	Aut.	1 Cycle	Aut.	1 Cycle	Aut.
Average Acceleration [m/s^2]	0.43	-4.05	-3.92	-6.58	-3.67	-0.62	-6.16	-7.12	-7.91
	0.45	-4.21	-4.47	-6.81	-4.25	-0.69	-6.51	-7.12	-8.23
	0.47	-4.43	-4.42	-7.21	-4.26	-0.71	-5.85	-8.47	-7.28
	0.69	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
	0.71	4.17	4.32	7.92	4.70	0.45	0.87	3.05	2.53
	2.13	56.05	50.28	71.98	50.61	38.63	47.28	46.78	33.23
Road Grade [%]	-15	-98.27	-100.00	-98.87	-100.00	-97.57	-100.00	-93.90	-94.30
	0	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	0.00	**0.00**
	5.75	105.54	116.86	185.09	120.59	15.29	82.75	153.56	232.28
	11.5	237.21	264.16	406.66	271.96	44.44	192.93	269.49	247.15
	17.25	401.61	427.07	671.09	441.63	94.84	294.10	481.36	565.51
Cargo Weight [kg]	**70**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
	140	2.59	2.89	5.01	2.99	0.11	2.00	4.96	4.23
	210	6.19	6.40	11.52	6.61	0.72	4.48	10.99	8.47
	280	10.88	8.73	20.01	9.03	1.48	5.99	15.25	11.40
Accessory Electrical Load [W]	**784**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
	5235	41.60	44.37	76.48	45.79	5.69	31.30	50.71	47.23
Initial SOC [%]	**100**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	75	22.42	-0.02	41.22	1.33	-32.92	-11.71	4.96	0.33
	50	45.92	-0.50	84.42	2.07	-63.57	-23.21	11.70	0.33
	25	70.42	-0.09	129.46	3.42	-86.63	-31.57	6.03	-4.56
		Vehicle C		Vehicle D		Vehicle E		Vehicle F	
		1 Cycle	Aut	1 Cycle	Aut.	1 Cycle	Aut	1 Cycle	Aut
Average Acceleration [m/s^2]	0.43	-8.03	-9.03	-9.90	-6.22	-5.23	-5.46	-1.18	-1.33
	0.45	-7.66	-9.03	-9.90	-6.22	-5.51	-5.76	-1.31	-1.65
	0.47	-8.03	-7.99	-5.21	-5.70	-6.21	-6.16	-2.04	-0.45
	0.69	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
	0.71	8.76	6.94	2.60	6.22	0.44	0.40	2.94	3.10
	2.13	58.76	53.82	77.08	87.05	24.57	24.69	31.55	31.57
Road Grade [%]	-15	-95.62	-95.83	-95.31	-95.34	-74.22	-80.23	-66.08	-66.42
	0	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
	5.75	193.43	198.26	--	175.65	87.07	103.72	85.97	87.23
	11.5	--	365.28	--	386.53	165.81	208.45	187.15	189.49
	17.25	--	586.11	--	607.77	319.89	444.22	296.05	299.49
Cargo Weight [kg]	**70**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
	140	5.51	4.55	6.21	5.73	4.43	3.30	2.06	2.58
	210	12.13	9.79	12.99	11.46	5.36	4.85	5.52	5.17
	280	16.91	13.99	19.21	14.06	6.30	6.96	6.62	6.15
Accessory Electrical Load [W]	**784**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
	5235	46.69	58.74	70.62	56.77	30.41	32.99	35.90	36.42
Initial SOC [%]	**100**	0.00	0.00	0.00	0.00				
	75	5.15	1.05	3.39	0.00				
	50	6.99	0.35	8.47	0.52				
	25	1.84	-2.10	9.04	0.52				

5. Conclusions

The different characteristics of the vehicles are very relevant, in particular the power/weight and torque/weight ratios, will define the evolution of the energy consumption in the studied cases. If on the one hand a higher power/weight (kW/kg) ratio could lead to higher energy consumption, on the other hand, the vehicles that have lower values for this ratio will be more likely to be hampered in its performance, and also more likely to have their energy consumption influenced, particularly consumption increases.

Of all the vehicles studied, vehicle D with a less powerful motor showed to be responsible for the highest increases of energy consumption. However the absolute value of the energy consumption was always lower than the consumption of the other vehicles. The same can be said for the CO_2 emissions.

Remembering that the vehicle A (PHEV-FC) has for the power/weight ratio 0.076kW/kg, vehicle B 0.150kW/kg, vehicle C 0.102kW/kg and vehicle D 0.044kW/kg, and that in the road grade case study the torque/weight ratio has also a major relevance (maintaining the same order as the power/weight ratio with the exception of vehicles C and D, the first one with the lowest torque) the most extreme results of each case study are presented next.

- For an acceleration raise of 209% relatively to the original driving cycle, it was obtained energy consumption increases near 47% for vehicle B, 59% for vehicle C, 62% for vehicle A (PHEV-FC), and 77% for vehicle D. The ICEV showed to have 71% more, and the HEV 17% more than the consumption of Vehicle A (PHEV-FC), which in turn has 50% more consumption than Vehicle B (highest consuming of the BEVs).

- For a road grade of 17.25%, vehicle B presented an increasing (relatively 0% of road grade) near 481% of energy consumption, vehicle A 502%, vehicle D 611%, and vehicle C 621%. The ICEV (presented to have 37% more and the HEV 6% more than the energy consumption of Vehicle A (PHEV-FC), which in turn has 41% more consumption than Vehicle B (highest values of the BEVs).

- With all four seats of the vehicle occupied, adding 280kg which corresponds to 18% of vehicle A ´s weight, 23% of vehicle B´s, 19% of vehicle C´s, and 26% of vehicle D´s, there were increases (relatively only one passenger, the driver) of near 14%, 15%, 17%, and 19% respectively. The ICEV and the HEV presented respectively 108% and 59% more energy consumption than Vehicle A (PHEV-FC), that has 29% more consumption than Vehicle B.

- Raising in 568% the electrical load to 5235W due to the HVAC systems, vehicle C presented increases of near 47%, vehicle B 51%, vehicle A 54%, and vehicle D 71%. The ICEV has 123%, and the HEV 71% more consumption than the Vehicle A in original cycle, and when the HVAC system is on these conventional vehicles have respectively 97% and 44% more consumption than the PHEV-FC.

- With only 25% of charge in the battery at the beginning of the driving cycle, vehicle C presented an increasing of near 2%, vehicle B 6%, vehicle D 9%, and vehicle A, due to the more sudden needing of hydrogen energy, 28%.

The CO_2 emissions are quite in agreement with the obtained relations in the energy consumption, with the exception of the PHEV-FC which depends highly in the different hydrogen's life cycle sources.

In terms of overall autonomy of the plug-in vehicles, despite to be lower than the conventional vehicles (though the PHEV-FC having higher autonomies than the BEVs, near 67% higher than Vehicle B but 37% less than the ICEV), there are already a large range of target users for this relatively young technology. A survey carried out by EUROSTAT[14] claims that a usual European car user travels nearly 30km to 40km a day.

For the PHEV-FC´s this is an advantage too, meaning that the electricity from plug-in stored in battery should cover most of this small daily distance and a smaller fraction of hydrogen should be spent.

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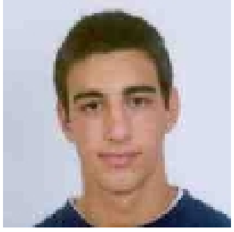

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