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Full life cycle analysis of market penetration of electricity based vehicles

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Abstract
The main objective of the present study is to analyze the impact of the market share increase of different vehicle technologies in terms of energy consumption and CO_2 emissions in the Portuguese mainland region. An extensive characterization of how road vehicle technologies energy consumption and CO_2 emissions compare in a full life cycle perspective was attained. The main conclusions are that plug-in hybrid, electric and fuel cell vehicles can have the potential to reduced energy consumption (up to 9%) and CO_2 emissions (up to 19%) in a full life cycle analysis.

Keywords: Vehicle technology; energy consumption; CO_2 emission; Portuguese road transportation sector.

1 Introduction

Portugal imports around 70% of its final energy consumption in the form of oil based fuels [1]. Around 35% of this foreign oil consumption goes to the transportation sector, mainly road transportation. In terms of greenhouse gas (GHG) emissions, namely CO_2, which are associated with climate change issues [2], the transportation sector was responsible for 21% of the total emissions, in 2005. Particularly, road transport accounted for 93% of the global emissions of the transport sector.
The urge for energy security of supply, air quality improvement in urban areas and CO_2 emissions reduction are pressing decision makers/manufacturers to act on the road transportation sector, introducing more efficient vehicles on the market and spanning the energy sources. For that reason, it is expected in the near future that the market share of hybrid vehicles will raise and that, in the long term future, the market share of hybrid plug-in vehicles will be significant.
Accordingly, this paper intends to exploit the benefits of introducing plug-in hybrid, electric vehicle and fuel cell technologies in the light-duty vehicle market for the Portuguese mainland region.
In order to evaluate the environmental impacts of these options, a life-cycle approach was considered for the Portuguese fleet, covering the materials cradle-to-grave life-cycle (including vehicle assembling, maintenance, dismantling and recycling) and fuel life-cycle: Well-To-Tank (WTT) and Tank-To-Wheel (TTW). The materials life-cycle energy consumption and CO_2 emissions are spread along the vehicle expected lifetime (in this case around 12 years). WTT accounts for

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energy consumption and CO_2 emissions from primary energy resource extraction through the delivery of the fuel/energy source to the vehicle tank, while TTW accounts for the emissions and fuel consumption resulting from moving the vehicle through its drive cycle [3].
Additionally, in order to assess the impact of the penetration of plug-in hybrid, electric vehicle and fuel cell technologies in the Portuguese light-duty vehicle fleet, three distinct scenarios with increasing substitution ratios were evaluated, in this life-cycle analysis framework.

2 Portuguese light-duty fleet characterization

The Portuguese fleet characterization in terms of diesel/gasoline distribution, weight and engine displacement vehicles' distribution is presented in Table 1 [4]. To estimate the Portuguese fleet fuel consumption and derived emissions COPERT 4 [5] was used, which is an European tool for estimating the emissions and fuel consumption of specific fleets (with conventional vehicle technologies). A typical annual and daily mileage of respectively 12800 and 35 km was assumed [4]. For COPERT a mix of urban (24 % of total distance), rural (57 % of total distance) and highway (19 % of total distance) driving was considered. The results obtained for the conventional fleet fuel consumption and annual emissions of carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x) and particulate matter (PM) are presented in Table 2, according to the categories of vehicle considered. Table 2 shows the results of energy consumption for 2005 and emissions at vehicle usage stage (TTW).

Table 1: Fleet characterization in terms if fuel distribution and engine displacement.

Displacement	Number ($\times10^3$)	Total	Global %	% Fuel
Gasoline				
<1.4 l	2337	2859	43%	53%
1.4 - 2.0 l	470		9%	
>2.0 l	52		1%	
Diesel				
<2.0 l	1801	2500	33%	46%
>2.0 l	699		13%	
LPG				
>2.0 l	22		0.42%	
Total	**5381**		**100%**	

Table 2: Annual TTW characterization for the Portuguese light duty fleet in terms of fuel consumption and emissions.

Vehicle category	Fuel consumption		Emissions (kton)				
	l/100km	TJ ($\times10^3$)	CO_2 ($\times10^3$)	CO	HC	NO_x	PM
Gasoline <1,4 l	6.9	56	4.0	112	15.7	16	0.05
Gasoline 1,4-2,0 l	8.2	15	1.1	18	2.5	2.6	0.01
Gasoline >2,0 l	10.3	2.0	0.2	1.2	0.14	0.15	0.001
Diesel <2,0 l	6.1	64	4.7	5.8	0.94	20.0	2.1
Diesel >2,0 l	7.9	29	2.1	2.9	0.83	7.1	1.0
LPG	2.9[a]	0.9	0.1	1.1	0.17	0.18	0
Total	**7.2**[b]	**167**	**12**	**141**	**20**	**46**	**3**

[a] in m^3 of liquid propane gas per 100 km.
[b] gasoline equivalent.

Summarizing, the light-duty conventional road transport sector consumes 167×10^3 TJ of fossil fuel energy and is responsible for a global annual CO_2 emission of 12×10^3 kton and for a local emission of 141 kton of CO, 20 kton of HC, 46 kton of NO_x and 3 kton of PM.

3 Vehicle penetration scenarios

For assessing the impact of the different vehicles technologies on the light-duty fleet energy consumption and emissions, the following representative vehicles were considered [6]:

- Plug-in hybrid (PH): Ni-MH battery of 6 kWh (dischargeable to 45% of its capacity), electric motor of 60 kW, internal combustion engine of 40 kW; generator of 40 kW and total weight of 1120 kg;
- Medium size electric vehicle (EV1): Ni-MH battery of 12 kWh, electric motor of 65 kW, total weight 1214 kg;
- Large size electric vehicle (EV2): Ni-MH battery of 24 kWh, electric motor of 75 kW, total weight 1393 kg;
- Hybrid (FC-HEV) : fuel cell vehicle with a 75 kW electric motor, Li-ion 6 Ah 267 V battery, 50 kW fuel cell and a total weight of 1388 kg;
- Plug-in hybrid (FC-PHEV): plug-in series hybrid with fuel cell. Fuel cell stack 50 kW, electric motor 75 kW, battery Ni-MH 45 Ah 335 V and a total weight of 1315 kg.

These vehicles have a total power-to-weight ratio of 55 W/kg since this is representative of the top sales of new vehicles sold in Portugal, with whom these new technologies will compete when they start entering the market. Additionally, it

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guarantees that similar vehicle performances are being compared.
The designed scenarios for the electric, plug-in hybrid and fuel cell vehicles are the following:

Table 3: Designed scenarios for the penetration of fuel cell vehicles.

Scenarios	Vehicle penetration (%)					
	Total fleet replacement	PH	EV1	EV2	FC-HEV	FC-PHEV
Base	0	0	0	0	0	0
Scenario 1	10	1.6	4.2	4.2	0	0
Scenario 2	30	6	11.4	11.4	0.6	0.6
Scenario 3	50	12	17	17	2	2

For the PH, EV1 and EV2 options the Portuguese electricity generation mix was considered. For the FC-HEV and FC-PHEV options, the hydrogen production pathway considered was centralized natural gas reforming.
The base scenario corresponds to the present situation that was described earlier. For scenarios 1, 2 and 3 the number of alternative technology vehicles continuously increases. Since COPERT 4 does not include any of the new vehicle technology considered, for simulating the daily commuting journeys of these new vehicle technologies ADVISOR vehicle simulation software [7] was used. ADVISOR is a micro-simulating tool to estimate the performance and fuel economy of conventional and advanced new vehicle technologies.
A real measured driving cycle was used, representing a mix of urban (24 % of km, speed below 50 km/h), rural (57 % of km, speed between 50 and 90 km/h), and highway (19 % of km, speed higher than 90 km/h) driving. Figure 1 shows the journey driving cycle [8], which corresponds to an experimentally measured real world driving cycle.

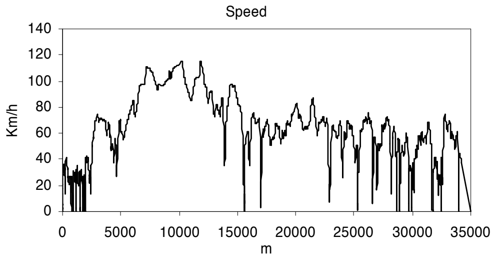

Figure 1: Experimentally measured driving cycle.

4 Fuel life cycle

In order to understand how road vehicle technologies energy consumption and CO_2 emissions compare, the fuel life cycle analysis and materials cradle-to-grave cycle was performed.
The program ADVISOR [7] was used to simulate the fuel consumption and emissions of each vehicle in the specified driving cycle (see Figure 1). Table 4 shows the obtained results for the in-use emissions of HC, CO, NO_x and PM, that are important regarding local air quality. Table 5 shows the in-use energy consumption and CO_2 emissions (Tank-to-Wheel part - TTW - of the fuel life cycle).

Table 4: In-use tailpipe emissions (local air quality).

Vehicle	HC g/km	CO g/km	NO_x g/km	PM g/km
ICEV Gasoline	0.121	0.164	0.157	0
ICEV Diesel	0.120	0.397	0.490	0
EV (electricity)	0	0	0	0
FC-HEV	0	0	0	0
FC-PHEV	0	0	0	0
PHEV Gasoline	0.116	0.174	0.090	0

For the fuels production and distribution stage part of its life cycle "Well-to-Tank" analysis WTT, a database [9] [10] was used for the calculation of the energy spent and CO_2 emissions for different fuels and different pathways. The fuel cycle has been defined as the energy spent to bring the fuel to the vehicle, not including the energy of the fuel itself. For each type of fuel a path was defined since its acquisition or production until it as available for use in the vehicles. The fuels used were gasoline, diesel, electricity and hydrogen from central natural gas reforming plants with steam co-generation. Table 4 shows results for complete fuel life cycle.

Table 5: Fuel life cycle energy and CO_2 WTW.

Vehicle	WTT		TTW	
	Energy MJ/km	CO_2 g/km	Energy MJ/km	CO_2 g/km
ICEV Gasoline	0.27	24.5	1.96	143.0
ICEV Diesel	0.27	23.7	1.67	124.4
EV (Electricity)	1.06	72.9	0.57	0.0
FC-HEV	0.62	95.4	1.08	0.0
FC-PHEV	0.31	56.7	0.55	0.0
PHEV Gasoline	0.55	40.1	1.13	65.7

For the study of the materials life cycle (cradle-to-grave) the program GREET was used. The program consists of a worksheet that was developed in open-source [11] (that deals with the materials cycle since the extraction, assembling till the dismantling and recycling. The electric mix of the database was adapted to European reality [12]. Table 6 shows the materials life cycle ("cradle-to-grave") results including tire, battery and fluids maintenance throughout 150000 km useful life.

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Table 6: Materials energy and CO_2 cradle-to-grave.

Vehicle	Energy (MJ/km)	CO_2 (g/km)
EV	0.77	47.8
FC-HEV	0.73	48.4
FC-PHEV	0.77	49.5
ICEV Diesel	0.50	32.0
ICEV Gasoline	0.48	30.7
PHEV Gasoline	0.70	43.7

Figure 2 shows the combination of tank-to-wheel with well-to-tank for the fuel life cycle with the materials cradle-to-grave for selected vehicles. For the total life cycle only the combustion of fossil fuels produces CO_2 (Figure 3).

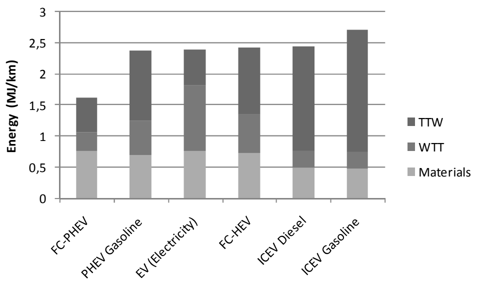

Figure 2: Full life cycle energy for selected vehicles.

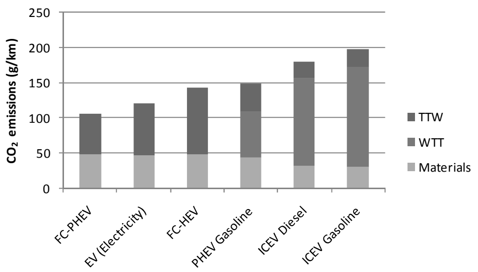

Figure 3: Full life cycle CO_2 for selected vehicles.

Figure 4 analyses the influence of distance travelled on CO_2 emissions (and energy consumption). If the vehicle is always parked in the garage, than energy consumption and CO_2 emission are those of the vehicle manufacturing/recycling. If in its total life the vehicle travels distances below 50000 km, conventional ICE vehicles are good choices. Otherwise, the more the vehicle travels the more the electric vehicles, fuel cell and plug-in hybrids gain relevance compared to conventional ones. Plug-in hybrids have the advantage of requiring a less complex infrastructure than hydrogen vehicles and of having higher autonomies than pure electric vehicles.

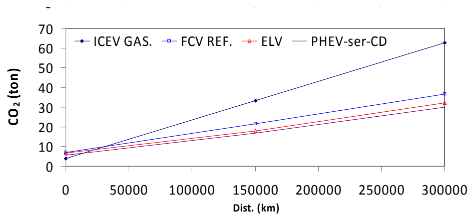

Figure 4: Influence of the distance travelled on full life cycle CO_2 emissions per vehicle.

5 Fleet results

For the TTW stage, the Portuguese fleet's annual fuel consumption according to the vehicle type and the considered scenarios is presented in Table 7.

Table 7: Annual TTW disaggregated total fleet fuel consumption (×10^3, TJ) for the three scenarios.

Vehicle	Energy source	Scenarios 1	2	3
Conven-tional	Gasoline/Diesel /LPG	155	127	93
PH	Gasoline	0.88	3.29	6.59
	Electricity	0.37	1.40	2.80
EV1	Electricity	1.64	4.46	6.65
EV2	Electricity	1.64	4.46	6.65
FC-PHEV	Hydrogen	0	0.28	0.92
	Electricity	0	0.17	0.58
FC-HEV	Hydrogen	0	0.44	1.48
	Total	**160**	**142**	**119**

As expected, the conventional fuels consumption decreases along the three scenarios (from 7% to 40%) while the hydrogen and electricity consumption increases. Global TTW energy consumption decreases from 4% to 29%.
By analyzing Table 8, it is possible to conclude that the replacement of older vehicles by less polluting ones allows a significant reduction in terms of local pollution, with 11%-26% reductions for CO, 30-35% for HC, 15-17% for NO_x and 17-60% for PM.

Table 8: Annual TTW local pollutants emissions.

Scenarios	CO (ton)	HC (ton)	NO_x (ton)	PM (ton)
Baseline	141	20	46	3.0
1	105	13	38	2.5
2	113	14	38	1.8
3	125	14	39	1.2

After combining the materials cradle-to-grave with the fuel TTW and WTT, the following energy and CO_2 emissions distributions were obtained.

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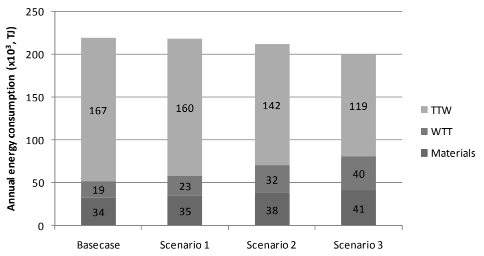

Figure 5: Annual fleet's life cycle results for materials, WTT and TTW regarding energy consumption in the considered scenarios.

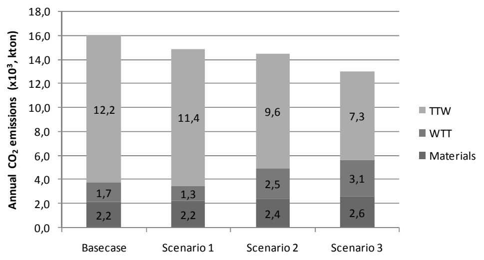

Figure 6: Annual fleet's life cycle results for materials, WTT and TTW regarding CO_2 emissions in the considered scenarios.

A clear shift from the magnitude of TTW to the WTT results is observed with the increasing penetration of hydrogen and electricity based vehicles. Additionally, as the number of these vehicles increases the materials stage also gains importance, since fuel cell, plug-in and electrical vehicles manufacturing is more energy intensive.

6 Conclusions

An extensive full life cycle vehicle technologies study was performed. The main focus was the introduction of plug-in hybrid, electric and fuel cell vehicle technologies. These technologies have the potential to decrease the TTW energy consumption (4-29% in the considered scenarios). However, these technologies represent a new concept for the road transportation, since the energy and CO_2 are shifted to the WTT stage. In these vehicles' substitution scenarios, the WTT energy consumption increases (26-115%), as do the materials cradle to grave energy consumption (5 to 23%). Combining the different stages, in the overall full life cycle analysis, these aggressive scenarios of new vehicle technology introduction, energy and CO_2 emissions reduction reach 9 and 19% respectively.

Considering environmental impacts, introducing the considered vehicle technologies has a clear advantage in terms of local air quality (with up to 60% emission reductions of HC, CO, NO_x and PM). In terms of global environment impact, CO_2 emissions can be reduced by up to 40% when running the vehicles, but this percentage is only 19% if a full cradle-to-grave analysis is accounted for.

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