THE IMPACT OF HYBRID POWERTRAINS ON THE ENVIRONMENT

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ABSTRACT: Automotive industry was hit hard by oil crisis and general financial crisis worldwide and now it seeks to overcome this situation by promoting as fast as possible the innovative technical solutions which have the ultimate goal to reduce the fuel consumption and the greenhouse gases emission. For this, the paper presents an analysis of energy losses on car and the measure of improvements of fuel consumption if is acting on these losses. The practical concerns regarding the implementation of these measures are discussed and the case of hybrid propulsion systems is detailed. Considerations regarding the additional costs for different hybrid architectures are also presented. The global CO_2 emissions of a car from middle-class is used to compare the overall efficiency of various propulsion systems.

1. INTRODUCTION

Reacting in support to the European industry, hit very hard by the current global crisis, the European Commission has launched a public private partnership, the “European Green Cars Initiative”, with an overall financial envelope of 5 billion Euros including loans from the European Investment Bank (EIB) and grants forFP7 projects.

The European governments have reached to an agreement to reduce greenhouse gases emissions by 20% and increase renewable energy use by 20% in 2020. The “European Green Cars Initiative” will help accelerate developments in technologies potentially leading to breakthroughs in CO2 reductions.

In ten years from now a large majority of new cars and vans will be hybrid. A survey carried out during AVL Engine & Environment 2009 conference between several hundred engineers, managers, academics and top management from automotive industry give the following results for the dominant hybrid architecture worldwide in 2020 (the pure electric vehicles are also included):40% - range-extender hybrid; 32% - mild hybrid; 14% - plug-in hybrid; 7% - full hybrid and 7% - pure electric. Whatever the future might offer us, the development of the hybrid cars is a major challenge for the European industry in the short and long term, [11].

2. DISTRIBUTION OF AVAILABLE ON-BOARD ENERGY

The energy analysis (vehicle energy distribution and possible ways to reduce energy consumption) can help to optimise the use of the available on-board vehicle energy. Depending on the desired goal (transmission losses, air and rolling drag resistance etc.), different areas of interest are detailed.

Table 1shows the distribution of the fuel tank energy for two conventional cars. The first is a middle-class car produced in 1994 for the U.S. market and equipped with a 4-speed automatic transmission, FTP-US driving cycle (urban and highway driving) [1]. The second is a middle-class car for the European market, NEDC cycle.

Table 1. Distribution of available on-board energy for urban, highway and NEDC driving

	Losses	Urban driving	Highway driving	NEDC
Available energy		**100%**	**100%**	**100%**
Engine	Engine Losses	64,2%	69,2%	77,4%
	Idling	17,2%	3,6%	
	Auxiliary systems	2,2%	1,5%	
Available energy		**18,2%**	**25,6%**	**22,6%**
Transmission	Transmission Losses	5,6%	5,4%	2,2%
Available energy		**12,6%**	**20,2%**	**20,4%**
Vehicle	Drag resistance	2,6%	10,9%	8,9%
	Rolling resistance	4,2%	7,1%	7,4%
	Braking Losses	5,8%	2,2%	4,1%

Analyzing the distribution of available on-board vehicle energy the methods for reducing energy consumption can be grouped as:

- Methods leading to better performances without increase in consumption;

- Methods leading to reduced energy consumption (Stop&Go, improvement of transmission efficiency, reduce driving resistances etc.).

Below are summarized the main methods of reducing energy consumption by highlighting the particular characteristics for hybrid propulsion systems.

3. IMPROVEMENTS TO INTERNAL COMBUSTION ENGINES (ICE)

At this moment the improvement of the highest efficiency of the vehicle ICE is minimal. Thus, a modern car turbo-diesel engine with liquid cooled high and low pressure exhaust gases recirculation systems (EGR), has a maximum efficiency of 44% [18]. If we compare the current level of technology with the `90 level [9], for passenger car diesel engines results an increase of only 1% of maximum efficiency.

There is greater potential for increasing the efficiency at partial loads using technologies as: variable valve timing and phases, variable displacement, variable compression ratio, Atkinson-Miller cycle, fuel direct injection etc. [16].

For a CSI engine (Compression and Spark Ignition) operating as HCCI (Homogeneous Charge Compression Ignition) at small and medium loads and as HCSI (Homogeneous Charge Spark Ignition) at high loads, the reduction in fuel consumption is about 26% compared to a conventional engine with indirect injection (MPI) , Figure 1 [7].

The Combined Combustion System (CCS) proposed by Volkswagen is implemented on diesel engine and uses partially homogenous compression-ignition combustion process at low loads [19]. This system promises a 15 to 20% fuel economy at low loads but needs a new type of fuel (kerosene or naphtha). In the NEDC, it achieved an 8% reduction of fuel consumption and a 65% reduction of NOx.

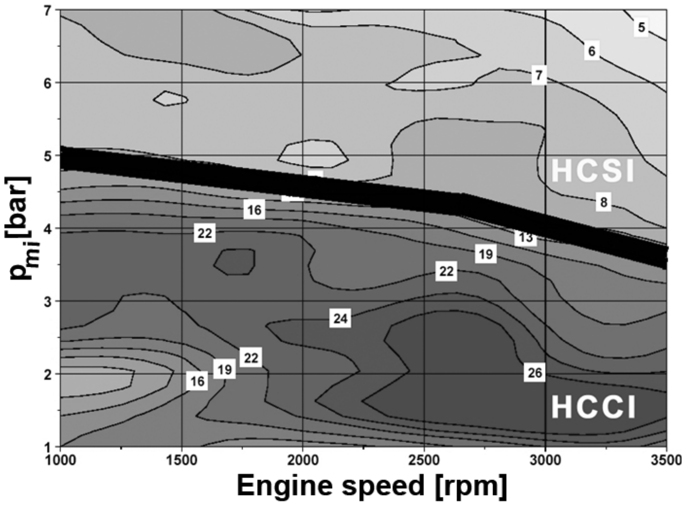

Figure 1. The economy potential of CSI engine comparing with MPI engine

4. SHIFTING THE OPERATING POINT FOR HIGHER EFFICIENCY

This is one of the most promising methods; using data from [4] for the extreme case when the engine is used only at the economic pole (point), it can be obtained a value of 30-40% economy for small and medium-class cars equipped with SI engine. This method can be implemented using a suitable transmission or hybrid propulsion systems.

Increased number of gears allows the configuration of top gears for fuel economy, Figure 1 [18]. For manual gearboxes, a number of six gears are the optimal compromise between operability, fuel consumption, sportiness and comfort. For automatic transmissions, increased number of gears to seven or eight and automatic gear change allows to maximize the efficiency of this method.

For manual transmissions the influence of the driver assist systems is not taken into account in the usual test cycles.

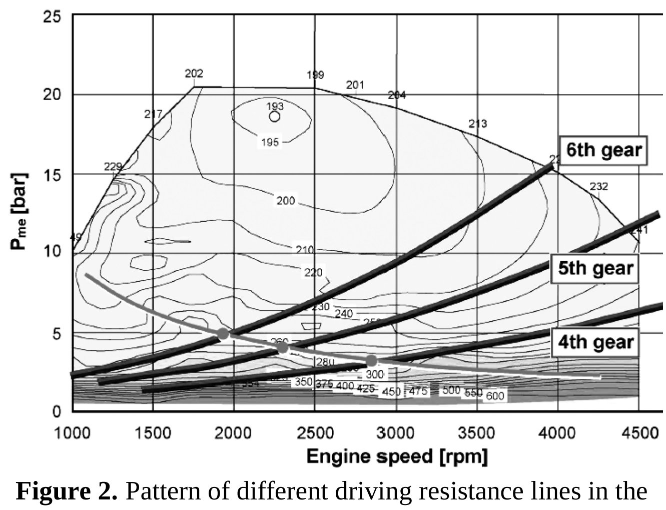

Figure 2. Pattern of different driving resistance lines in the engine fuel consumption map

To estimate the degree in which the engine is used to its maximum efficiency point, it is defined the engine operating efficiency, $\boldsymbol{\eta_{eo}}$:

$$\boldsymbol{\eta_{eo}} = \frac{\int(\boldsymbol{Minimumfuelconsumption})\,\boldsymbol{dt}}{\int(\boldsymbol{Actualfuelconsumption})\,\boldsymbol{dt}} \times \mathbf{100}\ [\%]$$

Table 2 presents the engine operating in association with different types of transmissions (AT, DCT, CVT), [15]. Comparing with other transmissions, the Continuously Variable Transmission ensures the best control system of engine operation. Unfortunately their low efficiency limits the fuel economy achieved.

More efficient usage of engine is performed when it is used with hybrid propulsion systems. This allows maintaining the engine operation at the economic pole. Even if fuel economy that belong to the engine operating efficiency is hard to quantify, for an HEV with SI engine and parallel electric architecture, it is estimated an improvement of fuel consumption of 5-9% in NEDC cycle [16].

There are also limitations of the method, so the conditions for using the engine have a direct influence on other emissions. In [18] it is indicated that the movement of the operating point of a diesel engine in the lower speeds can achieve a reduction in fuel consumption by 9% and increasing NOx emissions by 200%.

5. BRAKING ENERGY RECOVERY

This method is possible for electric cars or hybrid propulsion systems. The estimates show a potential to improve fuel consumption in European mixed cycle by 20-25% [4]. Real gain is lower mainly because of the limited power electrical machine and energy storage capacity. Thus, for an HEV, real reduction in fuel consumption is 5-9% [16].

6. EXHAUST GASES RECOVERY

They are considered only the methods that do not involve systems that act directly on engine processes, which are considered as ways to increase engine efficiency. Recovering a part of the exhaust energy can be made by turbines directly linked at the crankshaft or indirectly, using electricity generating systems.

Thermoelectric generator is a system without moving parts based on Seebeck effect to generate energy from heat dissipated by exhaust gas. It can be integrated into the exhaust system under the floor layout, in the radiator cooling recirculated exhaust gases or in the three-way catalyst. BMW, Benteler, DLR and Emitec developed a generator integrated in EGR radiator and presented in 2009, which has a potential to reduce fuel consumption by 2%.

7. IMPROVEMENT OF THE TRANSMISSION EFFICIENCY

Even if modern transmissions have a high efficiency, there are still reserves for improvements, especially when entry torque is low (urban use). Thus, the overall efficiency of the transmission may fall below 70% for urban traffic. Current lines of action are: the use of oils with low viscosity, low-friction bearings, reducing losses due to oil pump (for AT, CVT, DCT) and ensuring rapid heating of the transmission [18]. It is noted that any reduction of loss tends to be cancelled in urban and mixed test cycles, in the absence of thermal management systems. Normally, transmission efficiency is determined at 80-100^{o}C, whichmeans a temperature rarely reached in normal operating conditions. For example, in NEDC cycle and in the absence of additional heating systems, operating temperature range for transmission is 20-40°C, for manual transmissions, and up to 60^{o}C for other types.

Table 2. Global efficiency of transmission and the efficiency of engine operating point

Testing cycle	Transmission	η_t [%]	η_{eo} [%]
Highway	DCT (6 gears, wet clutches)	95,4	81,2
LA4		95,5	85,8
Highway	AT (6 gears)	93,1	86,9
LA4		92,3	87,7
Highway	CVT	88,4	90,2
LA4		89,6	93,2

8. STOP AND GO

Losses in engine idling varies depending on the test cycle, between 4-18%. However fuel economy for automatic stopping of the engine is far from these limits. This is explained by conditions to stop the engine (minimum ambient temperature, minimum temperature of the engine, the need for air conditioning compressor operation, etc.) and by energy needed for engine start (e.g. for a car, just stops longer than 5s are efficient), [12]. For a passenger car, the induced fuel economy is 3.5% at driving in NEDC cycle [12]which represents only 37% of idling losses (9.4% in NEDC cycle as [1]). In case of medium and full HEV, the economy reaches a value of 5-7% by increasing the stopping period (due to purely electrical starts) [14].

9. REDUCTION OF DRIVING RESISTANCES

The analyze of the major components of driving resistances, show us that the improvement of the energy consumption can be achieved by reducing vehicle mass, rolling resistance coefficient, drag coefficient and the maximum cross section of the car. Detailed analysis is presented in [1] [3] [4] and [16]. Using data from [4] for medium and small car classes, following reductions of fuel consumption in cycle MVEG-A was obtained:

- 6% for each decrease of rolling resistance by 20%;

- 6 - 6.5% respectively for a decrease in drag coefficient by 20%;

- 8% for each decrease of vehicle weight by 15% (also, increased performance and acceleration are obtained).

These measures are essential for all types of vehicles but their effectiveness is enhanced when using hybrid electric systems, by increasing energy recovery.

10. GLOBAL FUEL ECONOMY FOR HYBRID VEHICLES

Currently, the most advanced hybrid propulsion systems are the electrical type. Generally hybrid electric vehicles (HEV) can be divided according to installed power, additional features and storage capacity in electricity and fuel economy in four categories (Table 3), [6] [10] [13]: micro, medium, full and „plug-in” hybrid. To make a clear distinction between these categories may be used the hybrid factor, H, which is calculated according to engine power and the electric motor power, [6].

Table 3. Classification of Hybrid Electric Powertrains

		Type			
		micro	**medium**	**full**	**„plug-in”**
Available Functions	Electric Auxiliary Systems	X	X	X	X
	Start/Stop	X	X	X	X
	ICE Assistance (Boosting)		X	X	X
	Braking Energy Recovery		X	X	X
	Electric Driving			X	X
	High Electric Driving Range				X
Improvement of global fuel consumption*		5 - 7%	12 - 18%	20 - 25%	n.a.
Hybrid Factor, $H=P_e/(P_e+P_{ICE})*100$		ca. 5%	ca. 10%	ca. 25%	
Electric Power (for cars)		**4 - 6 kW**	**10 - 15 kW**	**30 - 50 kW**	
Complexity / additional costs*		+	+ +	+ + + +	

*Comparing with a conventional powertrain

It is visible that the fuel economy starts from minimum 5%, for a micro hybrid, and reach the level of 25%, for a full hybrid.

Further reductions can be achieved by using a forward-looking operating strategy. This strategy uses data about the vehicle environment and the followed route (actual position, road profile for the approaching stretch, relative speed and the distance to the preceding vehicle, general information about the traffic status) in order to optimize the energy flows in the vehicle. For a sub-compact class strong hybrid, supplementary fuel savings up to 3 to 5 % were achieved, [5].

Comparison of a diesel hybrid technology options for different vehicle usage patterns is shown in Figure 3, [20]. It can be seen that the actual vehicle driving cycle is highly influential on the fuel economy. For micro and mild SI or diesel hybrids the fuel economy benefits are high for congested city driving (due to many starts and stops) and in intra-urban driving (due to significant decelerations). However, in highway oriented application were the vehicle does not stop frequently, only the strong SI hybrids exhibits a clear efficiency advantages over the conventional powertrain.

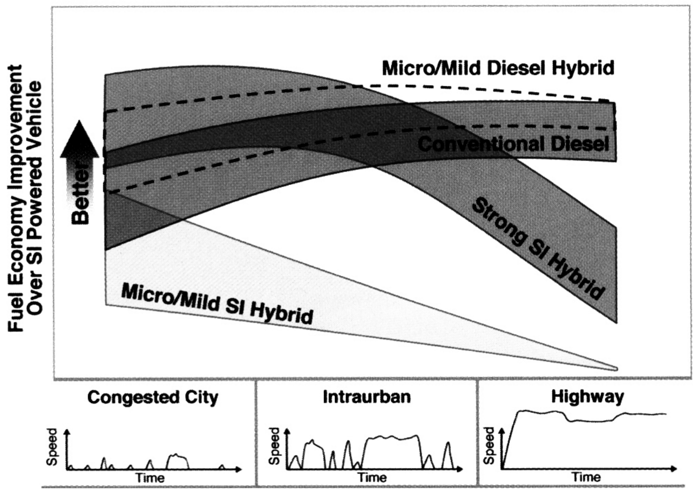

Figure 3. Comparison of diesel and hybrid technology options for different vehicle usage patterns

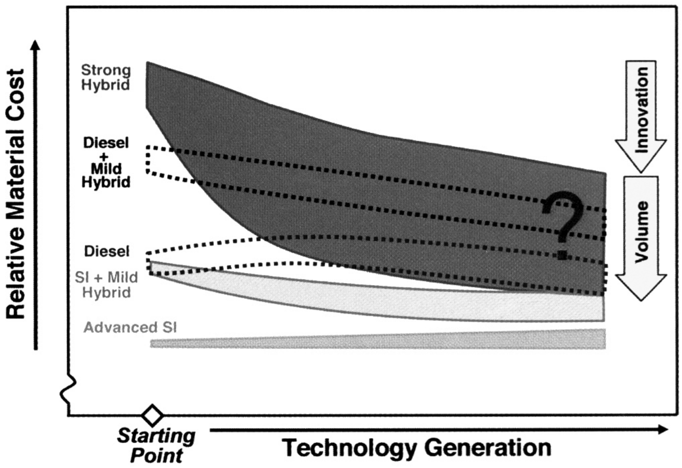

Figure 4. Long term cost and uncertainty trends for diesel and hybrid technologies

Accurate cost comparison between these technologies is problematic given their different maturity and volume of production. Such a comparison is presented in Figure 4, [20]. It can be seen that, for hybrid technologies, the cost are expected to fall as they mature and move to high volume. By comparison the more mature diesel engine technology is expected to fall in cost more slowly.

11. GLOBAL EFFICIENCY OF ENERGY CONVERSION

To compare the efficiency of various propulsion systems it must be compared the overall efficiency of energy conversion from primary sources (drilling wells) to the end user (wheel) ("well-to-wheel"). It is necessary to be considered at least three stages for a detailed analysis of energy conversion for a car. Starting from a primary energy source (fossil fuels, solar, nuclear etc.), in a first step, it is converted into a suitable form to be stored in vehicle (gasoline, hydrogen, bio-fuel, etc.) - conversion "well-to-tank". Following transformation into mechanical energy, part of this can be stored in the vehicle as kinetic or potential energy, in the flow „tank-to-vehicle". The third phase transformation ("vehicle-to-wheel") is determined by vehicle parameters and rules of motion and consists in conversion of mechanical energy into heat and its dissipation into the environment.

Such analysis is useful in determining the effects (e.g. on environment) that can play various technologies used in the energy chain. Table 4presents global CO_2 emissions, according to [8], for a middle-class car with three conventional propulsion systems that use different fuels: gasoline, diesel and compressed natural gas (CNG). For a proper environmental impact analysis is needed to consider also other influences. For example, to study the greenhouse effect, the methane losses from infrastructure must be quantified, being known that methane has a higher impact factor (21 times greater than CO_2 [2]).

Table 4. Global emission of CO_2 for conventional powertrains

Fuel	Petrol		Natural Gases
CO_2 Emission	25 kg /100km	21 kg /100km	20 kg /100km
Transformation Efficiency	Refinery, transportation		
	86 %	**90 %**	**86 %**
	Engine / Transmission		
	SI (gasoline)	Diesel	SI (CNG)
	17 %	**20 %**	**16 %**
	Vehicle (*m=1600 kg; C_d*A_f=0,86 m²; f=0,013*)		
Energy consumption for MVEG-95 cycle	50 MJ / 100km		

Table 5 shows the global CO_2 emission for a car with three middle-class hybrid propulsion systems, with different fuels and degrees of hybridization. Calculations have been performed using the data from [8], and results of fuel economy values achieved by Stop&Go, shifting the operating point for higher efficiency and braking energy recovery are obtained by simulations, [17].

Table 5. Global emission of CO_2 for Hybrid-Electric powertrains

Fuel	Petrol			
CO_2 Emission	21 kg/100km			21 kg/100km
Transformation Efficiency	Refinery, Transportation			
	86 %			**90 %**
	Engine / Transmission			
	SI engine (gasoline) micro	SI engine (gasoline) medium	SI engine (gasoline) total	Diesel medium
	20 %	**20 %**		**16 %**
	Vehicle (*m=1600 kg; C_d*A_f=0,86 m²; f=0,013*)			
Energy Recovery	0 MJ/100km			
Energy consumption for MVEG-95 cycle	50 MJ / 100km			

Table 6. Global emission of CO_2 for Electric Powertrains with Batteries

Fuel	Coal	Natural Gases	Solar / Nuclear
CO_2 Emission	29 kg/100km	8 kg/100km	0 kg/100km
Transformation Efficiency	Transportation		
	80 %	91 %	
	Electric power plant		
	Steam turbines PP	Combined cycle PP	. . .
	35 %	55 %	23 – 32 %
	Grid		
	94 %		
	Battery		
	80 %		
	Electric Motor		
	90 %		
	Vehicle (*m=1600 kg; C_d*A_f=0,86 m^2; f=0,013*)		
Energy consumption for MVEG-95 cycle	50 MJ / 100km		

Table 7. Global emission of CO_2 for Electric Powertrains with Fuel Cell

Fuel	Petrol	Natural Gases	
CO_2 Emission	18 kg/100km	12 kg/100km	21 kg/100km
Transformation Efficiency	Refinery, transportation		
	86 %	91 %	
			Combined cycle PP
			55 %
		Steam Reformer	Electrolysis
		74 %	76 %
	On-Board Reformer	H_2 Compression	
	65 %	94 %	
	Fuel Cell		
	40 %		
	Electric Motor		
	90 %		
	Vehicle (*m=1600 kg; C_d*A_f=0,86 m^2; f=0,013*)		
Energy consumption for MVEG-95 cycle	50 MJ / 100km		

Table 6 presents the global CO_2 emissions for an electric vehicle with batteries when using different primary sources of energy, [8].

Table 7 presents the global CO_2 emissions for a fuel cell electric car using different primary sources of energy and different technologies for producing the hydrogen.

12. CONCLUSIONS

Micro and mild hybridization for SI and Diesel powertrains is a promising technology for CO_2 emissions reduction, especially for applications with frequently stop and starts and significant decelerations. Strong hybrid SI powertrains also demonstrate a great potential but is penalized by the high cost.

The fuel cell powertrains shows an important CO_2 reduction potential but is not expected to count in the next decade due to the technological difficulties and prohibitive cost.

Battery electric vehicles can have a big impact on CO_2 global emissions and city air pollution but their expansion is still limited by their reduce autonomy.

In the last years, the gap between hybrids and electric vehicles is closing by new application such as plug-in hybrids and range extended electric vehicles in order to use the best of these technologies.

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