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Well-to-wheels Analysis of Future Automotive Fuels and Powertrains in the European Context

Tank-to-Wheels Report
Version 3c, July 2011

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WELL-TO-WHEELS ANALYSIS OF FUTURE AUTOMOTIVE FUELS AND POWERTRAINS IN THE EUROPEAN CONTEXT

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EUROPEAN COMMISSION
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Notes on version number:

This is the third version of this report replacing version 2c published in March 2007. The main changes and additions to the second version cover:

- Re-evaluation of 2010+ Diesel vehicle configurations (*section 5*)

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1 Introduction

This part of the study describes the final use of a fuel and the various powertrain options available. The issues related to fuel production and provision, are covered in the Well-to-Tank report. The Well-to-Wheels report provides the integrated view of the relative merits of the wide range of options studied.

The main issues addressed in this Tank-to-Wheels section are the fuel economy, the greenhouse gas (GHG) emissions and an evaluation of credible retail price for near and longer term technologies in Europe. The ADVISOR model[1] was used to simulate a virtual but credible and coherent, compact sized European sedan. The input fuel and technology data were checked and agreed by the EUCAR members. This model vehicle is used as a tool for comparing the various fuels and associated technologies; it is not deemed representative of the European fleet. This study makes no assumptions about the availability or market share of the technology options proposed for 2010 and beyond (2010+).

This version 3 of the Tank-to-Wheels report updates the previous one with regard to the following issues:

- Re-evaluation of 2010+ Diesel vehicle con figurations (*section 5*).

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[1] A vehicle simulation tool developed by NREL as open source. Now commercially available through AVL.

2 Fuels / Powertrain configurations

2.1 Fuel properties and vehicle characteristics

The key properties of the fuels considered are shown in ***Table 2.1*** (see also *WTT report*). For the 2010+ projections, gasoline and diesel fuel are assumed to comply with currently legislated specifications at that date, in particular with a maximum sulphur content of 10 mg/kg.

Table 2.1 Main properties of fuels

Fuel		Density	LHV	Carbon	CO_2 emissions	
		kg/m^3	MJ/kg	%m	kg/kg	g/MJ
Gasoline	2002	750	42.9	87.0%	3.19	74.35
	2010	745	43.2	86.5%	3.17	73.38
Ethanol		794	26.8	52.2%	1.91	71.38
Gasoline/Ethanol	2002	752	42.1	85.2%	3.12	74.25
blend 95/5	2010	747	42.3	84.6%	3.10	73.31
MTBE(1)		745	35.1	68.2%	2.50	71.23
ETBE(1)		750	36.3	70.6%	2.59	71.40
LPG(2)		550	46.0	82.5%	3.02	65.68
CNG/CBG(3)			45.1	69.2%	2.54	56.24
Diesel	2002	835	43.0	86.2%	3.16	73.54
	2010	832	43.1	86.1%	3.16	73.25
Bio-diesel(4)		890	36.8	76.5%	2.81	76.23
Diesel/bio-diesel	2002	838	42.7	85.7%	3.14	73.66
blend 95/5	2010	835	42.8	85.6%	3.14	73.39
Synthetic diesel		780	44.0	85.0%	3.12	70.80
DME(5)		670	28.4	52.2%	1.91	67.36
Naphtha		720	43.7	84.9%	3.11	71.22
Methanol		793	19.9	37.5%	1.38	69.10
Hydrogen			120.1	0.0%	0.00	0.00

(1) Methyl (Ethyl) -Tertiary-Butyl Ether

(2) Liquified Petroleum Gas

(3) Compressed Natural Gas / Compressed Bio Gas

(4) Figures are for FAME (Fatty Acid Methyl Ester), more specifically RME (Rape seed Methyl Ester)

(5) Di-Methyl-Ether

Further in the report the term "CNG" is used to represent a methane-rich gas as indicated above, regardless of its origin (which is only an issue for the WTT evaluation). The same applies to "bio-diesel" which represents a generic vegetable oil ester.

2.2 Vehicle characteristics

All simulations are based on a common, “virtual” vehicle, representing a typical European compact size 5-seater sedan, comparable to e.g. a VW Golf or others in that class. The theoretical vehicle is used as a tool for comparing the various fuels and associated technologies. It is not claimed to be representative of the European fleet. The reference is a 2002 Port Injected Spark Ignition gasoline (PISI) powertrain.

Table 2.2 Characteristics of the 2002 gasoline PISI reference vehicle

Curb weight	kg	1181
Weight class	kg	1250
Drag coefficient	-	0.321
Vehicle front area	m²	2.1
Tyre radius	m²	0.309
Tyre inertia	kg.m²	0.7
Engine displacement	l	1.6
Engine inertia	kg.m²	0.125
Efficiency differential+gear		0.9
Transmission ratio of differential gear		4.25
Transmission ratio 1st to 5th gear		3.455/1.944/1.370/1.032/0.850

2.3 Vehicle minimum performance criteria

To guarantee a fair comparison, minimum "customer performance" criteria were set so as to ensure that each fuel-powertrain combination met the same customer expectations (except where this was technically impossible). Depending on the fuels under consideration, the powertrain technologies were adapted to match these criteria.

Table 2.3 Minimum vehicle performance criteria

		Target
Time lag for 0-50 km/h	s	*<4*
Time lag for 0-100 km/h	s	*<13*
Time lag for 80-120 km/h in 4th gear	s	*<13*
Gradeability at 1 km/h	%	*>30*
Top speed	km/h	*>180*
Acceleration	m/s^2	*>4.0*
Range(1)	km	*>600*

(1) Where applicable 20 km ZEV range

2.4 Fuel/powertrain configurations

The following combinations of fuels and powertrains were assessed. The entries in ***Table 2.4*** indicate the time horizons of the technology assessments. The 2002 baseline situation was simulated for conventional, available vehicles and fuels: gasoline port injection (PISI), gasoline direct injection (DISI) and diesel direct injection (DICI). For 2010 and beyond, viable technology options were considered without any assumptions regarding availability and market share.

Table 2.4 Simulated configurations

Powertrains	PISI	DISI	DICI	Hybrid PISI	Hybrid DISI	Hybrid DICI	FC	Hybrid FC	Ref. + hyb. FC
Fuels									
Gasoline	2002 2010+	2002 2010+		2010+	2010+				2010+
Diesel fuel			2002 2010+			2010+			2010+
LPG	2002 2010+								
CNG Bi-Fuel	2002 2010+								
CNG (dedicated)	2002 2010+			2010+					
Diesel/Bio-diesel blend 95/5			2002 2010+			2010+			
Gasoline/Ethanol blend 95/5	2002 2010+	2002 2010+			2010+				
Bio-diesel			2002 2010+			2002 2010+			
DME			2002 2010+			2010+			
Synthetic diesel fuel			2002 2010+			2010+			
Methanol									2010+
Naphtha									2010+
Compressed hydrogen	2010+			2010+			2010+	2010+	
Liquid hydrogen	2010+			2010+			2010+	2010+	

PISI: Port Injection Spark Ignition

DISI: Direct Injection Spark Ignition

DICI: Direct Injection Compression Ignition

FC: Fuel cell

Hybrid FC: Fuel cell with large battery

3 Powertrain simulation

The open source vehicle simulation tool ADVISOR, developed by NREL, was used for all powertrains. The validity of this tool was checked against the in-house simulation codes of a number of European manufacturers and found to deliver analogous results.

The simulation tool was adapted to specific technologies by using detailed ”fuel efficiency” maps. For conventional internal combustion engines and fuel cells, European Manufacturers supplied the relevant "fuel efficiency" maps on a proprietary basis.

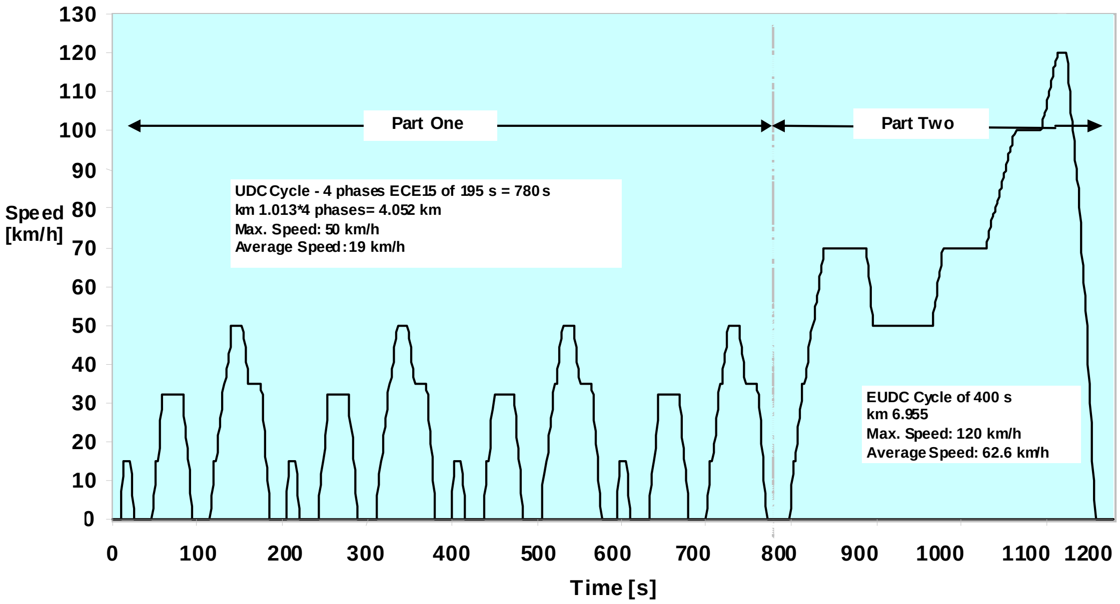
For gasoline direct injection, an adjusted map of the Mitsubishi 1.8 litre displacement engine was used.

For hybrids, the model existing in ADVISOR was adapted according to agreed strategies and constraints.

3.1 Test cycle, methodology

For each fuel/technology combination, the fuel consumption and the GHG emissions were simulated according to the standard European drive cycle, NEDC.

Figure 3.1 NEDC Cycle



To reflect accurately the “cold start” operation of the vehicle engine, the engine water temperature rise profile with time, and the evolution of the corresponding fuel efficiency figures, had to be implemented into ADVISOR. For the SI engine maps, this was done from experimental values. For Diesel (CI) engines, the equivalent sub-model was assumed and found in reasonable fit with the experience of the relevant experts.

For the simulated assessment of the various technologies the inertia class conditions were kept conform to the standard rules.

The figures were evaluated for each neat fuel separately (Gasoline, Diesel, CNG, LPG and hydrogen). For alternatives to gasoline (ethanol, MTBE/ETBE) and diesel (bio-diesel, synthetic diesel, DME) it was assumed that, whether used neat or in blends, the fuel consumption on energy basis would remain the same as for the base fuel. In other words these **alternatives fuels were deemed not to have any effect positive or negative on the energy efficiency of the engine**. The corresponding GHG emissions were then calculated from the compositional data (***Table 2.1***).

All fuel / vehicle combinations are meant to comply with the emissions standards in force at date i.e. EURO III in 2002 and EURO IV in 2010.

EURO III Diesel vehicles were assumed to be fitted only with an oxidation catalyst. EURO IV Diesel vehicles are considered to be equipped with a Diesel Particle Filter (DPF), with a fuel efficiency penalty resulting from the need for its periodic regeneration. A DPF system can be catalytic (C-DPF) or additive based (A-DPF). No distinction has been made here between the two systems although the A-DPF systems require somewhat less energy for the regeneration process. Hence, a general efficiency penalty was assigned to Diesel vehicles with DPFs of +2.5%[2]. An exception was made for DME DICI vehicles which, because of the favourable properties of that fuel, would not require a DPF to meet the EURO IV standard. An alternative option was also calculated for 2010+ Diesel vehicles without DPF, to represent a case where advanced combustion strategy concepts alone would be able to achieve the EURO IV emissions standard.

AUXILIARIES and fuel economy
The fuel consumption simulation and the crosscheck tests included electrical or mechanical load due to components inherent to the powertrain. Fuel penalty due to auxiliary devices was assessed in terms of total GHG emissions (g CO_{2eq} / km) for a typical additional load of 300 W.

For the performance tests, the following conditions applied:

- Vehicle mass: curb weight + 140 kg.
- Auxiliaries: Not powered
- Acceleration: time from 80 to 120 km/h in 4th gear to be less than 13 s; time from 80 to 120 km/h in top gear given for information only.
- Maximum acceleration: time from 0 to 50 km/h, 0 to 100, and 80 to 120 km/h: the original conventional ADVISOR model was used.
- Top speed is the result of an analytical calculation
- Gradeability (%): the vehicle speed is 1 km/h and the torque is maximum,
  e.g. 100 % gradeability represents a 45 ° angle slope (Analytical calculation).

3.2 Total GHG emission

Total GHG emissions were calculated. Methane (CH_4) and N_2O emissions were taken into account as CO_2 equivalent through their IPCC factor:

- For CH_4, the IPCC factor is 23. For gasoline, LPG, diesel fuel and DME, CH_4 emissions were considered to be 20 % of the applicable unburnt hydrocarbons limit. For the CNG engine, 80% of the unburnt hydrocarbon emissions were estimated to be CH_4.
- For N_2O, the IPCC factor is 296. For all configurations, N_2O emissions were considered to be 2% of the NOx emissions limit.

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[2] Reduced from 4% in version 1 of this study

Table 3.2 Impact of CH_4 and N_2O emission as CO_2 equivalent

All figures in g/km	Gasoline LPG	Diesel DME	CNG	Hydrogen
EURO III				
HC limit	0.20	0.06	0.20	
CH_4 emissions	0.04	0.012	0.16	
CO_2 equivalent	0.92	0.28	3.68	
NOx limit	0.15	0.5	0.15	
NO_2 emissions	0.003	0.010	0.003	
CO_2 equivalent	0.89	2.96	0.89	
EURO IV				
HC limit	0.10	0.05	0.10	
CH_4 emissions	0.02	0.01	0.08	
CO_2 equivalent	0.46	0.23	1.84	
NOx limit	0.08	0.25	0.08	0.08
NO_2 emissions	0.002	0.005	0.002	0.002
CO_2 equivalent	0.47	1.48	0.47	0.47

3.3 ADVISOR adaptation to NEDC and specific powertrains

In order to simulate the NEDC, a number of modifications were brought to ADVISOR. For conventional vehicles the modifications were:

- Gear ratio management: during the NEDC, the gear shift sequence is imposed as a function of time. In the original version of ADVISOR, it was not possible to run the vehicle at the same speed with two different gear ratios, as required under the NEDC (50 km/h has to be achieved in both 3rd and 4th gear).
- Fuel cut-off during vehicle deceleration.
- At idling, fuel consumption read from the data file.

Modifications to the energy management strategy were also required for hybrid and fuel cell vehicles.

3.4 Validation tests on the 2002 gasoline vehicle

Experimental data from Volkswagen for the Golf and the PISI 1.6 l engine were used to cross-check the simulation figures. Results were in close agreement: the simulated fuel consumption was 6.95 l/100 km, which is close to the measured result 7.0 l/100 km.

4 2002 configurations

4.1 Vehicles

All vehicles, except the CNG Bi-Fuel, complied with the performance criteria presented in ***section 2.3***. A larger engine displacement, and consequently vehicle mass, was necessary for the CNG vehicle to achieve the minimum performance criteria (see ***section 2.3***). Several iterations were necessary in ADVISOR to find the correct displacement allowing the dedicated CNG vehicle to achieve the specified acceleration criteria.

Table 4.1 Characteristics of 2002 ICE Euro III vehicles

		PISI				DISI	DICI
		Gasoline	LPG bi-fuel	CNG bi-fuel	CNG	Gasoline	Diesel/DME
Powertrain							
Displacement	l	1.6	1.6	1.6	1.9	1.6	1.9
Powertrain	kW	77	77/77	77/68	85	70	74
Engine mass	kg	120	120	120	150	120	145
Gearbox mass	kg	50	50	50	50	50	50
Storage System							
Tank pressure	MPa	0.1	1	25	25	0.1	0.1/1
Tank net capacity	kg	31.5	14/16.5	14/17.5	30	30	25/40
Tank mass empty	kg	15	12/12	12/61	103	15	15/30
Tank mass increase including 90% fuel	kg	0	8	59	87	0	0/28
Vehicle							
Reference mass	kg	1181	1181	1181	1181	1181	1248
Vehicle mass	kg	1181	1189	1240	1298	1181	1248/1276
Cycle test mass	kg	1250	1250	1360	1360	1250	1360
Performance mass	kg	1321	1329	1380	1438	1321	1388/1416

4.1.1 Gasoline

Both PISI and DISI configurations resulted in the same total mass.

4.1.2 Diesel

The Diesel version was powered by a 1.9 l turbo-charged engine (74 kW). The higher engine mass and corresponding structure reinforcements increased the total vehicle mass by about 70 kg compared to gasoline. We used the same vehicle characteristics for other potential liquid diesel fuels (bio- and synthetic diesel fuel) either neat or in blends with conventional diesel fuel.

DME needs a “LPG-type” steel tank. The excess mass of this 60 l tank was estimated at 28 kg (tank: 15, fuel: 13) as compared to the Diesel reference. The inertia class was kept at 1360 kg so that the fuel efficiency was unaffected.

4.1.3 Compressed Natural Gas (CNG)

2 options were considered for CNG vehicles:

Bi-Fuel adapted vehicle

An additional CNG injection system was fitted to the original gasoline 1.6 l engine, (as in the FIAT Multipla Bi Power). In order to respect the gasoline / gas range ratio of a typical CNG vehicle (57% CNG, 340 km / 43 % gasoline, 260 km), it was fitted with two fuel tanks: 18.7 l for gasoline and 121 l for CNG. The high pressure CNG vessel is made of composite and has a mass of 61 kg.

The gasoline operation must be preserved. As a result, due to the gaseous fuel volumetric occupancy the minimum acceleration criteria could not be met (***Table 4.1.4***). As the acceleration criteria could be met when operating on gasoline this was considered as an acceptable compromise.

Dedicated engine vehicle

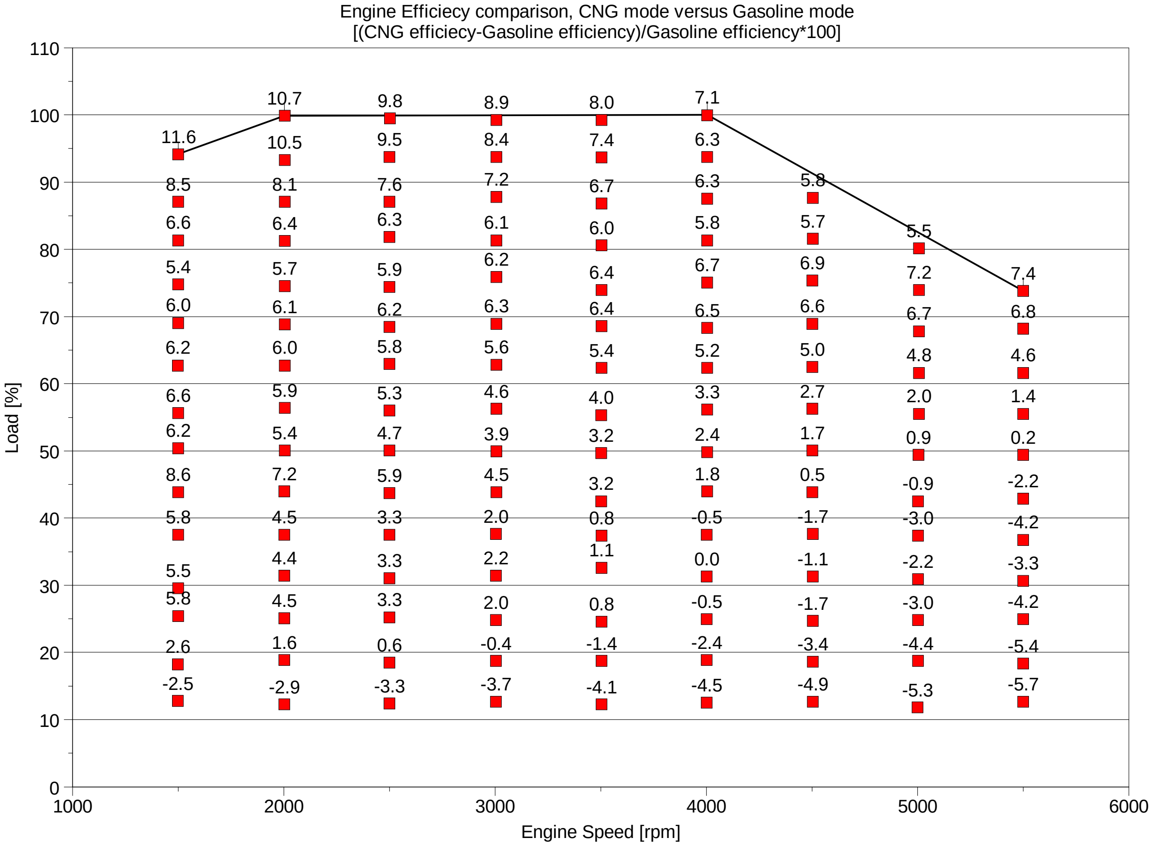
To compensate for the loss of torque due to the gaseous fuel and meet the performance criteria, the engine displacement was increased from 1.6 to 1.9 l, with a resulting 30 kg increase of engine mass (this was reduced from 2 l in version 1 of this study as a result of the more favourable engine map, see below). For a 600 km range, the amount of CNG required was calculated to be 30 kg and the high-pressure composite tank tare mass 103 kg. Subtracting the mass of the initial gasoline fuel system, the excess mass remained at 87 kg (***Table 4.1***).

With this “single fuel” engine, the compression ratio could be increased from 9.5:1 up to 12.5:1 to get the benefit from the higher “knock resistance” (octane number) of CNG.

Efficiency map of CNG vehicle

The original map used in version 1 of this study was replaced by a correction map (%) provided by EUCAR and presented in ***Figure 4.1.3***. This map reflects also the basic CNG trends (high knocking resistance under high load conditions, no need for full load enrichment, and lower combustion velocity at high rpm). New consumption maps (for both CNG Bi-Fuel and CNG dedicated) were derived from the gasoline PISI 2002 data. The maximum torque curve was also updated.

Figure 4.1.3 Efficiency difference between Gasoline and CNG



4.1.4 Liquefied Petroleum Gas (LPG)

A bi-fuel gasoline/LPG vehicle was considered. Energy consumption when running on LPG was considered to be the same as for gasoline. A LPG liquid injection was assumed. Hence, the maximum torque with LPG was the same as for the gasoline engine.

For an autonomy of 340 km on LPG (the same as for the CNG bi-fuel configuration), the vehicle needed 16.5 kg of LPG equivalent to 30 l. The composite LPG tank had specific mass of 0.4 kg/l of LPG i.e. an empty mass of 12 kg. The inertia class was, however, kept unchanged and so was the fuel efficiency.

Other characteristics of the vehicle were unchanged from the reference. In this configuration the bi-fuel LPG vehicle met all performance criteria (see ***Table 4.1.4***).

4.1.5 Conformance to performance criteria

With the adaptations described above, the closest available actual energy efficiency maps were implemented in the code. Consequently, all the vehicles (except the CNG bi-fuel as explained) were able to meet or exceed the performance criteria. Actual figures are summarised below.

Table 4.1.5 Performance of 2002 ICE vehicles

		Gasoline		LPG	CNG PISI		Diesel	*Target*
		PISI	DISI	PISI	Bi-fuel	Dedicated	DICI	
Time lag for 0-50 km/h	s	4.0	4.1	4.0	**4.5**	3.9	3.9	*<4*
Time lag for 0-100 km/h	s	11.7	12.9	11.7	**13.6**	11.8	11.5	*<13*
Time lag for 80-120 km/h in 4th gear	s	11.3	11.7	11.3	**13.8**	11.4	9.6	*<13*
Time lag for 80-120 km/h in 5th gear	s	15.1	15.8	15.1	18.6	15.1	12.4	-
Gradeability at 1 km/h	%	54	50	54	44	52	84	*>30*
Top speed	km/h	191	178	191	184	193	187	*>180*
Acceleration	m/s^2	4.3	4.2	4.3	**3.8**	4.4	4.8	*>4.0*

- Diesel fuel, DME, bio-diesel, synthetic diesel and diesel/bio-diesel blend configurations displayed the same performance as the diesel DICI configuration.
- The gasoline/ethanol blend configuration showed the same results as the gasoline configuration.
- The LPG bi-fuel configuration showed the same performance as the gasoline PISI.
- As expected the CNG bi-fuel configuration does not meet the acceleration and time lag criteria.

4.1.6 Energy and GHG Emissions (NEDC)

The fuel / energy consumption and GHG emissions results are presented for the NEDC.

The engine was started “cold” (20°C). The steady-state fuel over-consumption (in percentage by reference to hot operation) is only a function of the engine temperature. The rate of rise of the engine temperature and the resulting over-consumption over the cycle were validated with experimental data for the PISI gasoline reference configuration.

For the other configurations, such as DISI, the fuel over-consumption was calculated versus engine temperature with the same parameters. For the DISI configuration, the following assumptions were made:

- Below 50°C, the engine operates in “homogeneous” mode, at stoichiometric conditions (not “lean burn”),
- Above 50°C, in a range of low speed, low-to-mid load, the engine is under lean stratified conditions, with the typically lower fuel consumption of DI engines.

To account for the two different regimes on the DISI vehicle, a subsequent correction was applied. To comply with the “cold” stoichiometric conditions efficiency, the instantaneous fuel consumption was increased by 10% whenever the engine temperature was below 50°C and for the operating points appearing in the “lean burn stratified “zone of the relevant map.

The average fuel consumption and total GHG emissions over the NEDC for all the 2002 ICE configurations are shown in the tables and figures below.

Table 4.1.6-1 Average energy/fuel consumption and GHG emissions over the NEDC 2002 ICE vehicles

	Fuel consumption (/100 km)			GHG emissions (g CO_2 eq/km)				% change(2)	
	MJ	l(1)	kg	as CO_2	as CH_4	as N_2O	Total	Energy	GHG
PISI									
Gasoline 2002 (ref)	*223.5*	*6.95*	*5.21*	*166.2*	*0.9*	*0.9*	*168.0*	*Ref.*	*Ref.*
Ethanol (neat)	223.5	10.50	8.34	159.5	0.9	0.9	161.3	0%	-4%
(3) Gasoline/ ethanol 95/5	223.5	7.07	5.32	165.9	0.9	0.9	167.8	0%	0%
LPG bi-fuel	223.5	8.83	4.86	146.8	0.8	0.9	148.5	0%	-12%
CNG bi-fuel	226.9	7.05	5.03	127.6	3.7	0.9	132.2	2%	-21%
CNG dedicated	222.8	6.92	4.94	125.3	3.7	0.9	129.9	0%	-23%
DISI									
Gasoline	208.8	6.49	4.87	155.2	0.9	0.9	157.1	-7%	-7%
Ethanol (neat)	208.8	9.81	7.79	149.0	0.9	0.9	150.8	-7%	-10%
(3) Gasoline/ ethanol 95/5	208.8	6.60	4.97	155.0	0.9	0.9	156.8	-7%	-7%
DICI									
Diesel	183.1	5.10	4.26	134.6	0.3	3.0	137.9	-18%	-18%
Bio-diesel (neat)	183.1	5.59	4.98	139.6	0.3	3.0	142.8	-18%	-15%
(3) Diesel/Bio-diesel 95/5	183.1	5.12	4.29	134.9	0.3	3.0	138.1	-18%	-18%
DME	183.1	9.62	6.45	123.3	0.3	3.0	126.6	-18%	-25%
Synthetic diesel	183.1	5.34	4.16	129.6	0.3	3.0	132.9	-18%	-21%

(1) expressed in liters of equivalent gasoline for LPG and CNG

(2) from reference 2002 gasoline PISI

(3) blend figures were calculated assuming proportional contribution of each component

For each configuration except for gasoline PISI, an estimation of the variability of the energy consumption was made based on four main factors.

Table 4.1.6-2 Estimated energy consumption variability 2002 ICE vehicles

	Gasoline	Blend(1)		LPG	Diesel	Blend(2)	CNG PISI	
All figures in %	DISI	PISI	DISI	PISI	DICI	DICI	Bi-fuel	Dedicated
Overall (sum of variances)	-4/4	-1/1	-4/4	-2/2	-3/3	-3/3	-5/3	-6/3
Cold start	-4/4		-4/4		-3/3	-3/3	-5/2	-5/2
Blend effect		-1/1	-1/1			-1/1		
Torque / disp.								-3/0
Fuel consumption map				-2/2			-2/2	-2/2

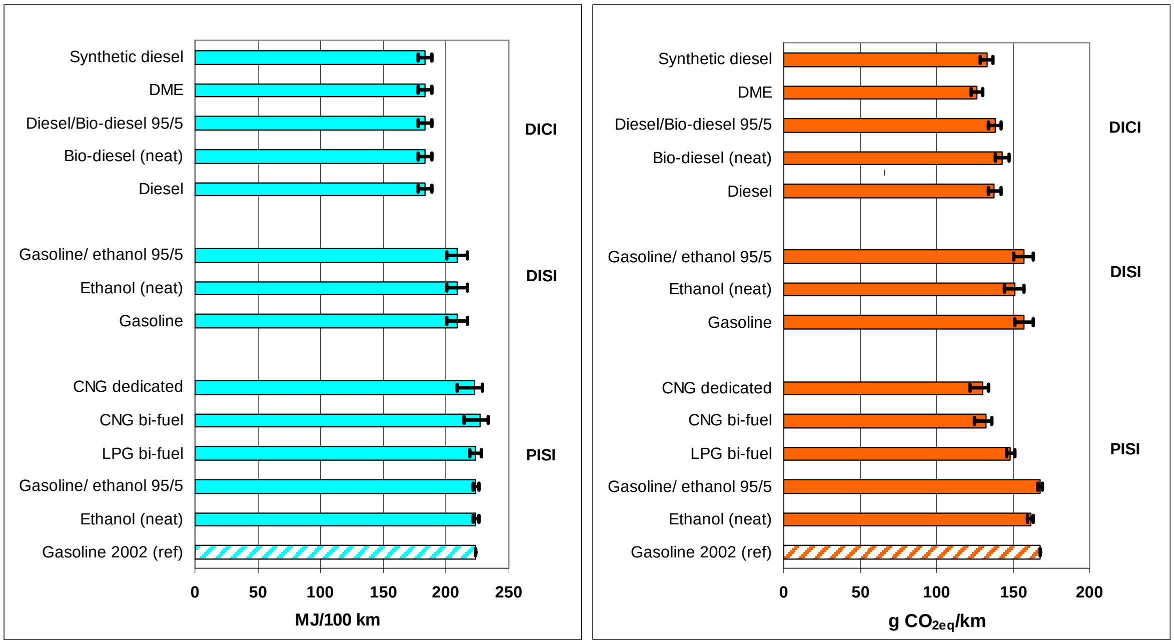
(1) Gasoline/Ethanol 95/5

(2) Diesel/Bio-diesel 95/5

Some of these figures can be accurately calculated while for others, the estimation was done on the basis of expert opinions.

- The most important uncertainty is on the cold start of direct injection engines (equation-based model, with parameters fitted on the gasoline PISI engine configuration).
- The uncertainty related to blended fuels stems from the fact that the energy impact of the vaporisation of the blended component is not perfectly known.
- For CNG fuel maps, the uncertainty stems from the creation of these maps from the gasoline PISI fuel map. Due to better air/gas mixture in cold condition, a reduced effect of cold start is expected in this case.
- For LPG, the uncertainty stems from the use of the standard PISI fuel map.

Figure 4.1.6a/b Average energy/fuel consumption and GHG emissions over the NEDC 2002 ICE vehicles



For the LPG bi-fuel vehicle, the same engine efficiency as gasoline was assumed. In spite of a slightly higher engine efficiency when running on CNG, The CNG bi-fuel vehicle energy consumption increased by approximately 2%, however, as a result of the additional mass of the high pressure tank (1380 kg for the CNG tank versus 1321 kg for the reference gasoline PISI vehicle tank). For the LPG vehicle the mass increase was small and did not justify a change in inertia class, resulting in the same energy efficiency as gasoline.

For the dedicated CNG vehicle the optimised compression ratio increases the engine efficiency. To recover the required acceleration potential, the engine displacement was raised from 1.6 to 1.9 l. As a result, over the Urban Driving Cycle (part of NEDC), the engine was operated at lower load, in a range of lower efficiency. Coincidently, the energy efficiencies obtained from both CNG engine configurations were similar, although the performance of the two vehicles was not equivalent: the bi-fuel CNG vehicle had slightly higher energy consumption than the gasoline reference (+1.5%) while the dedicated CNG vehicle showed a slightly lower figure (-0.3%).

The higher H/C ratio (4/1) of CNG played the major role, CO_2 emissions being about 24% lower than for the gasoline reference. This reduced to 22% after taking into account the contributions of methane and N_2O. This benefit remained discernible compared to the Diesel vehicle.

The "best in class" was obtained from DME with an adapted Diesel engine, with 126.8 g CO_{2eq}/km.

GHG emissions of the 2002 LPG configuration (148.5 g/km) have to be compared with the GHG emissions of the reference vehicle (168.0 g/km). The LPG configuration showed a GHG emissions saving of nearly 12% over the reference configuration due to lower carbon content of LPG compared with gasoline.

5 2010+ configurations

By 2010+ a diversification of fuels and powertrains is expected. In addition to the fuels and powertrains investigated for 2002 this study considered:

- Advanced internal combustion engines,
- Hybrid powertrains / vehicles,
- Fuel cell vehicles,
- Hydrogen as a new fuel, both for IC engines and fuel cells.

5.1 Fuels and Advanced Internal Combustion Engines

5.1.1 Projected improvements for advanced IC engines

The evolution of vehicle characteristics and the “technology-based” efficiency improvement assumed for 2010+ were widely discussed and agreed between the EUCAR members. These options were considered for their technical feasibility in 2010+. No consideration was given to actual implementation, availability, market share and customer acceptance. The expected fuel consumption reductions for the various technologies are presented below.

Table 5.1.1 2002-2010+ fuel efficiency improvements

Gasoline		LPG	Diesel		CNG	
PISI	DISI	PISI Bi-fuel	DICI no DPF(1)	DICI with DPF(1)	PISI	
					Bi-fuel	Dedicated
15%	10%	15%	12%	9.5%	17%	16%

For the vehicle-engine combinations using the SI engines, the main contribution to energy efficiency came from downsizing. The displacement of the gasoline engine could be reduced from 1.6 to 1.3 l, the full torque being restored by a turbo charging at 1.2:1.

This technology evolution had less scope for DISI engines as the “non-throttling” benefit is already included in the current engines.

Natural gas fuelled vehicles were credited with 1-2% extra energy efficiency improvement due to the mixing ability of the fuel with air, deemed to bring, after optimal aero kinetics, improved combustion essentially in the start-up phase.

2002 Diesel engines are already non-throttled and turbo-charged. Current developments showed a downsizing for Euro 4 Diesel applications, which were not anticipated at the initiation of the study. The “downsizing” route applied for 2010+ engines is from 1.9 to 1.6 l. If this trend will be continued in the future or maybe reversed due to tightened emission standards (Euro 5; Euro 6) can not be foreseen currently. The DPF option, when applied, does carry a fuel penalty of about 2.5% for the regeneration of the filter.

5.1.2 "Stop-and-Go" influence evaluation on fuel consumption

The "Stop-and-Go" fuel saving was evaluated with the gasoline PISI 2002 conventional configuration over the NEDC (with cold start). The fuel consumption when the vehicle is idling was calculated by post treatment of the results. Idling represented 7.5% of the total fuel consumption over the regulatory emission test cycle and could theoretically account for the maximum expected gain of the Stop-and-Go system.

Indeed, each time the engine restarts, no additional fuel consumption was taken into account. If the energy losses due to the engine restart was to be considered the fuel consumption gain due to the Stop-and-Go system would be lower. In addition, the thermal effect of this strategy was not taken into account either: the warm up of the engine would be slightly slower than with thermal engine idling and may influence the efficient treatment of pollutants under cold start conditions. These effects would decrease the fuel saving potential of the Stop-and-Go strategy. Therefore, taking into account some of the limitations mentioned above, the full theoretical potential of the Stop-and-Go could not be retained: a figure of 3% was considered more realistic and was applied on all 2010+ ICE configurations.

5.1.3 Hydrogen ICE Vehicle

The hydrogen engine considered for 2010+ was of newborn, advanced technology. It was a 1.3 l downsized turbocharged engine. Whatever the on-board storage mode (liquid or compressed), the same engine energy efficiency map was used for the simulation. The engine map was derived from experimental test bench data obtained from an actual single cylinder engine powered on hydrogen.

For stoichiometric air-fuel mixture, the volumetric energy content of a cylinder is slightly lower with hydrogen (3.17 kJ/l) than for gasoline (3.83 kJ/l). However, the poor octane number of hydrogen imposes operation of the engine in lean-burn mode. As a result, a torque curve equivalent to that of gasoline (1.3 litre, turbo-charged at 1.2:1) could be obtained through a higher turbo charging rate (about 1.8:1) in lean-burn mode (R = 0.8).

For compressed hydrogen (C-H_2) and a given fuel content the tank mass was nearly independent of the storage pressure. The shift from two 35 MPa tanks to a single 70 MPa tank was compensated by the increase in wall thickness.

For a range of 600 km, 9 kg hydrogen was needed. For a payload of 9 kg compressed hydrogen (C-H_2), the mass of the tank was 120 kg, an extra mass of 85 kg compared to the gasoline reference.

For liquid hydrogen (L-H_2) the tank was expected to be lighter than for compressed hydrogen (12.1 versus 13.1 kg / kg hydrogen).

Table 5.1.3 Characteristics of 2010 hydrogen ICE vehicles

		PISI	
		C-H_2	L-H_2
Powertrain			
Displacement	l	1.3	1.3
Powertrain	kW	77	77
Engine mass	kg	120	120
Gearbox mass	kg	50	50
Storage System			
Tank pressure	MPa	35/70	Atmo.
Tank net capacity	kg	9	9
Tank mass empty	kg	120	109
Tank mass increase including 90% fuel	kg	85	74
Vehicle			
Reference mass	kg	1181	1181
Vehicle mass	kg	1266	1255
Cycle test mass	kg	1360	1360
Performance mass	kg	1406	1395

5.1.4 ICE vehicles conformance to performance criteria

With the improvement described above, all vehicles (except the CNG bi-fuel, as explained), were able to meet or exceed the performance criteria. Actual figures are summarised hereunder.

Table 5.1.4 Performance of 2010+ ICE vehicles

		Gasoline		LPG	CNG PISI		Diesel	Hydrogen	*Target*
		PISI	DISI	PISI	Bi-fuel	Dedicated	DICI		
Time lag for 0-50 km/h	s	3.9	4.1	3.9	**4.4**	3.9	3.8	3.9	*<4*
Time lag for 0-100 km/h	s	11.3	12.4	11.3	**13.2**	11.4	11.2	12.4	*<13*
Time lag for 80-120 km/h in 4th gear	s	10.8	11.2	10.8	**13.2**	11.0	9.2	12.6	*<13*
Time lag for 80-120 km/h in 5th gear	s	14.5	15.0	14.5	17.7	14.4	12.1	16.2	-
Gradeability at 1 km/h	%	56	52	56.0	45	54	88	46	*>30*
Top speed	km/h	193	180	193	186	196	190	193	*>180*
Acceleration	m/s^2	4.5	4.3	4.5	**3.9**	4.5	4.8	4.0	*>4.0*

- The LPG bi-fuel PISI configuration delivered the same performance as the conventional gasoline.
- The CNG bi-fuel configuration remained *"off limits"* for the acceleration time: this was accepted as a specificity of this configuration.

5.1.5 Energy and GHG Emissions (NEDC)

The average fuel consumption and total GHG emissions over the NEDC are shown in the tables and figures below.

Table 5.1.5-1 Average energy/fuel consumption and GHG emissions over the NEDC 2010+ ICE vehicles

	Fuel consumption (/100 km)			GHG emissions (g CO_2 eq/km)				% change(2)	
	MJ	l(1)	kg	as CO_2	as CH_4	as N_2O	Total	Energy	GHG
PISI									
Gasoline	190.0	5.90	4.40	139.4	0.5	0.5	140.3	-15%	-16%
Ethanol (neat)	190.0	8.93	7.09	135.6	0.9	0.9	137.4	-15%	-18%
(3) Gasoline/ ethanol 95/5	190.0	6.00	4.49	139.3	0.5	0.5	140.2	-15%	-17%
LPG bi-fuel	190.0	7.50	4.13	124.8	0.5	0.5	125.7	-15%	-25%
CNG bi-fuel	188.3	5.85	4.18	105.9	1.8	0.5	108.2	-16%	-36%
CNG dedicated	187.2	5.82	4.15	105.3	1.8	0.5	107.6	-16%	-36%
Hydrogen (comp.)	167.5	5.21	1.40	0.0	0.0	0.5	0.5	-25%	-100%
Hydrogen (liq.)	167.5	5.21	1.40	0.0	0.0	0.5	0.5	-25%	-100%
DISI									
Gasoline	187.9	5.84	4.35	137.9	0.5	0.5	138.8	-16%	-17%
Ethanol (neat)	187.9	8.83	7.01	134.1	0.9	0.9	135.9	-16%	-19%
(3) Gasoline/ ethanol 95/5	187.9	5.94	4.44	137.8	0.5	0.5	138.7	-16%	-17%
DICI									
Without DPF									
Diesel	161.1	4.49	3.74	118.0	0.2	1.5	119.7	-28%	-29%
Bio-diesel (neat)	161.1	4.92	4.38	122.8	0.2	1.5	124.5	-28%	-26%
(3) Diesel/Bio-diesel 95/5	161.1	4.51	3.78	118.7	0.2	1.5	120.4	-28%	-28%
DME	161.1	8.47	5.67	108.5	0.2	1.5	110.2	-28%	-34%
Synthetic diesel	161.1	4.69	3.66	114.1	0.2	1.5	115.8	-28%	-31%
With DPF									
Diesel	165.7	4.62	3.84	121.4	0.2	1.5	123.1	-26%	-27%
Bio-diesel (neat)	165.7	5.06	4.50	126.3	0.2	1.5	128.0	-26%	-24%
(3) Diesel/Bio-diesel 95/5	165.7	4.64	3.88	122.1	0.2	1.5	123.8	-26%	-26%
Synthetic diesel	165.7	4.83	3.77	117.3	0.2	1.5	119.0	-26%	-29%

(1) expressed in liters of equivalent gasoline for LPG, CNG and hydrogen

(2) from reference 2002 gasoline PISI

(3) blend figures were calculated assuming proportional contribution of each component

The energy efficiency improvement (2010+ versus 2002) was a little less for CI Diesel engines than for their SI gasoline and CNG or LPG counterparts (see *section 5.1.1*). As a result, the advantage of the Diesel over the SI counterparts was slightly eroded from the current (2002) by 2010+.

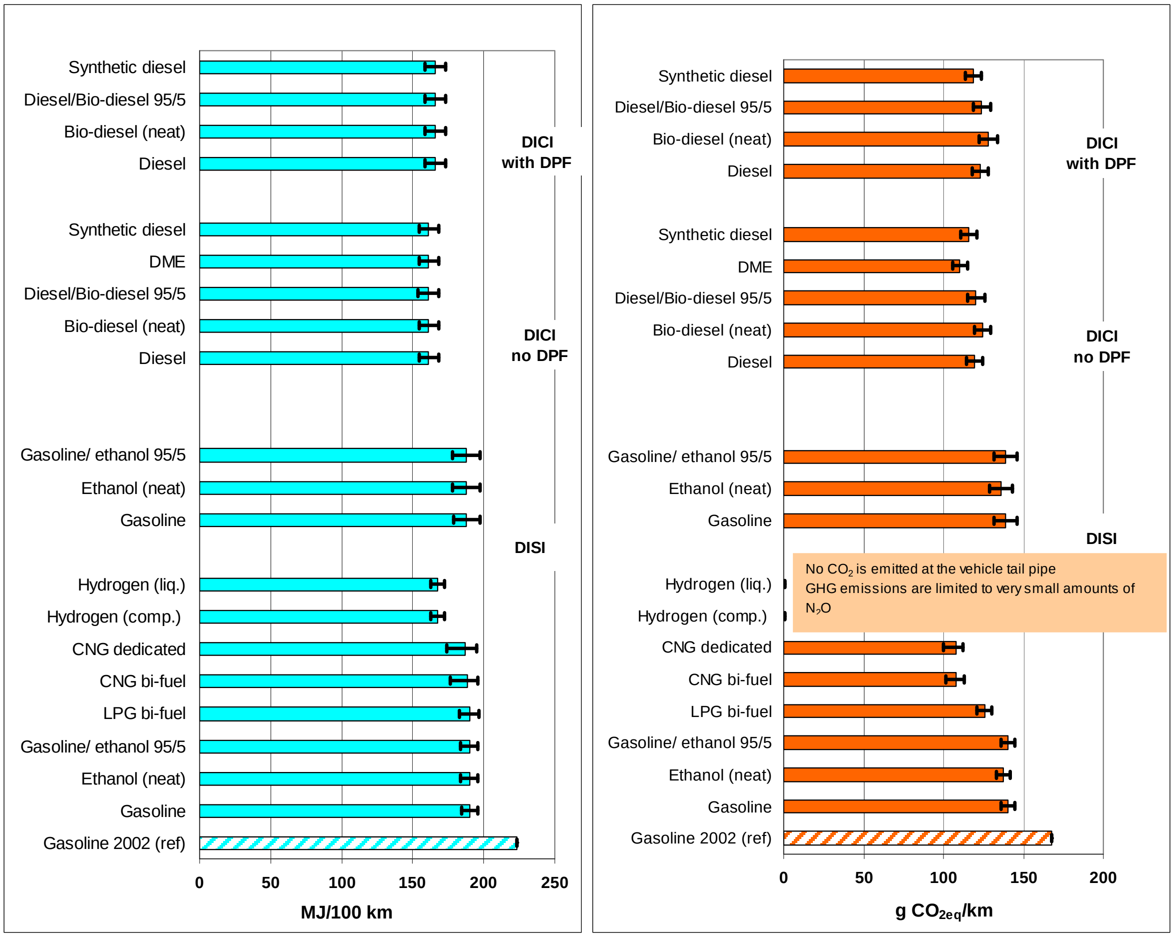
For each configuration, an estimation of the variabilty of the energy consumption is shown in the table below. The sources of uncertainty are the same as for the 2002 configurations (see ***Table 4.1.6-2***) with additional uncertainty stemming from the forecasts of expectable improvements by 2010+.

Table 5.1.5-2 Estimated energy consumption variability 2010+ ICE vehicles

	Gasoline		Blend[(1)]		LPG[(2)]	Diesel	Blend[(3)]	CNG PISI		Hyd.[(4)]
All figures in %	PISI	DISI	PISI	DISI	PISI	DICI	DICI	Bi-fuel	Dedicated	PISI
Overall (sum of variances)	-3/3	-5/5	-3/3	-5/5	-4/4	-4/4	-4/4	-6/4	-7/4	-3/3
Improvement from 2002	-3/3	-3/3	-3/3	-3/3	-3/3	-3/3	-3/3	-3/3	-3/3	
Cold start		-4/4		-4/4		-3/3	-3/3	-5/2	-5/2	-3/3
Blend effect			-1/1	-1/1			-1/1			
Torque / disp.									-3/0	
Fuel consumption map					-2/2			-2/2	-2/2	

(1) Gasoline/Ethanol 95/5
(2) Liquid injection
(3) Diesel/Bio-diesel 95/5
(4) Compressed or liquid

Figure 5.1.5a/b Average energy/fuel consumption and GHG emissions over the NEDC 2010+ ICE vehicles

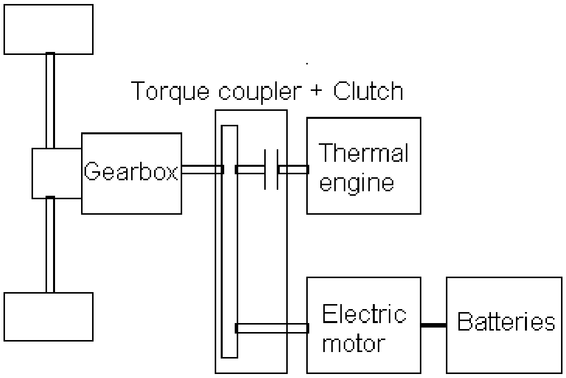


The lowest figures (<110 gCO_2/km) were obtained with the CNG ICEs on the gasoline side and with DME for the Diesel section, respectivley. Hydrogen vehicles obviously do not emit any CO_2 and their TTW GHG emissions were limited to very small amounts of N_2O.

5.2 Hybrid powertrains

In this study a parallel hybrid configuration was selected, combining two torque generators namely the IC engine and an electric motor with batteries.

Figure 5.2 Simulated hybrid configuration



5.2.1 Energy management strategy and code evolutions

The parallel hybrid model available in ADVISOR was modified to represent our vision of the most appropriate way to control such a powertrain.

The first modification was to use the same gear ratio sequence during the cycle as for conventional engines.

The second essential point was to consider the vehicle's driveability from a customer point of view, an issue which was not properly addressed by the original energy management strategy. For instance, the engine could be operated stop-run-stop or run-stop-run for very short periods, a mode of operation that is considered highly uncomfortable for usual drivers and, therefore, rejected by car manufacturers. During deceleration and when the vehicle is at a standstill, the thermal engine was turned off but the time sequence was never allowed to be shorter than 3 seconds.

To determine the working duration of the thermal engine, 4 parameters were used:

- The **State Of Charge (SOC) of the battery** had to remain between 60 and 70 % of the maximum charge.
- The **Recharge Mode (RM)** defined whether the battery was in charging phase. When the SOC decreased to 60%, RM was activated (=1) until the SOC increased back to 65%. Further charging through recuperation of braking energy was always applied.
- The **Minimum vehicle speed (V1)** is the speed below which the thermal engine is off while the recharge mode is not activated.
- The **Minimum vehicle speed (V2)** is the speed below which the thermal engine is off while the recharge mode is activated.

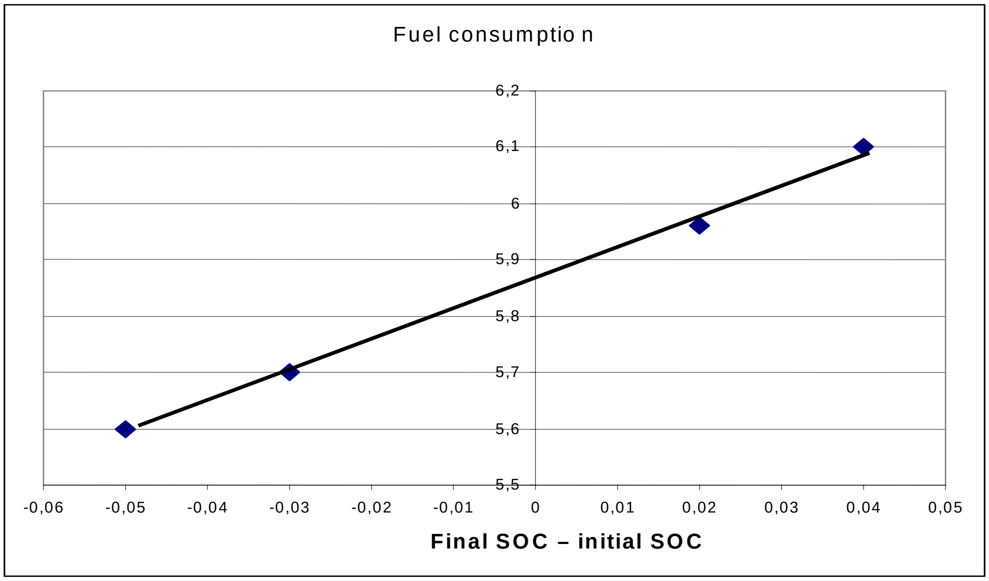
When the thermal engine charges the battery, the controller guaranteed optimum efficiency of the thermal engine while it is charging the battery.

In general, this energy management allowed the vehicle to drive the urban part of the NEDC mainly within the electrical mode. The thermal engine was activated according to the SOC and under the high load conditions of the EUDC part of the cycle (see also ***Figure 5.2.5-3***).

Methodology

The fuel consumption had to be evaluated at constant energy level in the battery i.e. the SOC has to be the same at the beginning and at the end of the cycle. In most cases this could be achieved by adjusting the initial SOC. When this was not possible we used an extrapolated or interpolated figure. An example is given in the figure below.

Figure 5.2.1 Interpolation of the fuel consumption versus the delta SOC



The optimisation of the fuel consumption on the NEDC was done with the V1 and V2 parameters defined above, using the correction of the powertrain efficiency map as per ***Figure 5.2.1*** as an iterative subroutine.

In its basic configuration, ADVISOR only calculates “hot start” cycle operation. To assess the “cold start” NEDC cycle consumption of a hybrid vehicle, the “cold start” sub-model was applied only to the thermal engine model, as was done for ICEs when assessing the 2002 and 2010 configurations (see *section 3.1*).

5.2.2 Hybrid vehicle characteristics

Thermal engine

In general the 2002 and 2010+ engine configurations were base for this calculation.

Gasoline: At the 2010 horizon, both Port Injection (PISI) and Direct Injection (DISI) engines will be on the market. Both configurations were therefore considered for hybridisation. Results are given for the standard engine as well as for the downsized configuration.

Hydrogen ICE: The 2010 version was used for lack of a 2002 version, but taking into account that the benefits of hybridisation and downsizing are not entirely additive.

CNG: Only the dedicated CNG ICE configuration was considered. The availability of the electric engine allows the acceleration criteria to be met with the ICE displacement of 1.6 l.

Therefore, basically friction improvements, as shown below in Table 5.2.2-1, are used with hybridisation.

Table 5.2.2-1 Efficiency improvements with hydridisation

Gasoline	Diesel		CNG
DISI	DICI no DPF(1)	DICI with DPF(1)	PISI
3%	3%	0.5%	4%

(1) Diesel Particulate Filter

Electric motor

The main characteristics of the electric motor (electronic inverter included) were:

- Power: 14 kW
- Mass: 10 kg
- Voltage: 42 V
- Maximum efficiency: 92 %

Battery

The 40 kg Lithium / ion battery (42 V) was designed to ensure the 20 km full ZEV range.

Table 5.2.2-2 Characteristics of 2010+ hybrid vehicles

		PISI	DISI	DICI	PISI				DICI
		Gasoline	Gasoline	Diesel	Gasoline	CNG	C-H_2	L-H_2	Diesel
Powertrain		non-downsized			downsized				
Displacement	l	1.6	1.6	1.9	1.3	1.6	1.3	1.3	1.6
Powertrain	kW	77	70	74	62	68	77	77	63
Engine mass	kg	120	120	145	100	120	120	120	130
Gearbox mass	kg	50	50	50	50	50	50	50	50
Storage System									
Tank pressure	MPa	liquid	liquid	liquid	liquid	25	35/70	liquid	liquid
Tank net capacity	kg	22	22	20	22	19	8	7	20
Tank mass empty	kg	15	15	15	15	66	100	85	15
Tank mass increase including 90% fuel	kg	0	0	0	0	40	63	48	0
Electric Parts									
Battery	kg	40	40	40	40	40	40	40	40
electric motor	kg	10	10	10	10	10	10	10	10
Torque coupler	kg	30	30	30	30	30	30	30	30
Vehicle									
Reference mass	kg	1181	1181	1248	1181	1181	1181	1181	1248
Vehicle mass	kg	1261	1261	1328	1241	1301	1324	1309	1313
Cycle test mass	kg	1360	1360	1470	1360	1360	1470	1360	1360
Performance mass	kg	1401	1401	1468	1381	1441	1464	1449	1453

5.2.3 Conformance to Performance criteria

For hybrid vehicle configurations, the specified minimum criteria were the same as for conventional engines / vehicles and were estimated in the same way. It is worth noting that:

- Top speed was achieved without electrical assistance[3] (continuous top speed),
- For acceleration, no peak power was taken into account for the electric motor[4].

---

[3] Top speed capability must be available at all times and for extended periods and cannot, therefore, rely on the battery.

[4] Acceleration capability is considered as a safety feature, in case of overtaking for instance. It may rely on a contribution of the electric motor as long as only its nominal power is considered. Using the higher “peak power”, which may be available but only for short periods, is not acceptable for safety reasons.

Table 5.2.3-1 Performance of 2010 hybrid vehicles

		Gasoline		CNG	Diesel	C-H_2	L-H_2	*Target*
		PISI	DISI	PISI	DICI	PISI		
Time lag for 0-50 km/h	s	3.7	3.7	3.7	3.7	3.4	3.4	*<4*
Time lag for 0-100 km/h	s	11.5	11.5	11.3	11.5	10.7	10.6	*<13*
Time lag for 80-120 km/h in 4th gear	s	10.8	10.8	10.4	10.8	9.8	9.7	*<13*
Time lag for 80-120 km/h in 5th gear	s	13.3	13.3	12.8	13.3	11.7	11.6	-
Gradeability at 1 km/h	%	77	77	72	77	68	69	*>30*
Top speed	km/h	180	178	183	180	192	192	*>180*
Acceleration	m/s^2	4.8	4.8	4.8	4.8	4.8	4.8	*>4.0*

The specificity of hybrids, combining the thermal engine with an electric complementary power, resides in the specific torque curve of the electric motor:

- Torque at maximal value with immediate rise time,
- Nominal value on a large range of rotation speed.

As a result, even with heavier masses, hybrids had a better acceleration performance in all configurations.

5.2.4 Energy and total GHG emissions (NEDC)

The average fuel consumption and total GHG emissions over the NEDC are shown in the tables and figures below.

Table 5.2.4-1 Average energy/fuel consumption and GHG emissions over the NEDC 2010 hybrid vehicles

	Fuel consumption (/100 km)			GHG emissions (g CO_2 eq/km)				% change(2)	
	MJ	l(1)	kg	as CO_2	as CH_4	as N_2O	Total	Energy	GHG
PISI									
Gasoline 1.6 l	161.7	5.02	3.74	118.6	0.5	0.5	119.6	-28%	-29%
Gasoline 1.28 l, 14 kW	152.9	4.75	3.54	112.2	0.5	0.5	113.1	-32%	-33%
Gasoline 1.28 l, 30 kW	150.8	4.69	3.49	110.7	0.5	0.5	111.6	-33%	-34%
CNG 1.6l	139.4	4.33	3.09	78.4	1.8	0.5	80.7	-38%	-52%
Hydrogen (comp.)	148.5	4.62	1.24	0.0	0.0	0.5	0.5	-34%	-100%
Hydrogen (liq.)	141.4	4.39	1.18	0.0	0.0	0.5	0.5	-37%	-100%
DISI									
Gasoline 1.6l	163.0	5.06	3.77	119.6	0.5	0.5	120.5	-27%	-28%
Gasoline 1.3l	154.1	4.79	3.57	113.1	0.5	0.5	114.0	-31%	-32%
(3) Gasoline/ ethanol 95/5	154.1	4.87	3.64	113.0	0.5	0.5	113.9	-31%	-32%
DICI									
Without DPF									
Diesel 1.9l	141.1	3.93	3.27	103.4	0.2	1.5	105.1	-37%	-37%
Diesel 1.6l	129.0	3.60	2.99	94.5	0.2	1.5	96.2	-42%	-43%
Bio-diesel (neat)	129.0	3.94	3.51	98.3	0.2	1.5	100.1	-42%	-40%
(3) Diesel/Bio-diesel 95/5	129.0	3.61	3.02	95.0	0.2	1.5	96.7	-42%	-42%
DME	129.0	6.78	4.54	86.9	0.2	1.5	88.6	-42%	-47%
Synthetic diesel	129.0	3.76	2.93	91.3	0.2	1.5	93.0	-42%	-45%
With DPF									
Diesel 1.9l	145.6	4.06	3.38	106.6	0.2	1.5	108.4	-35%	-35%
Diesel 1.6l	133.0	3.71	3.09	97.4	0.2	1.5	99.1	-40%	-41%
Bio-diesel (neat)	133.0	4.06	3.61	101.4	0.2	1.5	103.1	-40%	-39%
(3) Diesel/Bio-diesel 95/5	133.0	3.72	3.12	98.0	0.2	1.5	99.7	-40%	-41%
Synthetic diesel	133.0	3.88	3.02	94.2	0.2	1.5	95.9	-40%	-43%

(1) expressed in liters of equivalent gasoline for CNG and hydrogen

(2) from reference 2002 gasoline PISI

(3) blend figures were calculated assuming proportional contribution of each component

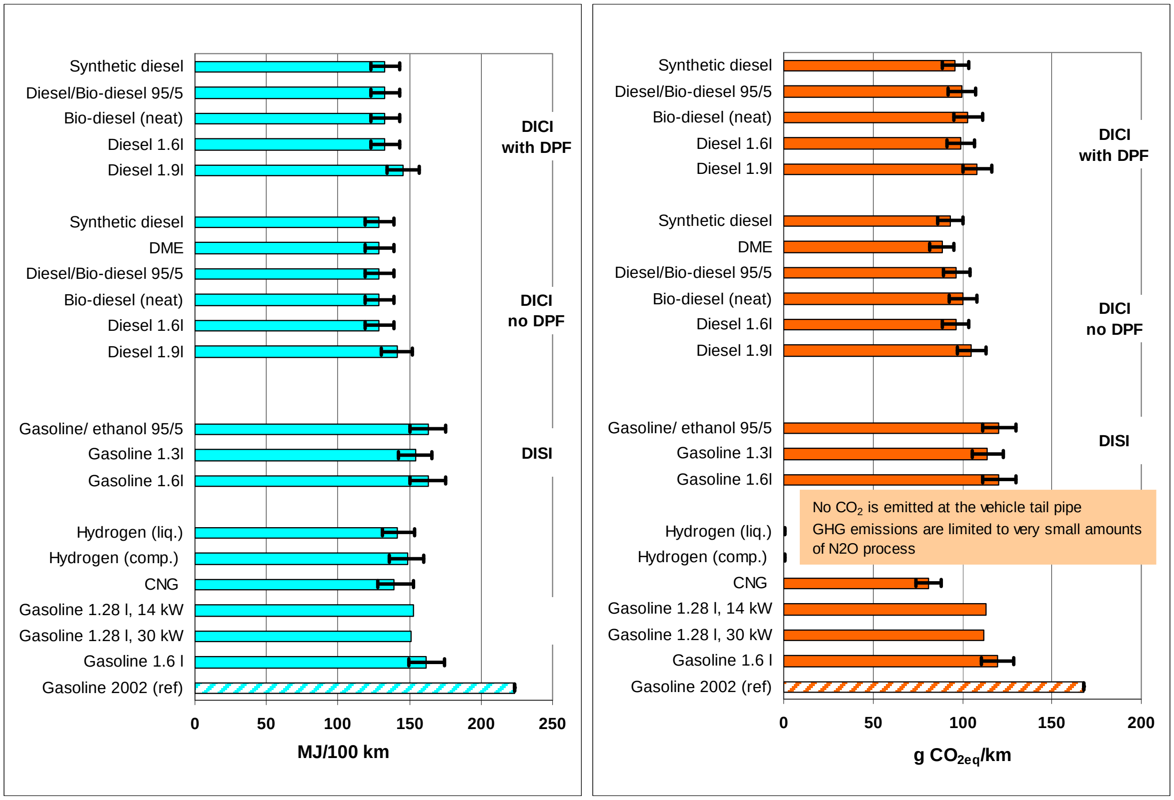
Table 5.2.4-2 Estimated energy efficiency variability
2010 hybrid vehicles

	Gasoline		Blend(1)	Diesel	Blend(2)	CNG	Hydrogen	
All figures in %	PISI	DISI	DISI	DICI	DICI	PISI	C-H2	L-H2
Overall (sum of variances)	-8/8	-8/8	-8/8	-8/8	-8/8	-8/9	-9/8	-8/9
Improvement from 2002	-1/1	-1/1	-1/1	-1/1	-1/1	-3/3		
Cold start	-7/7	-7/7	-7/7	-7/7	-7/7	-7/7	-7/7	-7/0
Blend effect			-1/1		-1/1			
Energy management	-3/3	-3/3	-3/3	-3/3	-3/3	-3/3	-3/3	-3/3
Fuel consumption map						-2/2		
Mass estimate						-0/4	--4/0	-0/4

(1) Gasoline/Ethanol 95/5
(2) Diesel/Bio-diesel 95/5

In addition to the effects listed for 2010, the energy management strategy was not optimised and the estimation of the masses, mainly for the configurations that are close to a change of the cycle test mass, may modify the consumption. Due to the strong hypothesis on the cold start calculation, values concerning the cold start were increased.

Figure 5.2.4a/b Average energy/fuel consumption and GHG emissions over the NEDC
2010 hybrid vehicles



The cumulated effect of continuous vehicle/powertrain improvements and of hybrid technology brought between 27 and 35 % energy efficiency improvement from the 2002 reference. As already seen with conventional engines in 2010, the gap between minimum and maximum energy consumptions was more modest for the hybrids than for the 2002 ICEs.

The hybrid architecture and downsizing / turbocharging (considered for the 2010 conventional configurations) are two routes that allow the thermal engine to be operated in a domain of better efficiency. The benefits are therefore not cumulative. The impact of both routes are summarised in the table below.

Table 5.2.4-3 Effects of hybridisation and other technology improvements

	Gasoline		Diesel	CNG	L-H_2
Energy figures in MJ/100 km	PISI	DISI	DICI+DPF	PISI	PISI
2002 conventional	223.5	208.8	183.1	222.8	
2010 advanced	190.0	187.9	165.7	187.2	167.5
2010 hybrid	166.6	167.9	150.0	145.0	
2010 advanced + hybrid	152.9	154.1	133.0	139.4	141.4
2002-2010 Conv. Improvement	15.0%	10.0%	9.5%	16.0%	
Hybridisation benefit 2010	25.5%	19.6%	18.1%	25.5%	15.6%
Total 2002-2010	31.6%	26.2%	27.4%	37.4%	

The net benefit of hybridisation was affected by several parameters:

- Hybridisation increased the vehicle test mass.
- Engine fuel efficiency was deemed to improve for all engines between 2002 and 2010 (approximately 3% for diesel fuel and gasoline, 4% for CNG and hydrogen).
- Hybridisation in general allows smaller engine displacements, the electric assistance restoring the acceleration performance with the smaller engine.
- The benefit of hybridisation was more modest for hydrogen engines, not because of hydrogen, but because the engine considered here was deemed to have already received the highest technical options in downsizing and supercharging.

5.2.5 Impact of the hybrid powertrain configurations

Within certain boundary conditions various hybrid vehicle configurations can be set up. The critical conditions for this study are the customer performance criteria. As seen in ***Table 5.2.3-1***, the above hybrid configurations exceeded some of the requirements, e.g. for accelerations. Hence, the current hybrid vehicle characteristics could be reconsidered with the objective of low fuel consumption but still fulfilling the performance requirements. Within this background, a limited set of simulations was carried out to optimize the PISI gasoline hybrid configuration towards low fuel consumption (ICE displacement / electric motor power).

Thermal Engine displacement

A set of simulations was performed to search for the minimum engine displacement but still keeping the vehicle top velocity of 180 km/h and also complying with the other performance criteria. The result was a reduction of the engine displacement to 1280 cc, with an engine power of 62 kW. With this new engine displacement, the vehicle mass was slightly lower (-20 kg), as shown in the table below.

Table 5.2.5-1 Characteristics of a optimized Gasoline PISI hybrid vehicle

		Gasoline hybrid PISI	
		Original	Optimised
Powertrain			
Displacement	l	1.6	1.28
Power	kW	77	62
Engine weight	kg	120	100
Gearbox weight	kg	50	50
Storage System (liquid hydrogen)			
Tank net capacity	kg	22	22
Tank mass empty	kg	15	15
Tank mass increase including 90% fuel	kg	0	0
Electric parts			
Battery mass	kg	40	40
Power electric motor	kg	10	10
Torque coupler + …	kg	30	30
Vehicle			
Total Vehicle			
Reference mass	kg	1181	1181
Vehicle mass	kg	1261	1241
Cycle test mass	kg	1360	1360
Performance mass	kg	1401	1381

For the performance tests, the vehicle mass of this optimised hybrid configuration was 1381 kg. The performance results as well as fuel consumption and CO_2 emissions in the next two tables.

Table 5.2.5-2 Performances of the optimized Gasoline PISI hybrid configuration

		Gasoline PISI	*Target*
Time lag for 0-50 km/h	s	3.7	*<4*
Time lag for 0-100 km/h	s	11.5	*<13*
Time lag for 80-120 km/h in 4th gear	s	10.8	*<13*
Time lag for 80-120 km/h in 5th gear	s	13.3	-
Gradeability at 1 km/h	%	77	*>30*
Top speed	km/h	180	*>180*
Acceleration	m/s^2	4.8	*>4.0*

Table 5.2.5-3 Energy/fuel consumption and GHG emissions over the cold NEDC

	Fuel consumption (/100 km)			GHG emissions (g CO_2 eq/km)			
	MJ	l$^{(1)}$	kg	as CO_2	as CH_4	as N_2O	Total
Gasoline 1.6 l	161.7	5.02	3.74	118.6	0.5	0.5	119.6
Gasoline 1.28 l	152.9	4.75	3.54	112.2	0.5	0.5	113.1

For these two configurations, the electric motor and the energy management strategy were the same. As shown on ***Figures 5.2.5-1/2*** the use of a smaller engine displacement decreased the fuel consumption by 5%, the smaller engine operating in a higher efficiency range. This can be seen even more explicitly on ***Figure 5.2.5-3***, which shows a comparison of the instantaneous engine efficiency during the NEDC.

It should be noted that the simulation was done with a hot start cycle. To obtain the final NEDC fuel consumption, a correction was applied as in the previous simulations.

Figure 5.2.5-1   1.6 l engine operating points during the NEDC

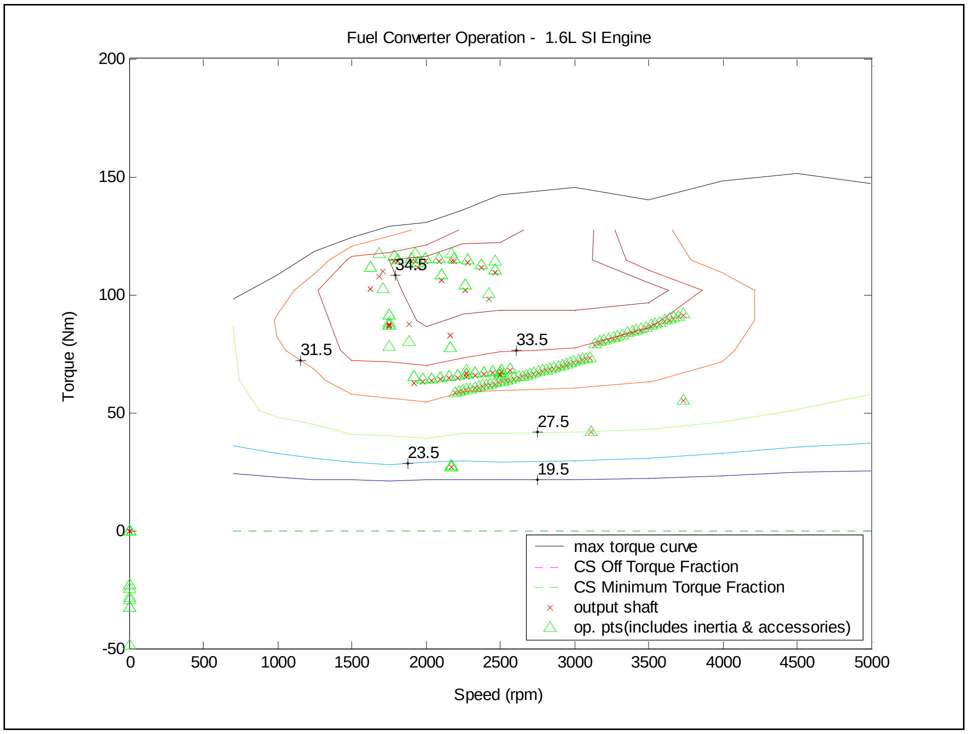


Figure 5.2.5-2   1.28 l engine operating points during the NEDC

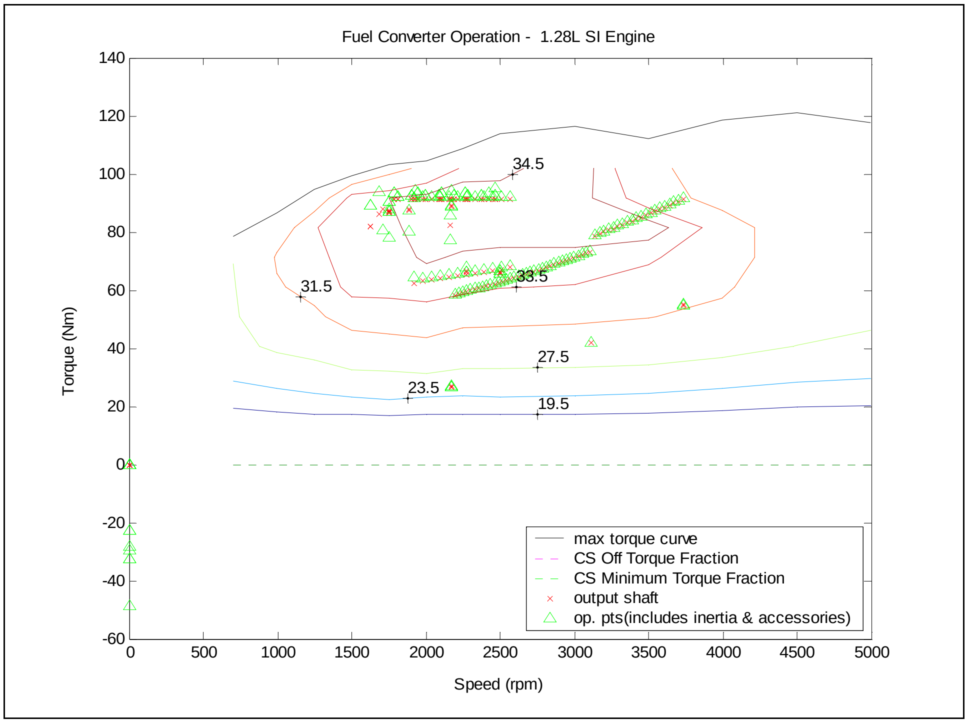
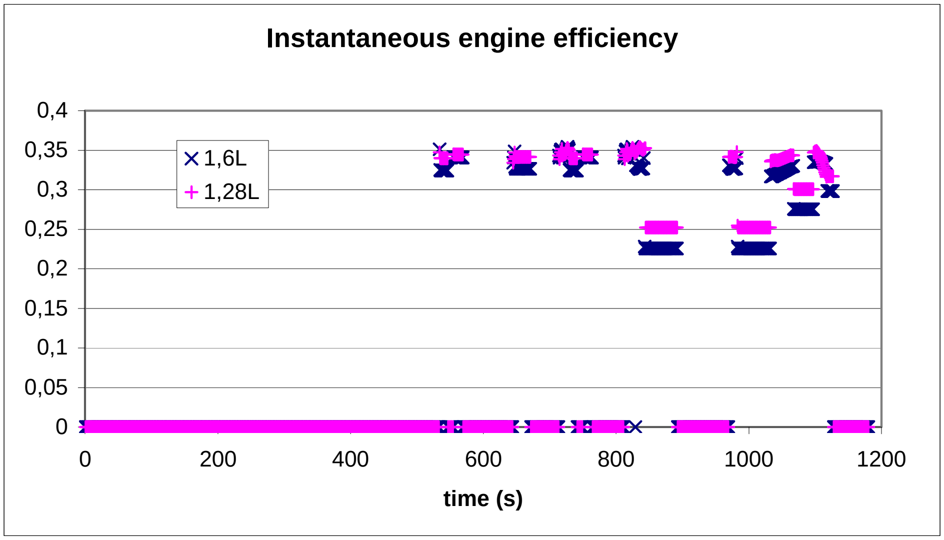


Figure 5.2.5-3 Comparison of the instantaneous engine efficiency on the NEDC

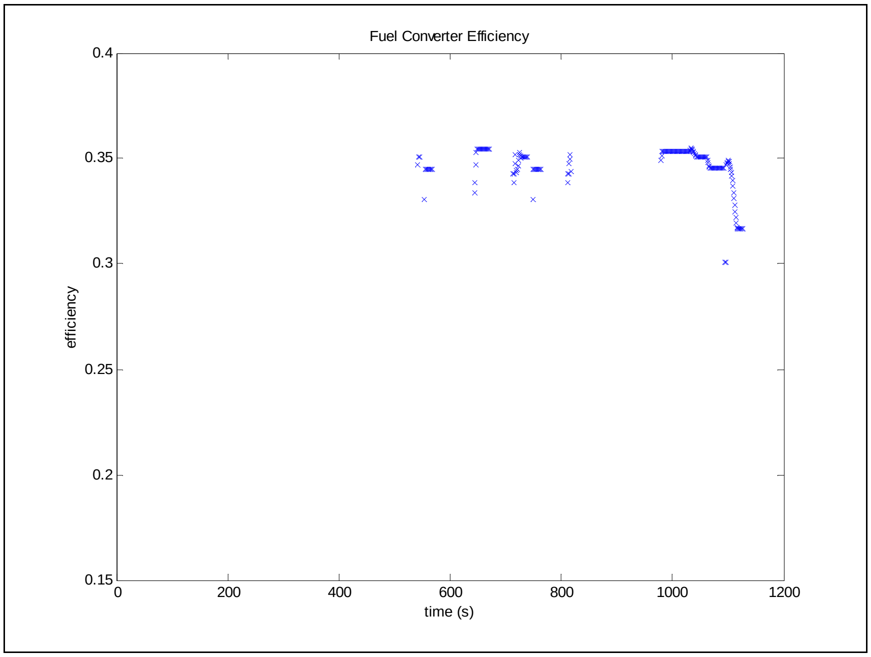


Electric motor power

To optimise the use of the thermal engine, an increase of the output power of the electric motor can be simulated. With the initial 14kW electric motor, the required performance criteria were already matched. With a more powerful electric motor, acceleration performance would obviously be even better. Therefore a hybrid configuration with a 30 kW power electric motor and with a 1.28 L engine was simulated.

Once the energy management strategy optimisation had been done, it appeared that the main difference with the previous configuration was the possibility to achieve a 70 km/h stabilised vehicle speed in pure electric mode. In ***Figure 5.2.5-3***, with the 1.28 l / 14 kW hybrid configuration, the lowest thermal engine efficiency was obtained for a speed of 70 km/h. The instantaneous efficiency of the thermal engine in the hybrid with 30kW electric motor is presented Figure 5.2.5-4 below.

Figure 5.2.5-4 Instantaneous engine efficiency during the NEDC (30kW electric motor)



The fuel consumption results are shown next.

Table 5.2.5-4 Energy/fuel consumption and GHG emissions over the cold NEDC for increased electrical power

	Fuel consumption (/100 km)			GHG emissions (g CO_2 eq/km)			
	MJ	l(1)	kg	as CO_2	as CH_4	as N_2O	Total
Gasoline 1.28 l, 30 kW	150.8	4.69	3.49	110.7	0.5	0.5	111.6
Gasoline 1.28 l, 14 kW	152.9	4.75	3.54	112.2	0.5	0.5	113.1

The use of a more powerful electric motor allowed a slight (less than 2%) decrease of the fuel consumption.

Table 5.2.5-5 shows the mean efficiency and resulting fuel consumption of the different powertrain components of the hybrid vehicle configurations, on the NEDC with hot start. The figures for a conventional PISI engine 1.6 l, obtained using the same fuel consumption map as the hybrid 1.6 l vehicle with hot start, are also shown.

Table 5.2.5-5 Mean engine efficiency on the warm NEDC (with hot conditions)

	Mean Efficiency on the NEDC (%)					Fuel consumption
	Thermal engine	Electric motor		Battery	Vehicle	kg/100 km
		Motor	Generator			
Gasoline PISI						
Hybrid configuration						
1.28 l 30 kW	34.5	86.5	83.3	92.5	28	3.19
1.28 l 14 kW	32.3	84.3	80.6	94.1	27.7	3.24
1.6 l 14 kW	30.8	84.3	79.9	94	26.2	3.41
Conventional ICE						
1.6 l (hot start)	21.1				18.7	4.62

The effect of hybridisation of the gasoline 1.6 l PISI engine was to increase the mean efficiency of the thermal engine by about 50%. Even with the losses of the electric part, the total fuel consumption improvement on the warm NEDC was very noticeable, i.e. 26%.

The first improvement of the hybrid configuration was obtained with the decrease of the engine displacement (1.6 l to 1.28 l) resulting in an increase of the engine efficiency, with the same electric behaviour (the energy management strategy had been kept unchanged). The increase of the engine efficiency (nearly 5%) resulted in an equivalent fuel consumption decrease (about 5%).

The use of a more powerful electric motor allowed increasing the thermal engine efficiency by about 7%. However, the decrease of the fuel consumption was less than 2%. The use of a more powerful electric motor had different consequences on the fuel consumption. On the one hand, the mean efficiency of the 30 kW engine was slightly higher than the 14 kW engine, but on the other hand more electric power was charged and discharged from the battery and the electric losses were thus larger than with the smaller electric motor. Therefore, the fuel consumption decrease was lower than the thermal engine efficiency increase.

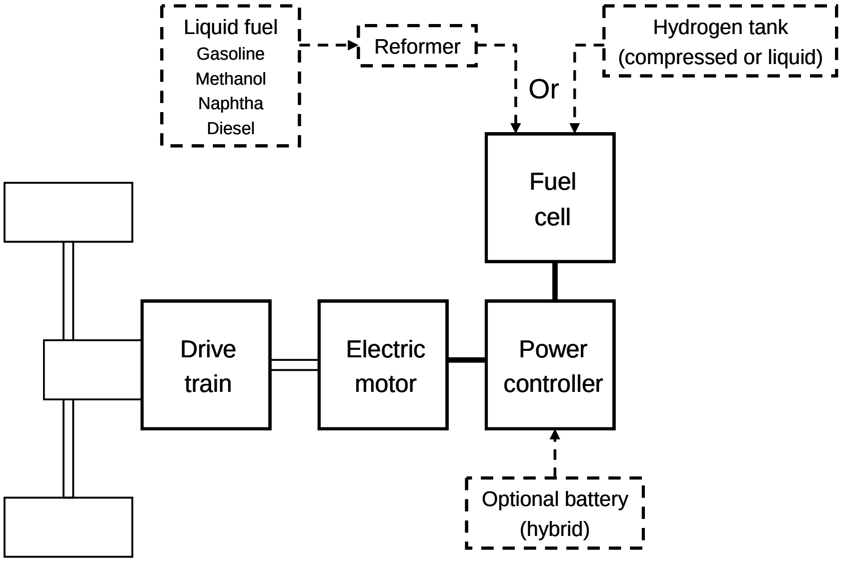
Optimisation of the hybrid powertrain configurations / Conclusions

Hybrid technology, whilst still under global cost optimisation, offers some new degrees of freedom for the improvement of the fuel economy over an ever-wider range of driving conditions while fulfilling ever more demanding polluting emission regulations. As described in this study, and for a large spectrum of foreseeable 2010 ICE / conventional fuel type configurations, the potential GHG reduction and related fuel economy of the hybrid technology when applied on standard size powertrains was estimated by the simulation model at around 19 % (19.3 % for DISI – 18,1% for DICI).

5.3 Fuel Cells

In this study, only PEM (Proton Exchange Membranes) fuel cells were considered. Alternative technologies (such as Solid Oxide Fuel Cells or SOFC) are also under development, but the level of maturity of these high temperature systems is not sufficient to make credible fuel efficiency assumptions for possible road transport applications. These PEM fuel cells can be either fed by hydrogen from a tank or combined with a reformer turning a liquid fuel into hydrogen on-board the vehicle. The former ("direct hydrogen") option was further considered with or without hybridisation. The term hybridisation here refers to the addition of a large battery capable of storing recovered braking energy and to contribute to the powertrain energy supply. The non-hybrid version only had a conventional vehicle battery as required for e.g. start-up. The reformer could be fuelled by gasoline, methanol, naphtha or diesel fuel. The version with reformer was only considered in hybrid configuration.

Figure 5.3 Fuel cell powertrains configurations



5.3.1 Energy management strategy and ADVISOR code modifications

The following energy management strategy was adopted:

- The fuel cell was off during vehicle deceleration (all configurations)

In the hybrid configuration:

- The fuel cell was operated at idle[5] when the vehicle was stopped or when the battery was supplying the motive power.
- At very low vehicle load level the fuel cell was kept at idle the battery providing the energy, thereby avoiding operation in the poor efficiency domain**.** This feature was obviously only active when the battery SOC was high enough (>60 %)**.**
- When the battery needed to be charged, the fuel cell ran at its maximum efficiency power**.**
- The battery SOC was kept between 60% and 70%.

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[5] A Fuel Cell is considered "at idle" when it delivers just the minimal power needed to stabilise its temperature and to power its auxiliaries(see *section 5.3.3*)

Modifications, specific to our vision of the right way to control such a powertrain were brought to the basic fuel cell model available in ADVISOR.

The ADVISOR model required the overall efficiency of the system to be entered as a function of the power delivered.

- For direct hydrogen configurations, the efficiency curve of the fuel cell was used as input.
- For reformer configurations, the efficiency of the power module “Fuel cell + Reformer“ was used.

The main changes from the initial ADVISOR model included:

- The possibility to run the model without using the battery,
- Fuel cell cut off during vehicle deceleration,
- Fuel cell operating at maximum efficiency when the battery was being charged (in the original version a constant load was added),
- Addition of a specific fuel cell consumption at idle.

5.3.2 Fuels and vehicles

The fuels considered for the 2010+ fuel cell configuration are listed below:

- On-board stored hydrogen (liquid and compressed),
- On-board generated hydrogen (reformer) from gasoline, conventional diesel fuel, methanol, refinery naphtha.

Table 5.3.2 Mass characteristics of 2010+ fuel cell vehicles

		Non Hybrid		Hybrid		Hybrid+reformer	
		C-H$_2$	L-H$_2$	C-H$_2$	L-H$_2$	Gasoline(1)	Methanol
Powertrain mass substitution							
Engine mass	kg	-120	-120	-120	-120	-120	-120
Gearbox mass	kg	-50	-50	-50	-50	-50	-50
Fuel Cell							
Fuel cell stack mass	kg	150	150	150	150	150	150
Reformer mass	kg	0	0	0	0	90	90
Cooling system additional mass	kg	50	50	50	50	50	50
Electric parts							
Battery mass	kg	0	0	20	20	40	40
Electric motor+electronics mass	kg	73	73	73	73	73	73
Storage System							
Tank netto capacity	kg	4.7	4.7	4.2	4.2	23	45
Tank mass empty	kg	69	57	56	51	15	15
Tank mass increase including 90% fuel	kg	30	18	16	11	-8	12
Vehicle							
Enlarged vehicle additional mass	kg	50	50	50	50	50	50
Reference mass	kg	1181	1181	1181	1181	1181	1181
Vehicle mass	kg	1364	1352	1370	1365	1456	1476
Cycle test mass	kg	1470	1470	1470	1470	1590	1590

(1) also valid for naphtha and diesel

Electric motor

The characteristics of the electric motor (including electronic inverter) used in the fuel cell configuration were:

Power	Mass	Maximum efficiency	Voltage
75 kW[6]	73 kg	92 %	42 V

Battery

42 V Li-ion batteries was assumed, with a mass of 20 kg for the direct hydrogen configuration. For the reformer case a larger, 40 kg battery, was required in order to satisfy the full ZEV range criterion.

Storage tank

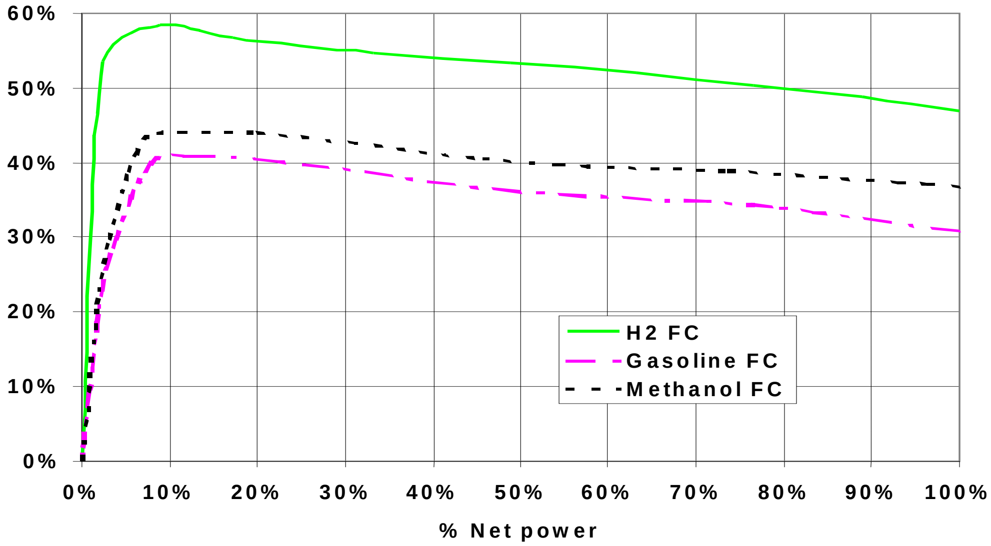
Storage tanks (liquid or compressed) had the same characteristics as for hydrogen ICE applications, albeit with a lower capacity consistent with the higher efficiency of the fuel cell and therefore the smaller hydrogen quantity necessary to comply with the range criterion.

5.3.3 Fuel cell system efficiency

For direct hydrogen fuel cells, efficiency maps were obtained from three different sources: General Motors (GM), DaimlerChrysler and the European programme FUERO (FUEL cell Research Organisation). The GM map, being close to the average of the other two, was used for the simulations and is shown in ***Figure 5.3.3***.

For the reformer case gasoline and methanol maps were also provided by GM. They take into account the best estimate for the energy efficiency of the reformer. For lack of other data, the same efficiency was used for diesel fuel and naphtha.

Figure 5.3.3 Global fuel cell powertrain efficiency maps for different fuels



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[6] Taking into account the mass estimated for those vehicles and the “flat” characteristic of the torque (electric motor), this value was found adapted to comply with the specified performance criteria.

Relevant assumptions

Idle consumption (Source: GM)

- Direct hydrogen fuel cell: 0.3% of the consumption at full power.
- Gasoline and methanol with reformer: 2% of the consumption at full power

Cold start extra consumption (cycle is assessed under hot conditions)

- Direct hydrogen fuel cell: +3 %
- Gasoline and methanol reformer: 1.46 MJ fuel was added (warm-up, for each cycle) to take into account the energy burnt to bring the metal mass of the reformer at the operating temperature.

5.3.4 Conformance to performance criteria

The performance parameters achieved by the fuel cell powered vehicles are shown below and are all within the defined criteria.

Table 5.3.4 Performance of 2010+ fuel cell vehicles

		Non Hybrid		Hybrid		Hybrid+reformer		*Target*
		C-H_2	L-H_2	C-H_2	L-H_2	Gasoline[(1)]	Methanol	
Time lag for 0-50 km/h	s	3.5	3.4	3.2	3.2	3.3	3.3	*<4*
Time lag for 0-100 km/h	s	11.7	11.5	10.3	10.1	10.7	10.8	*<13*
Time lag for 80-120 km/h in 4th gear	s	9.8	9.6	8.2	8.1	8.7	8.8	*<13*
Gradeability at 1 km/h	%	>100	>100	>100	>100	>100	>100	*>30*
Top speed	km/h	184	184	184	184	183	183	*>180*
Acceleration	m/s^2	4.8	4.8	4.8	4.8	4.8	4.8	*>4.0*

(1) also valid for naphtha and diesel

Fuel cell vehicles were the heaviest of all the simulated configurations. Two factors strongly influenced the acceleration performance:

- The torque of the electric motor at low speed (possible torque limitation due to mechanical or electrical design have not been considered).
- The power available form the fuel cell (the power rise rate was assumed to be 15 kW/s in all cases).

5.3.5 Energy and total GHG emissions (NEDC)

The average fuel consumption and total GHG emissions over the NEDC are shown in the tables and figures below.

Table 5.3.5-1 Average energy/fuel consumption and GHG emissions over the NEDC 2010+ fuel cell vehicles

	Fuel consumption (/100 km)			GHG emissions (g CO_2 eq/km)				% change[(2)]	
	MJ	l[(1)]	kg	as CO_2	as CH_4	as N_2O	Total	Energy	GHG
Direct hydrogen	94.0	2.92	0.78	0.0	0.0	0.0	0.0	-58%	-100%
Direct hydrogen hybrid	83.7	2.60	0.70	0.0	0.0	0.0	0.0	-63%	-100%
Reformer fuelled by									
Gasoline	162.4	5.05	3.76	119.2	0.5	0.5	120.1	-27%	-29%
Methanol	148.0	9.38	7.44	108.5	0.5	0.5	109.4	-34%	-35%
Naphtha	162.4	5.16	3.72	115.7	0.8	1.5	118.0	-27%	-30%
Diesel	162.4	4.53	3.77	119.0	0.8	1.5	121.3	-27%	-28%

(1) expressed in liters of equivalent gasoline for hydrogen

(2) from reference 2002 gasoline PISI

The results are valid for both compressed and liquid hydrogen inasmuch as both corresponding vehicles have the same cycle test mass and efficiency map.

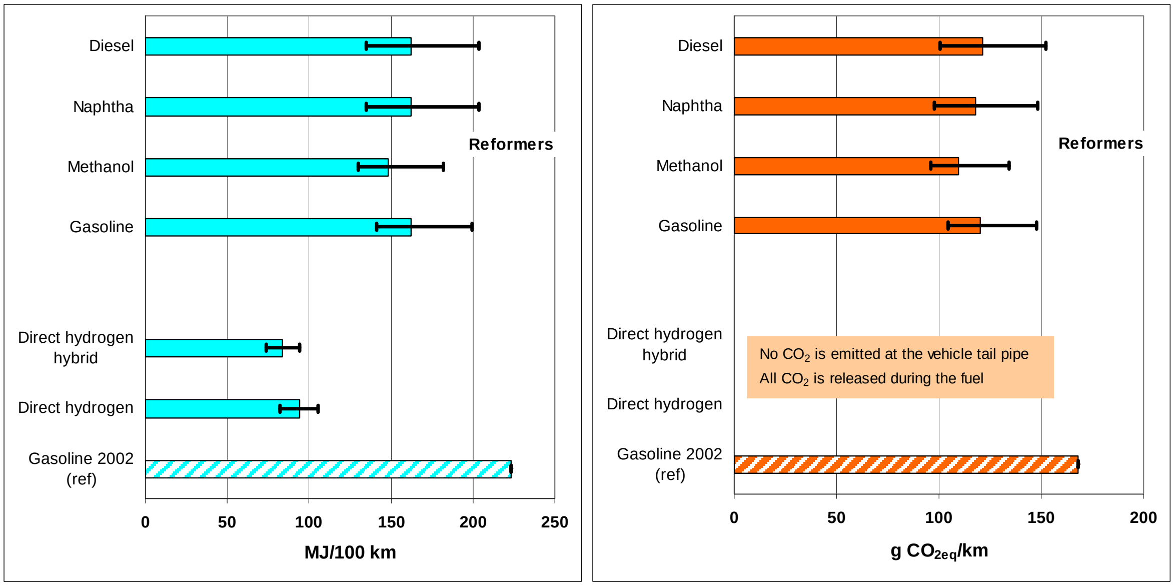
CO_2 emissions for fuel cell with reformer were all below 120 g/km, in the same range as most of the ICE hybrid configurations. Nevertheless, it has to be mentioned that the uncertainty on the simulation results was quite large for these fuel cell configurations (mainly due to the evaluation of the cold start over-consumption).

The uncertainty range on energy consumptions was estimated, for each vehicle-fuel combinaison, according to experts views and are presented here-under.

Table 5.3.5-2 Estimated energy efficiency variability 2010+ fuel cell vehicles

	Direct hyd. FC		Reformer + FC			
All figures in %	No bat.	Hybrid	Gasoline	Methanol	Naphtha	Diesel
Overall (sum of variances)	-12/12	-12/12	-13/23	-12/23	-17/25	-17/25
Cold start	-5/5	-5/5	-5/20	-5/20	-5/20	-5/20
Energy management	-5/5	-5/5	-5/5	-5/5	-5/5	-5/5
Fuel consumption map	-10/10	-10/10	-10/10	-10/10	-15/15	-15/15
Mass estimate			-4/0	-0/0	-4/0	-4/0

Figure 5.3.5-1a/b Average energy/fuel consumption and GHG emissions over the NEDC 2010+ fuel cell vehicles



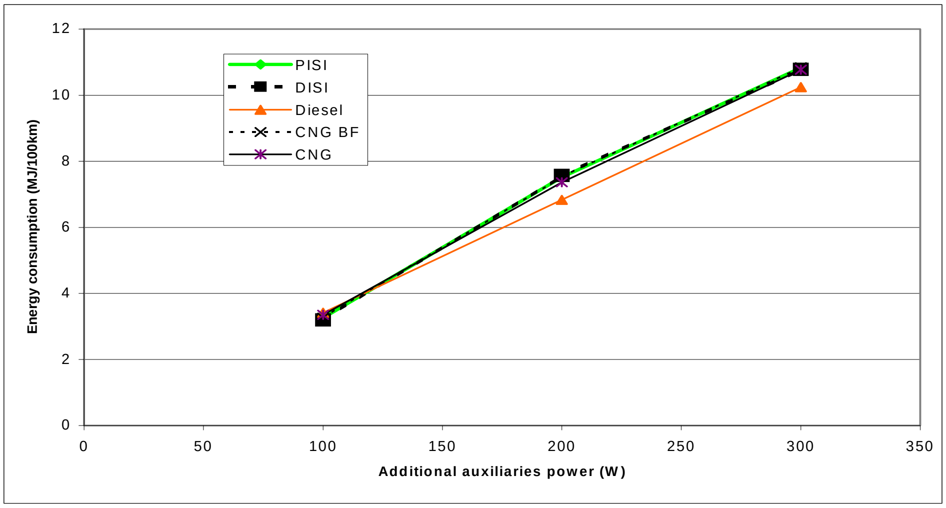
Once again these charts illustrate the limitation of the simple well-to-tank analysis, suggesting that hydrogen vehicles make no contribution to GHG emissions. Only the overall well-to-wheels analysis is relevant, particularly when it comes to hydrogen. Even if hydrogen vehicles applications are relevant for local regulated emissions control, the GHG impact of pure hydrogen applications is highly depending on the fuel production pathway. Some of the most usual hydrogen pathways will be found globally less attractive.

6 Impact of additional electric auxiliaries

The fuel penalty and GHG impact of additional auxiliaries were assessed for every configuration. Three levels of additional power consumption were considered namely 100, 200 and 300W. In this respect, the efficiency of the generator has a major influence. A value of 60 % was assumed for the present state of the art, increasing to 72 % in 2010+.

The following figure shows the additional energy consumption of 2002 ICE vehicles as a function of auxiliary power demand.

Figure 6 Energy consumption impact of auxiliaries power on the NEDC



Whatever the fuel/powertrain combination, the energy penalty versus the auxiliaries power demand is nearly linear. The slope depends on the mean energy conversion efficiency of the powertrain, as clearly shown by the Diesel line compared to the SI engines. The GHG contribution is directly related to the energy consumption through the specific energy and carbon content of the fuel.

For the 2002 state-of-the-art technology and on the NEDC cycle, the average power developed by the vehicle for propulsion is around 4 kW. Taking into account the 60 % efficiency of the alternator, 300 W of power demand for auxiliaries would impose an extra load of 500 W on the powertrain, i.e. and increase of 12.5 %. On the urban drive part of the cycle, the engine is under-loaded, usually resulting in low energy efficiency so that this extra load actually improves the intrinsic engine efficiency. As a result, the energy penalty is limited to around 10 MJ/100 km for 300 W, or roughly 5 % instead of 12.5 %. Depending on the efficiency maps of the different engines and the path of the operating point during the cycle, the result may be slightly different. This is illustrated in figure 6 where the diesel engine is shown to be somewhat more efficient.

In 2010+, the combined impacts of improved alternator efficiency and supplementary engine load reduce these figures some more, reducing the energy impact to 8.5 MJ/100 km for gasoline, or 4.5% instead of 5%, corresponding to 6.5 g CO_2 / km.

For hybrid configurations, two opposing effects play a part: the hybrid powertrain is, globally, a better energy converter than the thermal engine and this should reduce the fuel penalty. However, the thermal engine is already operated near its optimal efficiency and no noticeable benefit can be expected from the extra engine load. As a result, the net energy and GHG penalties due to auxiliaries are roughly the same as those for the conventional 2002 ICE.

The above effect also applies to hybrid fuel cells powertrains with reformers for which the energy penalty due to auxiliaries, added to that of the reformer system itself, bring to figures equivalent to the 2010 ICE engines.

The case of direct hydrogen fuel cells is very specific, as, contrarily to thermal powertrains, increasing the load decreases the energy converter efficiency, mainly in urban driving phases. As a result the energy impact of 300 W auxiliaries load over a NEDC cycle is assessed at 12 MJ/100 km or around 13 %.

7 Vehicle Retail Prices estimation

7.1 Introduction

The economical assessment of future technologies, in a trade competitive domain, is probably among the most risky challenge ever proposed to a crystal ball.

The methodology we selected intended to estimate the retail price increment expectable at the 2010+ horizons for the various technologies under consideration. Maintenance costs were not considered.

7.2 Methodology

Inspired from the MIT study "On the road in 2020"[7], the calculation delivered orders of magnitude in a simple and transparent way. Subtracting the price impact of the original internal combustion engine and components and adding the impact of the new powertrain components obtained the retail price. Specific price increments for special tanks (hydrogen or natural gas), or electric components (batteries, electric motors) were also added when relevant.

For the retail prices detailed assessments, the following rules were used:

- When the powertrain could be identified as a spark ignition (SI) combustion technology, the retail price was evaluated relative to the 2002 PISI vehicle.
- When the powertrain could be identified as a compression ignition (CI) technology, the retail price was evaluated relative to the 2002 DICI vehicle.
- When the powertrain could not be identified as either a SI or a CI technology, the retail price was evaluated relative to the 2002 PISI vehicle.

Details of the sources, individual component price assumptions and calculations for each vehicle type can be found in ***TTW Appendix 1***.

7.3 Results

The figure 7.3 shows the percent retail price increase for the 2010+ vehicles, compared to the PISI ICE Gasoline 2010+ vehicle (assumed retail price **19560 €**). These figures are deemed to represent fair price differentials based on commercial realities or reflecting the lack of reliable consolidated data. They are one of the components in the economic assessment of the alternative pathways in the Well-to-Wheels integration.

The figure also shows the estimated uncertainty ranges. The range is fairly narrow for established technologies but widens when it comes to less developed options such as hybrids. For fuel cell technology we have applied a 100% upwards range reflecting the many uncertainties attached to these technologies.

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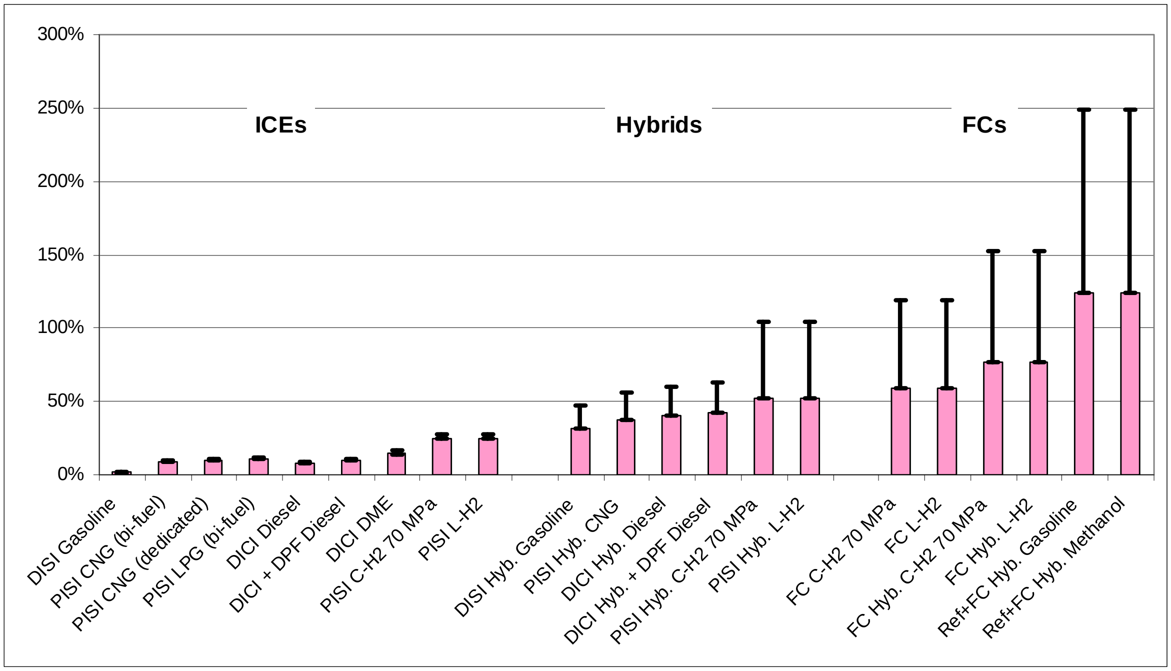
[7] "On the road in 2020", Malcolm A. Weiss, John B. Heywood, Elisabeth M. Drake, Andreas Schafer and Felix F. Au Yeung, October 2000.

Figure 7.3 % increase of vehicle retail price compared to gasoline PISI vehicle



Acronyms and abbreviations used in the WTW study

ADVISOR	A powertrain simulation model developed by the US-based National Renewable Energy Laboratory
BTL	Biomass-To-Liquids: denotes processes to convert biomass to synthetic liquid fuels, primarily diesel fuel
CAP	The EU's Common Agricultural Policy
CCGT	Combined Cycle Gas Turbine
CC&S	CO_2 capture and storage
C-H_2	Compressed hydrogen
CHP	Combined Heat and Power
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO_2	Carbon dioxide: the principal greenhouse gas
CONCAWE	The oil companies' European association for environment, health and safety in refining and distribution
DDGS	Distiller's Dried Grain with Solubles: the residue left after production of ethanol from wheat grain
DG-AGRI	The EU Commission's General Directorate for Agriculture
DICI	An ICE using the Direct Injection Compression Ignition technology
DME	Di-Methyl-Ether
DPF	Diesel Particulate Filter
DISI	An ICE using the Direct Injection Spark Ignition technology
ETBE	Ethyl-Tertiary-Butyl Ether
EUCAR	European Council for Automotive Research and Development
EU-mix	The average composition of a certain resource or fuel in Europe. Applied to natural gas, coal and electricity
FAEE	Fatty Acid Ethyl Ester: Scientific name for bio-diesel made from vegetable oil and ethanol
FAME	Fatty Acid Methyl Ester: Scientific name for bio-diesel made from vegetable oil and methanol
FAPRI	Food and Agriculture Policy Research Institute (USA)
FC	Fuel Cell
FSU	Former Soviet Union
FT	Fischer-Tropsch: the process named after its original inventors that converts syngas to hydrocarbon chains
GDP	Gross Domestic Product
GHG	Greenhouse gas
GTL	Gas-To-Liquids: denotes processes to convert natural gas to liquid fuels
HC	Hydrocarbons (as a regulated pollutant)
HRSG	Heat Recovery Steam Generator
ICE	Internal Combustion Engine
IEA	International Energy Agency
IES	Institute for Environment and Sustainability
IFP	Institut Français du Pétrole
IGCC	Integrated Gasification and Combined Cycle
IPCC	Intergovernmental Panel for Climate Change
JRC	Joint Research Centre of the EU Commission
LBST	L-B-Systemtechnik GmbH
LCA	Life Cycle Analysis
L-H_2	Liquid hydrogen
LHV	Lower Heating Value ('Lower" indicates that the heat of condensation of water is not included)
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gases
MDEA	Methyl Di-Ethanol Amine
ME	The Middle East
MTBE	Methyl-Tertiary-Butyl Ether

MPa	Mega Pascal, unit of pressure (1 MPa = 10 bar). Unless otherwise stated pressure figures are expressed as "gauge" i.e. over and above atmospheric pressure
Mtoe	Million tonnes oil equivalent. The “oil equivalent” is a notional fuel with a LHV of 42 GJ/t
N_2O	Nitrous oxide: a very potent greenhouse gas
NEDC	New European Drive Cycle
NG	Natural Gas
NOx	A mixture of various nitrogen oxides as emitted by combustion sources
OCF	Oil Cost Factor
OGP	Oil & Gas Producers
PEM fuel cell	Proton Exchange Membrane fuel cell
PISI	An ICE using the Port Injection Spark Ignition technology
PSA	Pressure Swing Absorption unit
RME	Rapeseed Methyl Ester: biodiesel derived from rapeseed oil (colza)
SMDS	The Shell Middle Distillate Synthesis process
SME	Sunflower Methyl Ester: biodiesel derived from sunflower oil
SOC	State Of Charge (of a battery)
SRF	Short Rotation Forestry
SSCF	Simultaneous Saccharification and Co-Fermentation: a process for converting cellulosic material to ethanol
SUV	Sport-Utility Vehicle
Syngas	A mixture of CO and hydrogen produced by gasification or steam reforming of various feedstocks and used for the manufacture of synthetic fuels and hydrogen
TES	Transport Energy Strategy. A German consortium that worked on alternative fuels, in particular on hydrogen
TTW	Tank-To-Wheels: description of the burning of a fuel in a vehicle
ULCC	Ultra Large Crude Carrier
VLCC	Very Large Crude Carrier
WTT	Well-To-Tank: the cascade of steps required to produce and distribute a fuel (starting from the primary energy resource), including vehicle refuelling
WTW	Well-To-Wheels: the integration of all steps required to produce and distribute a fuel (starting from the primary energy resource) and use it in a vehicle
ZEV	Zero Emission Vehicle

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Abstract

WELL-TO-WHEELS ANALYSIS OF FUTURE AUTOMOTIVE FUELS AND POWERTRAINS IN THE EUROPEAN CONTEXT

The JEC research partners [Joint Research Centre of the European Commission, EUCAR and CONCAWE] have updated their joint evaluation of the well-to-wheels energy use and greenhouse gas emissions for a wide range of potential future fuel and powertrain options.

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