CO₂ Reduction and Cost Efficiency Potential of Natural Gas Hybrid Passenger Cars

2011-24-0110

Published
09/11/2011Christian Bach, Patrik Soltic
EMPACopyright © 2011 SAE International
doi:10.4271/2011-24-0110

ABSTRACT

CO₂ reduction targets are a big challenge for the mobility sector because about 20% of all CO₂ emissions origin from road traffic. The problem is intensified by the expected traffic growth which will mainly take place in developing countries. Several powertrain and fuel technologies are competing regarding their CO₂ reduction potential compared to conventional gasoline and diesel vehicles. Hybrid electric vehicles with a certain energy saving potential as well as natural gas vehicles (NGVs) with their lower fuel carbon content are expected to gain on importance. But why not combining dedicated natural gas engine and hybrid powertrain technology to achieve very low CO₂ emissions even for mid size passenger cars? At a first glance, such a powertrain combination looks just like a combination of two expensive technologies without any market potential. A more detailed analysis shows, however, that NGV hybrids allow high CO₂ reductions without additional end-user costs over the vehicle's entire lifetime. The present study addresses both topics: it presents the CO₂ reduction potential of mid-size passenger cars driven with an average natural gas-hybrid powertrain and it addresses end-user costs compared with today's gasoline technology.

INTRODUCTION

TARGET OF THE STUDY

Due to the high importance of traffic based CO₂ emissions [1], low carbon fuels as natural gas, hydrogen or biofuels are of increasing interest. Due to the high market share, fuel and powertrain concepts for mid-size passenger cars are particularly concerned.

Within the present study, the energy efficiencies and the CO₂ emissions of several Euro-4 gasoline, gasoline-hybrid and natural gas vehicles are experimentally investigated on a chassis dynamometer according to 70/220-98/69/EC regulations. These results have been used as a baseline for evaluating the energy needs and the CO₂ emissions of a natural gas hybrid powertrains for a mid-size passenger car over a broad operational range. Exhaust gas pollutants were also measured and are published in other papers [2].

Furthermore, the end-user costs of a natural gas-hybrid vehicle are calculated using vehicle and fuel cost scenarios. The operational costs of a natural gas-hybrid vehicle are compared with those of a conventional gasoline vehicle.

EXPERIMENTAL SETUP

Nine gasoline, eight natural gas and two hybrid passenger cars were investigated at our laboratory in an international emission inventory project. The exhaust emissions were measured on a chassis dynamometer in different driving cycles (see next chapter). The fuel consumption was determined according the 80/1268-2004/3/EC regulations.

Private owners provided their used vehicles for the experiments. The vehicles were checked against failures. They have been operated during the tests with a typical market fuel which was analyzed for net heating value, density etc. For the natural gas calculations, the mean density and net heating values from the Swiss gas grid 2010 were used.

Swiss market gasoline:

- Research octane number (RON):	95
- Density (15°C):	0.732 kg/l
- Net heating value (NHV):	42.5 MJ/kg
- Carbon mass fraction (CMF):	0.866

Natural gas (from Swiss grid):

- Methane:	89.3 vol-%
- Density (15°C; w/o inert gases):	0.699 kg/m ³
- Net heating value (w/o inert gases):	31.61 MJ/m ³
- Carbon mass fraction (w/o inert gases):	0.695

DRIVING CYCLES

Energy efficiency and CO₂ emission issues of light duty vehicles are often discussed using fuel consumption data measured in the New European Driving Cycle (NEDC). This synthetic driving cycle (Fig. 1), however, does not represent how vehicles are normally driven in reality. For more relevant data, driving cycles based on the real world driving behavior have to be used. Such cycles were developed within different research programs and are particularly used for emission inventory reasons.

In the present paper, following driving cycles are used for evaluating the fuel consumption and the CO₂ emissions of gasoline, natural gas and gasoline hybrid vehicles:

Fig. 1 Cold started driving cycle "L2" with sub-cycles NEDC (consisting of ECE, EUDC) and BAB (German "Bundesautobahn-Zyklus")

Fig. 2 Warm started Common Artemis Driving Cycle "CADC" with sub-cycles CADC_1, CADC_2, CADC_3, developed in the EU project "ARTEMIS"

Fig. 3 Warm started driving cycle "Ra" with sub-cycles Ra_1, Ra_2, Ra_3 from a Swiss emission inventory program

Fig. 4 Warm started driving cycle "Rb" with sub-cycles Rb_1 and Rb_2 from a Swiss emission inventory program

Fig. 5 Cold started driving cycle FTP-75 cycle with sub-cycles FTP_1, FTP_2, FTP_3 (U.S. mandatory emission test cycle)

Cycle	Sub cycle	Type	V_{Ave}^+	a_{Ave}^+
L2	ECE ¹⁾	Statutory	18.7 km/h	0.15 m/s ²
	EUDC	Statutory	62.6 km/h	0.20 m/s ²
	BAB	Real world	109.8 km/h	0.16 m/s ²
CADC	CADC_1	Real world	17.5 km/h	0.35 m/s ²
	CADC_2	Real world	60.4 km/h	0.30 m/s ²
	CADC_3	Real world	120.4 km/h	0.36 m/s ²
Ra	Ra_1	Real world	104.8 km/h	0.12 m/s ²
	Ra_2	Real world	97.1 km/h	0.26 m/s ²
	Ra_3	Real world	67.0 km/h	0.45 m/s ²
Rb	Rb_1	Real world	52.3 km/h	0.22 m/s ²
	Rb_2	Real world	32.7 km/h	0.55 m/s ²
FTP75	FTP_1 ¹⁾	Statutory	38.8 km/h	0.18 m/s ²
	FTP_2	Statutory	15.1 km/h	0.35 m/s ²
	FTP_3	Statutory	40.2 km/h	0.56 m/s ²

¹⁾ Cold started sub-cycles (ambient temperature 23°C)

Table 1: Driving cycles and sub-cycles with main characteristics

Prior the warm started driving cycles CADC, Ra and Rb, the engines were heated up to an engine oil temperature of 80°C. All sub-cycles of the warm-started driving cycles as well as the second and third sub-cycles of the cold started driving cycles were used for evaluating the fuel consumption behavior of the test vehicles. The tests of the hybrid vehicles are started with fully charged batteries (vehicle powered by chassis dynamometer until state of battery charge achieved 100% for achieving a defined starting point), meaning that external energy is provided into these tests. For evaluating the fuel consumption behavior of the two hybrid vehicles, the first sub-cycles of all driving cycles are therefore not considered.

FUEL CONSUMPTION BEHAVIOR OF GASOLINE, NATURAL GAS AND HYBRID VEHICLES

The mean chemical (fuel) power and the mean positive wheel-power of all sub-cycles are evaluated based on the fuel consumption measurements on the chassis dynamometer and driving cycle analysis. Based on these data, the mean energy efficiency for each sub-cycle was calculated as follows:

$$\bar{\eta} = \frac{\text{mean pos. wheel power}}{\text{mean chemical power}} = \frac{\bar{P}_w^+}{\frac{NHV}{t_{\text{sub-cycle}}} \cdot \int_{\text{sub-cycle}} m_f^* \cdot dt} \quad (1)$$

- $\bar{P}_w^+$ is the mean positive wheel-power
- NHV is the lower fuel heating value of the used fuel
- m_f^* is the fuel flow.

$\bar{P}_w^+$ is calculated as follows:

$$\bar{P}_w^+ = \frac{1}{t_{\text{sub-cycle}}} \cdot \int_{\text{sub-cycle}} \max(F_{\text{wheel}}, 0) \cdot v \cdot dt \quad (2)$$

- F_{wheel} is the wheel force
- v is the vehicle speed
- $t_{\text{sub-cycle}}$ is the time of the sub-cycle

Fig. 6 shows as example the mean energy efficiency values of a turbo charged natural gas vehicle with 7-gear direct-shift-gearbox (NGV-1).

Fig. 6 Energy efficiency of a turbo-charged natural gas vehicle over mean positive wheel-power with logarithmic fit for 13 sub-cycles (the fit was performed with exclusion of the two cold start cycles)

Fig. 6 and 7 also shows the values for the “New European Driving Cycle” (NEDC), which is a distance weighted combination of the sub-cycles ECE and EUDC. The NEDC value is not used for further evaluation and is introduced in the diagrams in different color for information reasons only.

The energy efficiency in the 13 sub-cycles of the warm started driving cycles are fitted in Fig. 6 over the mean positive wheel-power in a logarithmic function. The results show a high correlation coefficient.

Fig. 7 shows the mean speed of the different sub cycles over the mean positive wheel power. It can be seen, that the mean positive wheel-power is a good indicator for separating different driving pattern. Low-speed sub-cycles (Rb_3, FTP_2, ECE, CADC_1, etc) are typically for city driving at low load while high-speed sub-cycles (BAB, CADC_3, Ra_1 etc) typically need high propulsion power.

Fig. 7 Mean speed of the different sub-cycles over mean positive wheel-power, measured with a turbo-charged natural gas vehicle with polynomial fit for several sub-cycles

The measurements give energy efficiency values for urban driving cycles of 15-22%, for rural driving cycles of 22-27% and for motorway driving cycles of 27-32% for this particular vehicle (Fig. 6).

The mean chemical (fuel) power versus the mean positive wheel-power of the turbo-charged natural gas vehicle is shown in Fig. 8. It is known that internal combustion engines show a nearly affine behavior of torque versus fuel flow rate for constant engine speed [3]. This behavior is known as the Willans approximation [4]. Fig. 8 depicts that the Willans approximation is also very useful for the whole system “car”. The straight lines in light grey represents the points along with the mean energy-efficiency are constant.

Fig. 8 Mean chemical (fuel) power over mean positive wheel-power with linear fit for several sub-cycles (Willans approximation)

Among others, the affine approach shown in Fig. 8 allows to estimate the fuel consumption at idle (needed chemical power for zero wheel-power) which is 6.3 kW or 0.6 Sm³ CNG/h in this example (vehicle NGV-1).

In the following, several gasoline, natural gas and gasoline-hybrid vehicles were analyzed regarding fuel consumption behavior in the different sub-cycles and the data are used for generating a Willans approximation for the corresponding vehicle sample.

a) Euro-4 gasoline vehicle sample (with gearbox and model year indication):

- Gas-1: Mini Cooper 1.6 m5 (2003)
- Gas-2: Renault Scenic 2.0 m5 (2004)
- Gas-3: Renault Megane 1.6 m5 (2003)
- Gas-4: Honda Civic 1.8 m5 (2006)
- Gas-5: VW Touran 1.4 TSi DSG6 (2007)
- Gas-6: VW Passat 2.0 m5 (2000)
- Gas-7: Opel Corsa 1.8 m5 (2002)
- Gas-8: Nissan Micra 1.2 m5 (2003)
- Gas-9: Opel Astra 1.4 m5 (2001)

Fig. 9 shows the mean chemical (fuel) power versus the mean positive wheel-power of the gasoline vehicle sample including a linear Willans fit over all data and a variation of ± 4 kW, covering 90% of the data. Using this fit, the fuel consumption of the mean gasoline fleet can be calculated for several driving cycles based on the mean positive wheel-power of the individual driving cycle. Vehicle “Gas-5” for example is equipped with a modern, turbo-charged and downsized engine (indicated with $\blacktriangle$) with direct-shift-gearbox (DSG), showing the lowest fuel consumption over the whole operation range. Vehicle “Gas-6” is equipped with a relatively old naturally aspirated two-valve engine, marking the upper end of the fuel consumption range.

Fig. 9 Willans approximation of 9 Euro-4 gasoline vehicles in 13 warm started driving cycles over mean positive wheel-power (mean ± 4 kW covering 90% of data)

Following efficiency behavior of the gasoline sample is resulting:

Fig. 10 Mean efficiency values of 9 Euro-4 gasoline vehicles in 13 warm started driving cycles over mean positive wheel-power (mean $\pm 3\%$ -P covering 90% of data)

For city driving with a mean positive wheel-power of about 4 kW, an efficiency of 17-22% is resulting, 22-28% for rural driving with a mean pos. wheel-power of about 9 kW and 27-32% for motorway driving with a mean positive wheel-power of about 18 kW.

b) Euro-4 natural gas vehicle sample:

- NGV-1: Opel Zafira 1.6T m5 (2009)
- NGV-2: Fiat Multipla 1.6 m5 (2006)
- NGV-3: Citroen C3 1.4 m5 (2007)
- NGV-4: VW Golf Variant 2.0 m5 (2004)
- NGV-5: Opel Combo 1.6 m5 (2005)
- NGV-6: Fiat Punto 1.2 m5 (2006)
- NGV-7: VW Caddy 2.0 m5 (2006)
- NGV-8: VW Passat Ecofuel 1.4 TSI DSG7 (2009)

For chassis dynamometer testing, the fuel consumption

$$F.C. = \int_{\text{cycle}} m_f^* \cdot dt \quad (3)$$

is usually not calculated by measuring the fuel mass flow directly but by using the “carbon balance method” (e.g. as described in the European Directive 80/128/EC). For the carbon balance method, the gaseous mass emissions of all measured carbon containing compounds (HC, CO, CO₂) are converted in a fuel consumption value, using standard values for the fuel’s carbon mass fraction (CWF_{std}) and the density (ρ_{std}). In case of gasoline or diesel fuel, the standard values correspond to real fuel specification but a special attention has to be paid to natural gas vehicles. The standard density is specified to 0.654 kg/m³ and the standard CWF is specified to 0.7487, which do not correspond neither to the values of the standard fuels nor to market fuels. In order to get physically correct values, the standard fuel consumption values have to be corrected for the NGVs as follows:

$$F.C._{corr} = F.C._{80/128/EC} \cdot \frac{CWF_{std}}{CWF_{real}} \cdot \frac{\rho_{std}}{\rho_{real}} \quad (4)$$

Fig. 11 shows the Willans approximation of the NGV sample. The values are quite similar to those of the gasoline sample. This has to be expected, because both vehicle samples are using similar engine and transmission technologies. Some efficiency advantages are possible for optimized NGV engines due to de-throttling effects at part load and stoichiometric operation even at high engine loads (motorway driving).

The deviation among the NGV-sample is bigger than those of gasoline vehicles, due to the fact, that some car manufacturer are using quite old engine technology for their own natural gas vehicles while some car manufacturer are using also their newest engine and gearbox technology. However, this higher deviation is not linked to the gaseous fuel but the used technology.

Fig. 11 Willans approximation of 8 Euro-4 NGVs in 13 warm started driving cycles over mean positive wheel-power (mean ± 5 kW covering 90% of data)

The two turbo-charged NGVs are showing the lowest fuel consumptions over the whole range while older vehicle concepts as NGV-2 and NGV-4 are at the upper limit of the fuel consumption range.

Beside the potential for extremely low emissions with conventional exhaust aftertreatment technology (especially in the field of unregulated pollutants such as ozone precursors, toxic compounds, particles), natural gas contains 25% less carbon per energy unit compared with gasoline. Assuming unchanged engine efficiency, this lower carbon content leads to a 25% reduction of energy specific CO₂ emissions compared with gasoline engines.

Due to the 200 bar gas storage, NGVs have a higher vehicle mass. Today, mainly steel cylinders with a mass of about 1 kg per dm³ of storage volume are used. On the other side, NGVs are usually equipped with only a minor gasoline tank of 13-30 l. Therefore, the additional weight of a typically 150 dm³ (24 kg) gas storage including mounting parts, gas supply and injection system can be estimated to about 150 kg for a mid-size passenger car. In the near future, light-weight full composite (so-called type IV) gas cylinders with 60% reduced mass may be used. Assuming a dense refueling infrastructure and additional powertrain efficiency improvements, the gasoline tank could even be removed completely. Therefore, the additional weight of a conventional NGV with full composite gas storage concept compared with a gasoline vehicle is estimated to be at about 100 kg and of a dedicated NGV (without gasoline operation) at about 50 kg.

c) Euro-4 Hybrid vehicles:

- HEV-1: Toyota Prius II CVT (full hybrid)
- HEV-2: Honda Insight CVT (mild hybrid)

Fig. 12 shows the Willans approximation of the gasoline-hybrid sample. Because all tests were started with fully charged battery, the first sub-cycles are not considered. The vehicle test setup and the battery conditioning is described in [5]. Interestingly, the linear Willans approximation is able to represent the efficiency behavior very well even for hybrid electric vehicles with complex energy management strategies.

HEV-1 (full hybrid concept) shows slightly lower fuel consumption over the whole range than HEV-2 which is a mild hybrid concept without pure electric operation.

Fig. 12 Willans approximation of 2 Euro-4 gasoline-hybrid vehicles in 10 warm started driving cycles over mean positive wheel-power (mean ± 4 kW covering 90% of data)

The energy efficiency of the two hybrid vehicles is nearly constant at about 30 – 35% over the whole operational range. Further more, the mean Willans assumption of the gasoline-hybrid sample shows an about 5 times lower idle consumption than the conventional gasoline or NGV sample due to engine-off phases in idle.

The dispersion at very low mean positive wheel-power in Fig. 12 is due to the fact, that HEV-1 is able to run fully electric at low loads which is energetically advantageous at low load cycles while HEV-2 uses a torque assist hybrid structure only without the possibility of pure electric driving.

Hybrid vehicles need high-performance batteries and an additional electric motor with power electronics. The additional weight of full hybrid vehicles can be estimated to about 100 kg. It is likely, that this additional weight will not decrease significantly in the future.

COMPARISON OF GASOLINE, GASOLINE-HYBRID, NGV AND NGV-HYBRID VEHICLES

This section describes the energy demands and CO₂ emissions of a base case gasoline mid-size passenger car and its alternatives (gasoline-hybrid, NGV and NGV-hybrid). According to assumption described above, the additional mass of the hybrid components are set to 100 kg and the additional mass of components for dedicated methane operation are set to 50 kg, which is possible by completely removing the gasoline part and the use of full composite gas cylinders.

The mean positive wheel power of the base case and the alternative cases in different driving cycles can be calculated using Equation (2). Table 2 lists the resulting mean positive wheel power values for a mean city, rural and motorway driving with 4 kW, 9 kW and 18 kW for a typical gasoline vehicle, while the mean positive wheel-power for the gasoline-hybrid, the NGV and the NGV-hybrid vehicles are corrected according the increased vehicle mass. Thus, following road load coefficients are used in analogy to the exhaust emissions certification. To simplify matters, the impact of the vehicle mass was limited to the first term (V = speed in km/h).

Gasoline vehicle (curb weight = 1'537 kg):

$$\text{- Road load curve: } 124[N] + 0.789\left[\frac{Nh}{km}\right] \times V + 0.0273\left[\frac{Nh^2}{km^2}\right] \times V^2$$

Gasoline-hybrid (curb weight = 1'637 kg (+100 kg)):

$$\text{- Road load curve: } 132[N] + 0.789\left[\frac{Nh}{km}\right] \times V + 0.0273\left[\frac{Nh^2}{km^2}\right] \times V^2$$

NGV (curb weight = 1'637 kg (+100 kg)):

$$\text{- Road load curve: } 132[N] + 0.789\left[\frac{Nh}{km}\right] \times V + 0.0273\left[\frac{Nh^2}{km^2}\right] \times V^2$$

NGV-hybrid (curb weight = 1'687 kg (+150 kg)):

$$\text{- Road load curve: } 136[N] + 0.789\left[\frac{Nh}{km}\right] \times V + 0.0273\left[\frac{Nh^2}{km^2}\right] \times V^2$$

Table 2 shows the resulting mean positive wheel-power for the comparison.

Mean pos. wheel power	Mean city driving	Mean rural driving	Mean m-way driving
Gasoline	4.00 kW	9.00 kW	18.00 kW
Gasoline-Hybrid	4.16 kW	9.24 kW	18.22 kW
NGV	4.16 kW	9.24 kW	18.22 kW
NGV-Hybrid	4.24 kW	9.36 kW	18.32 kW
Average speed	35 km/h	70 km/h	110 km/h

Table 2: Mean positive wheel power of the different vehicle concepts in mean city, rural and motorway driving

Based on the mean positive wheel-power values of Table 2, the chemical energy demand can be calculated using the Willans approximations, respectively the Willans coefficients A and B indicated in the corresponding diagrams in the previous section. While the Willans coefficients A and B for gasoline, gasoline-hybrid and NGV vehicles are evaluated out of measurements, the coefficients A and B for the NGV-hybrid vehicle has to be calculated using the Willans approximation of gasoline hybrids (Fig. 11), whereat the coefficients A and B are corrected as follows:

$$Coeff. A_{NGV-Hybrid} = Coeff. A_{Gasoline-Hybrid} \cdot \frac{Coeff. A_{NGV}}{Coeff. A_{Gasoline}} \quad (5)$$

$$Coeff. B_{NGV-Hybrid} = Coeff. B_{Gasoline-Hybrid} \cdot \frac{Coeff. B_{NGV}}{Coeff. B_{Gasoline}} \quad (6)$$

The results are listed in Table 3.

Chemical energy demand	Mean city driving	Mean rural driving	Mean motorway driving
Gasoline	0.55 kWh/km	0.50 kWh/km	0.58 kWh/km
Gasoline-Hybrid	0.39 kWh/km	0.41 kWh/km	0.50 kWh/km
NGV	0.61 kWh/km	0.53 kWh/km	0.59 kWh/km
Dedicated NGV-Hybrid	0.40 kWh/km	0.41 kWh/km	0.50 kWh/km

Table 3: Chemical energy demand of the different vehicle concepts for mean city rural and motorway driving

Table 4 shows the CO₂ emissions for the different vehicle concepts resulting from the chemical energy demand of Table 3:

CO ₂ emissions	Mean city driving	Mean rural driving	Mean motorway driving
Gasoline	149 g/km	135 g/km	155 g/km
Gasoline-Hybrid	105 g/km	110 g/km	135 g/km
NGV	122 g/km	106 g/km	118 g/km
Dedicated NGV-Hybrid	80 g/km	83 g/km	100 g/km

Table 4: CO₂ emissions of the different vehicle concepts based on their chemical energy demand (Table 3).

COSTS AND CO₂ EMISSIONS

The total costs of different motor vehicles differ mainly by different amortization costs and by different fuel costs. All other costs (insurance, taxes, etc) are usually quite similar and their influence can therefore be neglected for most countries. Capital costs are also neglected in this section.

For the following cost calculations, a purchase price of EUR 30'000 is assumed for the base case (mid-size gasoline vehicle). Fig. 13 shows the amortization of the purchase price of the different vehicle concepts over a lifetime of 180'000 km, assuming additional cost of 2'000 EUR for the NGV technology and 5'000 EUR for the hybridization. The additional cost for hybrid technology however is strongly depending of the used hybrid concept [6], [7]. No residual value after 180'000 km is assumed for all concepts.

The additional costs to be amortized compared to the gasoline vehicle are therefore: NGV: +2'000 EUR, gasoline-hybrid: +5'000 EUR and NGV-Hybrid: +7'000 EUR.

Fig. 13 Amortization of the purchase price of the different vehicle concepts over a vehicle operation time of 180'000 km

For the fuel cost and CO₂ calculations, we assume 4'000 km/a city driving, 8'000 km/a rural driving and 4'000 km/a motorway driving. This results in a total annual mileage of 16'000 km. The fuel costs of the different vehicle concepts are calculated using the consumption values of Table 2 and assuming the following end-user fuel prices:

- Gasoline: 1.6 EUR/l (5.1 Cent/MJ)
- Natural gas: 1.6 EUR/kg (3.4 Cent/MJ)

These fuel prices are strongly influenced by the fuel taxation strategy of the individual countries. This is particularly the case for natural gas, leading to increased or decreased price difference between the two fuels compared with the values used here. A sensitivity analysis of the fuel price difference and operational conditions is presented later on.

Fig. 14 shows the end user fuel costs over the vehicle's entire life time of 180'000 km.

Fig. 14 End user fuel costs of the different vehicle concepts over a vehicle operation time of 180'000 km

Based on the above mentioned end user fuel price assumptions, the NGV-hybrid shows reduced fuel costs of 8'070 EUR over 180'000 km. The additional vehicle purchase costs of 7'000 EUR are even overcompensated by the lower fuel costs. The same calculation shows, that the fuel cost savings of the gasoline-hybrid vehicle with about 3'600 EUR is only covering about 70% of the additional vehicle costs. However, the additional costs (2'000 EUR) of the NGV are overcompensated by the fuel cost savings of about 5'100 EUR by more than a factor 2.5.

The CO₂ emissions over 180'000 km are shown in Fig. 15:

Fig. 15 Tailpipe CO₂ emissions of the different vehicle concepts over a mileage of 180'000 km

The tailpipe CO₂ emission over 180'000 km of the NGV-hybrid vehicle are 9'360 kg or 36% lower than those of the gasoline vehicle. The gasoline-hybrid and the conventional NGV show very similar tailpipe CO₂ emissions in the assumed vehicle use.

The fuel costs of a natural gas hybrid vehicle and its comparison with conventional gasoline vehicles is strongly influenced by the operation (city, rural, motorway) and the natural gas – gasoline fuel price difference. The impact of these two conditions can be quantified by assuming different operational profiles and different fuel prices as shown in Fig. 16.

Fig. 16 Sensitivity analysis regarding operational modes (share of city, rural and motorway driving) and fuel price difference (-0.522 EUR/l gasoline equivalent as actual situation in CH)

The sensitivity analysis shows, that the additional costs of a natural gas-hybrid vehicle are fully compensated at 100% city driving up to a fuel price difference of 0.0449 EUR/l. At mixed operation, the additional vehicle costs are fully compensated until the end-user fuel price difference falls below about 0.578 EUR/l. If the end-user fuel price difference increased to 0.85 EUR/l or even 0.98 EUR/l, a natural gas hybrid vehicle is 3'000 – 5'000 EUR cheaper over 180'000 km than a conventional gasoline vehicle.

If taxations, insurance cost etc. differs significantly for a country or region of interest, the reader can significantly repeat these calculations with adapted numbers and draw conclusions for the respective case.

SUMMARY/CONCLUSIONS

Today's natural gas passenger cars achieve a range of typically 400 – 450 km running on the gaseous fuel. Due to increased powertrain efficiency, natural gas hybrid vehicles would achieve a range of about 500 – 600 km with the same gas storage concept. Due to the higher density of natural gas at lower ambient temperature, the range of NGVs is increased during winter time by about 50 km. Further improvements on the gas storage due to optimized under-floor designs will allow additional range extensions of natural gas vehicles, which could make these powertrains very widely applicable.

The combination of actual “average technology” natural gas powered internal combustion engines and electric hybrid electric powertrains allows a tailpipe CO₂ reduction of 36% assuming a usage scenario of 25% urban, 50% rural and 25% motorway driving. Taking into account the lower well-to-tank CO₂ burden of natural gas (0.593 kg CO₂ eq./kg fuel) compared to gasoline (0.768 kg CO₂ eq./kg fuel) [8], the CO₂ reduction on a well-to-wheel approach is even higher.

A today's natural gas hybrid powertrain for mid size passenger cars with 1'687 kg curb weight would achieve 85 g CO₂/km in the NEDC, which is clearly below the target CO₂ limit of the European Commission for the mean new passenger car fleet in 2020. Taking into account a general fuel consumption reduction of 5% until 2020 due to general enhancements in vehicle and engine technology, mid-size passenger cars with natural gas hybrid powertrains would achieve CO₂ values below 80 g/km.

Further CO₂ reductions are possible using blended bio-methane. Because bio-methane is chemically comparable to natural gas, no problems for the operation of gas vehicles have to be expected for low and high biomethane contents.

The specialty of natural gas hybrid powertrains however is the fact, that the CO₂ reduction of nearly 40% is “free of charge” for the end-user over a life time of 180'000 km. NGV hybrid technology could therefore be especially interesting for vehicle fleets of companies which want to reduce their greenhouse gas emissions and focus on total costs of ownership. Such a strong CO₂ reduction is not possible with any other fuel or powertrain technology at so low costs.

REFERENCES

- [1] EU Commission, Climate Action; Road transport: Reducing CO₂ emissions from light-duty vehicles (2010)
- [2] D. Schreiber et al.; Particle Characterization of Modern CNG, Gasoline and Diesel Passenger Cars; SAE-Paper 2007-24-0123
- [3] L. Guzzella and C. H. Onder; Introduction to modeling and control of internal combustion engine systems; Springer, Berlin, 2010
- [4] S. J. Pachernegg; A Closer Look at the Willans-Line, SAE Paper 690182
- [5] R. Alvarez et al; Effect of hybrid system battery performance on determining CO₂ emissions of hybrid electric vehicles in real-world conditions; Energy Policy (2010)
- [6] A. G. Boulanger, et al; Vehicle Electrification: Status and Issues; Proceedings of the IEEE, Vol. 99 (2011)
- [7] G. Wang; Advanced vehicles: Costs, energy use, and macroeconomic impacts; Journal of Power Sources (2011)
- [8] Swiss Centre for Life Cycle Inventories; Ecoinvent v2.2

CONTACT INFORMATION

Christian Bach

Empa
Swiss Federal Laboratories for Material Science and Technology
Ueberlandstrasse 129
CH-8600 Duebendorf

christian.bach@empa.ch

ACKNOWLEDGMENTS

The authors would like to thank the CLEVER-project and funding partners, working on natural gas hybrid powertrain:

- ETH Zurich, Institute for Dynamic Systems and Control
- ETH Zurich, Aerothermochemistry and Combustion Systems Laboratory
- Volkswagen AG Research
- Robert Bosch GmbH
- Swiss and German Technical and Scientific Associations for Gas and Water (SVGW, DVGW)
- Swiss Federal Office for Energy
- Swiss Federal Office for Environment
- Novatlantis – Sustainability in the ETH-Doma

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. This process requires a minimum of three (3) reviews by industry experts.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior written permission of SAE.

ISSN 0148-7191

Positions and opinions advanced in this paper are those of the author(s) and not necessarily those of SAE. The author is solely responsible for the content of the paper.

SAE Customer Service:

Tel: 877-606-7323 (inside USA and Canada)

Tel: 724-776-4970 (outside USA)

Fax: 724-776-0790

Email: CustomerService@sae.org

SAE Web Address: <http://www.sae.org>

Printed in USA

SAEInternational[®]