

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

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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/m³
- Net heating value (w/o inert gases): 31.61 MJ/m³
- 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:

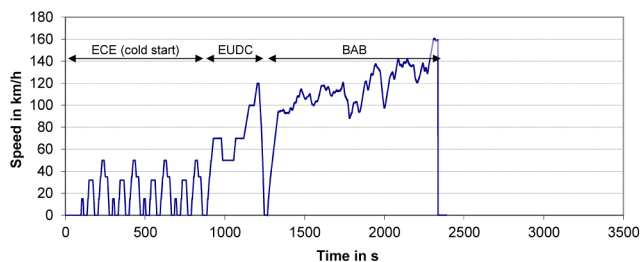


Fig. 1. Cold started driving cycle "L2" with sub-cycles NEDC (consisting of ECE, EUDC) and BAB (German "Bundesautobahn-Zyklus")

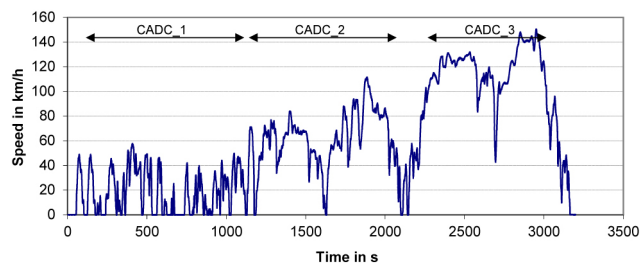


Fig. 2. Warm started Common Artemis Driving Cycle "CADC" with sub-cycles CADC_1, CADC_2, CADC_3, developed in the EU project "ARTEMIS"

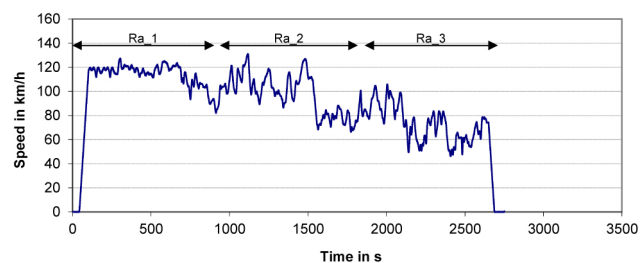


Fig. 3. Warm started driving cycle "Ra" with sub-cycles Ra_1, Ra_2, Ra_3 from a Swiss emission inventory program

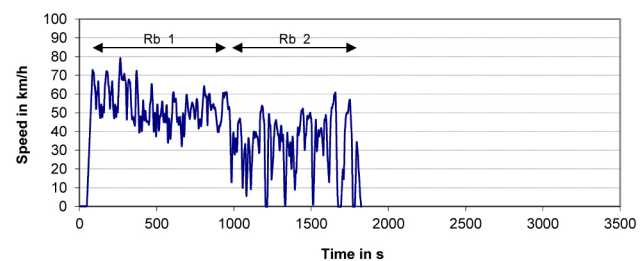


Fig. 4. Warm started driving cycle "Rb" with sub-cycles Rb_1 and Rb_2 from a Swiss emission inventory program

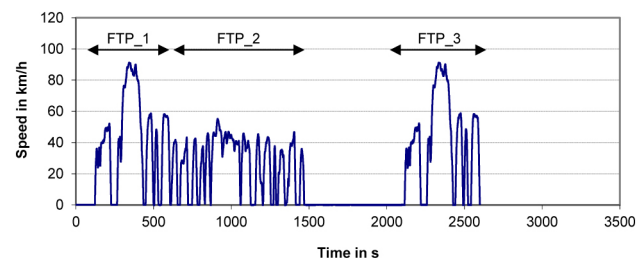


Fig. 5. Cold started driving cycle FTP-75 cycle with sub-cycles FTP_1, FTP_2, FTP_3 (U.S. mandatory emission test cycle)

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

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)

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:

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

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

$\overline{P_w^+}$ is calculated as follows:

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

- F_{wheel} is the wheel force
- v is the vehicle speed
- $t_{sub-cycle}$ 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).

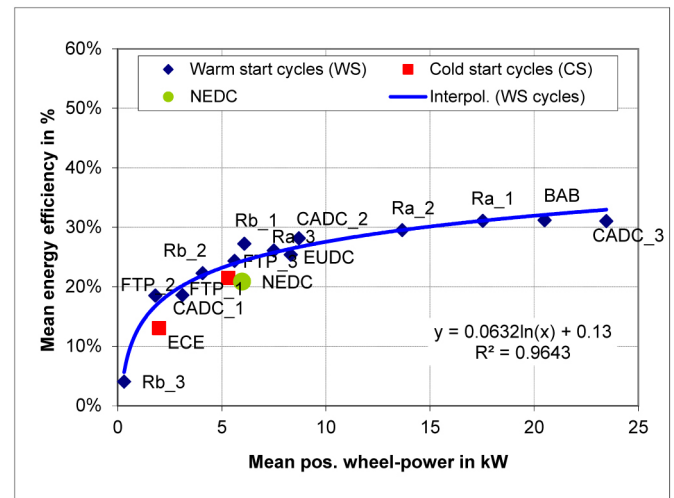


Fig. 6. Energy efficiency of a turbo-charged natural gas vehicle over mean positive wheel-power with logarithmic fit for 13 sub-cycles (the fit was performed with exclusion of the two cold start cycles)

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.