

Off-road Emission Performance of SUV with Diesel and Natural Gas Powertrain

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ABSTRACT

This study is based on a project which addresses the reduction of CO₂ and pollutant emissions of off-road vehicles. For this purpose the use of CNG drive trains in high alpine areas is an interesting alternative to the standard diesel technology. The same SUV with CNG and diesel powertrain has been measured and methodically compared with regard to fuel consumption and exhaust emission performance. These real-world measurements have shown the potential when applying a CNG concept for this utilization. Subsequently, the real-world on-board measurements were compared with the results of a simulation program for SUV off-road performance.

INTRODUCTION

Due to the alpine topography as well as their operational performance, off-road vehicles strongly affect the emissions in mountain areas. There are possibilities to reduce CO₂ emissions as well as to dramatically decrease the pollutant emissions of NO_x with alternative drive train concepts [1]. Gaseous energy sources, like natural gas and bio-methane, should become fundamental fuel supplies as they offer lower CO₂ and pollutant emissions thanks to their chemical composition and higher energy density. The research project "COR" – Clean Off-Road – part of the Austrian Advanced Automotive Program (A3) aims to reduce the aforementioned emissions in sensitive regions of alpine nature. The high specialization of the equipment in the off-road sector and the low number of units in operation compared with on-road traffic have, in the past, shown this sector as negligible with regards to environmental impact. Over the years, driven by legislative pressure, the pollutant emissions from on-road vehicles have been cut down in such a way that off-road vehicles, despite

their small numbers, have become a significant factor in the environmental impact of mobile sources. Therefore, the application of low emission CNG powertrains at alpine conditions has been analyzed.

METHODOLOGY OF THE REAL-WORLD EMISSION MEASUREMENT

The scientific methodology of this study is divided into four main tasks (Figure 1):

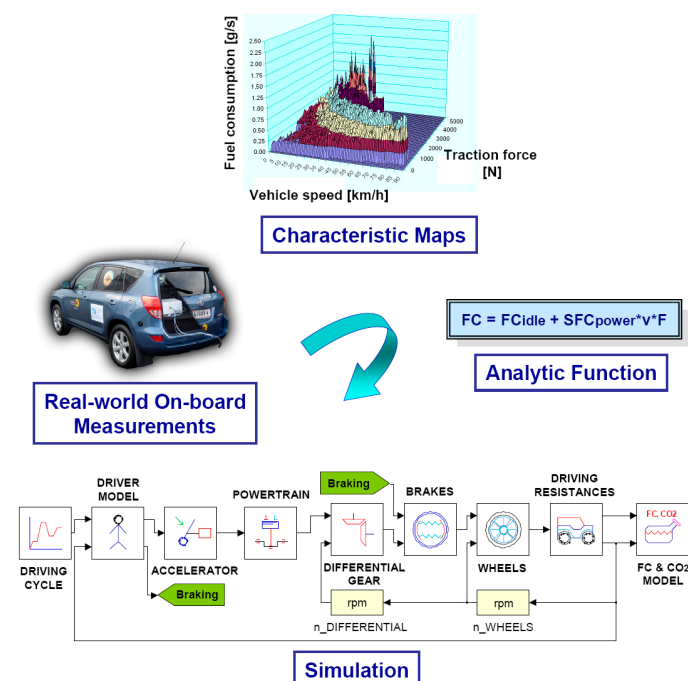


Figure 1: Methodology of the study

- Real-world on-board emission measurements
- Identifying specific fuel consumption by characteristic maps and developing analytic functions.
- Simulation of the fuel consumption for test drives by a Matlab-Simulink model.
- Validation of the experimental and calculation results.

REAL-WORLD EMISSION MEASUREMENT

For the off-road test drives a representative route in alpine region was selected, including sections with regular on-road driving conditions. The real-world measurement results constituted the data base to calculate the fuel consumption characteristic maps of the test vehicles.

ON-BOARD MEASUREMENT SYSTEM – For the exhaust emission measurements under real-world conditions the test vehicles were equipped with a newly developed experimental on-board measurement (OBM) device. The ultra compact OBM with a total weight of less than 15 kg (Figure 2) measures the emitted exhaust gas mass emissions of the vehicle in real-time without affecting the powertrain and vehicle characteristics. The gas concentration measurement works on the basis of a constant partial flow, which is taken from the exhaust gas in the tailpipe.

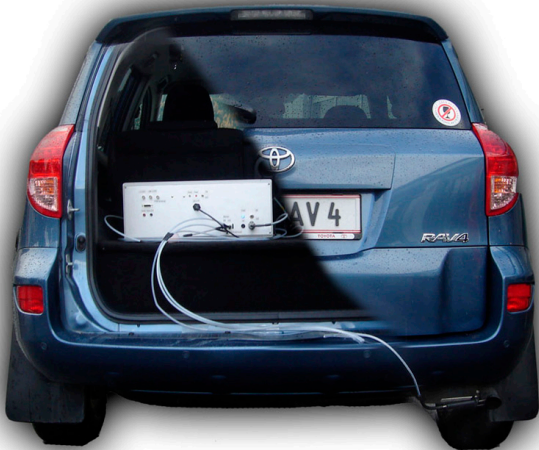


Figure 2: OBM installed in the test vehicle

Emission components measured by the OBM system were CO₂, CO, HC, NO_x, and O₂. The CO₂, CO and total HC concentrations were measured with non-dispersive infra-red absorption. Comparable investigations between infra-red and FID HC measurements showed satisfying results and provided a particular compensation function. NO_x and O₂ concentrations were detected using electrochemical sensors. The on-board measurement system is equipped with separate NO and NO_x channels. The NO_x channel was based on a laboratory

type electrochemical thick film ZrO₂ sensor. However, the post processing of the measurement results was only completed for the total NO_x emissions.

Combined with the intake air mass flow and the vehicle speed, mass emissions of the exhaust gas for every detected component were calculated. The results can be observed in real time on the control subnotebook in the vehicle. For subsequent analysis, every second a complete data string was saved.

The OBM provides the following data:

- Air-fuel ratio.
- Exhaust gas mass flow.
- Exhaust gas mass emissions of the measured components in [g/s] and [g/km].
- Fuel consumption in [g/s], [l/100 km] or [kg/100 km] by means of carbon balance method according to EU Commission directive 1999/100/EC [2].

To determine the mass emissions, the application of a chemical reaction model [3] is required to calculate the time related exhaust gas mass flow (Figure 3).

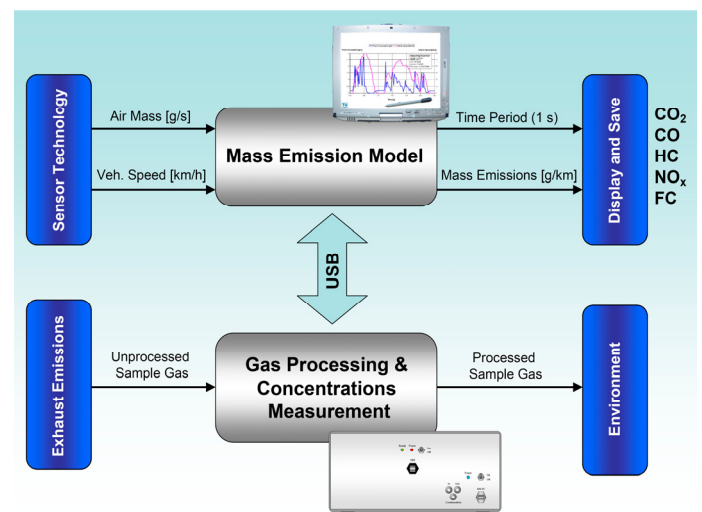


Figure 3: Exhaust gas mass calculation flow diagram

The distance related mass emissions are then calculated by means of equation 1, adopted from the European Council directive 91/441/EEC relating to measures to be taken against air pollution by emissions from motor vehicles [4].

$$M_i = \frac{V_{EG} * Q_i * k_H * C_i * 10^{-6}}{v} \quad (1)$$

where:

M_i ... mass emission of the pollutant i in gram per kilometer,

V_{EG} ... volume of the undiluted exhaust gas expressed in liters per second and corrected to standard conditions (273.2 K and 101.33 kPa),

Q_i ... density of the pollutant i in gram per liter at normal temperature and pressure (273.2 K and 101.33 kPa),

k_H ... humidity correction factor used for the calculation of the mass emissions of nitrogen oxides,

C_i ... concentration of the pollutant i in the undiluted exhaust gas expressed in ppm,

v ... vehicle speed corresponding to the operating cycle in km per second.

The fuel consumption is calculated by means of carbon balance method according to the following equations, from EU Commission directive 1999/100/EC.

For vehicles with a positive ignition engine fuelled with natural gas:

$$FC_{norm} = \frac{CH_f}{D} * (0.273 * CO_2 + 0.429 * CO + 0.749 * HC) \quad (2)$$

For vehicles with a compression ignition engine:

$$FC_{norm} = \frac{CH_f}{D} * (0.273 * CO_2 + 0.429 * CO + 0.866 * HC) \quad (3)$$

where:

FC_{norm} ... fuel consumption in kilogram per 100 kilometer in case of CNG or liter per 100 km in case of diesel,

CH_f ... fuel blend factor depending on carbon and hydrogen content in the fuel blend,

D ... density of the test fuel at 15°C,

CO_2 , CO , HC ... exhaust emission masses in gram per kilometer.

To link the geographic data of the drive test with the distance related mass emissions of the exhaust gas components a GPS tracking was used. Figure 4 shows an off-road section driven by both test vehicles. The multicolor track on the map shows the measured vehicle speed along the drive test. Also the measured exhaust emissions could be represented along the profile of the sections.

The extreme conditions of real-world measurements in the off-road area showed clearly that some adaptations of the meter had to be carried out. Due to the uneven road surfaces, arrangements were made to curb the acceleration of the measuring device.

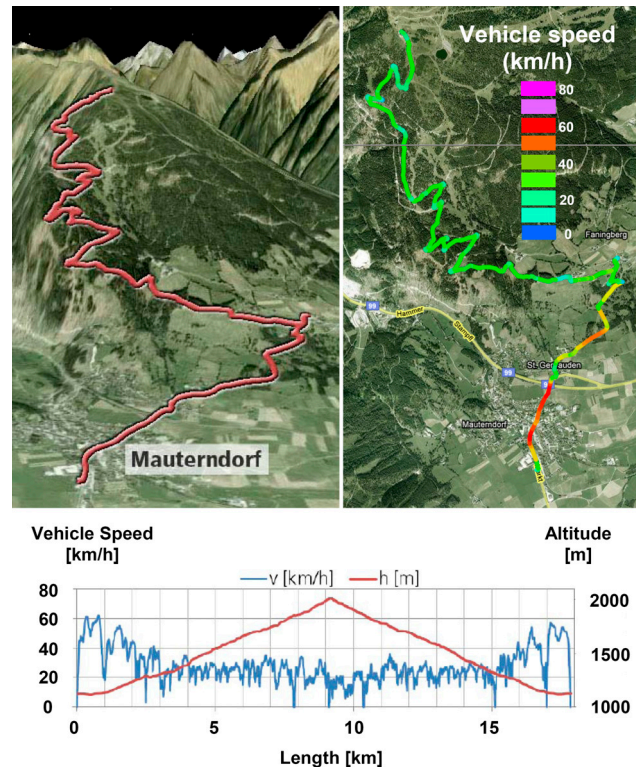


Figure 4: Altitude profile of the route “off-road uphill”

TEST VEHICLES – The same SUV, Toyota RAV4, with petrol and diesel powertrain was investigated for the study. Table 1 and Table 2 show the specifications.

Table 1: Specifications of the CNG SUV test vehicle

Toyota RAV4 2.0 VVT-i	
Power train / transmission	
Combustion engine	
Type	2.0 VVT-i
Working principle	4-Stroke naturally aspirated SI engine
Number of valves per cylinder	4
Displacement	1998 cm ³
Bore / Stroke	86/86 mm / mm
Compression ratio	9.8:1
Rated output	82 kW at 5900 rpm
Max. torque	145 Nm at 4000 rpm
Exhaust after treatment	3-way catalytic converter
Emission standard	EURO 4
Fuel consumption	N.A.
CO ₂ -Emissions	N.A.
Transmission	5-speed manual gearbox 4-wheel drive system
Chassis	
Chassis design	5-seat SUV
Drag coefficient, c_w	0.31
Measured in-test weight*	1840 kg
Mileage	8500 km

* The measured in-test weight includes two persons and equipment.