Fuel consumption and emissions investigation on a passenger car, operated with natural gas - hydrogen mixtures

Christian Bach, Thomas Bütler, Mathias Huber

Empa – Swiss Federal Laboratories for Materials Science and Technology,
Internal Combustion Engines Laboratory, Ueberlandstrasse 129, CH-8600 Duebendorf

christian.bach@empa.ch

Abstract

Pollutant emissions of road vehicles have been significantly reduced over the past 30 years. Quite literally, Euro-6 standard passenger cars do no longer contribute significantly to air pollution. Unfortunately, this is not true for CO_2 emissions. Mobility, contributing some 20 – 30% of the CO_2 emissions in Europe, is an important and relevant energy sector for the greenhouse-gas mitigation for many countries.

Natural gas has the potential to offer a clear and significant reduction of the CO_2 emissions of road vehicles at reasonable costs for several reasons: natural gas has a 25% lower energy-specific carbon content, it is comparatively cheap and can also be used in the important mid-size passenger car segment. Furthermore, future compliance with CO_2 legislation for passenger cars is much easier with natural gas than with gasoline or diesel powertrains.

Of course, natural gas is a fossil fuel, but the integration of renewable energy carriers is comparatively simple. While the blending of bio-methane produced during the fermentation of organic waste is state of the art in many countries, the blending of hydrogen or synthetic methane (power-to-gas) could further increase the share of renewable energy in future. The integration of biogenically or synthetically produced methane has only negligible impact on engine combustion characteristics, while in contrast the blending of hydrogen may change the combustion and emission behavior.

This paper shows results of experimental investigations on a passenger car, operated with methane as well as with hydrogen enriched methane (HCNG) in several driving cycles. It can be seen that the blending of 4 – 9 energy-% of hydrogen with methane leads to an engine efficiency increase up to 4%, even without engine modification. At the same time, significantly reduced HC and NOx emissions are measured at the tailpipe.

1 Introduction

Low cost electricity storage system with high capacities are of growing interest, due to increasing temporary and local decoupling of production, and the use of renewable electricity. Electrolytic hydrogen production represents such an electricity storage process, and is one which has been considered over recent years as part of new energy strategies (keywords: power-to-gas, e-gas, wind gas) [1]. In this process excess electricity is converted to hydrogen by electrolysis. This hydrogen may then be used either as motor vehicle fuel for fuel cell vehicles or for blending with compressed natural gas (HCNG) for gas vehicles. Alternatively, hydrogen could be used for further conversion with CO_2 to methane, to liquid fuels or for reconversion to electricity by combined heat and power cogeneration plants or fuel cell systems. These further conversion processes involve significantly higher energy losses and investment compared to the direct use of hydrogen in fuel cell or gas vehicles.

Decentralized on-site hydrogen production at sites where hydrogen can be used directly (e.g. H_2 and HCNG refueling stations, combined heat and power systems (e.g. operated on low-calorific-gas) would avoid expensive investment in hydrogen distribution infrastructure. While fuel cell vehicles remain quite expensive, at least for the near future, an economically interesting approach could be realized by blending hydrogen with natural. This seems to be possible with low concentrations (<10 vol%) into the gas grid and with higher concentrations (up to 30 vol%) at natural gas filling stations (with separate HCNG dispensers).

HCNG as fuel is fundamentally of great interest for fuelling internal combustion engines due to improved ignition and inflammation [4], [2], [4] and blending seems to be economically feasible if an end-user price of compressed hydrogen in the range 0.10 – 0.12 €/kWh could be achieved. Due to the stringent requirements of future CO_2-legislation for passenger cars and light duty trucks, this CO_2-free fuel component could assist both in achieving compliance with CO_2-limits as well as aiding the turnaround to renewable electricity production.

As a further advantage, gas vehicles do not depend on hydrogen blending. Therefore, the hydrogen addition could be reduced to periods where excess electricity is available, while the vehicles would be operated with pure natural gas (or bio-methane) when no excess electricity is available. This reduces the pressure to produce hydrogen at times where renewable electricity is short.

Blending hydrogen and natural gas also presents some challenges. Beside safety issues on the vehicle and filling station side, material degradation (mainly due to the embrittlement of unalloyed steel components in the fuel path of vehicles) must also be taken into account.

For the seasonal storage of electricity as well as for improving the methane production of biogas power plants, hydrogen may also be used for the methanation of biogenic CO_2. Since biogas consists of about 50% bio-methane and 50% biogenic CO_2, the methane production of biogas power plants can be almost doubled by methanation. This synthetic methane can then be stored by feeding it into the existing natural gas pipeline network.

In this project, a standard series-production CNG vehicle was used to investigate energetic fuel consumption, CO_2 emissions and regulated (and some unregulated) pollutant emissions during different driving cycles.

2 Experimental

2.1 Chassis dynamometer setup

Emissions and fuel consumption investigations were performed on a chassis dynamometer (Fig. 1) as used for emission tests according 692/2008/EC.

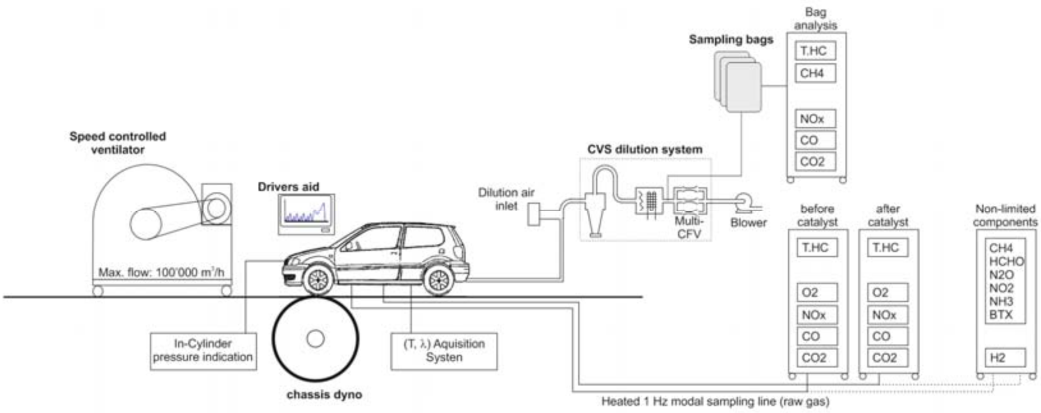

Figure 1: Chassis dynamometer setup with conventional bag analysis as well as online pre and post catalyst exhaust gas sampling and analysis points

The limited and some non-limited pollutant emissions (see Table 1) as well as the energetic fuel consumption calculated according the carbon balance method were measured in the official European Driving Cycle NEDC (Fig. 2) and in the real world driving cycle CADC (Fig. 3).

Pollutant emission	Sampling system	Measurement device	Manufacturer Type
T.CH	Bag, pre/post cat	H.FID	Horiba MEXA 7400
CO, CO_2	Bag, pre/post cat	NDIR	Horiba MEXA 7400
NO, NOx	Bag, pre/post cat	CLD	Horiba MEXA 7400
CH_4, HCHO, N_2O, NO_2, NH_3, BTX,	pre/post cat	FTIR	Gasmet CR-2000 S
H_2	pre/post cat	MS	V&F H-Sense

Table 1: Measured pollutant emissions components (before/after catalyst)

The impact of hydrogen blending on the position of the center of energy-conversion during the combustion was investigated using a Kistler KiBox® combustion analysis system. Using this technique, a shift of the center of energy-conversion to earlier crank-angles (CA) of up to 3.25 °CA for $HCNG_{4.1}$ and up to 5.25 °CA for $HCNG_{9.2}$ (see table 2 for fuel specification) was detected in the NEDC operational range (1720 – 4500 rpm, 10 – 50 % load). This can be attributed to a faster flame development phase when hydrogen is present [4].

The NEDC investigations were performed with the original methane-optimized ignition map (…/org) as well as with a modified ignition map (… /mod). In the modified ignition map, the center of combustion was corrected by retarding the ignition accordingly (constant crank angle position of 50% energy-conversion). All measurements were performed at least twice.

2.2 Driving cycles

Following driving cycles were used:

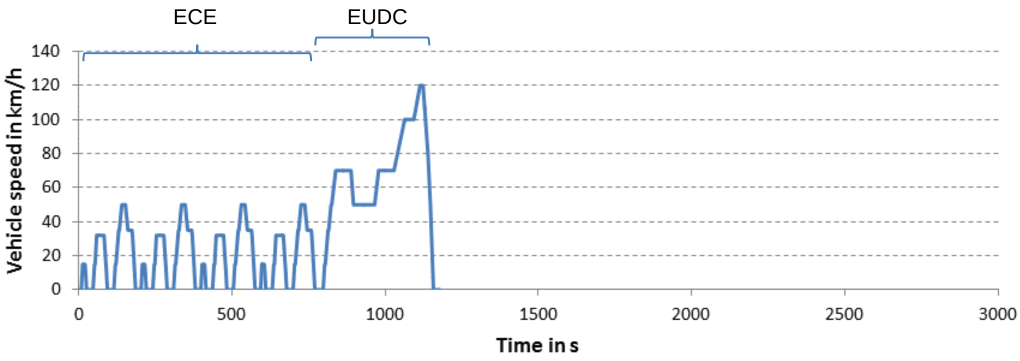

Figure 2: Official European Driving Cycle (NEDC)

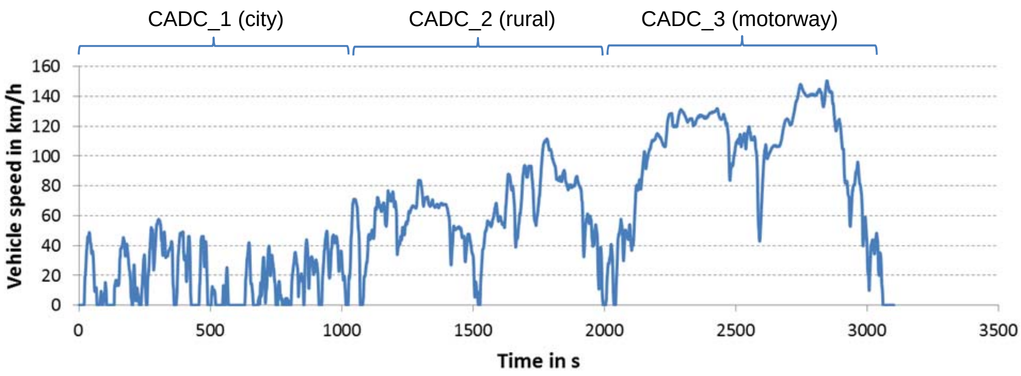

Figure 3: Artemis driving cycle (CADC)

2.3 Fuels used

Natural gas typically consists of methane (80 – 98 vol%), higher hydrocarbons (ethane, propane, butane; max. 10 vol%) and inert gases (CO_2, N_2; max. 10 vol%). Some specifications are standardized for the use as motor vehicle fuel [5] in Germany, such as minimum net heat value, density, methane number and maximum hydrogen content. Hydrogen is actually permitted up to a maximum value of 2 mol%. Adding more hydrogen – as proposed by this presentation – is therefore not possible within the DIN natural gas fuel specifications.

In our study, we used three types of fuel: pure methane (G20) and hydrogen-methane mixtures with 4.1 and 9.2 energy-% of hydrogen ($HCNG_{4.1}$ and $HCNG_{9.2}$). The impact on main fuel specifications is shown in Table 2:

Fuel Designation	**Fuel 1** G20	**Fuel 2** $HCNG_{4.1}$	**Fuel 3** $HCNG_{9.2}$
Vol.-fraction H_2 [vol%]	**0**	**15**	**25**
Vol-fraction CH_4 [vol%]	100	85	75
Energy-fraction H_2 [E-%]	**0**	**4.1**	**9.2**
Energy-fraction CH_4 [E-%]	100	94.9	91.8
Density at 15°C [kg/m^3]	0.632	0.549	0.494
Net heat value [MJ/kg]	49.65	51.18	52.48

Table 2: Specifications of fuels used

Beside energy related fuel specification changes, the impact of hydrogen blending on the knock behavior is of particular importance. This is normally described by the methane number, where high methane numbers mean high knock resistance. But in fact no standardized method for determining the methane number exists. Several methods are currently used, such as the methane number method of AVL dating from the 1970s or the E.ON GasCalc tool [6].

Combustion investigations show that hydrogen blending with natural gas has a significant impact during the ignition and inflammation phase but rather a low impact on global combustion in stoichiometric gas engines. Hydrogen blending improves the flame kernel formation which leads to less cyclic variations and a shortening of 0…5% combustion time. This, in contrast to what would be expected by lowering the methane number with hydrogen addition, reduces the tendency to knock, even if slightly higher combustion pressures and temperatures result.

2.4 Vehicle

The investigations were performed using a conventional Euro-4 passenger car with a stoichiometric 2.0 liter, 4 cylinder gas engine, equipped with a state of the art three-way catalytic converter and model based lambda control system.

3 Results

3.1 CO_2 emissions and energetic fuel consumption

The CO_2 emissions were directly measured in the driving cycles according the corresponding European Directive **Fehler! Verweisquelle konnte nicht gefunden werden.**. Figure 4 shows the CO_2 emissions reduction of the two HCNG fuels in % compared with pure methane operation (G20) over mean positive wheel power and mean positive acceleration. The impact of the corrected ignition map on CO_2 emissions is rather small (and therefore not shown in Fig. 4).

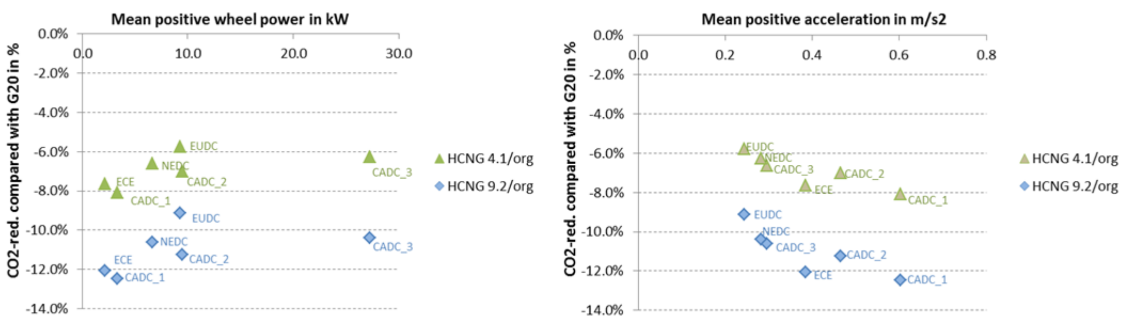

Figure 4: CO_2 emissions reduction in HCNG operation compared with G20 operation over mean positive wheel-power (left diagram) and over mean positive acceleration (right diagram)

CO_2 emissions are reduced by 5.8 - 8.1% with hydrogen blending of 4.2 energy-% and by 9.2 – 12.5% with hydrogen blending of 9.2 Energy-%. This disproportionate CO_2 reduction identifies an increased efficiency of the internal combustion engine during HCNG operation compared to G20 operation.

Figure 5 shows the energetic fuel consumption reduction of HCNG operation compared with G20 operation. The hydrogen blending of 4.1 energy-% improves the engine efficiency by 0.7 – 3.2% while the efficiency increase with 9.2 energy-% of hydrogen is 0.1 – 3.8%.

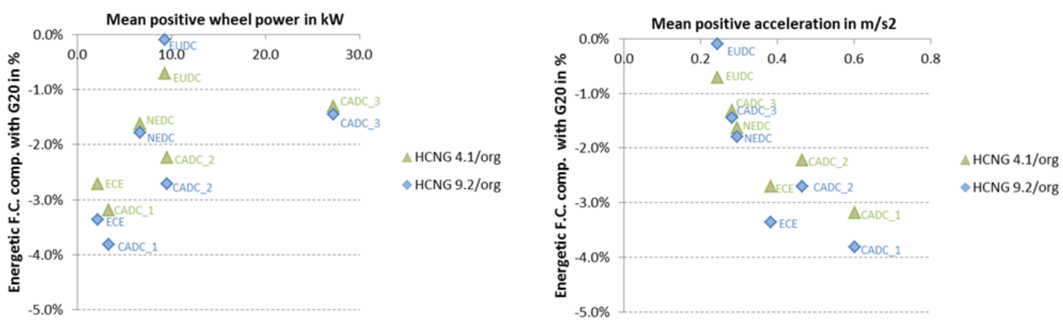

Figure 5: Energetic fuel consumption reduction in HCNG operation compared with G20 operation over mean positive wheel-power and mean positive acceleration

The efficiency increase correlates quite well with mean positive acceleration. The highest efficiency increase is observed during city cycles, which are characterized by low loads and frequent accelerations. The combustion analysis in NEDC-relevant operating points shows no de-throttling effect (Fig. 6) but a significant reduction in 0 – 5% and, for some reason, reduced 5-90% combustion duration, mainly at low engine speed (Fig. 7).

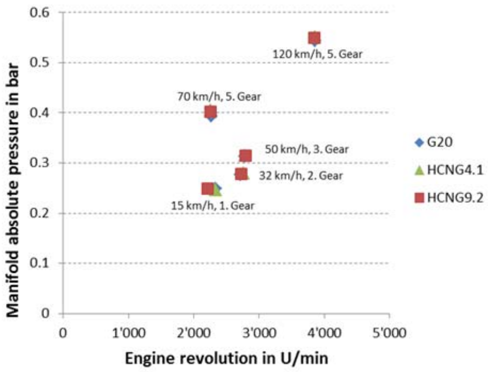

Figure 6: Absolute manifold pressure at different constant speed

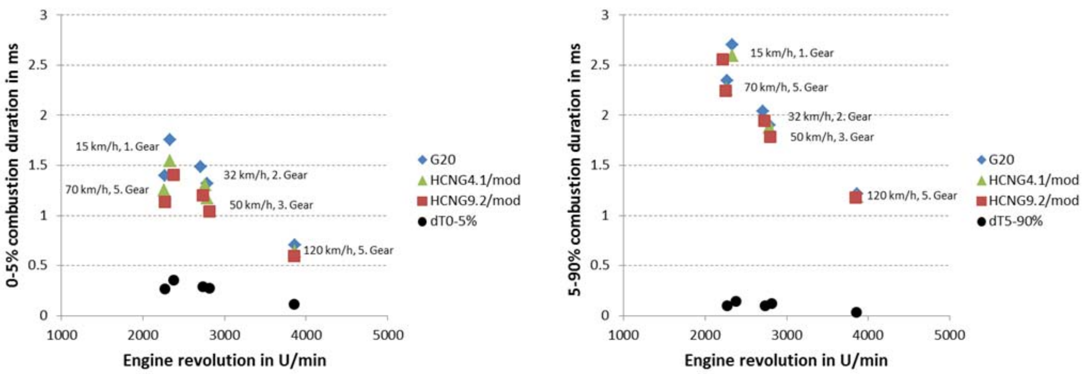

Figure 7: Combustion duration of 0-5% (left diagram) and 5-90% (right diagram) energy conversion

3.2 T.HC emissions

Hydrogen blending improves flame kernel formation and flame propagation, so lower HC engine out emissions and, as a consequence, reduced HC tailpipe emissions are expected. Fig. 8 shows that the T.HC tailpipe emissions reduction with $HCNG_{4.1}$ and original ignition map was 10 - 15%. This increased with $HCNG_{9.2}$ and original ignition map to 10 – 40%. The T.HC reduction due to HCNG operation with original ignition map could be increased significantly with the modified ignition map. In this case, the T.HC tailpipe emissions were reduced up to 76% (from 24 mg T.HC/km to 6 mg/km in EUDC).

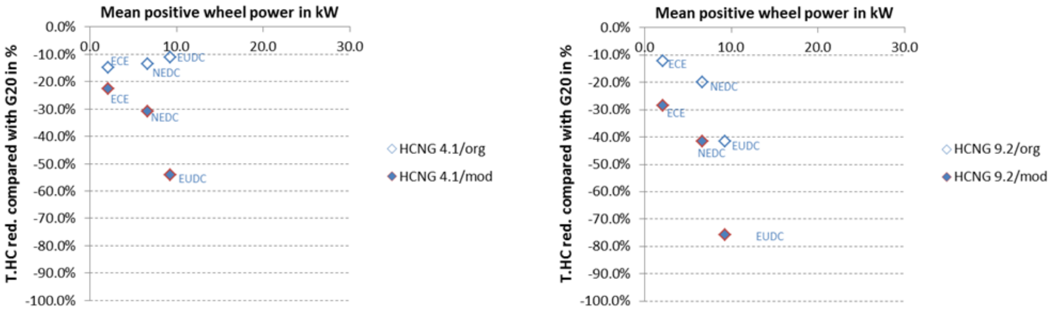

Figure 8: Tailpipe T.HC emissions reduction in HCNG operation compared with G20 operation over mean positive wheel-power for $HCNG_{4.1}$ (left diagram) and $HCNG_{9.2}$ (right diagram) with original and modified ignition map

As mentioned above, H_2 blending is expected to reduce HC engine out emissions. In our case, this reduction is about 45% in $HCNG_{9.2}$ operation with original ignition map and 50% with modified ignition map. Fig. 9 (left diagram) shows frequent T.HC peaks at load change in G20 operation, but no such peaks in HCNG operation.

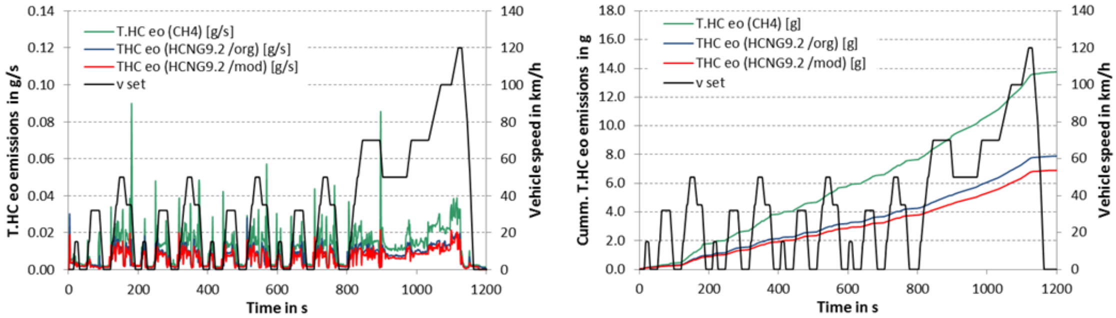

Figure 9: T.HC engine out emissions in G20 and $HCNG_{9.2}$ operation with original and modified ignition map.

On comparing T.HC engine out values (Figure 9) with T.HC tailpipe emissions (Fig. 8), it can be seen that hydrogen blending has a significant impact on engine out emissions, while the ignition map correction has a high impact on the catalytic T.HC conversion. This interesting effect is not fully understood and needs further investigation.

3.3 NOx emissions

NOx tailpipe emissions show similar behavior to T.HC tailpipe emissions (Fig. 10). The impact of H_2 blending with original ignition map is 0 - 20% for $HCNG_{4.1}$ and 20 - 30% for $HCNG_{9.2}$ operation. High tailpipe NOx emissions reduction of up to 55% ($HCNG_{4.1}$) and even up to 70% ($HCNG_{9.2}$) is achieved with the modified ignition map.

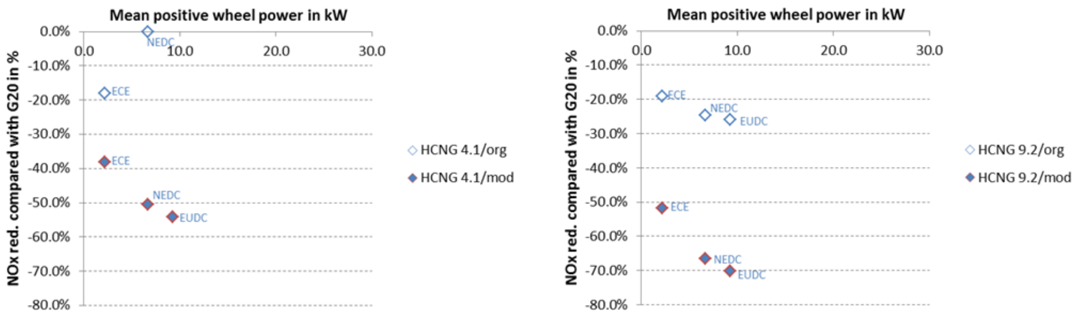

Figure 10: Tailpipe NOx emissions reduction in HCNG operation compared with pure CH_4 operation over mean positive wheel-power for $HCNG_{4.1}$ (left diagram) and $HCNG_{9.2}$ (right diagram) with original and modified ignition map

While H_2 blending improves the inflammation phase and reduces T.HC engine out emission, higher NOx emissions must be expected due to higher combustion temperatures. Fig. 11 shows that in NEDC the NOx engine out emissions increase with $HCNG_{9.2}$ and original ignition map by 25% and with modified ignition map by 8% only. Assuming a well-adapted ignition map, the impact on hydrogen blending on engine out emissions could be rather small.

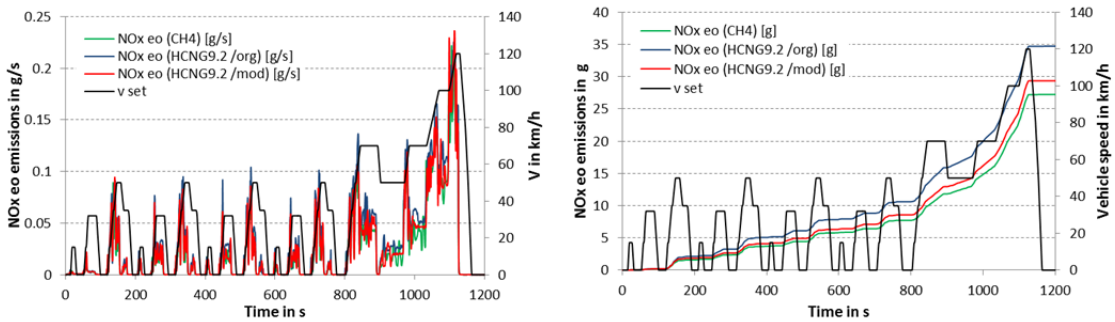

Figure 11: NOx engine out emissions in CH_4 and $HCNG_{9.2}$ operation with original and modified ignition map.

While the increase in NOx engine out emissions is clearly comprehensible, the strong NOx tailpipe emissions reduction with modified ignition map, shown in Fig. 10, need further investigation. Two main reasons could be responsible for the increased catalytic converter efficiency with modified ignition map at HCNG operation: improved conditions for the catalytic converter or more nearly optimal chemical exhaust gas mixtures for NOx conversion.

For the evaluation of the general catalyst conditions, the lambda sensor signal, the oxygen concentration and pre-catalyst temperatures were analyzed. During HCNG operation all these signals are very similar to the original and modified ignition map, and do not explain the higher conversion efficiency. The reason has therefore to lie in a more optimal chemically exhaust gas composition.

One obvious chemical reason for improved NOx conversion would be the potential SCR reaction of hydrogen in a three-way-catalyst (TWC). Figure 12 shows the H_2 engine out emissions for $HCNG_{9.2}$ operation with original and modified ignition map. In our case, no significant difference in H_2 engine out emissions with original and modified ignition map was detected. Therefore, a H_2 based NOx reduction does not explain the significantly improved catalytic NOx conversion efficiency with modified ignition map.

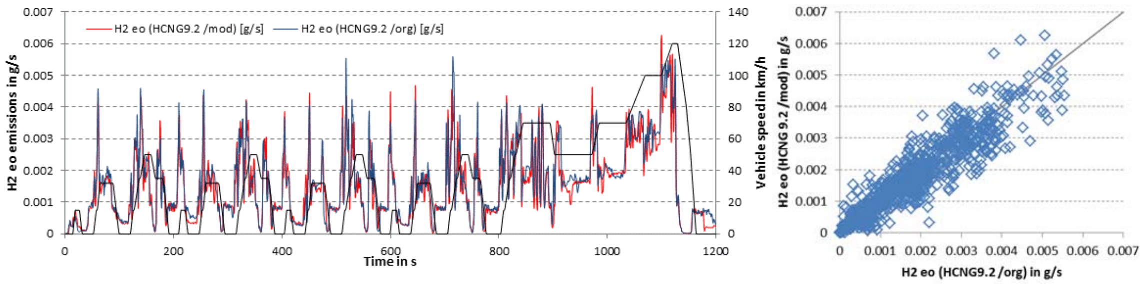

Figure 12: H_2 engine out emissions in $HCNG_{9.2}$ operation with original and modified ignition map.

Several other exhaust gas components, such as NO/NO_2 ratio, carbon monoxide, methane, propane, benzene, toluene, p-xylene, formaldehyde, nitrous oxide and ammonia were measured by pre-catalyst FTIR and analyzed regarding their dependency on the ignition map. For all these components only minor differences have been observed between the original and modified ignition map. Further research is necessary to explain the high and reproducible impact of the modified ignition map on catalytic NOx converter efficiency in HCNG operation.

4 Conclusions

As a result of the turnaround to renewable electricity production, hydrogen could be produced in large quantities from excess electricity and be used in the mobility sector. Economically interesting is the direct use of hydrogen without any further conversion. Decentralized production and blending with compressed natural gas at fueling stations is a cost effective possibility for the direct use of hydrogen as a fuel, compared to fuel cell vehicle operation. Due to the increase of the renewable fuel component in natural gas with ignition improving behavior and the resulting increase in efficiency, hydrogen blending with natural gas supports main trends in the development of internal combustion engines.

In parallel, pollutant emissions can potentially be significantly reduced with only minor modifications to the engine or catalytic converter. HC emissions are thereby already reduced during combustion due to improved ignition and inflammation phase with less misfiring and less cyclic variations while NOx engine out emissions are slightly increased. However, HC and NOx emissions are much better converted in the three-way catalytic converter during HCNG operation with adapted ignition map than in G20 operation.

However, challenges to be taken into account include hydrogen embrittlement of the gas cylinders, pressure regulator and injectors.

5 Literature

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