Unregulated Emissions with TWC, Gasoline & CNG

Czerwinski, J.; Zimmerli, Y. Hilfiker, Th.
AFHB, University of Applied Sciences, Biel, Switzerland

Bach, Ch.; Forss, A-M.; Heeb, N.
EMPA, Swiss Federal Laboratories, Dübendorf, Switzerland

Copyright © 2010 SAE International

ABSTRACT

Analysis of non-legislated engine-emission components, with different exhaust-gas after-treatment techniques, is an important air quality objective.

This paper reports the results for various nitrogen oxides, ammonia and differentiated hydrocarbons emitted at part load from a small 4-SI-engine. It was operated with gasoline, with CNG *) and with two different three-way catalytic converters.

CNG produces less HC and less aromatics. But the HC conversion rate is insufficient. This is due to the lower exhaust gas temperatures, at part load with CNG, and due to the higher stability of light HCs.

CNG affects the λ -regulation window, of the investigated system, such that the NO_x conversion rate is lowered.

In the rich domain of the λ -regulation window, the NO & NO_x emissions after catalyst were lowest, while the NH₃ formation was most intense, and vice versa.

The catalyst type: precious metal, and its content, influences the conversion rates and emissions of the investigated components during light-off.

INTRODUCTION

The potential of gaseous fuels to curtail engine emissions is, since many years, generally accepted. Lower emissions are mostly due to the much easier and consequently strongly improved gas mixture preparation.

Several investigations and engine developments have shown that compressed natural gas (CNG) is a cleaner fuel. Several manufacturers offer vehicle versions with CNG, mostly as dual-fuel design [1, 2, 3, 4, 5, 6]*).

The electronic systems for multipoint gas injection are continuously refined. This enables further improvements of the mixture preparation, mixture distribution on the individual cylinders and Lambda regulation, [6, 7, 8, 9, 10, 11, 12, 13].

During the development of new exhaust gas after-treatment systems, as well as with the introduction of alternative fuels, there is concern about several non-legislated emission components. These are recognized as especially toxic. Expert groups propose these as candidate substances for future limitations.

*) References & Abbreviations: see at the end of paper

The Swiss Federal Lab EMPA has a long tradition in the analyses of such substances for different national and international programs [14, 15, 16, 17, 18, 19].

This paper reports some results of collaboration between the IC-Engines Labs of the EMPA and of the University of Applied Sciences, Biel, Switzerland.

The tests were performed on a special research engine. It can be operated with gasoline and with CNG (both with MPI). The principal parameters, e.g. ignition- and injection timing and the air excess factor, can be varied by access to the ECU of the engine, [20].

The principal objectives of the study were to:

- Clarify the conversion behavior of different components, by varying the air excess factor λ in the lambda-window near to $\lambda = 1$.
- Investigate the cold start, warm-up and catalyst light-off with both fuels (gasoline & CNG) and with two different catalysts.

The on-line measurements of non-legislated substances like NO, NO₂, NH₃ and 7 differentiated hydrocarbons (see appendix) were done using the chemical ionization mass spectrometry (CI-MS) from EMPA.

TESTED ENGINE, FUELS, CATALYSTS

The engine used for investigations was a small 4-SI Lombardini LGW 523 OHC. Fig. 1 shows the engine in the test cell. The most important data of this engine are:

Lombardini LGW 523 OHC

2-cylinder, B/S 72/62 mm
Displacement 505 cc
Compression ratio 8.7
Max. RPM 5000 rpm
Max. Torque 37 Nm at 2200 rpm
Rated power 15 kW (20.4 HP)
Idling 1100 rpm
Water cooling
Multi-unit port injection

The Lombardini LGW engine was equipped with the electronic engine control system for ignition, multipoint injection and λ -regulation, already in the previous projects of the IC-engine Lab at the University of Applied Sciences, Biel. This system was modernized and completed with a second separate system for the multipoint gas injection. To provide enough gas flow, two gas injectors per cylinder were installed.

The electronic engine systems enabled variability of spark timing, of sequential injection timing and of injection duration.

The fuels used in the investigations are: gasoline (Swiss market quality) and compressed natural gas (CNG) from the Biel city net. Table 1 shows the most important data.

Fig.1: Lombardini LGW523 engine in the test cell

Fuel	Gasoline	CNG
Density ρ_{nf} [kg/m ³]	735	0.78
Lower calorific value H_u [MJ/kg]	42.5	49
Air _{min} (kg _{air} /kg _{fuel})	14.44	16.35
c/h	6.1429	3.0742

Table 1: Data of used fuels

An example of the average composition of the Swiss city net-gas is given in Table 2, [6]:

Component		Concentration [% vol]
CH ₄	Methane	93.97
C ₂ H ₆	Ethane	3.25
C ₃ H ₈	Propane	0.71
C ₄ H ₁₀	i-Butane	0.13
C ₄ H ₁₀	n-Butane	0.11
C ₅ H ₁₂	Iso-Pentane	0.05
C ₅ H ₁₂	n-Pentane	0.18
C _x H _y	Large HC molecules	0.12
N ₂	Nitrogen	1.29
CO ₂	Carbon dioxide	0.18
O ₂	Oxygen	<0.01

Table 2: Average composition of city net-gas (Biel)

Two catalysts with different coatings were used, Fig. 2. The data are given in Table 3.

Fig.2: Investigated catalytic converters

Manufacturer	ECOTEC	ECOTEC
Number	18603	18604
Diameter [mm]	70	70
Length [mm]	74.5	74.5
Volume [mm ³]	0.29	0.29
Cells/in ²	350	350
Precious metals [g/dm ³]	1.77	3.18
Pr. metal ratio [Pt : Pd : Rh]	05:00:01	00:14:01
Symbol	Pt / Rh	Pd / Rh

Table 3: Data of the investigated catalysts

MEASURING SET-UP & INSTRUMENTATION

Fig. 3 shows the scheme of the fuel system and the measuring set-up of this engine.

The instrumentation consists of:

- Schenck eddy current dynamometer W40
- Air flow: Degussa Deguflow, Typ 8740
- Fuel consumption:
Gasoline API-Com S.r.L. MP 324/R
Gases – RHEONIK Remag RHM 015 GNT
- Pressure indication system: Kistler – DATAC-1,
Pressure transducer Kistler Type 7061B
- Exhaust gas λ -measurement – Sonde λ NGK
- Exhaust gas components
Horiba: infrared analyzers for CO, CO₂, HC_{IR},
Magnos for O₂,
Flame ionization detector for HC_{FID},
Chemo-luminescent analyzer (CLD) for NO, NO_x
- Ambient conditions: pressure, temperature and humidity.

CHEMICAL IONIZATION MASS SPECTROMETRY

Mass spectrometric analysis of raw exhaust gas was performed at 180°C using a chemical ionization mass spectrometer (Airsense, V&F, Absam, Austria) in the

low energy ionization mode with mercury as ionization gas (Hg⁺, 10.4 eV). The presence of ammonia, NO, NO₂, C₂H₄, C₃H₆, C₄H₆, C₄H₈, C₆H₆, C₇H₈, and C₈H₁₀ was tracked in the selective ion monitoring mode (SIM) recording cations at m/z = 17, 30, 40, 28, 42, 54, 56, 78, 92, and 106 amu respectively, at low ionization gas pressure. Calibration of the CI-MS was performed prior to every test run applying calibration gas standards in synthetic air.

Fig.3: Fuel system and measuring set-up of the 2-cyl. LGW engine

Correction of chemical background, compensation of retardation effects and integration of the obtained emission profiles, were performed after the test run.

CI-MS measurements were validated with independent methods based on gas chromatography flame ionization detection (GC-FID) for hydrocarbons [16] and with fourier transformation infrared spectroscopy (FT-IR) and ion chromatography (IC) for ammonia [17]. As reported, correlation with these independent methods were convincing at comparable sampling methods. Raw gas sampling was strongly recommended for ammonia measurements [17].

TEST PROCEDURES

According to the objectives of the study, two types of test procedures were applied:

For the investigation of conversion of the gaseous components near to $\lambda = 1$, the engine was operated at two stationary operating points. These are: 2000 rpm / 2 bar and 2000 rpm / 4 bar [n/pme], which are generally recognized as representative for the average part load operation during city driving.

The objective was to investigate changes of reduction and oxidation near to $\lambda = 1$. Hence, the λ -variations in the λ -window were performed in small steps. The values of Lambda were estimated in two ways: by means of a continuous λ -sonde, and by calculating with the Brettschneider equation [21].

Investigations of the cold start & warm-up of the engine were done with the engine cooled down to the ambient temperature (approx. 20°C). Before cooling down, the engine was operated at the operating point 2000/ 2 [rpm/bar] with setting of α_z , λ and $\alpha_{throttle}$ for this point. These settings were kept for the cold start.

All the test series were performed with both fuels (gasoline & CNG) and with both catalysts (Pt/Rh & Pd/Rh).

RESULTS

Emissions in the λ -window

Prior CNG investigations showed no conversion of NOx with the activated λ -regulation (λ -regulation can be activated and deactivated by the ECU of this engine.) A careful variation of λ in small steps should clarify this.

Fig. 4 shows an example of NOx-conversion rate, as a function of Lambda, for the two fuels and two catalysts at 2000 rpm / 2 bar. With the measured λ and CNG, richer λ -values are indicated, than the calculated λ (differences of Lambda are small 0.010 to 0.015). Nevertheless, this is enough to provoke too much leaning and the strong decrease of conversion rate with CNG (moving of the λ -window to the rich side). The results were similar at the operating point 2000/4,.

After some repetitions and careful scrutiny of all possible error sources, the primary reason of the different behavior with CNG was identified. It is the change of λ -signal, due to the cross sensitivity of the λ -sensor against some of the CNG exhaust components. Buglass et al. [22] show that particularly H_2 has a significant influence in this respect. The influences of other possible reduction agents (CH_4 , aromatic HC, NH_3) are much weaker.

Depending on fuel and catalyst type, ammonia (NH_3) is produced, which depends on temperature and on the equivalence ratio λ . Fig. 5 shows the results of Lambda variations in the λ -window near to $\lambda = 1$. In the rich, reducing conditions, there is more formation of

ammonia but no NO (which is reduced by ammonia). In the lean oxidizing conditions, this relationship is inverted: no ammonia, but much NO. With gasoline the ammonia production is more intense, due to higher exhaust gas temperatures.

$\alpha_z=40^\circ\text{CA}$ b. TDC, $\alpha_{throttle}=\text{const.}$

Fig.4: NO_x conversion efficiency in the λ -window with measured an calculated λ

$\alpha_z=40^\circ\text{CA}$ b. TDC, $\alpha_{throttle}=\text{const.}$

Fig.5: Emissions of NH_3 and NO in the λ -window with different fuels and catalysts

The Pt/Rh-catalyst shows increased NH_3 or NO production at slightly richer conditions ($\Delta \lambda \leq 0.01$), than the Pd/Rh-catalyst.

Fig. 6 shows the comparison of NO_x and NO_2 values measured with different methods at $\lambda = 1$. The NO_x values, obtained with CI-MS (Airsense), are generally comparable with those of CLD (except for CNG Pd). The correlation is good. The NO_2 -values with Pt-catalyst are higher, than with Pd-catalyst.

2000 rpm, 2 bar, $\lambda=1.02$,
 $\alpha_z=40^\circ\text{CA}$ b. TDC, $\alpha_{\text{throttle}}=\text{const.}$

Fig.6: Comparison of NO_x - and NO_2 - values measured with different methods

The CNG hydrocarbons HC are not well oxidized, Fig. 7. The most important reason for it is the low exhaust gas temperature, at this part load operating point. Methane, the principal HC component of CNG, is a very stable molecule and needs higher temperatures to be oxidized in catalysts. Thus the oxidation of light HCs, as well as the exothermic heating, are inactive.

The CNG engine-out HC-emissions are lower than with gasoline. Nevertheless, the emissions after the catalyst with CNG are higher, at this part load operation, due to the lower catalytic conversion.

Fig. 8 shows the oxidation (above $\lambda = 1.01$) of some unregulated HC-components, with gasoline and with both catalysts. The Pt/Rh-catalyst shows the increase, i.e. lower oxidation intensity of HC at slightly richer conditions ($\Delta \lambda \leq 0.01$), than the Pd/Rh-catalyst.

Fig. 9 demonstrates some aromatic HC emissions at $\lambda = 1$ with both fuels and both catalysts. Very low emission levels for aromatic hydrocarbons are observed for CNG.

Aromatic hydrocarbons substantially contribute to the overall HC emissions of the gasoline engine, but were low for the CNG engine. Aromatic hydrocarbon emissions increase by an order of magnitude at $\lambda < 1$. At low air-to-fuel ratios, benzene levels exceeded those of toluene and C2-benzenes. It was reported that benzene is formed de novo over a Pd-containing TWC under fuel-rich conditions [23, 24]. Alkylbenzenes such as toluene and C2-benzenes were found to be the benzene precursors. We hypothesize

that similar processes occur in the examined catalysts.

Emissions at cold start & warm-up

Following Figures show the plots of unregulated hydrocarbons emitted during the cold start & warm-up with Pt/Rh-catalyst: Fig. 10 with gasoline and Fig. 11 with CNG. After reaching the light-off temperature of the catalyst, almost all components are efficiently oxidized.

$\alpha_z=40^\circ\text{CA}$ b. TDC, $\alpha_{\text{throttle}}=\text{const.}$

Fig.7: HC conversion rate in the λ -window with different fuels and catalysts

$\alpha_z=40^\circ\text{CA}$ b. TDC, $\alpha_{\text{throttle}}=\text{const.}$

Fig.8: Some unregulated HC in the λ -window with gasoline and different catalysts

2000 rpm, 2 bar, $\lambda=1.00$,
 $\alpha_z=40^\circ\text{CA}$ b. TDC, $\alpha_{\text{throttle}}=\text{const.}$

Fig.9: Some aromatics at $\lambda=1$ with different fuels and catalysts

2000 rpm, $M=0-4\text{Nm}$, $\alpha_z=40^\circ\text{CA}$ b. TDC, $p_B=3$ bar, $m_{\text{Air}}=8\text{kg/h}$, $\lambda=1$ with regulation

Fig.11: Unregulated HC during cold start & warm-up with Pt/Rh-catalyst and CNG

2000 rpm, $M=0-4\text{Nm}$, $\alpha_z=40^\circ\text{CA}$ b. TDC, $p_B=3$ bar, $m_{\text{Air}}=8\text{kg/h}$, $\lambda=1$ with regulation

Fig.10: Unregulated HC during cold start & warm-up with Pt/Rh-catalyst and gasoline

The light-off with CNG is generally earlier (approx. 100s). The emission level with CNG is clearly lower, than with gasoline. With the other catalyst (Pd/Rh), the relationships are very similar and are not further represented.

The comparison of NO, NO₂ and NH₃ plots, with both fuels and both catalysts, is illustrated in Fig. 12.

With gasoline, there are similar results for both catalysts. However, there are different light-off times (Pt-cat. is quicker for NO, but slower for NH₃). At stationary operation, there is a remarkable emission of NH₃ (approx. 200ppm with Pt-cat. and approx. 300 ppm with Pd-cat.)

With CNG, the plots are not similar for both catalysts. Particularly in the period until the light-off cannot be clearly attributed to the different catalyst. After the light-off, clearly the Pt-cat produces more NH₃ and less NO, than the Pd-cat, which produced more NO but considerably less NH₃.

Finally, the cold start attempts were carefully prepared and performed according to the same schedule. It was not possible to perform more repetitions of the same test, to demonstrate the repeatability of emission behavior. Nevertheless, the presented results of single trials contain several consistent and valuable indications.

2000 rpm, $M=0-4\text{Nm}$, $\alpha_z=40^\circ\text{CA}$ b. TDC, $p_B=3\text{ bar}$, $m_{\text{Air}}=8\text{kg/h}$, $\lambda=1$ with regulation

Fig.12: Comparison of NO-, NO₂- and NH₃-plotts after cold start with both fuels and both catalysts

CONCLUSIONS

Following results were obtained:

- With CNG, the λ -regulation window is changed (moved to the rich side), due to the cross sensitivity of the λ -sensor to other exhaust constituents. This deteriorates the conversion rate of NO_x.
- In the rich domain of the λ -regulation window, ammonia is produced and conversion of NO is very good. Conversely, on the lean side, no ammonia is formed and NO conversion is poor. These effects depend on: fuel, catalyst type, temperature and air excess factor λ .
- The unburned hydrocarbons (HC) from CNG contain mostly methane, a very stable component. This together with lower exhaust gas temperatures with CNG, at part load operation, causes lower HC-conversion rates.
- With CNG, there are much lower emissions of aromatic hydrocarbons.
- Two different catalysts show different light-off behavior for different components. This is the effect of the catalytic precious metal and metal content.

The investigations showed, that scrutiny of the non-legislated emission components, offers several incentives for further improvements:

- With CNG, the adaptation of λ -regulation system and of the catalyst type are recommended.
- With gasoline, quite high ammonia peaks can result. These can be minimized by avoiding the λ -rich excursions and optimizing the catalyst composition.

NOMENCLATURE

AFHB	... Laboratories for IC-Engines & Emission Control University of Applied Sciences, Biel, Switzerland
B/S	... bore/stroke
CI-MS	... Chemical Ionization Mass Spectrometry
CLD	... Chemo-Luminescence Detector
CNG	... Compressed Natural Gas
CO	... carbon monoxide
CO ₂	... carbon dioxide
ECU	... Electronic Control Unit
EI	... end of injection [deg. CA] before intake valve closes
EMPA	... Swiss Federal Laboratories for Testing Materials
FID	... Flame Ionization Detector
Gas	... gasoline
HC	... unburned hydrocarbons (FID)
H _u	... Lower Calorific Value
L _{st}	... Stoichiometric air requirement
LGW	... Lombardini Gasoline Water-cooling
m	... mass
$\dot{m}$	... mass flow
M	... torque
MPI	... multipoint port injection
n	... engine speed
N ₂	... nitrogen
NO _x	... nitric oxides
p_{RG}, p_{CNG}	... pressure in the gas rail
p_{me}	... b.m.e.p (brake mean effective pressure)
p_{mi}	... mean indicated pressure
Pd	... Palladium
Pt	... Platinum
Rh	... Rhodium
t_{Exh}	... temperature measured near λ -Sonde
throttle	... throttle opening rate
TDC	... top dead center
TWC	... three way catalyst
WOT	... wide open throttle
$\alpha_{50\%}$	... crank angle of 50 % heat release
α_z	... spark angle
α_{zopt}	... optimum spark timing [deg. CA b. TDC] for the best torque
λ	... air excess factor ($m_{\text{air}} / m_{\text{air stoichiometric}}$)
4-S	... 4 stroke engine

REFERENCES

- [1] Bach Ch., Heeb N., Mattrel P., Mohr M.: Wirkungsorientierte Bewertung von Automobilabgasen. EMPA, Switzerland, Ber. Nr. 160'928/2, Januar 1998.
- [2] Kubesh J. T., Podnar D. J.: Ultra Low Emissions and High Efficiency from an On-Highway Natural Gas Engine. SAE Paper 981394, South West Research Institute.
- [3] Maier F.; Müller P.; Heck E.; Langen P.: Erdgasmotorkonzept mit EZEZ-Potential. BMW, MTZ 58(1997)9, S. 544.
- [4] Heck E.; Langen P.: Potential of Natural Gas Powertrain to meet EZEZ-Standards. 18. Intern. Wiener Motorensymposium 97, VDI Reihe 12, Nr. 306, Band 1, S. 327.
- [5] Stodart, A.; Aitchison, I.; Lapetz, J.: Emissions Performance of Bi-fuel CNG and Bi-fuel LPG Passenger Cars Using Sequential Multipoint Injection Systems. SAE Technical Paper 2001-01-1195.
- [6] Bach. Ch.; Rütter, J.; Soltic P.: Diesel- und Erdgasmotoren für schwere Nutzfahrzeuge, Emission, Verbrauch und Wirkungsgrad. EMPA Dübendorf, CH, MTZ 5/2005, S. 394.
- [7] Allgeier T.; Klenk M.; Landenfeld T.: Motorsteuerung für Erdgasfahrzeuge. Robert Bosch GmbH, 3. IAV-Symposium 2001, Berlin.
- [8] Allgeier T.; Klenk M.; Landenfeld T.: Bewertung alternativer Kraftstoffe für den Einsatz im Krafffahrzeug. Robert Bosch GmbH, VDI-Tagung Innovative Fahrzeugantriebe 2002, Dresden.
- [9] Czerwinski J.; Comte P.; Janach W.; Zuber P.: Sequential Multipoint Trans-Valve-Injection for Natural Gas Engines. SAE Technical Paper 1999-01-0565.
- [10] Czerwinski, J.; Comte, P.: Influences of Gas *quality on a Natural Gas Engine*. SAE Technical Paper 2001-01-1194.
- [11] Czerwinski, J.; Comte, P.; Zimmerli, Y.: Investigations of the Gas Injection System on a HD-CNG-Engine. SAE Technical Paper 2003-01-0625.
- [12] Allgeier T.; Klenk M.; Landenfeld T.: Advanced Emission and Fuel Economy Concept using Combined Injection of Gasoline and Hydrogen in SI-Engines. SAE Technical Paper 2004-01-1270
- [13] Czerwinski, J.; Comte, P.: Addition of CNG and Reformer Gas to the Gasoline Fuelled SI-Engine. SAE Technical Paper 2004-01-0973.
- [14] Emmenegger, L.; Mohn, J.; Siegrist, M.; Marionov, D.; Steinemann, U.; Zumsteg, F.; Meier, M.: Int. J. Env. and Poll. 22 (2004) 326-341 "Measurement of ammonia emissions using various techniques in a comparative tunnel study".
- [15] Heeb, N.V.; Forss, A-M.; Bach, Ch.: Atmospheric Environment 33 (1999) 205-215 "Fast and quantitative measurement of benzene, toluene, and C₂-benzenes in automotive exhaust during transient engine operation with and without catalytic exhaust gas treatment".
- [16] Heeb, N.V.; Forss, A-M.; Bach, Ch.; Mattrel, P.: Atmospheric Environment 34 (2000) 1123-1137 "Velocity dependent emission factors of benzene, toluene and C₂-benzenes of a passenger car equipped with and without a regulated 3-way catalyst".
- [17] Mohn, J.; Forss, A.; Brühlmann, S.; Zeyer, K.; Lüscher, R.; Emmenegger, L.; Novak, P.; Heeb, N.: Int. J. Env. and Poll. 22 (2004) 342-356 "Real-time ammonia measurement in vehicle exhaust".
- [18] Heeb, N.V.; Forss, A-M.; Brühlmann, S.; Lüscher, R.; Saxer, C.J.; Hug, P.: Proc. 13th Int. Symp. Transport and Air Pollution, 149-156 "Three-way catalyst-induced formation of ammonia -velocity- and acceleration-dependent emission factors" (2004) Boulder.
- [19] Heeb, N.V.; Saxer, C.; Forss, A-M.: Ammoniak-Emissionen von benzinbetriebenen Euro 3-Personenwagen, EMPA, Untersuchungsbericht 203425
- [20] Urwyler, A.; Rubolino, P.: Untersuchungen verschiedener Emissionen im reinen Benzin-, Erdgasbetrieb, oder im Gemischtbetrieb mit RG. Projektarbeit Verbrennungsmotoren 2006, BFH-TI, Biel, CH.
- [21] Brettschneider, J.: Berechnung der Luft-Kraftstoff-Zusammensetzung mit der Abgasanalyse. Bosch Techn. Berichte, 1996 Heft 57.
- [22] Buglass J.G. et al.: Interactions between exhaust gas composition and oxygen sensor performance, SAE International, 982646, (1998)
- [23] Bruehlmann, S.; Forss, A.-M.; Steffen, D.; Heeb, N.V.: Environmental Science and Technology, 39, (2005) 331-338 "Benzene - a secondary pollutant formed in the three-way-catalyst".
- [24] Bruehlmann, S.; Novak, P.; Lienemann, P.; Trottmann, M.; Gfeller, U.; Zwicky, C.N.; Bommer, B.; Huber, H.; Wolfensberger, M.; Heeb, N. V.: Applied Catalysis B, Environmental, 70, 276-283, 2007 "Three-way-catalyst-induced benzene-formation: A precursor study".

Investigated unregulated exhaust emission components

Nitrous components: NH_3 , NO , NO_2

Appendix

Name (engl.)	Formula	Structure	Description	Exposure / Effect
Nitrogen monoxide	NO		Transparent gas, severe blood gas	Hazard category: T+, C, O
Nitrogen dioxide	NO_2		Reddish brown gas, acrid, penetrative odor, irritates the lung	Highly toxic, corrosive, can provoke headache, dizziness, breathlessness and pulmonary edema
Ammonia	NH_3		Is formed in the catalyst, with NO and H_2 , depending on lambda and the light-off temperature. acrid smelling, strongly hygroscopic gas, pronounced water solubility	Hazard category: C, N, T Highly toxic, soil acidification

It is also interesting to note the GHP-green house potential of some gases compared to CO_2 (based on mass, over 100 years) under complete oxidation to CO_2 :

compound	CO_2	CO	NMHC	NO_x	CH_4
GHP-green house potential	1	1-2	3 - 8	8	21

Information taken out of Climate Change, The IPCC Scientific Assessment, WMO/UNEP, J.T. Houghton, Cambridge University Press, 1990 (ISBN 0521 40720 6)

Hydrocarbons

The different substances are listed in order of their toxicity. The classes of danger can be found at the homepage of the Swiss Federal Office of Health, www.bag.admin.ch/themen/chemikalien/

Name (engl.)	Formula	Structure	Description	Exposure / Effect
Butadiene	C_4H_6		An unsaturated hydrocarbon	Hazard category: T carcinogenic, highly inflammable, toxic, ozone precursor
Benzene	C_6H_6	Mesomerism	Degraded in the atmosphere within 2-5 days, enhances anti-knock properties of gasoline.	Vapors are toxic, carcinogenic
C2-Benzene	C_8H_{10}	Benzene-ring + 2 CH_3 -groups	Hardly soluble in water but in Benzene. Enhances anti-knock properties of gasoline.	Hazard category: F, Xn Hazardous to waters Affects brain and nerves.
Toluene	C_7H_8		Aromatic hydrocarbon	Hazard category: F, Xn Neural-and renal damages, ozone precursor
Ethane	C_2H_4		An unsaturated hydrocarbon	Anaesthetic in high concentrations, has biological effects, ozone precursor
Propane	C_3H_6		An unsaturated hydrocarbon synonym: Propylene	Hazard category: F+
Butane	C_4H_8	$\text{CH}_2=\text{CH}-\text{CH}_2-\text{CH}_3$	A member of the alkane series	Hazard category: F+ narcotic