Use of blends of hydrogen and natural gas in urban vehicles in the transition towards an hydrogen economy

Agostino Iacobazzi [a], Maria Chiesa [b], Antonino Genovese [c], Ennio Rossi [d]

[a] Department of Energy Technologies
Casaccia Research Center
Italian National Agency for New Technologies, Energy and the Environment (ENEA)
iacobazzi@casaccia.enea.it

[b]Environmental Physics Department
Catholic University of Brescia (Italy)
maria.chiesa@unicatt.it

[c] Department of Energy Technologies
Casaccia Research Center
Italian National Agency for New Technologies, Energy and the Environment (ENEA)
antonino.genovese@casaccia.enea.it

[d] Department of Energy Technologies
Casaccia Research Center
Italian National Agency for New Technologies, Energy and the Environment (ENEA)
ennio.rossi@casaccia.enea.it

ABSTRACT:

The use of both hydrogen as a fuel and fuel cells as ultimate power technology can make the vehicles much more environmental-friendly, while in an early phase (in the short-medium term) the atmospheric emissions could be significantly reduced by using hydrogen mixed with natural gas (HCNG) with different percentages in internal combustion engines.

In this study the most polluting urban vehicles, garbage truck fleet and urban bus fleet, are concerned and a comparison analysis will be made between different hydrogen utilizations: in ICE vehicles with a blend of natural gas and hydrogen or in pure hydrogen vehicles.

Results of lab tests showed a fair improvement of the efficiency and of the CO_2 emissions of the ICEs when running on HCNG as well as an overall improvement regarding local pollutants.

KEYWORDS: *HCNG, hydrogen, ICE, carbon dioxide*

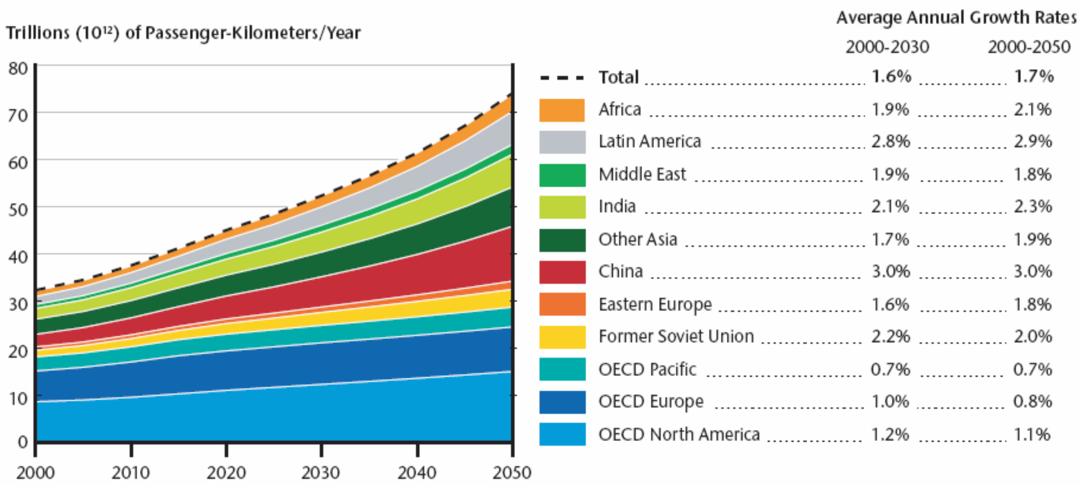
Introduction

The growing sector of transports rises a big alarm either for the day-by-day increasing number of vehicles and for the sensible contribution to the degradation of air quality in urban areas, as well as for the global pollution.

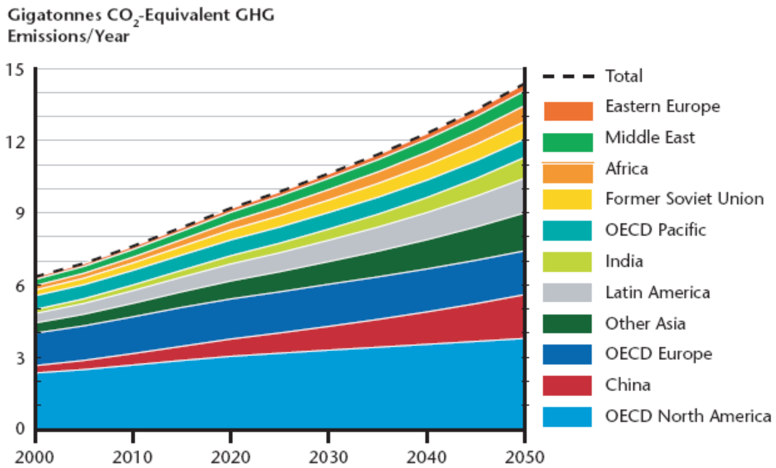
In Italy, with beyond 35 million of circulating vehicles, the consumption of primary energy, coming all from fossil sources, accounts for more than 30%, which roughly leads to a corresponding 30% increase in CO_2 emissions.

Worldwide carmakers foresee to produce, with a huge effort in terms of research and investments, non-harmful emission vehicles by 2015.
The European Union committed to the goal of reducing its dependence on imported fossil fuels (oil, natural gas, coal), by using at least 20% of alternative fuels within the year 2020; the corresponding commitment in the reduction of Greenhouse Gases (GHG) is the well-known 8% with respect to 1990 by 2012, as required by the Kyoto Protocol.
In Europe the sector of transports is responsible for the 25% of CO_2 emissions, 40% of which is related to the vehicles circulating in urban areas. External costs due to the degradation of air quality related to transports had been estimated in about 11.7% of EU GDP, corresponding to an outstanding value of 360 €/year per citizen.

Those alarming data have to be added to the contribution to the total emissions from the energetic sector (carbon dioxide, natural gas, nitrogen oxides, sulphur, aromatic compounds,….), which amounts at about 50% of the total. Deaths caused by the smog, due to particulates and other emissions, are about 8000 per year just for Italy; on the other side the global change becomes a “real” problem, with an increasing concern about GHG emissions. Nowadays a last-generation Euro4 car emits slightly less than 150 grCO_2/km, with scarce perspectives to be able to reduce, with fossil fuels, that value very much.
It had been worldwide agreed that the introduction of hydrogen as a “new” fuel could have contributed to the realization of a sustainable energy system in the long term (2050 and beyond); according to this vision, emissions of both global and local pollutants can be maintained under “safe” values.
Even if the transition towards a hydrogen-based economy will be surely very long, its sustainability is achievable since now, also considering the limitations in the substitution of conventional fuels with alternative ones, less polluting. Also the contribution of the introduction of biomass-derived fuels, for a limited quota of total consumption, is counterbalanced by the still growing demand of vehicles in the world. [1]



Source:
Sustainable Mobility Project calculations.



source: "Mobility 2030: Meeting the challenges to sustainability"
World Business Council for Sustainable Development, 2004

Even if it's difficult to forecast the future concerning the next decades, it has been agreed worldwide that climate change is closely connected with GHG emissions, so we may ask for some important decisions for the beyond-Kyoto years. The stabilization of CO_2 concentration at values not higher than 550 ppm (today's value is 380 ppm) requires a strong emissions reduction: some of the IPCC scenarios aiming at that values shows a required decrease of GHG of 40-60% with respect to 1990, which means a "real" reduction of 70-90% of the emissions with respect to the "business-as-usual" forecast.

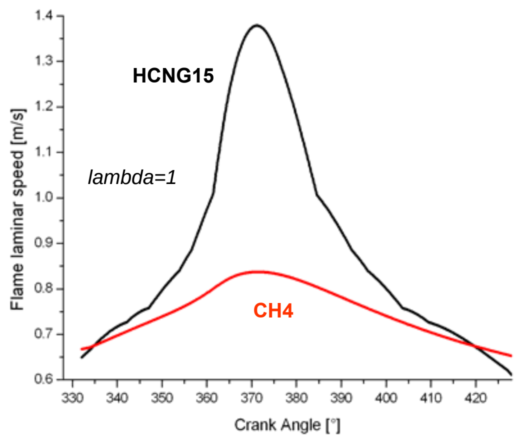
Such a reduction won't ever be achieved by using any actual available sustainable technology. Nevertheless, a "cultural shift" will be necessary, in order to reach that goal: the introduction of hydrogen as an energy carrier seems to be a real contribution to that goal, making possible, in the long term, the realization of a cleaner World.

Physical and chemical properties of Hydrogen and natural gas

	Hydrogen	Natural gas
Low Heating Value, kWh/kg	33.33	13.9
Flame temperature, °C	2045	1875
Flammability limits in air, % vol	4-75	5.3-15
Detonation limits, % vol	13-65	6.3-13.5
Ignition energy, °C	0.02	0.29
Ignition temperature, °C	585	540
Flame speed in air, m/s	2.65	0.4
Detonation speed, m/s	1.48-2.15	1.39-1.64
Diffusion in air, cm2/s	0,61	0.16

Unfortunately the introduction of hydrogen technologies requires a huge effort for the development of the related technologies in the field of production, distribution, storage and utilization of this fuel, as well as an enormous investment for the realization of the infrastructures. Furthermore, public awareness is very important for the introduction of hydrogen as a new fuel, in order to avoid unsustainable delays to this "Ultimate energy carrier".

A good opportunity in the short term can be represented by the utilization of blends of hydrogen with other fuels, first of all with natural gas (HCNG).
When used in an Internal Combustion Engine (ICE), even the addition of a small amount of hydrogen to natural gas (5-30% by volume, that means ~1.5-10% by energy) leads to many advantages, because of some particular physical and chemical properties of the two fuels.

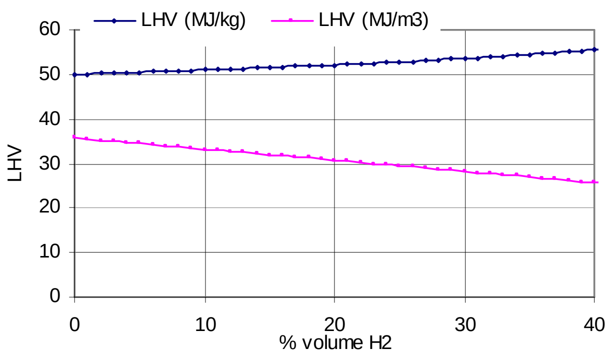


Methane has a slow flame speed while hydrogen has a flame speed about eight times higher; when the air/fuel ratio (lambda) is much higher than for the stoichiometric condition the combustion of methane is not as stable as with HCNG.

As a consequence of the addition of hydrogen to natural gas an overall better combustion had been verified, even in a wide range of operating conditions (lambda, compression ratio, etc.), finding the following main benefits:

- a higher efficiency
- lower emissions

Because of the characteristics of hydrogen, HCNG, despite its higher LHV per kg, has a LHV per Nm^3 lower, depending on the hydrogen content. Therefore, a natural gas engine, when fuelled with HCNG, shows a lower power output, while maintaining its better efficiency.



In case of turbocharged engines, power output can be increased again by a simple increase of the charging pressure, possible even because of the higher reluctance to detonation of hydrogen.

Experimental tests

Before starting the tests on the roller bench in Casaccia Research Centre (Rome, Italy), some considerations had been done in order to verify the potential benefits of this technology experimentally. According to literature [2-16] an analysis of utilization of HCNG had been done for two cases, comparing the benefits of using the blends with respect to natural gas:

- a garbage collecting vehicle fleet in Brescia (Italy)
- a urban bus fleet in Rome (Italy)

The following hypotheses had been done:

- Use of HCNG with 30% hydrogen by volume (HCNG30)
- $\text{Efficiency}_{HCNG} = 1.12 \times \text{Efficiency}_{NG}$
- $\text{HC emission}_{HCNG} = 0.71 \times \text{HC emission}_{NG}$
- $\text{CO emission}_{HCNG} = 0.83 \times \text{CO emission}_{NG}$

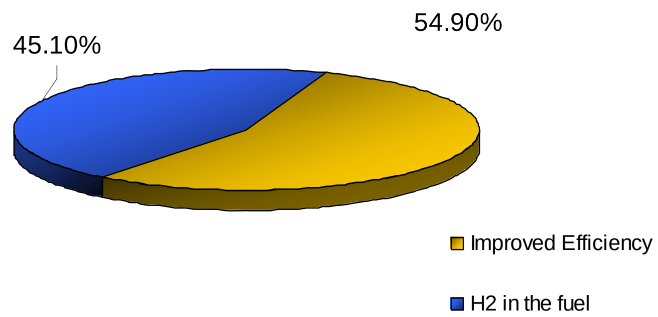
- NOx $emission_{HCNG}$ = 0.40 x NOx $emission_{NG}$

In the following tables the results are showed for both cases

Emissions for garbage collection fleet in Brescia			
Number of trucks	81		
Total km/year	2.3×10^6		
	Natural gas (t/year)	**HCNG30 (t/year)**	**ΔCNG**
HC	1.97	1.40	- 0.57
NOx	11.34	6.80	- 4.54
CO	8.91	7.38	- 1.53
CO_2	4668	3745	- 923

Emissions for urban bus fleet in Rome			
Number of buses	2709		
Total km/year	132.6×10^6		
	Natural gas (t/year)	**HCNG30 (t/year)**	**ΔCNG (t/year)**
HC	96.8	68.9	- 27.9
NOx	175.0	105.0	-70.0
CO	437.6	362.8	-74.8
CO_2	182,300	141,300	- 41,000

As far as CO_2 emissions are concerned it had been very important to evaluate the contribution of the different phenomena (increased efficiency, no carbon content of hydrogen in the fuel) to that reduction.



Contribution to the reduction of CO_2 emissions

The ratio of percent emissions reduction to percent hydrogen energy is a measure of the effectiveness of hydrogen utilization and it is called “leverage factor”. Hydrogen leverage is defined as the following ratio : (% Emissions Reduction)/(% Energy Supplied as Hydrogen).
The increased efficiency makes this value higher.

In this case the two fleets have a ~20% reduction in CO_2 emission by using 10% hydrogen by energy (30% by volume). The leverage of using hydrogen is 20%/10% = 2.0.
The meaning of this figure is that emission reduction with a fixed amount of hydrogen achievable with HCNG30 is the same of that possible with pure-H2 vehicles, only if H2 vehicles have an efficiency 2 times higher.

Another benefit of the leverage effect is that a CO_2 reduction is possible even if needed hydrogen is produced by natural gas without any “sequestration” of CO_2.

In the following table results from the analysis of this specific aspect of Brescia fleet are reported.

Emissions for hydrogen production from natural gas without CO_2 sequestration (case of Brescia)		
Carbon factor of NG	$kgCO_2/MWh_{NG}$	205
Steam reformer efficiency	%	80
CO_2 specific emissions	$kgCO_2/MWh_{H2}$	256
Total amount of H_2 needed	MWh_{H2}/year	2381
CO_2 emission from H_2 production	t/year	609.5
CO_2 reduction from HCNG use	t/year	923.8
CO_2 total reduction	t/year	314.3
	%	-6.7

In the framework of an EU Interreg IIIC project called BONG-HY (parallel application of Blends Of Natural Gas and Hydrogen in internal combustion engines and fuel cells) bench tests on a natural gas vehicle had been carried on one lab of the Casaccia Reasearch Center of ENEA. The main Italian partners involved in the project had been the Municipality of Brescia (lead partner), ASM SPA (the energy multiutility of Brescia), the Catholic University of Brescia, the University “Tor Vergata” of Rome and ENEA.

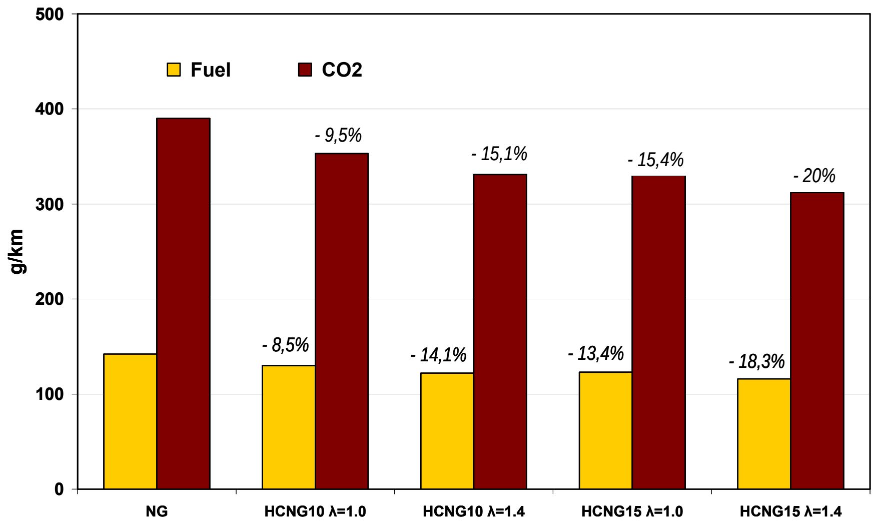
'ECO NG Daily during tests at ENEA

The vehicle was an IVECO Daily, belonging to the ASM fleet, that had been mainly modified in the control system for the first optimization with two different blends.

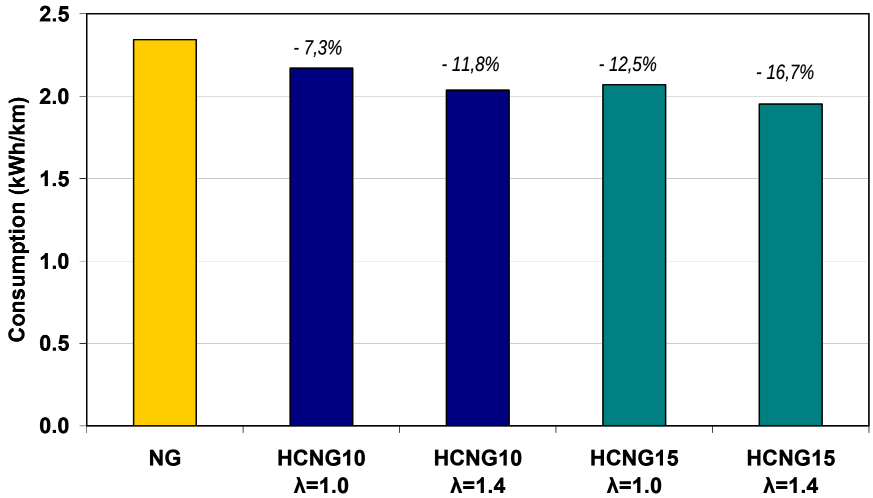
Two blends had been tested, characterised by 10 and 15% by volume in hydrogen (HCNG10 and

HCNG15) and used as a fuel for the "urban part"
of the ECE-15 driving cycle. The main parameters that had been investigated are lambda (with values of 1 and 1.4), different ignition advance angles and different values for the enrichment of the blends during transients.

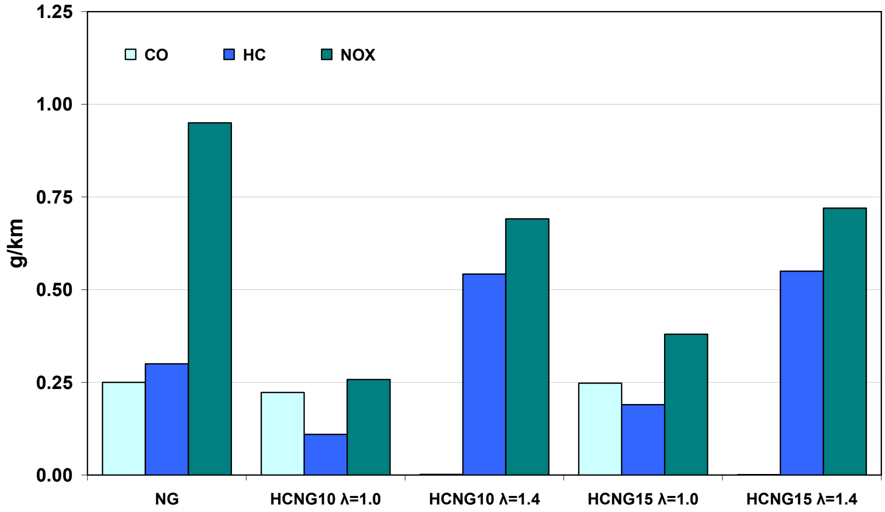
In the following pictures the obtained values for both the consumption and the emissions in the first 6-month test campaign for different operating conditions are showed.



Gas consumption and GHG emissions for different contents of hydrogen in HCNG



Energy consumption for different contents of hydrogen in HCNG



Local emissions for different contents of hydrogen in HCNG

Conclusions

Many aspects of the technology have still to be investigated, but its potential seems to be very promising. Probably different ICE models present different behaviours so it would be very interesting to carry out some “field” tests for different vehicles, in different operating conditions and with different hydrogen contents in HCNG. In any case, for percentages of hydrogen less than 30-40% vol, above which important corrosion phenomena can occur, the modifications required to the vehicles are minimal, mainly concerned with a different setup of the control system. Furthermore, the existing refuelling stations for NG can be adapted in order to supply HCNG simply by adding an “hydrogen line” of limited capacity, since the mixing of the two gases is made directly by the dispenser during the filling of the vehicle.

The use of HCNG can allow a significative reduction of both global (GHG) and local pollution in the short term and with limited money investments.

In the meantime, this technology could represent a “bridge” toward the introduction of pure hydrogen vehicles into the market, allowing the realization of hydrogen infrastructures before the diffusion of fuel cell vehicles.

References

[1] The Sustainable Mobility Project, *Mobility 2030: Meeting the challenges to sustainability, World Business Council for Sustainable Development, Switzerland, 2005*

[2] Riddell, B., *Malmo Hydrogen and CNG/Hydrogen filling station and Hythane bus project, Carl Bro Energiekonsult AB, Sweden, 2004*

[3] Tunestal P., Einewall P., Stenlaas O., Johansson B., *Possible short term introduction of hydrogen as vehicle fuel/fuel additive*, P. Duret and Editions Technip, Paris, 2004,
[4] Karner D., Francfort J., *Freedom car & vehicle technologies program – Advanced vehicle testing activity- Arizona public service- Alternative fuel (Hydrogen) pilot plant, US DOE*, 2003
[5] Dembski N., Rizzoni G., Soliman A., Fravert J., Kelly K. *Development of Refuse Vehicle Driving and Duty Cycles,* SAE TECHNICAL PAPERS SERIES, 2005
[6] CRASL (Centro di Ricerche per l'Ambiente e lo Sviluppo sostenibile della Lombardia), *Impatto sull'inquinamento atmosferico dei mezzi pubblici per il trasporto delle persone e perla raccolta di RSU a Brescia. Valutazione dei costi e vantaggi del passaggio a gas naturale"*, 2005
[7] Alberici F., Florio S., *Determinazioni sperimentali delle emissioni allo scarico dei motori diesel di mezzi adibiti al trasporto pubblico ed al servizio di raccolta RSU ed estensione relativa all'uso del biodiesel*, 2003
[8] F. Linch, *Hythane: a bridge to an ultraclean renewable hydrogen energy system, Atti del Workshop IEA in Denver, 1991*
[9] R. Sierens, E. Rosseel, *Variable Composition Hydrogen/Natural Gas mixtures for increased engine efficiency and decreased emissions, Journal of Engineering for Gas turbines and Power, 2000,*
[10] Hoekstra R. L., Collier, K and Mulligan N., *Demonstration of Hydrogen Mixed Gas Vehicles, Proceedings, 10th World Hydrogen Energy Conference, Cocoa Beach, Vol. 3,* anno 1994
[11] Hoekstra R. L., Van Blarigan P., and Mulligan N., *NOx emissions and efficiency of Hydrogen, Natural Gas and Hydrogen/Natural Gas blended fuels, SAE Paper 961103,* 1996
[12] Swain M. R., Yusuf M., Dulger Z., and Swain M. N., *The effects of hydrogen addition on natural gas engine operation, SAE Paper 932775*, 2003
[13] Larsen J. F., and Wallace J. S., *Comparison of emissions and efficiency of a turbocharged lean-burn natural gas and hythane-fuelled engine, ASME Journal of Engineering for gas turbines and power, Vol. 119,* 1997
[14] Yusuf M., Swain M. R., Swain M. N., and Dulge Z., *An approach to lean burn natural gas fuelled engine through hydrogen addition, Proceedings, 30th ISATA Conference, Florence, paper 97EL081*, 1997
[15] Raman V., Hansel J., Fulton J., Lynch F., and Bruderly D., *Hythane – an ultraclean transportation fuel, Proceedings, 10th World Hydrogen Energy Conference, Cocoa Beach Vol. 3 , pp. 1797-1806,* 1994
[16] Bell S. R., and Gupta M., *Extension of the lean operating limit for natural gas fuelling of a spark ignited engine using hydrogen blending, Combustion Science and Technology, Vol. 123, pp. 23-48,* 1997