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Road Test Results in Public Transport with Hydromethane (2009)

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Less emissions - more efficiency: test results in public transport with HCNG (Hydromethane) in Ravenna

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Ravenna – ATM's bus powered with Hydrogen Natural Gas blend (HCNG)"

Foreword

ATM - Azienda Trasporti e Mobilità of Ravenna was one of the first public transport companies to introduce CNG vehicles in their fleet (already in the '80ies) and has since continued to pursue a 'methanization' program, as well as a sustainable transport policy. To this purpose, ATM in 2006 started an experimental program to improve environmental performance of its vehicles, lowering CO2 emission, introducing Hydrogen Natural Gas blend (HCNG).

Natural gas is an energy source used in different areas of application: residential, industrial, power generation and not least transport.

For public transport, natural gas is considered the new fuel that can replace diesel fuel, which for decades has been the reference fuel. Many analysts agree that the hydrogen is the fuel of the future that can replace fossil fuels in many areas including transport. However, the transition to a hydrogen-powered vehicle is a step that requests a remarkable time for the adjustment of the fuel distribution system. A soft approach to the transition to the intensive use of hydrogen as transport fuel is the introduction of hydrogen mixed with methane.

This solution is supported by the holding of motoring technology that has already in production specific motor to be fuelled by methane. The introduction of hydrogenated mixtures are subject to almost no change in the car mechanics or, at most, small changes concerning the regulation of motor or modification of small mechanical parts.

The promise of reducing harmful emissions and reducing CO2 emissions, the cause of global warming, have focused on hydrogen-methane mixtures the interest of manufacturers and operators in the world of transport.

Several studies have been conducted in the laboratory to test the potential of mixtures of Hydrogen-enhanced fuel and some partial experimentations were done on the road.

This study conducted by ENEA commissioned by ATM is certainly the first study conducted in Italy to check on the road of hydrogen-methane mixtures in the field of public transport and, perhaps, the first in Europe. The study aimed at evaluating the emissions directly while the vehicle was operating on the road, through the use of equipment placed on board.
Environmental sensitivity and attention shown by the local public transport company of Ravenna, under the spirit of innovation of the Emilia-Romagna region, allowed to carry out experiments on the hydrogenated mixture for applications for public transport, involving ENEA in energy and environmental research and evaluation.

1 - Methane and hydrogen as fuel for public transport

Natural gas is considered by many years the most promising alternative fuel from the environmental point of view. Annual consumption is constantly increasing in many countries in Europe and beyond. In Italy consumption for transport grew differentiating between North and South (in the latter part of the country LPG - liquid petroleum gas – predominates and much depends on the problems related to the spread of methane service stations).
Public transport, however, has found natural gas vehicles in a way capable of maintaining high standards of service without cost to the urban environment. In fact, the low emissivity of particulate matter (PM) and gaseous pollutants bring to the intensive use of natural gas for public service.
Manufacturers have been able to fully meet the expectations of trucking companies placing on the market vehicles with engines no longer arising from diesel engines converted to spark ignition but directly designed and manufactured to be powered by natural gas.
NOx emissions at stoichiometric conditions are sufficiently high for natural gas vehicles and their reduction needs a catalytic converter (a converter in three ways: by oxidizing and reducing) that acts on nitrogen oxides, on HC and on CO). The reduction of NOx emissions can also be implemented employing lean burn engines (lean.burn). In these engines the ratio of air and gas moves from the stoichiometric value and goes towards the area of excess air. Values of the air / fuel ratio at stoichiometric conditions, indicated as Lambda, equal to 1.5 provide very low NOx emissions.
The presence of unburned emissions consist mainly of methane molecules that can be oxidized with an oxidizing catalytic converter. Using lean burn engines, the speed of combustion can be slow and produces a high rate of HC. The conversion takes place in the catalytic converter if the temperature is high enough (greater than 400 ° C); in the case of low speeds, this may be difficult to occur with resulting significant emission of unburned hydrocarbons .
To remedy the emission problems, lean burn engines are electronically controlled allowing a richer mixture (near stoichiometric conditions) in the transition to high loads and engine operating in lean conditions at low loads.
The main aspect relating natural gas fuelled vehicles' emissions is undoubtedly linked to the low PM emission, the molecule being a light weight one and easily oxidisable. The presence of residual PM is generally attributed to the presence of oil droplets in the cylinder passing through bands.
The reduction in fuel consumption and NOx emissions are improved using engines with a very lean burn mode. However, the slow combustion of methane prevents the onset of leaning too much, otherwise the ignition of the mixture into the cylinder would not occur (misfiring) with a consequent decrease in engine efficiency and increase in HC.
The use of hydrogen as an additive to methane can exceed the limit imposed on the leaning of the mixture into the cylinder through the best performance of hydrogen as for the aspects directly related to combustion.
Table 1 shows the physical characteristics of methane and hydrogen.

	Methane	**Hydrogen**
Density (1 atm 273 ° K) kg/m3	0.072	0.082
Value stoichiometric AFR (kgaria / kgfuel)	17.2	34.2
Air / fuel ratio stoichiometric (m3 aria/m3 fuel)	9.52	2.42
Laminar flame speed (m / sec)	0.37-0.45	2.65-3.25
Ignition energy (mJ)	0.29	0.02
Lower calorific value mass (MJ / kg)	50	120
Quenching distance (mm)	2.03	0.64
Lower calorific value by volume (MJ/m3)	35.7	10.71

Table 1: physico-chemical properties of methane and hydrogen

The burning of hydrogen appears to be up to 10 times faster than methane and therefore leads to a more rapid combustion. This speed allows a reduction of the content of fuel in the mixture inside the cylinder being able to maintain a good spread of flame in the air-fuel mixture.
The superior combustion characteristics of hydrogen led to the testing of methane and hydrogen mixtures in order to exploit the advantages of natural gas along with the interesting features of combustion of hydrogen. In recent years studies of hydrogen mixed with methane have shown the possibility of interesting developments for transport and led to the commercialization of a fuel called Hythane ®, whose composition typically includes the presence of a 20% of hydrogen in volume.
The possibilities of using hydrogenated mixtures (hereinafter referred to as Hydromethane) finds support in several aspects:

- Opportunities for use in gas engines without any modification of the motor parameters (at low levels of hydrogen in the mixture);
- Reduction of pollutant emissions (especially NOx) using the leaning of the mixture and / or adjustment of the ignition;
- Improving the efficiency of combustion resulting in reduced energy consumption;
- Reduction of greenhouse gas (CO2) due both to the lower presence of carbon in the fuel and to the improved combustion (“leverage effect”);
- Exploitation of natural gas pipeline for the supply of the mixture, with no changes requested for the hydrogen production and its mixing with methane.

The feasibility of using hydrogen in addition to methane was tested in several international laboratories to demonstrate the interest paid from the world of transport to this solution. The National Renewable Energy Laboratory (NREL agency of the U.S. Department of Energy) has tested some buses on the road (2002-2004) after having conducted the necessary bench tests to optimize engine combustion. The mixture of 20% was chosen for the road tests and the development was done leaning the air / fuel and delaying the advance of ignition, trying to reduce NOx emissions, to maintain torque levels supply equal to those of methane and to increase the efficiency of the engine. Tests on the road and on the chassis dynamometer have shown an increase in consumption equivalent to 10 -15%. This is explained by the improper development of the engine (using a few points in steady state). The emissions detected on a chassis dynamometer (using a sub-urban and urban cycles) have indicated a reduction (over 50%) of nitrogen oxides and an invariance for the other emissions.
In Malmö, Sweden, two vehicles of the local public road transport fleet fuelled with natural gas were tested with a mixture of Hydrogen-enhanced fuel (8% by volume) without any modification to the vehicle (Malmö Hythane ® Project 2003). The tests have shown a better efficiency (at 2000 rpm) by about 15%, at values of Lambda increasingly higher. NOx emissions did not change or were slightly higher. Laboratory tests performed with a mixture of 25% of hydrogen, have shown an increased efficiency and reduced emissions of NOx, with a less rich mixture and optimal ignition advance. Road tests under specific operating conditions showed a reduction in fuel consumption and emissions.
In many other studies gas engines fueled by mixtures with a variable percentage of hydrogen have been tested. The majority of tests were performed on bench and the results showed a better engine efficiency and reduced emissions of NOx. However it was emphasized the need to make an adjustment of the ignition and to operate a leaning of the mixture to obtain the benefits of efficiency improvement and NOx reduction with the increase of hydrogen content in the fuel.
In conclusion, the studies agree on the positive actions derived from the introduction of hydrogen in mixtures with methane, reiterating the need for tuning the engine for high values of hydrogen. In particular, the ability to lean the fuel mixture and control of the ignition advance, are two options to control NOx emissions and improved energy efficiency.

2 - The project Bus to Hydromethane

The region Emilia Romagna has shown interest in the use of hydrogenated mixtures of methane as transport fuel. In particular the subject of interest is the possibility of introducing the Hydrogen-enhanced fuel for public transport community. As a result of this attention the Region has launched a study program that developed into a demonstration

project for the evaluation of the performance of Hydromethane mixtures for public transport vehicles. The "Hydromethane project" has involved two public transport companies, ATM and ATR, respectively of the Provinces of Ravenna and Forlì-Cesena, which participated actively in the project through the provision of two vehicles on which to perform the tests foreseen by the project.
The experiment aims to verify the performance in terms of emission and energy of two natural gas vehicles fueled with Hydromethane blends and in particular:

- Verify the operability of the means of transport with Hydromethane mixtures:
- What could be the optimal mix to reduce energy consumption;
- Assess the reduction of CO2 emissions;
- Characterize the emissions of pollutants subject to pollution control (HC, CO and NOx).

This involves testing of various hydrogen-methane mixtures in order to identify the mixture able to provide the best performance and emissive energy without producing side effects on the stability of combustion. During the study changes in the management of the ignition of the mixture (ignition advance changes) were applied in order to optimize combustion and reduce emissions of any unburned hydrocarbons and nitrogen oxides. No changes were done on the leaning of the mixture, as the engine optimization by acting simultaneously on two parameters exclusively on road tests resulted too complex.
The experiments were carried out in two phases: the first one employing a long vehicle (12 mts.) provided by ATR Forli and the second a short vehicle (8 meters) from ATM Ravenna, a company that has a long experience (the first in Italy) with the use of natural gas in public transport. In the first phase only a mixture of H2-CH4 (by volume in hydrogen content of 5%) was used and the results were compared with measures of performance benchmark with methane reference. In the second phase various formulations of the methane-hydrogen mixture were tested (5%, 10%, 5%, 20% and 25% by volume of hydrogen) to develop a full spectrum of benefits derivable from the adoption of hydrogen mixtures for road transport.
During the first part of the trial the execution of sub-urban work cycles in simulation of vehicle operating conditions was carried out while the second phase simulated operational characteristics of an urban cycle.
To the Tests on the circuit also followed the tests listed below:

- Consumption measures according to CUNA cycle;
- Test of PM emission (with stationary vehicle);
- Test for emissions of VOC (with stationary vehicle).

The tests were conducted on a street circuit which reproduces a typical path of the working bus.
The instrument was such to be used directly on board the vehicle for the detection of actual emissions.

2.1 – The on board measurement system

The assessment of CO2 emissions was carried out using instrumentations placed on the vehicle and in particular the measurement system Horiba OBS-1000, which can detect the emissions of CO2, NOx, HC and CO (see Figure 1). The system also performs the detection of consumption by an indirect measure based on the carbon balance.
The system is also equipped with a GPS receiver in order to track the position of the vehicle and indicate the speed.

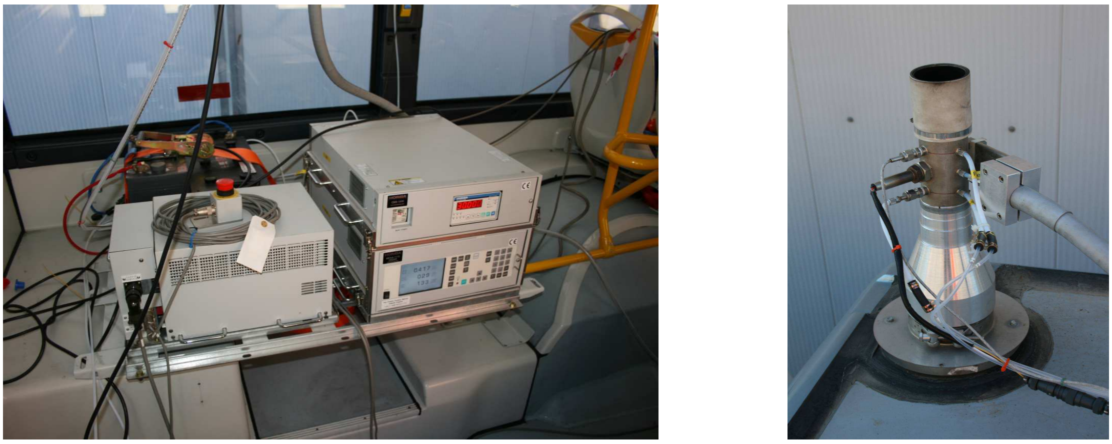

Figure 1 : on-board instrument: gas analyzer (a) and exhaust gas flowmeter (b)

2.2 The measurement system for particulate matter and VOC

To complete the test, an indicative emission behavior was also outlined for PM and VOC (volatile organic compounds). In particular, we want to highlight the possible emission variation in percentage terms with respect to the sole methane rather than the emission value in absolute terms. The assessment of PM emissions has been operated in steady state on a stationary engine at 1000 rpm.

The same type of measures was performed to evaluate the emissions of VOC still considering methane as reference fuel. For the measurement of VOC a detector GREYWOLF TG 502 VOC probe was used, inserting it from the end of the measuring tube until it penetrates into the chamber of dilution.

2.3 – Vehicles

The first phase of tests was carried out using a 12 meters long vehicle produced by Bredamenarinibus Avancity Model 240 CNG owned by ATR Forli. The vehicle is a classic 12 meters one whose laden weight reaches 17 tonnes and can carry 93 people at a maximum speed of 60 km / h.

Traction is provided by a four-stroke engine powered by natural gas with a maximum power of 205 kW @ 2200 rpm and maximum torque of 1000 Nm at 1400 rpm. The engine is a Mercedes-Benz M906 LAG turbocharged with intercooler features EEV (Enhanced Environmentally friendly Vehicle, a term that indicates in a European standard emissive low-emission vehicles over 3.5 tonnes in category M2 or M3). The total displacement of 6880 cm3 six-cylinder in line. The storage facility for natural gas is composed of four cylinders on the roof of the vehicle for a total capacity of 1284 lt.

The second vehicle used for road tests is a short vehicle of Bredamenarini - 8 meters long - model Vivacity CNG, owned by ATM Ravenna; its laden weight reaches 9.100 kg, can carry 61 people at a maximum speed of 75 km / h. Equipped with the same engine Mercedes of Avancity model with the same engine capacity but weakened up to 170 kW. The cylinders for natural gas are always four and are located on the roof of the medium.

The engine is lean-burn type and this can reduce NOx emissions and obtain high efficiencies. Lean burn engines work in excess air reducing fuel consumption, being able to fully exploit the fuel used in the mixture. The more difficult ignition of the mixture is overcome by an appropriate mixing between air and fuel so as to make the air-fuel mixture more homogeneous in the cylinder.

In this way you avoid the nasty knock or misfire of the mixture (no burst). However, given the same output power (BMEP Brake Mean Effective Pressure on the Chart 1) engine knocks or engine misfire may occur with varying excess air and therefore it is necessary to monitor carefully the operating point of the engine in order to avoid critical areas. Alternatively, you can reduce the available power and avoid the drawbacks of the engine knocks but this would reduce the engine performance.

Both vehicles were ballast using sandbags to simulate during the tests a payload equals to half the maximum load.

Both vehicles are equipped with electronic control and engine management. In this unit maps setting of the engine are stored.

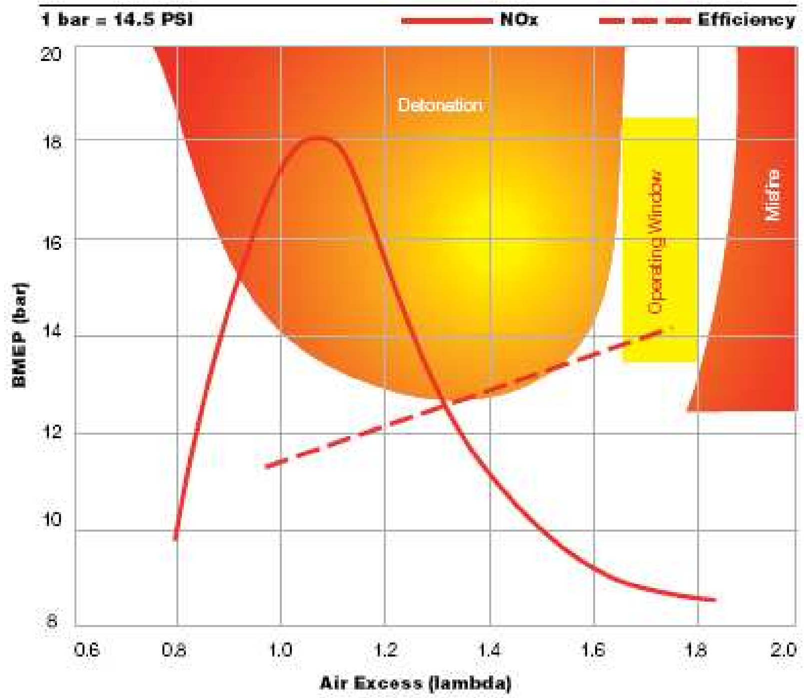

Chart 1: advanced lean burn engine features

2.4 Test procedure

Performance evaluation of energy-emission aspects was held under a procedure agreed with ATM and ATR, which foresees the execution of different tests as listed below. For the test, 3 of the 4 gas cylinder of the vehicles were shut down in order to minimize the amount of fuel needed to test the various hydrogenated mixtures.

The protocol provides:

1. emptying tanks from gas residues;
2. CNG refueling with reference CNG;
3. running tests on test circuit;
4. CUNA cycle performance test;
5. PM and VOC emissions stationary test;
6. emptying tanks from gas residues;
7. filling with predefined mixture;
8. developing the engine control unit;
9. tests as from point 3.

In particular, the contract provided for the use of blends at 5% by volume for the long vehicle of ATR and mixtures at 5, 10, 15, 20 and 25% by volume for the short vehicle of ATM.
Methane and the mixtures were in pre-packed bottles and were poured into the vehicle by the use of a portable recharging station (herinafter referred to as “minirete”). The minirete has a three-stage compressor which can load up to 200 bar the vehicle tank. However, due to pressure drops the pressure on the vehicle did not exceed 190 bar. Methane G20 used for the execution of measures of reference is 99% pure methane. This differs from the commercial natural gas for which the content of methane is between 95% and 99%, depending on the supply. The use of the G20 methane results

in a higher energy content than the commercial natural gas. Mixtures of hydrogen and methane were then made up of hydrogen and methane G20 to maintain the comparison.
The change in the control unit have been performed following the interventions reported in Table 2, depending on the concentration of hydrogen in the mixture and on the vehicle:

Changes to the engine management (0% - No change in setup for NG)		
12 Meters	5%	As the NG mapping
8 Meters	5%	As the NG mapping
	5%	1 degree of delay for all load
	10%	1 degree of delay for all load
	15%	Partial load: no change with load < 50% and advance > 29 degrees of delay 75% >load >50%: 2 degrees of delay Full load: 3 degrees of delay
	20%	As for 15% blend
	25%	4 degree of delay for all load

Table 2: engine control unit adjustments

For each mixture test were carried out for 60 km running for 16 consecutive times the path identified as the reference cycle.

3 - The test run

The road tests were conducted on a circuit located within the ENEA Research Center "Casaccia". The choice to run the tests at this location was dictated by the need to be able to move safely on a road comparable to a typical path of the line. The path chosen is responsive to the needs of operability of the vehicle on the roadway for both the size of the roadway and the altitude. The size of the roadway is an important factor especially for the tests with the long vehicle. In fact, some sections are characterized by a 90 ° bend, how it can usually be found at town road intersections, and the size of the roadway is such that the steering of the vehicle in relation to its overall dimensions is allowed.
The circuit is 3.8 km long with an altitude varying between 132 and 152 m above sea level. The route alternates flat with its ups and downs that show no noticeable slope except for a single stretch of the journey.
The tests carried out on the road foreseen the simulation of two types of transport services: the urban and sub-urban areas. Therefore along the route obligatory stops have been placed every 250 m, equal to the typical distance between two stops for the urban public transport service. In total, the stops are 16 (the last segment has a reduced distance). During the simulation of the sub-urban service the bus has stopped at every other stop in order to drive for stretches of 500 m. In the simulation of the urban service stops have been performed systematically in order to drive for stretches of 250 m.

Table 3 summarizes the typical features of the test cycles.

	Urban	**Sub-urban**
Circuit lenght	3800 m	
Mean speed	20 km/h	22 km/h
Max speed	40 km/h	47 km/h
Time	730 sec	700 sec

Table 3: Characteristics' of the Casaccia Urban and Sub-urban cycles (CUC and CSC)

4 - Test results

Here are the results of tests performed on the vehicles described above in accordance with procedures identified and agreed.

4.1 Tests on the circuit: energy consumption

The evaluation of consumption is done by using two indirect methods: the carbon balance and the measure of the air-fuel ratio. The first method uses the emissions of carbon dioxide (CO_2, CO and HC) from which the weight of carbon emitted is derived. The carbon in the exhaust comes from the fuel therefore, known composition by mass of the fuel, the amount of fuel consumed can be worked out. The air-fuel ratio (AFR) tells how much fuel is burned in relation to the input air. Knowing the load of the exhaust gases the quantity of fuel burned in relation to the air can be traced.
The measure of consumption shows similar results for both methods (see Table 4).

Fuel consumption - g/km				
	8 m		12 m	
	AFR method	Carbon method	AFR method	Carbon method
CH4	309.18	307.31	385.26	380.94
Hy 5%	293.56	292.98	358.96	352.20
Hy 5% 1g	289.49	286.59		
Hy 10%	274.43	277.15		
Hy 15%	259.73	261.26		
Hy 20%	256.82	257.23		
Hy 25%	248.76	246.39		

Table 4: Consumption measured on the typical cycle

On the basis of the experimental results, it can be stated that using hydromethane mixtures brought to savings in terms of mass of fuel used with reductions, related to the consumption of natural gas G20, reported in Table 5:

Difference in consumption - g/km				
	8 m		12 m	
	AFR method	Carbon method	AFR method	Carbon method
Hy 5%	-15.62	-14.33	-26.30	-28.74
Hy 5% 1g	-19.69	-20.72		
Hy 10%	-34.75	-30.16		
Hy 15%	-49.45	-46.05		
Hy 20%	-52.36	-50.08		
Hy 25%	-60.42	-60.92		

Table 5: Difference in mass consumption measured on the typical cycle

The percent reduction in weight of fuel consumed per kilometer, is shown in Table 6.

Difference in consumption - %				
	8 m		12 m	
	AFR method	Carbon method	AFR method	Carbon method
Hy 5%	-5.1	-4.7	-6.8	-7.5
Hy 5% 1g	-6.4	-6.7		
Hy 10%	-11.2	-9.8		
Hy 15%	-16.0	-15.0		
Hy 20%	-16.9	-16.3		

Hy 25%	-19.5	-19.8		

Table 6: Difference in % by mass consumption measured on the typical cycle

The reduction of consumption, in mass of fuel, varies between 5% and 20% for the short vehicle while it is about 7% for the long vehicle.
It is more indicative to express the consumptions as consumption of natural gas equivalent (Table 7). In fact, since the mixtures are at different levels of hydrogen they have different energy content and a proper comparison should be performed on the same metrics, such as bringing them back the kWh / km of fuel or energy content of methane, or indicating the G20 consumption that would have been necessary in order to provide the same energy content of the tested mixture.

Difference in consumption- methane- equivalent - %				
	8 m		**12 m**	
	AFR method	**Carbon method**	**AFR method**	**Carbon method**
Hy 5%	-4.2	-3.8	-6.0	-6.7
Hy 5% 1g	-5.5	-5.9		
Hy 10%	-9.5	-8.1		
Hy 15%	-13.5	-12.4		
Hy 20%	-13.4	-12.7		
Hy 25%	-15.0	-15.3		

Table 7: Percentage reduction in equivalent consumption

By comparing the results of the consumption equivalent it can be noted that the mixtures at 15% and 20% show the same results, while the 25% mixture brings to a decrease of another point in the energy consumption. The reduction in consumption can be ascribed to the improved performance of the engine that is under the positive effect of the higher burning rate of hydrogen added to methane. The efficiency appears to increase in a range between 4% and 15%, depending on the proportion of hydrogen.

4.2 - Tests on the circuit: CO2

The emission of CO2 is equal to the percentage by volume of methane (CH4 produces 1 mole of CO2, while a mole of mixture produces CvCH4 moles of CO2).

CV $_{H2}$%	**moles CO2/mole mixture**	**gCO2/mole mixture**	**Kg $_{Co2}$/kg $_{mixture}$**
0	1	44	2.75
5	0.95	41.8	2.73
10	0.90	39.6	2.71
15	0.85	37.4	2.69
20	0.80	35.2	2.67
25	0.75	33	2.64

Table 8: theoretical CO2 produced per mole of mixture

Table 8 shows the decrease in CO2 emissions by substitution of the carbon atoms with those of the hydrogen atom with the increase of hydrogen content decreases the emission of CO2.

Table 9 shows the data measured in CO_2 emissions and how the value of output per kg of fuel is within the measurement error of the instrument.

CO2 emissions - g / km				
	8 m		12 m	
	CO2 g/km	kgCO2/kg mixture	CO2 g/km	kgCO2/kg mixture
CH4	833.32	2.71	1032.46	2.71
Hy 5%	782.06	2.67	950.75	2.70
Hy 5% 1g	769.68	2.69		
Hy 10%	734.44	2.65		
Hy 15%	691.75	2.65		
Hy 20%	671.00	2.62		
Hy 25%	640.86	2.60		

Table 9: CO_2 emissions

The introduction of hydrogen in the mixture so reduces CO_2 emissions because carbon atoms are replaced with hydrogen atoms.

Table 10 shows the percentage reductions related to methane.

Reducing CO2 emissions - g / km and %				
	8 m		12 m	
	ΔCO2 g/km	ΔCO2 %	ΔCO2 g/km	ΔCO2 %
CH4				
Hy 5%	-51.26	-6.2	-81.71	-7.9
Hy 5% 1g	-63.64	-7.6		
Hy 10%	-98.88	-11.9		
Hy 15%	-141.56	-17.0		
Hy 20%	-162.32	-19.5		
Hy 25%	-192.46	-23.1		

Table 10: CO_2 emissions reduction

Reduction in CO_2 emissions reaches 23% using a mixture of 25% hydrogen. The reduction found is attributable to two factors: the reduction of the carbon atoms in the mixture and the decrease in consumption due to an increased engine performance.
The use of hydrogen-methane mixtures produces a reduction that goes beyond the mere substitution of carbon and this is defined as leverage effect.
If we define leverage effect the ratio between the actual and theoretical reduction, a reduction factor of 3 to 5 points (i.e. reduced emissions from 3 to 5 times the theoretical value) can be calculated, as shown in Table 11.

Leverage factor - reduction of CO2 emissions		
	8 m	12 m
CH4		
Hy 5%	3.97	5.11
Hy 5% 1g	4.93	
Hy 10%	3.68	

Hy 15%	3.38	
Hy 20%	2.79	
Hy 25%	3.97	

Table 11: Leverage factor

5 - CO, HC and NOx

CO emissions were very low, down to the limit of instrument sensitivity, and did not show significant variation respect to the values already at the limit. Table 12 shows the emissions for CO observed with the different mixtures used:

CO emissions - g / km		
	8 m	**12 m**
CH4	0.07	0.64
Hy 5%	0.09	0.18
Hy 5% 1g	0.10	
Hy 10%	0.18	
Hy 15%	0.20	
Hy 20%	0.11	
Hy 25%	0.12	

Table 12: CO emissions (g / km)

HC emissions are substantially unchanged. The measure is inclusive of all HC compounds, both methane and non-methane. Most of the residues of organic compounds detected is still attributable to the non-combusted methane emitted to the exhaust while the non-methane component should be very low.

5.1 NOx emissions

In literature it is reported that the use of hydrogen mixed with natural gas produces substantial reductions in emissions of oxides of nitrogen (up to 50%) compared with emissions of mere natural gas. Even if the hydrogen would produce an increase in temperature in the combustion chamber and consequently increased emissions of NOx, the reduction of ignition and the leaning of the fuel / air ratio can offset this tendency and produce a reduction in the emissions of oxides of nitrogen.

Table 13 shows the NOx emissions for both vehicles in urban and sub-urban cycles. For the long vehicle, whose map of ignition was not changed, emission of NOx was reduced by 6%. For the short vehicle, using the same mixture without altering the map of ignition (Hy 5%) the emission reduction is close to null.

NOx Emissions g / km		
	8 m	**12 m**
CH4	3.76	3.56
Hy 5%	3.75	3.35
Hy 5% 1g	2.02	
Hy 10%	2.34	
Hy 15%	2.15	
Hy 20%	3.91	
Hy 25%	5.47	

Table 13: NOx emissions

Moving the adjustment of ignition of 1 degree in delay, the emission of NOx in the short vehicle is reduced by 46%. For values of 20 and 25% of hydrogen there is an increase of NOx for the reasons already mentioned.

It is to be remarked that on the short vehicle the interventions on the engine has been limited to the advance of ignition and did not affect the degree of enrichment of the mixture (leaner mixture).
Increasing the levels of H2, the lower emissions of NOx are kept moving further forward the advance of ignition. With mixtures with high hydrogen content the adjustment of the advance is no longer sufficient to guarantee a reduction of emissions. To 25% with 4 degrees of advance you get an increased levels of NOx emitted at both low and high loads (see Chart 2).

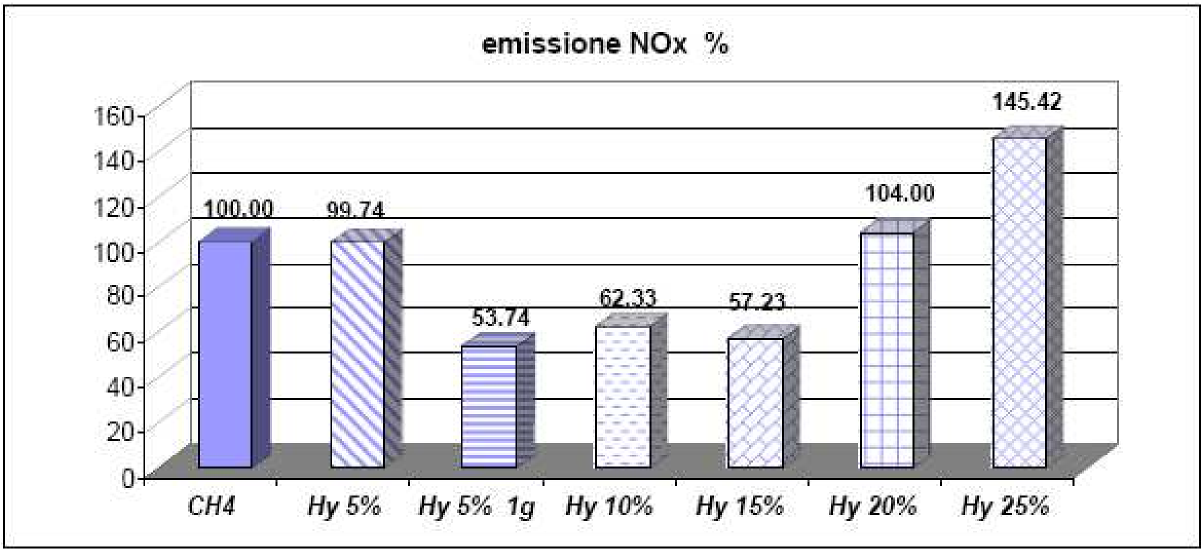

Chart 2: NOx emissions in urban cycle

6 - Emission of PM and VOC

The test performs a comparison of the PM emitted at steady at 1000 rpm with the stationary vehicle. Obviously the load is almost zero and the PM emitted into real exercise are different from those in this test.
Before the tests, the blank test were performed, i.e. the PM due to ambient air were measured, because the exhaust gases are diluted by the ambient air in a volumetric ratio of 2 to 1 (2 parts of air and 1 gas).
The measurement site is classified as a green area outside the city and the level of PM is low compared with that of the city.
Chart 3 shows the measurements of total PM detected in ambient air, each day of measurement. The values refer to average values during 3 minutes of the measure.

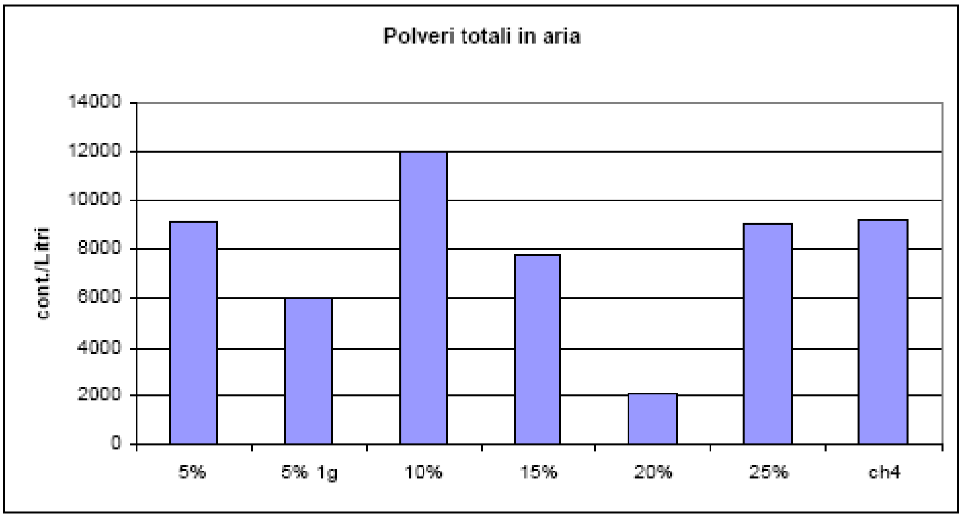

Chart 3: total PM in the ambient air (counts / liter)

The values are fairly uniform for all days of testing to demonstrate the peripheral location of the area. Only the air sample taken during the day of test of the 20%H2 mixture has lower values of PM, due to weather conditions (day with intermittent rain). The tests carried out with the vehicle stationary are not exhaustive in relation to the real PM emissivity, because the engine needs to deliver less power than necessary to overcome the inertial resistance and friction.
Greater detail can be reached through the implementation of bench test or with the aid of appropriate on-board instruments. During the trial, VOC emissions were detected using the same methodology described for the PM.
It was not intended to provide a quantitative survey on VOC emitted from the vehicle, but only to perform a comparison with the reference emissions for the natural gas-powered vehicle.
Chart 4 reports the results of the surveys, which show that the VOC emissions have no changes using the different mixtures with values higher than those detected in the air. The survey was conducted with an instrument that indicates the total VOC speciation and all compounds are therefore included, including methane ones, which in this case are high.

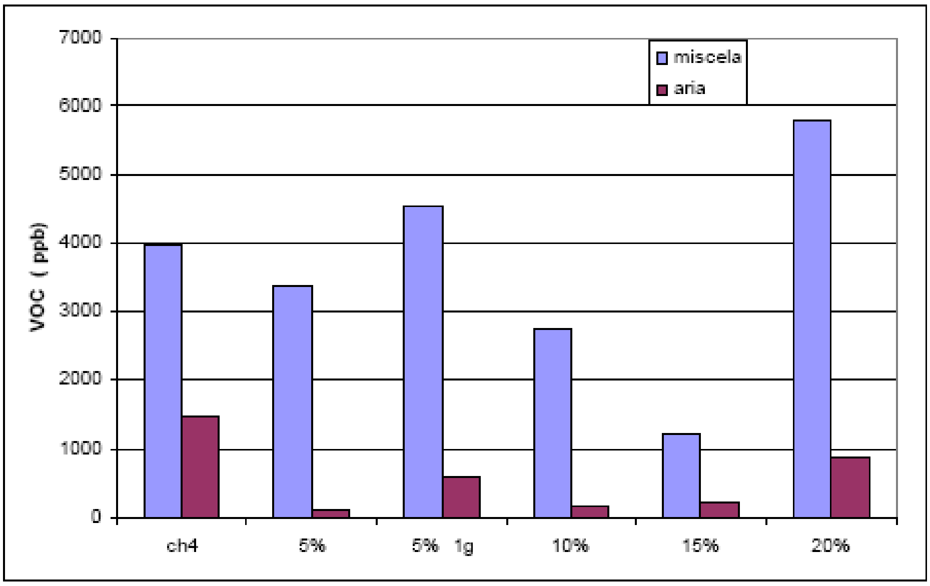

Chart 4: Concentrations of VOCs in comparison to air

7 – Conclusion

The experiment brought to positive conclusions on the use of hydrogen mixed with methane but also highlighted some aspects of technology for the best use of methane-hydrogen mixtures in normal commercial applications.

1. In urban driving the vehicle fuelled with mixtures showed an improvement of energy performance, symptom of a greater yield of mixtures with increasing content of H2. The performance undergoes a positive influence already at low values of hydrogen content showing a gain of around 4% with the mixture of 5%. This value was confirmed also by the introduction of 1 degree of delay in the anticipation of ignition. The reduction seems to settle around 15% for blends of 15 to 25% in volume of hydrogen, showing a slight advantage of the 25% mixture compared to the 15% one. It should be stressed however that the comparison is indicative of improved performance with increasing the quantity of hydrogen in the mixture of fuel but the differences may be partly different operating a power-delay optimization (searching optimal ignition angle as a function of the mixture used).
2. The energy benefits derivable from the use of hydrogen depend on the type of operating cycle that the vehicle is facing. Already in the literature it has been sought to address the problem of the dependence of engine performance in function of the driving cycle and of the search for ideal hydrogen fraction in the blend. Bearing in mind that the optimum is relative to the output parameter that is intended to be maximized, the response cannot be one. It is possible to compare the energy performance by comparing the results on the urban cycle of Casaccia and those on the cycle CUNA. The CUNA cycle that simulates a typical route with stops every 300 m is less energy demanding having a limited profile in terms of acceleration (starts and stops are always equal in the limit of the driver's ability to maintain the same driving directions). The reduction in consumption is much more pronounced at low levels of hydrogen (5% and 5% modified) than at higher hydrogen content. In the cycle CUNA, in percentage terms, at low rates of H2 the performance seems improved by over 25% compared to the use of sole methane. At higher rates of H2 the gain in performance declines in the cycle CUNA and moves toward values similar to those of urban cycle Casaccia.
3. The perspective of reducing CO2 emissions is one of the strengths for the use of hydrogen and methane mixtures. From the surveys performed, the actual reduction is beyond the theoretical one expected for the simple reduction of the carbon atoms with hydrogen atoms. This essentially occurs as a leverage effect happens, able to amplify the reduction in CO2 emissions beyond the theoretical limit. The increase of the reduction is attributed to the improved fuel efficiency that reduces energy consumption, and therefore the emission of combustion products. The leverage effect observed is between 3 to 5 times the expected theoretical value, calculated with the assumption of invariance of engine performance. The mixture of 25% produces a 25% reduction in CO2 emissions compared with theoretical 9% expected and is the largest absolute reduction detected. In relative terms, compared to the theoretical reduction, the 5% blend coupled with the delay of 1° of the ignition advance, is the one that has the strongest leverage.
4. CO emissions are very low and show no appreciable changes at the top or bottom. Detections are at the limit of instrument sensitivity but the measures have shown that the CO are below the limits imposed by European standards, particularly for class EEV. Emissive CO levels do not seem to be strongly influenced by the driving cycle used for the tests, being very small in both the urban cycle Casaccia and the cycle CUNA.
5. NOx have a more varying behavior compared to CO. In urban cycle Casaccia NOx emissions occur up to 47% less, using the 5% blend with 1° of delay in the anticipation of ignition. Similar values also occur with mixtures of 10 and 15% (with delays in advance of ignition of 1° and 2° respectively). By increasing the H2 content in the mixture, the NOx emissions are increasing and can not be recovered with the advance of ignition adopted (up to 4° at 25%). The strategy for the reduction of NOx, beside increasing the advance of ignition, is based on greater leaning of the fuel / air mixture. Indeed the addition of hydrogen allows better and faster combustion, which allows to use a mixture of fuel poor even further reducing the emission of NOx.
6. The emission measurements in urban cycle Casaccia showed that the vehicle is fully within Euro III for all the mixtures used. But only for 5% modified, 10% and 15% values are within the EEV standards. In cycle CUNA NOx emissions are within EEV classes only for the mixture of 5 to 15% and with sole methane. The other two formulations of the hydrogenated mixtures exceed these limits. The increase in emissions for blends of 20 and

25% is indicative of higher temperatures in the combustion chamber due to the presence of hydrogen in large quantities. The reduction in burning time (reduced ignition advance of 4°) or the leaning of the mixture may serve to reduce NOx emissions. This is true even at levels of H2 over 15%.

7. Emissions of nitrogen oxides have shown a clear dependence on the test circuit. In fact, while in urban cycle Casaccia EEV limits were exceeded, the cycle CUNA has confirmed the class EEV. European official cycle ETC, used for certification of emissive cycle, is more similar to the cycle CUNA than to the cycle Casaccia. Therefore the limits are clearly observed. However, the urban cycle Casaccia is more alike an operating cycle in town and therefore actual emissions are certainly closer to those found on the cycle Casaccia. In cycle CUNA NOx emissions are lower in Class EEV with the mixture 5 to 15% and with methane alone. These limits are exceeded by the other two formulations of the hydrogenated mixtures (20 and 25%).
8. The emissions of unburned hydrocarbons are generally opposite to those of oxides of nitrogen. With increasing percentage of hydrogen, HC emissions tend to decline as a result of better combustion conditions, while increasing those of NOx for increased combustion temperature. The measures carried out have shown that the levels of HC emitted for the cycle Casaccia are basically stable but above the EEV limits. In the cycle CUNA vehicle powered with natural gas or a mixture of 20% has respected the EEV limits (including methane + non-methane hydrocarbons).
9. The assessment of emissions of NOx-HC indicated that in urban cycle Casaccia the emissive levels, with the exception of the 25% mixture, are outside the area foreseen by the EEV standard but also by the EURO III ones. Using the cycle CUNA the emissions with methane match the EEV constraints, while the others respond on the overall to the EURO III-EUROV limits.
10. The measures of NOx and HC showed that the engine fuelled with blends of hydrogen can be optimized to reduce emissive levels by adopting appropriate strategies of adjustment of the combustion. In particular the ignition advance must be varied. The change is made in relation to the percentage of hydrogen as a function of the engine load. This way it is possible to work at points of maximum engine performance (optimum ignition angle). Furthermore, in order to operate more effectively the air-fuel mixture should be further leaned to reduce NOx emissions and consumption.
11. Particulate matters and VOC are not substantially changed by using mixtures of hydrogen and their emissions are maintained at very low levels.

8 – New trials

In line with the just completed trial and in order to contribute to a sustainable mobility ATM is partner together with ENEA and ASTER of a project financed by the EC under the LIFE+ program, under the coordination of the Emilia-Romagna.

This new project, called MHyBus will last three years and intends to obtain ministerial authorization to use a mixture of hydrogen and methane as fuel for public transport.

More details on the project objectives and updates on its results can be found in the project website: www.mhybus.eu.