COMPARATIVE STUDY ON EXHAUST EMISSIONS FROM DIESEL- AND CNG-POWERED URBAN BUSES [*]

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ABSTRACT

Couple years ago, ADEME engaged programs dedicated to the urban buses exhaust emissions studies. The measures associated with the reduction of atmospheric and noise pollution has particular importance in the sector of urban buses. In many cases, they illustrate the city's environmental image and contribute to reinforcing the attractiveness of public transport. France's fleet in service, presently put at about 14,000 units, consumes about 2 per cent of the total energy of city transport. It causes about 2 per cent of the HC emissions and from 4 to 6 per cent of the NO_x emissions and particles. These vehicles typically have a long life span (about 15 years) and are relatively expensive to buy, about 150.000 euros per unit.

Several technical solutions were evaluated to quantify, on a real condition cycle for buses, on one hand pollutants emissions, fuel consumption and on the other hand reliability, cost in real existing fleet.

This paper presents main preliminary results on urban buses exhaust emission on two different cases:

- existing Diesel buses, with fuel modifications (Diesel with low sulphur content, Diesel with water emulsion and bio-Diesel (30% oil ester in standard Diesel fuel);
- renovating CNG powered Euro II buses fleet.

over representative driving cycles, set up by ADEME and partners. On these cycles, pollutants (regulated and unregulated) were measured as well as fuel consumption, at the beginning of a program and one year after to quantify reliability and increase/decrease of pollutants emissions.

At the same time, some after-treatment technologies were tested under real conditions and several vehicles. Information such as fuel consumption, lubricant analysis, problem on the technology were following during a one year program.

On the overall level, it is the combination of various action, pollution-reduction and renewal that will make it possible to meet the technological challenge of reducing emissions and fuel consumption by urban bus networks.

INTRODUCTION

The will to reduce polluting emissions from public and goods urban transports has become a major issue in the last few years. A specific effort is made on urban buses which must be exemplary in terms of polluting emissions. For these expensive and long lasting vehicles (life-cycle of approximately 15 years), exhaust emission reduction not only involves buying new vehicles fitted with new emission control devices, but also improving the efficiency of the buses currently into circulation.

Traditional Diesel engine types are at present undergoing many modifications intended to reduce polluting emissions (EGR, electronic injection…). Emissions standards are tending to be more severe. It will force testing the performance of vehicles according to cycles nearer real operating conditions. The effect of improving fuels will contribute to the technological development.

Although enjoying a great deal of technological expertise, the Diesel sector has inconveniences in terms of polluting emissions:

- it generates more particles emissions that those of other road fuels,
- with Diesel's being a heavy product, its combustion creates heavy unburned hydrocarbons,
- Diesel engines emit NOx hen carrying heavy loads.

Even though the new exhaust emission control devices give rise to hope for reducing polluting emissions (especially particles), it is nonetheless advisable to call for new technology with an eye to protecting the environment and encouraging energy diversification. Because of their great lightness, gaseous fuels (CNGs or LPGs) in relation to classic fuels demonstrate undeniable environmental benefits due to their composition. They offer characteristics that enable good compatibility with command ignition engine types.

The French Agency of Environment and Energy Management (ADEME) engaged a comprehensive program in 1998 concerning urban buses. The measures associated with the reduction of atmospheric and noise pollution has particular importance in the sector of urban buses. In many cases they illustrate the city's environmental image and contribute to reinforcing the attractiveness of public transport.

France's fleet in service, presently put at about 14,000 units, consumes about 2 per cent of the total energy of city transport (**figure n°1**). It causes about 2 per cent of the HC emissions and from 4 to 6 per cent of the NOx emissions and particles. These vehicles typically have a long life span (about 15 years) and are relatively expensive to buy, about 150.000 euros per unit.

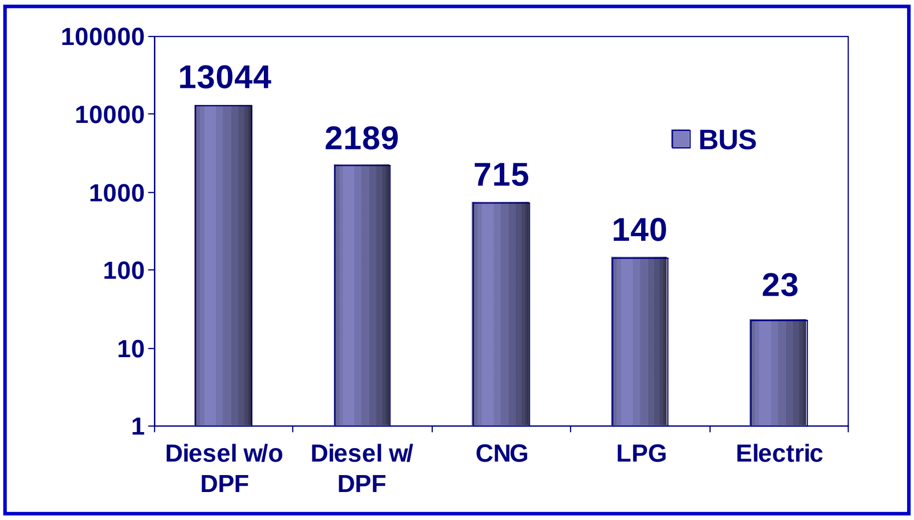

Figure 1: Buses distribution in France (2002)

Several technical solutions were evaluated to quantify, on a real condition cycle for buses, on one hand pollutants emissions, fuel consumption and on the other hand reliability, cost in real existing fleet. These evaluations continue in 2003 and 2004.

There are two different actions types:

- Actions to implement for reducing the pollution caused by existing fleet (retrofitting):
  - Fuel modifications: Diesel with low sulphur content, Diesel with water emulsion (Aquazole™) and Diesel with bio-fuel content (30% oil ester).
  - Particulates filters: different systems were tested (catalyzed- and fuel-borne catalyst-based filters). New systems will be tested in 2003.

    - NOx control systems: an EGR system will be tested in 2003.
- New measures to be adopted when renovating a fleet, opting for vehicles whose emissions are lower than Diesel.
    - CNG vehicles: stoichiometric and poor solutions were tested with Euro II engines. Euro III will be tested in 2003.
    - LPG vehicles: DAF engine was tested. MAN Euro III will be evaluated in 2003 if vehicle is available.
    - Hybrid buses: Neoplan which is a real hybrid and Mercedes CITO which is a Diesel electric engine were tested. Neoplan evolution will be tested in 2004.

Only preliminary details about Diesel and CNG evaluations are presented in this paper.

Natural gas is a mixture made of majority methane (more than 80% of volume); ethane light hydrocarbons, propane and neutral compounds (CO2, nitrogen) can also be found. Thanks to its characteristics, this gas is compatible with current alternative engines (octane number above 110, mass thermal power 10% above Diesel fuels).

The main implementation specificity for natural gas comes from its difficult liquefaction capacity, involving gaseous on-board storage. In order to reach an acceptable autonomy, compressed storage is used (200 bars).

Use of CNG is therefore characterised by:

- a lower autonomy in comparison with vehicles using liquid fuels (between 300 and 350 kilometres for a storage of 1,100 litres of CNG at 200 bars).
- the necessity to use a means of compression coming from the network (the pressure of which does not generally exceed 30 bars).

In the current state of technologies, that fuel is therefore mainly meant for heavy urban vehicles linked to a centralised workshop (for example: dump trucks, city vehicles, buses).

Engines have an ignition management system. In other words, they are equipped with a complete ignition system following the example of fuel or LPG engines. To prepare the combustion air/fuel mixture, three solutions are currently available on the market:

- a system that prepares a stoichiometric mixture with no excess of air, with the advantage of using a three-way-catalyst.
- an electronic injection system that prepares a mixture with a low fuel content : this technology is associated with the use of an oxidation catalyst.
- a carburettor system that prepares a low content mixture associated with an oxidation catalyst.

The potential advantages of CNG are widely known. Let us recall that, from an environmental point of view, these advantages come from its very light formula which naturally limits the emission of heavy un-burnt and generally toxic compounds (benzene, aromatic compounds) as well as particles.

The use of CNG in transports puts us on the right track to energetic diversification towards petroleum.

The aim of this comparative study is to check benefits and drawback of current solutions in the real fields operations, and to define the area where improvements could be expected.

THE ADEME PROGRAM ON CNG / DIESEL BUSES

In order to inform operators and transport authorities about this path, the ADEME, the GART (Groupement des Autorités Responsables de Transports), the UTP (Union des Transports

Publics) and Gaz de France entered into partnership and invited applicants in order to select six transport networks desirous of equipping themselves with CNG buses (**figure n°2**).

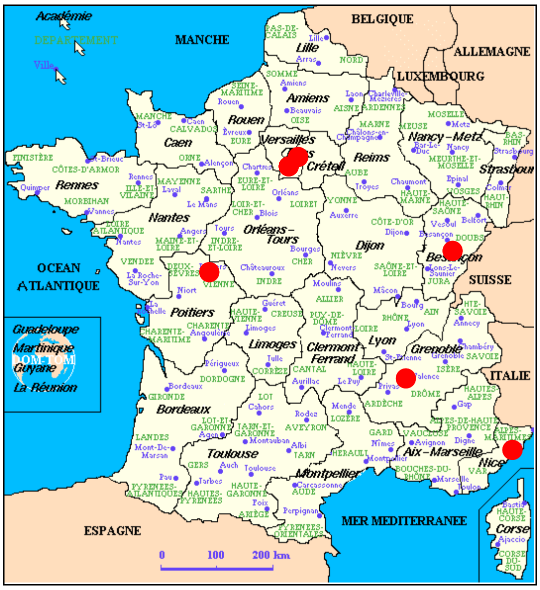

Figure 2: ADEME National Program of bus evaluations

In order to learn all the technical and economic lessons from the projects, an analysis program was implemented by the partners with the help of the PREDIT. This program was based on:

- a technical follow up of the buses over a period of use of at least one year.
- an analysis of the environmental performances of these vehicles through on-road and laboratory tests.
- a perception survey of the CNG solution among several population categories.
- collection of consumption data as well as of investment and operating costs.

This report concerns environmental analysis and preliminary feedbacks from operation: it shows the comparative results of exhaust emissions and consumption between CNG and recent Diesel buses (Euro 2 / 1995-1996).

At first, representative driving cycles for each vehicle were established by ADEME and specialised partners (**figure n°3**). On these cycles, pollutants (regulated and unregulated) were measured as well as fuel consumption, at the beginning of a program and one year after to quantify reliability and evolution in pollutants emissions.

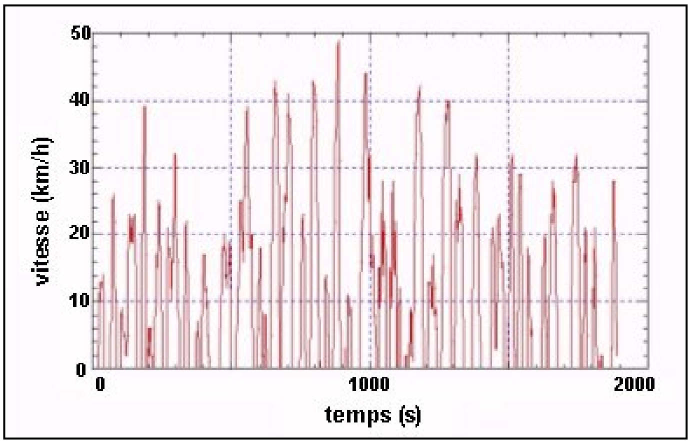

Figure 3: ADEME-RATP representative urban cycle (bus line #21)

The following cycle was established by ADEME and RATP using an urban line in Paris (line #21). This cycle (speed vs. time) is then considered representative for urban buses by professionals (RATP line #21, with an average speed of 10,5 km/h).

At the same time, in real condition, each technology was tested on several vehicles, for example a buses fleet in use in a city. Information such as fuel consumption, lubricant analysis, problem on the technology were following during a one year program.

Seven vehicles representing five configurations were tested within this program:

- CNG Mercedes bus working at the stoichiometric mixture
- CNG HEULIEZ Volvo bus working with electronic injection system working at lean conditions.
- CNG Renault Truck AGORA bus with a carburettor system and working at lean conditions.

The Euro 2 Diesel buses as reference are:

- two Renault Truck AGORA Diesel vehicles using a 10-litre-engine
- two Mercedes O 405 Diesel vehicles using a 12-litre-engine

The technological solutions in this category have the common characteristic of being able to be applied quickly and on a large number of vehicles. They therefore offer an immediate impact on the fleet's emissions and consumption.

Two experimental campaigns were carried out, with complementary methodologies and goals:

Certification tests (made at the UTAC): they were made on a bus with no setting modification when placed on a chassis dynamometer (HC, CO, NOx, PM), and non-regulated emissions (aldehydes, cetones, light hydrocarbons speciation), as well as fuel consumption are measured while the vehicle is following a representative driving cycle in urban area (line #21 ADEME-RATP cycle). Performances (power and torque) and smoke opacity are measured in full engine capacity conditions.

Fleet follow-up tests (made by the CRMT): these tests are based on the analysis of regulated pollutants at the vehicles exhaust and on the performances (power-torque) of the vehicles. A cycle made of a sequence of acceleration without load is used. The procedure is the AUTONAT/SYCADY method developed in partnership with the ADEME and proposed by the CRMT. These workshop tests aim at a quantitative evaluation of the performances of a fleet of CNG identical vehicles and of a fleet of similar Diesel buses. The tests concerned 20 vehicles on a network duty (10 CNG and 10 Diesel type Renault Truck vehicles).

RESULTS ON EXHAUST EMISSIONS (OVER ADEME-RATP CYCLE)

CO EXHAUST EMISSIONS: CNGs show similar to higher CO emissions compare with the Diesel emissions; dispersions in CO exhaust emissions versus CNG technologies were observed (**figure n°4**). For the CNG stoichiometric combustion, a large drift was recorded after one year ageing (from 12 to 33 g/km). In the case of Diesel, factor 2 was observed between buses over the ADEME-RATP cycle.

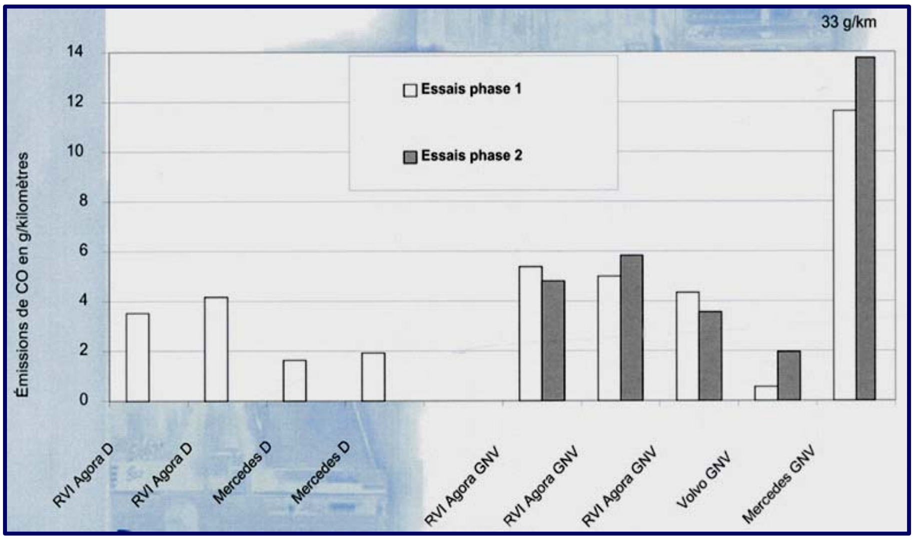

Figure 4: Comparison on CO exhaust emissions

HYDROCARBONS EXHAUST EMISSIONS: the first rough estimate shows that the composition of un-burnt hydrocarbons is close to the one found for the natural gas used in the test, which means that methane is in a large majority and that Non-Methane Hydrocarbons emissions are almost insignificant for CNG engines, except for the carburettor-based technology (**figure n°5**). No particular aromatic compound was detected.

Significant drifts in methane emissions were observed over the year evaluation.

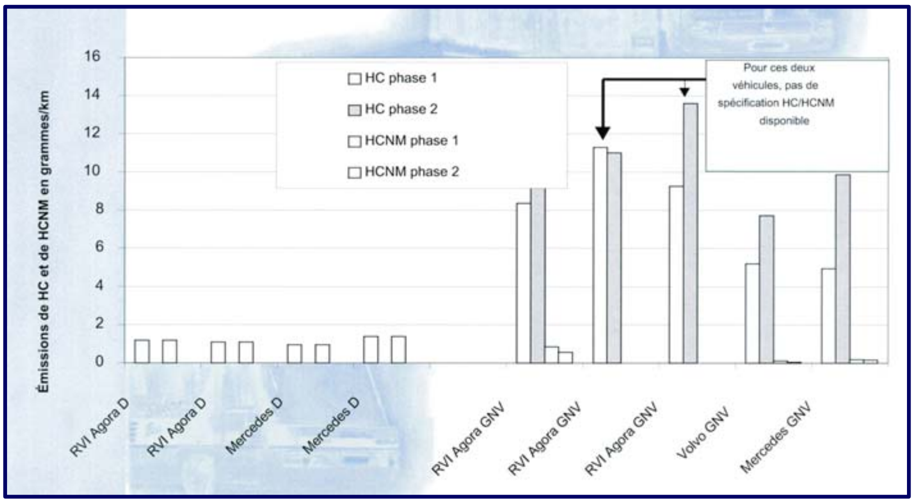

Figure 5: Comparison on Hydrocarbons exhaust emissions

NOX EXHAUST EMISSIONS: the use of CNG leads to an important decrease in NOx emissions compared to Diesel vehicles; an average decrease of about 50% was observed on the whole tested fleet) (**figure n°6**). This is a major advantage because the post-treatment of this pollutant is very difficult for all engines with low content mixtures (also presenting numerous advantages environmentally speaking). The dispersion in Renault CNG buses seems related to the engine tuning. No correlation could be set up between the combustion technologies and the NOx levels.

In the case of Diesels, dispersions were also observed versus buses, from 20 to 30 g/km over the ADEME-RATP cycle.

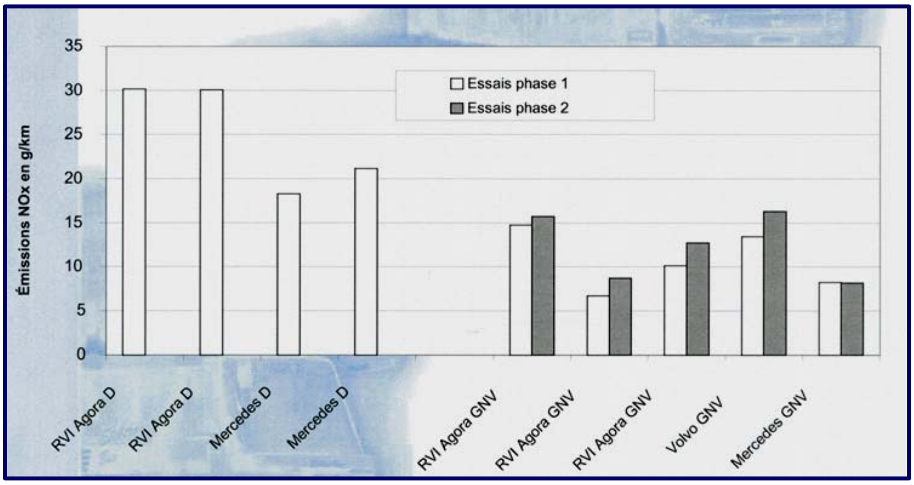

Figure 6: Comparison on NOx exhaust emissions

PARTICULATE EXHAUST EMISSIONS: the mass of particles emitted by CNG engines is approximately 10 times lower than for recent Diesel engines (EURO 2) (**figure n°7**). According to the first analysis, these particles come in priority from the burning of motor oil. But, it would be desirable to run precise tests on the content and the composition, the size and the number of these particles emitted by CNG buses. Again, the Diesels show differences in PM exhaust emissions.

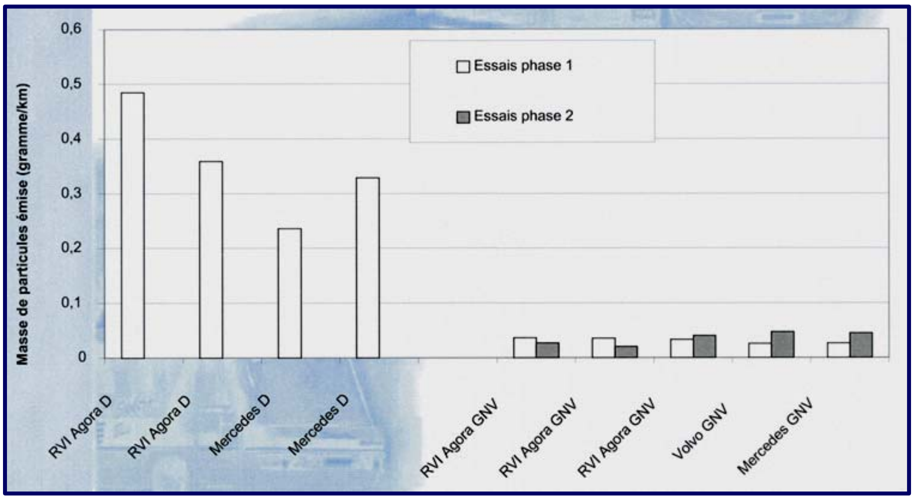

Figure 7: Comparison on PM exhaust emissions

NON-REGULATED HYDROCARBONS EXHAUST EMISSIONS: non-regulated compounds emissions for CNG buses were checked over the ADEME-RATP cycle:

- ***at the initial point*** (**figure n°8**), hydrocarbons speciation are mainly methane, C2 (ethane, ethene), C3 (propane, propene); no significant emissions of other hydrocarbons could be observed with CNG buses, except for carburettor-based technology.
- with carburettor-based technology, high non-regulated hydrocarbons levels were observed: ethane (732mg/km), C3, C4, C5, C6, acetaldehyde (150mg/km) and acrolein, with about 10 times higher than other CNG technologies.

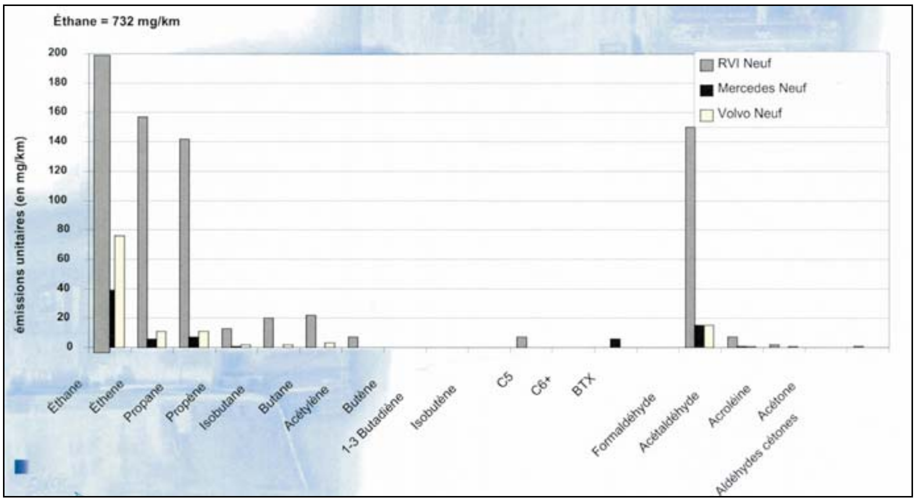

Figure 8: Non-regulated Hydrocarbons emissions over ADEME-RATP cycle (CNGs)

- ***after ageing***, evaluations showed increase in non-regulated hydrocarbons emissions, with aldehydes, regardless of CNG technologies. In addition, heavy hydrocarbons (> C5) were observed. Effect of lubricant (consumption, combustion) could explain this change.

Diesel non-regulated emissions are more specific, without significant difference between buses types (**figure n°9**). Heavy hydrocarbons (>C5) are the main components, and oxygenated emissions related to formaldehydes (50%, with 70mg/km) and acetaldehyde (25%).

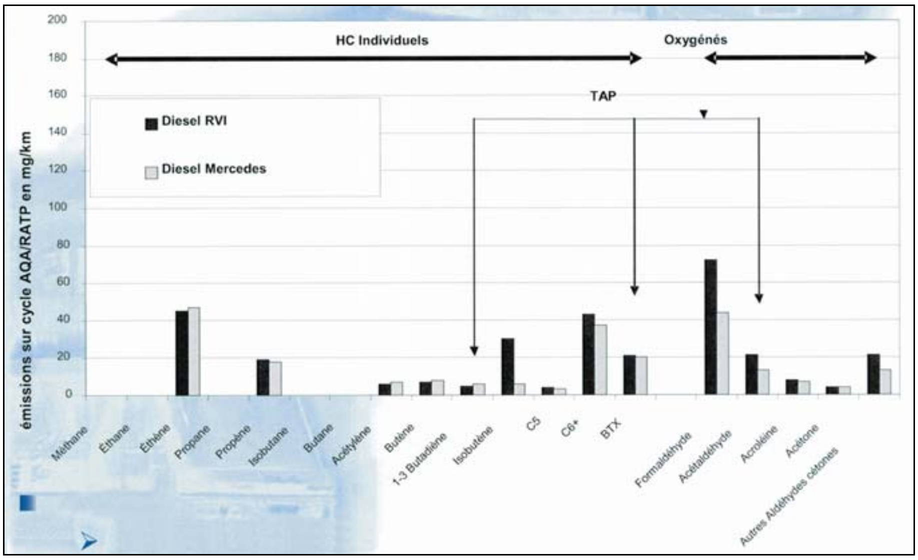

Figure 9: Non-regulated emissions over ADEME-RATP cycle (Diesel)

FUEL CONSUMPTION

Fuel consumption depends very much on use and technology conditions. Depending on the cases, medium over-consumption was observed, varying between 20 and 45 per cent (with the basic correspondence of 1 Nm^3/100km equivalent to 1 l Diesel/100km):

- over the ADEME-RATP cycle, CNG leads to an over-consumption compared with Diesel, with +30 to +60% depending on the technology
- on site, it depends strongly on the bus technology, the urban conditions, the air-conditioning, the compartment heating… For instance, Nice area reported the impact

of the air-conditioning system (78 Nm3/100km in Winter, with 85 Nm3/100km in Summer time) on the average fleet consumption (**figure n°10**).

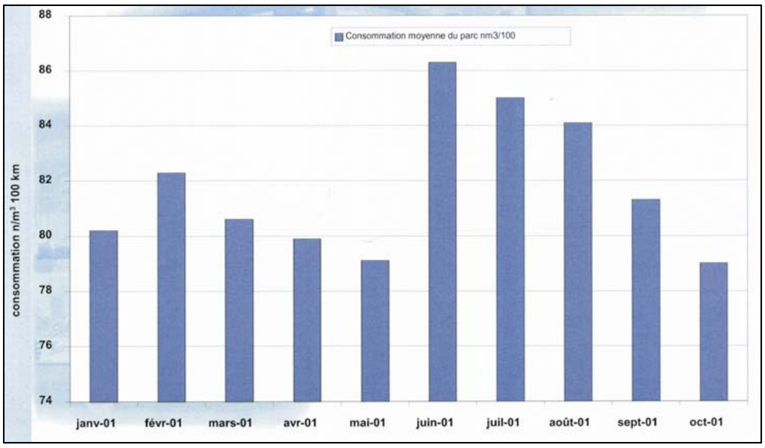

Figure 10: Climate impact on CNG consumption in Nice

GENERAL COMMENT ON THE CNG PERFORMANCE DISPERSIONS

The performance measured on CNG vehicles are representative, within the same generation of vehicles, of uneven technologies in terms of advancement. This diversity results in a great dispersion of performances, fuel consumption or polluting emissions

- between two vehicles with two different technologies,
- between two similar vehicles.

DISPERSIONS BETWEEN SIMILAR VEHICLES result in:

- uneven mechanical performances from one vehicle to another, though they are inferior to Diesel : a 25% difference of the torque value was found between two similar vehicles from the same fleet.
- very variable CO emissions from one vehicle to another (showing the instability of the catalyst activity).
- instabilities in slow running on a number of vehicles.

DISPERSIONS BETWEEN TECHNOLOGIES result in:

- a very uneven fuel over-consumption[1] from one technology to another (between +28% and +62%[2] according to the CNG and Diesel vehicles concerned). It must be outlined that these consumption rates were achieved on the ADEME-RATP cycle indicative of severe conditions of use in a dense urban environment (average speed 10,5 km/h). Some complementary elements concerning this aspect will be shown through the results of the running vehicles follow-up.
- the technology using the carburettor offers the lowest consumption and results in a graduated transitory handling. The settings seem to vary from one vehicle to another.

[1] Over-consumption should be understood as the difference to 1 between the CNG volumetric consumption ratio (given in nm3/100km) and the volumetric consumption (given in l/100km) of the Diesel bus measured in driving conditions. The content of a normal cubic metre of natural gas is comparable to the content of 1 litre of gas-oil.

[2] These values come from the comparison between CNG and Diesel vehicle consumption tested within the program. The typed comparison, usually made with equivalent technologies, has no physical significance here. For a similar type of vehicle, the Diesel and CNG engine technologies are different.

- the vehicle using a multiple injection technology with a low content mixture seems to show the best performances in terms of power and exhaust emissions. Its greater consumption is related its greater performances.
- the vehicle working at stoichiometry achieves very low NOx emissions and a reduced consumption considering the technology used. It seems to suffer from a setting problem (rich mixture ?) corrupting CO emissions.

DIESEL PARTICULATE FILTERS

Effective after-treatment systems could clean the Diesel exhaust of existing vehicles (retrofit). These systems make it possible to finish combustion after the chamber and thereby to reduce the emission of unburned products (CO, HC and particles).

In the case of Diesel exhaust particulates, filters technologies (catalyzed- and fuel-borne catalyst-based) were evaluated over the ADEME-RATP cycle as well as during field operation (Renault buses).

In term of efficiency, all the tested technologies are efficient on the particulate matter abatement. This effect is related to the filter materials and design (ceramic-based trap, with wall-flow filtration mechanism). Typical efficiency is reported on the **figure n°11** for a Catalyzed-DPF technology.

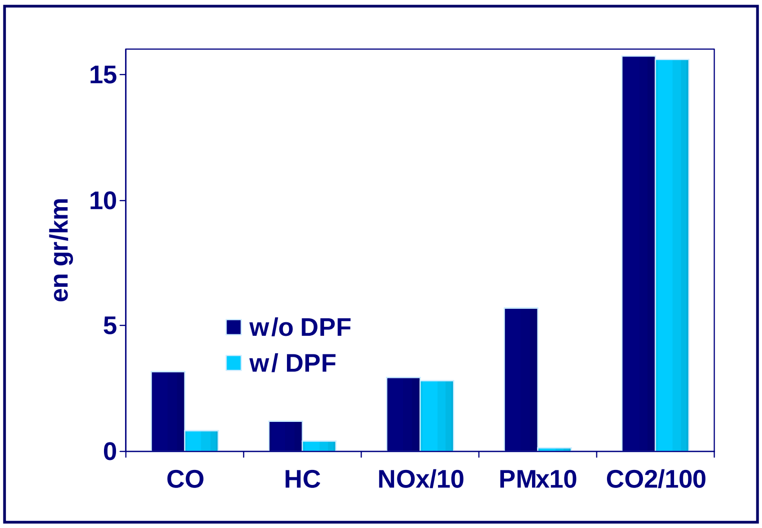

Figure 11: DPF efficiency over the ADEME-RATP cycle

Over the ADEME-RATP cycle, important changes could be observed, in comparison with the raw Diesel engine-out emissions:

- about 98% of PM reduction in mass per km
- 75% of CO reduction and 65% of hydrocarbons reductions
- no real impact on the NOx and the Diesel fuel consumption

However, the sustainability of these DPF systems is conditioning by the regular occurrence of regeneration of the filter (combustion of the retained soot in the trap), which should be as complete as possible, otherwise the filter clogs up by generating unacceptable counter-pressure and possible trap damages. The exhaust temperature is in this regard a key parameter in the functioning of these vehicles.

ADEME recommends to evaluate the exhaust temperature as well as conducting a regular diagnosis of the counter-pressure on a few circulating vehicles in order to test the filter compatibility with the vehicles and their operating conditions before large-scale purchasing. Moreover, quality maintenance is a required condition for success.

GREEN HOUSE EFFECT EVALUATIONS

The CNG technologies are penalized by the yield of combustion engines in use and the CH4 emissions (around 10% of the global effect), with an average of 2200g/km, compare with the 1800g/km for EURO2 Diesel technologies (**figure n°12**).

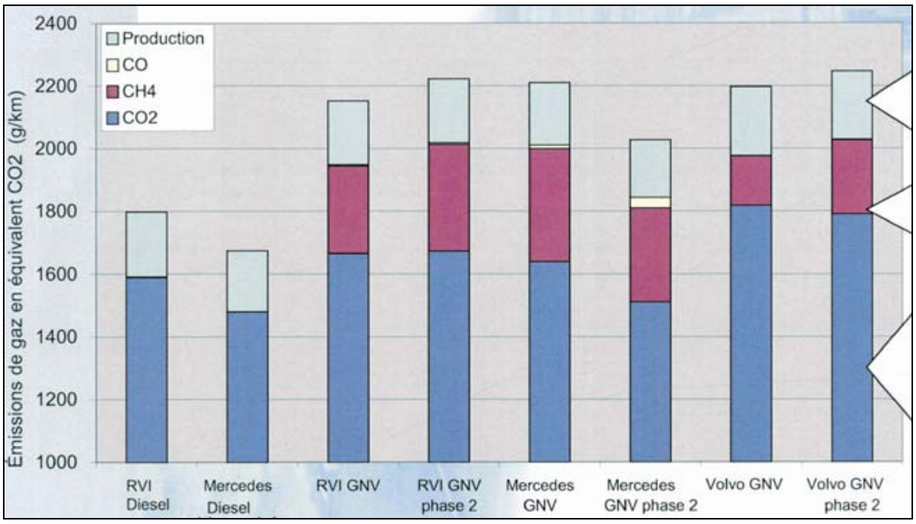

Figure 12: Comparison in Green House Gas Emissions effects

These data were calculated with the compressed operation (0,16 kWh/Nm^3) and the specific French electricity distribution (70% of nuclear and 30% of thermal). For the Diesel fuel, only the 350ppm Sulfur was taken into account.

CONCLUSIONS

According to the first results of the various tests, the performances obtained by the CNG vehicles are promising and confirm the environmental interest of the solution. Performance comparisons are summarized on the **table 1**.

Pollutants (g/km)	RVI AGORA Diesel	Mercedes Diesel	*RVI AGORA CNG*	*Volvo CNG*	*Mercedes CNG*
Max. Power	110 kW	136 kW	103 kW	127 kW	103 kW
CO	3,90	1,8	5,4	0,6	12,0
HCs	1,2	1,2	8,4	5,3	5,0
NOx	30,2	20,0	14,8	13,5	8,3
PM	0,42	0,28	0,036	0,025	0,026
Consumption (line 21) /100km	61 lit.	56 lit.	78 Nm3	91 Nm3	81 Nm3

Table 1: Summary of performance

In comparison with Diesel-powered buses, CNG-powered buses lead to about a 50 per cent reduction of NOx emissions and a near-total absence of particles that could be improved using specific lubricant characteristics.

In order to obtain low CO and HC emissions, it is necessary to lean towards advanced engine technology by favouring injection systems rather than older technology using a carburetor. To date the reliability of control systems of fuel mixture is not yet perfected.

Fuel consumption depends very much on use and technology conditions: depending on the cases, medium over-consumption was observed, varying between 20 and 45 per cent.

Incidents occurring on vehicles concerned the ignition and gas-compression system. Numerous "teething" technical problems were resolved.

The solution's economic assessment is quite variable from one site to another because of the technical choices (vehicles, workshops) done when the operation was mounted, as well as the fuel-supply contracts for each site. Harmonising the regulations and practices would be a bonus worth developing for the CNG solution.

The CNGs are generally very well received by various groups of people, in particular for the noise and odours level.

GHG Emissions considering CO2, CH4 and fuel cycle emissions for are higher than Diesel EURO 2 version. This point has to be improved in EURO 3 version by acting on lean burn process and/or mixture control.

In the case of Diesel-powered bus, the use of adapted after-treatment can decrease exhaust emission pollutants level, especially for PM abatement. In that case, some trap technologies must be associated with adapted Diesel-fuel formulations (for instance, ultra-low sulphur fuel for some filter technologies), constant filter maintenance (for instance, stationary heating machine for trap regeneration, trap cleaning to remove ashes…).

There is therefore a choice on offer to organising authorities and networks between these different solutions. They each have their strong and weak points for markets that are most often complementary (**figure n°13**), and all the criteria have to be taken into account from the fuel cycle emission to cost for security aspect concerning gaseous fuel. Feasibility studies must shed light on choices by decision-makers on the best solution to implement for their bus fleets by taking into consideration the size of the fleet, average speed, the length of routes and constraints of infrastructure and capacity inherent to the planned solutions.

	CO	HC	NOx	PM	NRP	GHE	D	I	O	A
Diesel (EURO 2)										
Diesel w/ DPF	+	+	=	++	+	=	=	-	=	-
CNG		+	++	++	++	- -	++	- -	=	-

Worse	- -	-	EURO 2	+	++	Better

D: Diversification (energy)
I: Investment
O: Operation
A: Adaptation

Figure 13: Global comparison of CNG/Diesel buses

On the overall level, it is the combination of various action, exhaust emission reduction and renewal that will make it possible to meet the technological challenge of reducing emissions and fuel consumption by urban bus networks.