Emissions and fuel consumption of natural gas powered city buses versus diesel buses in real-city traffic

L. Pelkmans, D. De Keukeleere & G. Lenaers
Vito – Flemish Institute for Technological Research, Belgium

Abstract

In the frame of the IEA-AMF project "Real Impact of New Technologies for Heavy Duty Vehicles", three state-of-the-art city bus technologies were evaluated for fuel consumption and emissions in real city traffic and in a number of test cycles, both on engine and on vehicle level. The three buses were a diesel bus, a natural gas bus with stoichiometric fuel control and three-way catalyst, and a natural gas bus with lean burn fuel control.

The paper will compare fuel consumption and emissions of the three buses measured in real-city traffic using Vito's VOEM measurement system. The measurements showed that the natural gas buses had clearly higher fuel consumption (in diesel equivalents) than the diesel bus, caused by the lower average engine efficiency. Concerning the emissions, the natural gas bus with stoichiometric fuel control totally fulfilled its expectations with about 10 times lower NO_x, THC and CO emissions than the diesel bus. The natural gas bus with lean burn fuel control had low CO emissions, but rather high THC and NO_x emissions. In order to lower NO_x emissions, the lambda control system needed some adjustments.

The buses were tested with three different loads. Vehicle weight had a clear impact on fuel consumption and CO_2 emissions for the three buses. Considering the other emissions, only NO_x emissions of the diesel bus clearly related to vehicle weight. The actual function of a bus is to transport passengers from one point to another, so it is justified to relate fuel consumption and emissions to the number of passengers. This allows a comparison with other vehicles like passenger cars, vans or minibuses.

1 Introduction

City traffic occurs in the immediate presence of high people concentrations and therefore the sensitivity for city traffic emissions is very high. Future evolutions tend either to avoid city traffic as much as possible, either to use clean vehicle technologies in city traffic. With this respect, a lot of effort is put into clean city buses.
The main effort to reduce the environmental impact of buses focuses on optimising the use of diesel technology. Expected in this area are the general application of electronic diesel fuel control (EDC) and the gradual introduction of aftertreatment catalysts and particulate traps.

An increasing number of manufacturers also offer compressed natural gas (CNG) as a commercially viable solution, as it is currently the fuel which seems to have most potential for competing with petrol and diesel. Natural gas is available in large quantities, reserves are spread throughout the world, the gas is easy to extract and it generally offers lower emissions than today's other fossil fuels. The development of natural gas power also creates an opening for biogas power.

In the IEA-AMF project "Real Impact of New Technologies for Heavy Duty Vehicles" (IEA-AMF, annex XVII), three city bus technologies were selected to compare emissions and fuel consumption in real traffic, in several vehicle test cycles and in the main official engine test cycles [1]. The purpose was to look for clear relations between these test procedures. Meanwhile it was also interesting to compare the real impact (meaning fuel consumption and exhaust gas emissions in real traffic) of these state-of-the-art technologies. This comparison will be highlighted here.

2 Measurements

Three buses were selected for extensive evaluation. All were 12-m buses, with a gross weight around 19 tons and engine power between 150 and 200 kW. The buses had automatic transmission, however with a different number of gear ratios.

The first bus was a Belgian in-service bus, type Van Hool A600, with a 160 kW DAF diesel engine (Euro 2 certified). The fuel system was direct injection with a mechanical diesel pump. No exhaust aftertreatment was installed. The gearbox was a ZF 5HP500 with 5 gear ratios. The bus will be referred to as 'Diesel bus'.
The second bus was an Italian demonstration bus (type IVECO CityClass), with a 161 kW IVECO CNG engine. The fuel system was multi-point injection, with closed loop stoichiometric control. Exhaust gases were treated in a three-way catalyst. The gearbox was a Voith D581.3 wit 3 gear ratios. The bus will be referred to as 'Stoichiometric CNG bus'.

Transactions on the Built Environment vol 52, © 2001 WIT Press, www.witpress.com, ISSN 1743-3509

The third bus was a Canadian in-service bus, type Orion V, with a 206 kW Cummins CNG engine. The fuel system was a central gas mixer with closed loop lean burn control. No aftertreatment was installed. The gearbox was an Allison B400R with 6 gear ratios. The bus will be referred to as 'Lean Burn CNG bus'.

The buses were tested in real-city and rural traffic in Belgium (diesel bus and stoichiometric CNG bus) and in Canada (lean burn CNG bus). In addition the buses were tested on proving ground according to three simulated city cycles: the time-based CBDC (Central Business District Cycle) and DUBDC (Dutch Urban Bus Driving Cycle) and the distance based city cycle "De Lijn". All vehicle tests were performed for three load situations: low load (only measuring system and staff), medium load and full load. The different curb weight and gross vehicle weight have to be taken into account when comparing the results.

Figure 1 compares the curb weight and the gross vehicle weight of the three buses. The curb weight of the CNG buses is about 2 tons higher than the diesel bus, because of the extra weight of the CNG cylinders. This will cause that either the energy use of the CNG buses is higher for the same performances, either the acceleration possibilities of the CNG buses will be lower.

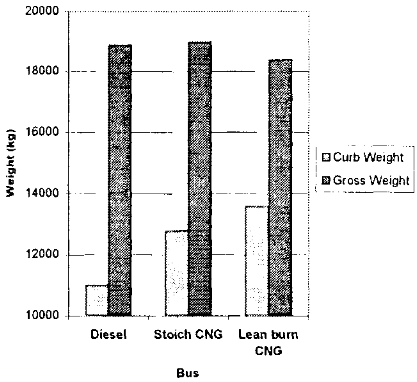

Figure 1: curb weight and gross vehicle weight of the three buses

For the vehicle measurements a dedicated system for on-road measurements was used, called VOEM (Vito's On-the-road Energy & Emission Measurement System). The VOEM system measures the emission concentration measurements (CO_2, CO, THC and NO_x), combined with the total mass flow of the exhaust gases, which is calculated from fuel consumption and lambda value determination [2]. The system consists of the sampling system of the exhaust gases, the analysers, the measurement of fuel consumption, vehicle speed and engine speed, the power supply, and the data-acquisition and automated data treatment system.

3 Results

3.1 Average

The following results are the average of 6 measurements for each bus performed in real-city traffic (3 loads x 2 lines). Fuel consumption of the CNG buses is recalculated into diesel equivalents.

Table 1: General overview of the average fuel consumption and emissions of the three buses in city traffic.

		Diesel bus	Stoich. CNG bus	Lean Burn CNG bus
Fuel cons.	*l/100 km*	62,8	73,5 *	83,2 *
CO_2	*g/km*	1633	1475	1634
CO	*g/km*	3,5	0,7	0,8
THC	*g/km*	1,7	0,2	7,5
NO_x	*g/km*	15,2	1,8	25,1

* expressed in dieselequivalents (35700 kJ/l)

Fuel consumption of the natural gas buses (recalculated to diesel equivalents) is clearly higher than the diesel bus. This is mainly caused by the lower average engine efficiency of the natural gas buses.

Due to the different specifications of the three buses, some caution should be taken when comparing these results. Because of a clearly different gear shifting strategy of the automatic transmission (emphasis on lower engine speeds), the stoichiometric CNG bus has lower acceleration capabilities than the other buses, especially below 50 km/h. This results in less demanding city cycles. The following table shows the estimated road load energy in the city cycles, calculated from the speed profiles and the bus dimensions.

Table 2: Average road load energy (kWh/km) in the city cycles

RLE (kWh/km)	Diesel bus	Stoich. CNG bus	Lean burn CNG bus
High load	1,89	1,47	1,69
Medium load	1,50	1,28	1,54
Low load	1,34	1,12	1,22
Average	**1,57**	**1,29**	**1,48**

The extra weight of the natural gas buses (due to the heavy CNG cylinders) apparently does not cause the road load energy to be higher. The buses will just have lower performances in real-city traffic.

While the average road load energy demand is about the same for the diesel bus and the lean burn CNG bus, the city cycles of the stoichiometric CNG bus are about 15% less demanding. This reflects clearly on fuel consumption and CO_2 emissions, when comparing the two natural gas buses.

Transactions on the Built Environment vol 52, © 2001 WIT Press, www.witpress.com, ISSN 1743-3509

Natural gas has an advantage over diesel fuel because the CO_2 production per unit of energy is about 25 % lower. This means that when energy efficiency is the same, the natural gas powered engine will have 25% lower CO_2 emissions. In reality, the natural gas engines have lower energy efficiency than diesel engines, so the effect will only partly be exploited. In practise CO_2 emissions of the diesel bus and the lean burn CNG bus are about the same. The stoichiometric CNG bus has lower CO_2 emissions, which again is rather due to the lower road load energy demand.

The natural gas buses have 4 to 5 times lower *CO emissions* than the diesel bus. For the stoichiometric natural gas bus this has to do with the high conversion efficiency of CO in the three-way catalyst. For the lean burn natural gas bus this has to do with the lean burn fuel control.

The stoichiometric natural gas bus has about 10 times lower *THC emissions* than the diesel bus, mainly related to the high conversion efficiency of hydrocarbons in the three-way catalyst. The lean burn natural gas bus on the other hand had 4 times higher THC emissions than the diesel bus. If methane emissions are left out of the comparison (this means only NMHC) the lean burn engine is expected to reach lower non-methane hydrocarbon levels than the diesel engine.

The stoichiometric natural gas bus had about 8 times lower *NO_x emissions* than the diesel bus, mainly related to the high conversion efficiency of NO_x in the three way catalyst. The lean burn natural gas bus on the other hand had on average 60% higher NO_x emissions than the diesel bus, while the lean burn technology is supposed to reduce the NO_x emissions.

Figure 2 shows that the lean burn lambda control keeps the air to fuel ratio (lambda) around 1.4 at high fuel consumption. In order to really lower NO_x emissions however this is not high enough. An increase of this air to fuel ratio (especially at high engine load) would certainly reduce the total NO_x emissions.

On the other hand, this may also have a negative effect on THC emissions and fuel efficiency [3].

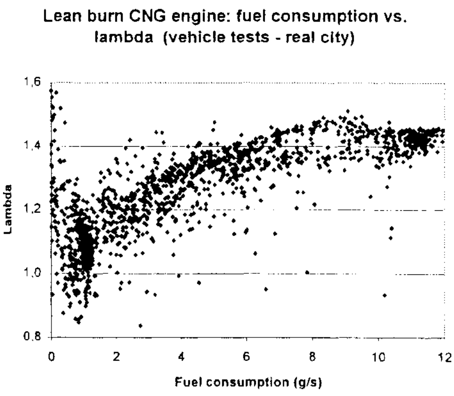

Figure 2: Relation between fuel consumption and lambda for the lean burn engine

This shows the difficulty in the choice of the settings of a lean burn lambda control, because the manufacturer always has to make a compromise between different factors.

3.2 Vehicle weight

The weight of the vehicle is an important influencing parameter on fuel consumption and exhaust gas emissions. As is shown in figure 3 it has a direct effect on the acceleration possibilities of the vehicle and on the road load energy demand of the cycle (see table 2).

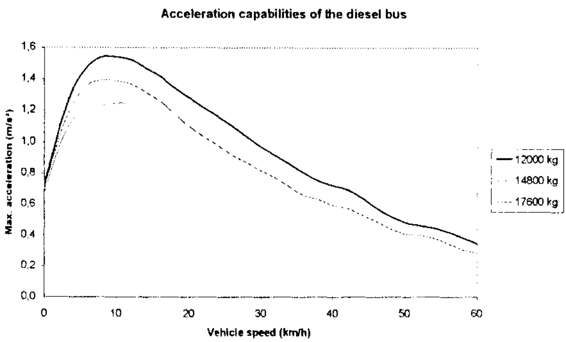

Figure 3: influence of vehicle weight on the acceleration capabilities of the diesel bus

Figure 4 gives an overview of all measurements performed on the buses in real-city traffic plotted against vehicle weight. Table 3 shows the average influence (% weight increase vs. % fuel consumption/emission increase) considering all measurements on the different buses (real city and simulated test cycles) and the significance of these results.

Table 3: Regression parameters on relation between (relative) weight increase vs. (relative) fuel consumption/emission increase.

	Diesel bus			Stoich CNG bus			Lean burn CNG bus		
	Gr.	St.dev	p-level	Gr	St.dev	p-level	Gr.	St.dev	p-level
Fuel	**0.58**	**± 0.04**	**<0.001**	**0.45**	**± 0.07**	**<0.001**	**0.39**	**± 0.09**	**<0.001**
CO_2	**0.58**	**± 0.04**	**<0.001**	**0.45**	**± 0.07**	**<0.001**	**0.39**	**± 0.09**	**<0.001**
CO	0.16	± 0.08	0.047	0.42	± 0.50	0.42	0.78	± 0.51	0.14
THC	0.38	± 0.17	0.041	0.95	± 0.70	0.19	0.17	± 0.23	0.46
NO_x	**0.47**	**± 0.06**	**<0.001**	0.33	± 0.47	0.50	0.15	± 0.20	0.45

Gr. = gradient

Transactions on the Built Environment vol 52, © 2001 WIT Press, www.witpress.com, ISSN 1743-3509

The figures in bold indicate a significant trend. Especially fuel consumption and CO_2 emissions of the three buses have a significant upward trend for higher loads for all three buses. A weight increase of 25% leads to a fuel consumption increase of about 10% for the lean burn CNG bus and 15% for the diesel bus.

Concerning the regulated exhaust gas emissions, the load effect is only significant for the NO_x emissions of the diesel bus.

THC, CO and NO_x emissions (in case of the CNG buses) emissions do not show a clear effect of vehicle weight. This is quite surprising for NO_x, which is always considered to be very load dependent. The lambda control system in both CNG buses seems to be more decisive for NO_x than the vehicle weight.

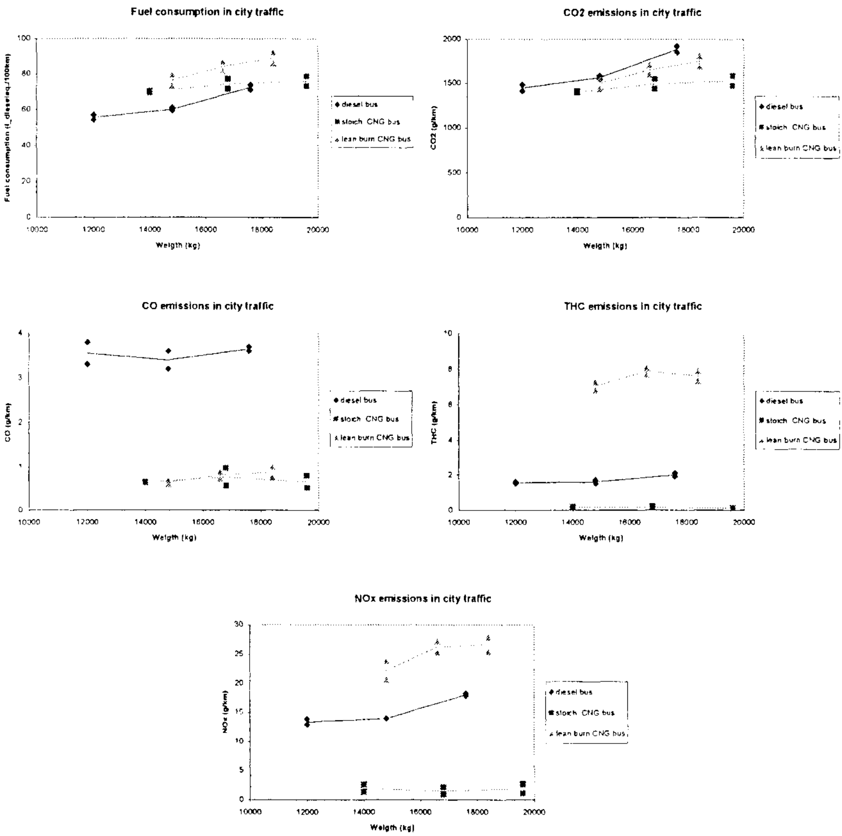

Figure 4: Effect of vehicle weight on fuel consumption and emissions

3.3 Passenger related

The actual function of a bus is to transport passengers from one point to another. So it is justified to relate fuel consumption and emissions to the number of passengers. Figure 5 shows an overview, in which the buses can actually be compared, based on the passengers they carry.

It is clear that the more passengers in the bus, the lower the fuel consumption and emissions per passenger.

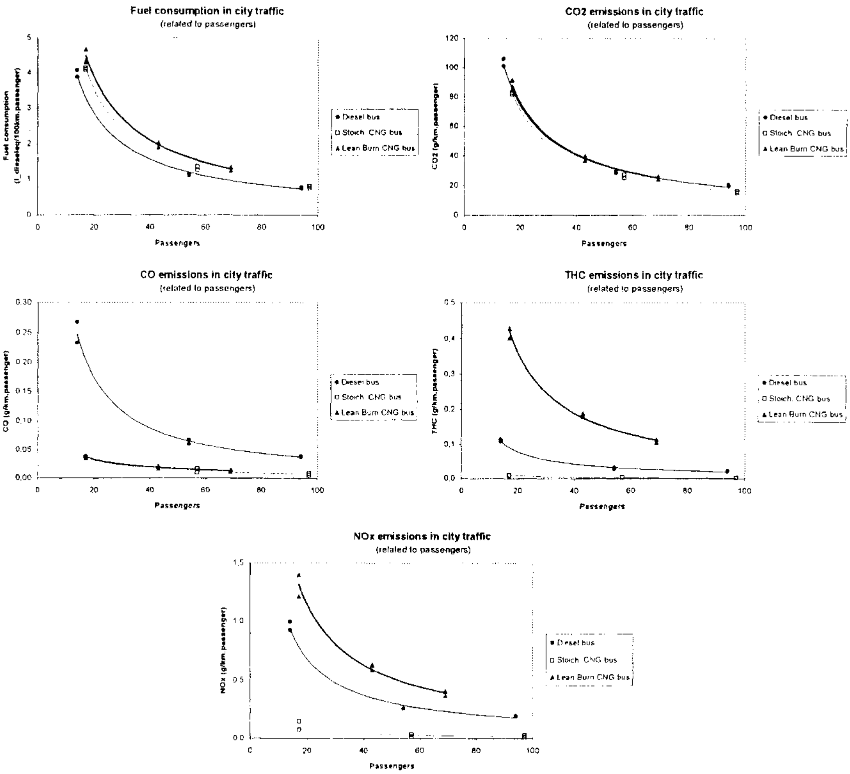

Figure 5: Fuel consumption and emissions, related to the equivalent number of passengers

The figures also allow comparison with other vehicles, like passenger cars, vans or minibuses. Some previous measurements with the VOEM system have shown that a typical passenger car (diesel) in city traffic with 4 people in it has a fuel consumption of about 12 l_dieseleq/100km and emits 315 g/km CO_2, 2 g/km CO, 1.2 g/km NO_x and 0.6 g/km HC [4].

Of course, the buses normally have higher fuel consumption and emissions than the passenger cars if they carry the same amount of passengers. Only with a sufficient number of passengers the buses will be better than the passenger car. The following table gives an overview of the number of passengers the buses minimum have to carry to achieve lower passenger-related fuel consumption and emissions than the passenger car. Of course this comparison only focuses on one car; the comparison with other cars may give different results.

Table 4: Equivalent number of passengers of the three buses to reach better passenger-related fuel consumption and emissions than a diesel car with 4 passengers

Break-even n° of passengers	Diesel bus	Stoich. CNG bus	Lean burn CNG bus
Fuel consumption	19	24	27
CO_2	19	18	19
CO	7	2	2
THC	10	1	51
NO_x	52	6	85

Fuel consumption of the buses is better than the passenger car from 19 for the diesel bus and from 27 for the natural gas buses. So this number of passengers has to be reached to have an advantage in energy consumption.

Concerning the emissions the stoichiometric CNG bus performs better than the diesel car from a very low number of passengers. For the diesel bus and the lean burn CNG bus NO_x emissions seem to be an issue, because the number of passengers has to be very high to reach the same passenger-related NO_x emissions as the passenger car.

4 Conclusions

Natural gas engines are considered to be a more environmentally friendly alternative for diesel engines. It can certainly be confirmed that there is potential for emission reduction. Especially the stoichiometric natural gas engine gives spectacular results. However the use of natural gas is not a guarantee that emissions will actually drop. The lean burn technology, which is very often preferred above the stoichiometric technology because of his higher fuel efficiency, in the tests even had clearly higher NO_x emissions than the Euro 2 diesel technology. With adjustments in the lambda control settings, and perhaps addition of a different fuel injection system, the NO_x emissions of the lean burn engine concerned could be lowered.

The influence of vehicle weight on fuel consumption and emissions was looked into. Fuel consumption and CO_2 emissions significantly increase with increasing vehicle weight for all three technologies.

The influence of weight on regulated emissions is less clear. Only for the diesel bus the NO_x increase with increasing weight was significant. For the other buses, the influence of the lambda control system was more decisive for the NO_x emissions. CO and THC emissions were not significantly related to vehicle weight.

When relating fuel consumption and emissions to the equivalent number of passengers, a comparison can be made with other vehicles like passenger cars, vans or minibuses. A comparison with a diesel car (containing 4 passengers) showed that a certain number of passengers is always needed to get better results with a city bus. NO_x emissions of the diesel bus and the lean burn CNG bus still stay an issue, even when compared to passenger cars.

Acknowledgements

The authors want to thank all members of IEA-AMF, participating in annex XVII 'Real Impact of New Technologies for Heavy Duty Vehicle', in the frame of which the project was carried out. The parties participating in this annex were DOE, ORNL (USA), IM-CNR (Italy), LEVO (Japan), NOVEM (Netherlands), STEM (Sweden), VITO (Belgium), VTT (Finland).
Also thanks to Irisbus-IVECO & Fiat Research Centre, Cummins Technical Centre and the Transport Companies Hamilton Street Railways, De Lijn and MIVB for their contribution in the carry out of the tests.

References

1. Pelkmans, L. et al. (2000): *Real Impact of New Technologies for Heavy Duty Vehicles*, IEA-AMF study.
2. Lenaers, G. (1994): *A Dedicated System for On-the-road Exhaust Gas Emission Measurements on Vehicles*, Proc. of the 3rd Int. Symp. On Transport and Air Pollution.
3. Corbo P. et al. (1998): *Lean burn natural gas engines as a possible power unit in urban fleets of heavy duty vehicles with low environmental impact*, International Journal of Vehicle Design 20, pp. 231-239.
4. Pelkmans L. (1998): *Used Vegetable Oil Methyl Ester Demonstration in Belgium*, Vito Report.