CNG Bus Emissions Roadmap: from Euro III to Euro VI

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1. EXECUTIVE SUMMARY

This report is focused on heavy-duty natural gas engine technologies that can achieve Euro III, IV, V and VI emission compliance levels. An international perspective was intended, but due to lack of sources of technical information from developing countries, most of the report is based on information from the US and Europe. A comprehensive review of technical literature and reports regarding emission performance and technologies was performed for compressed natural gas engines of model year 2000 and newer.

In the 1990's, there were several motivations for an increased interest in the use of compressed natural gas (CNG) buses around the globe. In the US and the EU the need for significant emission reductions from urban buses to address serious urban air pollution problems, and the desire to use alternative fuels to offset growing oil imports, stimulated a growing CNG bus market since particulate matter (PM) and nitrogen oxide (NO_x) emissions were initially easier to control from natural gas engines than from conventional diesel engines.

However, the imposition of more stringent emission standards for new engines over the last 20 years has stimulated the development of new diesel engine and fuel technologies in the US and the EU, and has made new "advanced" diesels competitive with CNG engines from an emissions standpoint (see Figures 1 and 2 which show the phase-in of US and EU new engine emission standards). In consequence, US and EU interest in CNG buses has waned somewhat; CNG buses currently comprise less than 10% of the total urban bus fleet in industrialized countries. By contrast, the availability and low cost of natural gas, less stringent new engine emissions standards, and fuel sulfur levels higher than required to utilize the most advanced diesel engines, all contribute to a continued high level of interest in CNG vehicles in many developing countries.

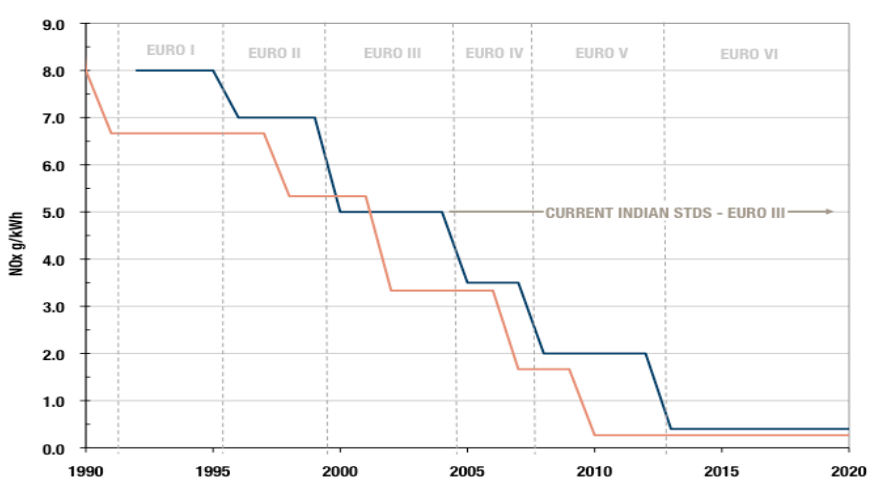

FIGURE 1. Phase-in of more stringent NOx emission standards for new heavy-duty engines in the EU and the US

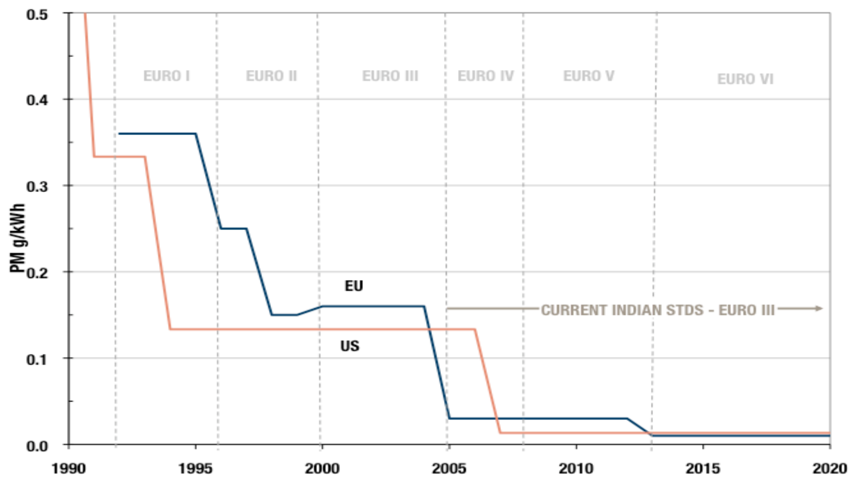

FIGURE 2. Phase-in of more stringent PM emission standards for new heavy-duty engines in the EU and the US

As shown in Figure 3, "conventional" diesel engines operated on high sulfur fuel can not quite achieve Euro III emission levels for NOx and PM, which is the current standard for new engines in India. For lower emission levels, "advanced" engine and after-treatment technologies are required, including electronic control of fuel injection, and exhaust gas recirculation (EGR) and/or selective catalytic reduction (SCR) to further reduce NOx, and diesel oxidation catalysts (DOC) and/or diesel particulate filters (DPF) to further reduce PM. The use of PM after-treatment technologies also generally requires diesel fuel with lower sulfur content than is typically found in many developing countries. Diesel fuel sulfur content must be less than about 500 parts per million (ppm) to effectively use DOCs, and must be less than about 50 ppm to use most commercially available DPFs.

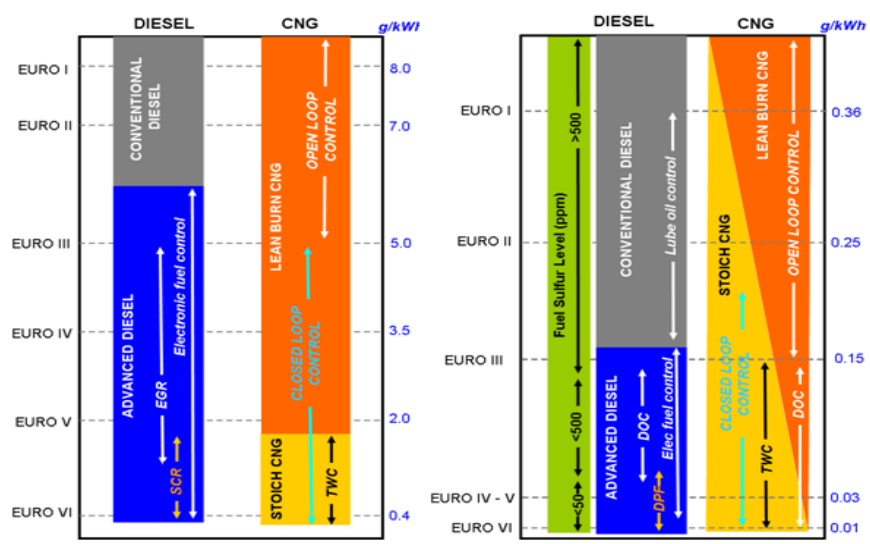

FIGURE 3. Technology evolution of heavy-duty engines to meet more stringent emission standards in the EU and the US

While diesel engines use a lean combustion mixture and compression ignition, natural gas engines are spark-ignited and can use either a lean-burn or stoichiometric combustion mixture. To this day, most light-duty natural gas engines used around the world are stoichiometric engines derived from gasoline engine designs (or are direct conversions of existing gasoline engines). The first generation of heavy-duty natural gas engines introduced in both developed and developing countries were lean burn engines based on diesel engine designs, with fuel injection systems borrowed from stationary natural gas engine technology. The earliest engines also employed simple open-loop fuel control systems and did not employ any after-treatment.

Lean-burn heavy-duty natural gas engines were initially popular due to their inherently lower engine-out NO_x emissions and higher fuel efficiency compared to stoichiometric engines, and their ability to provide power and torque levels similar to those from a conventional diesel engine. The engine-out PM and NO_x emission levels from a lean-burn CNG engine without any after-treatment system are low enough to outperform a conventional diesel engine (Euro III), or an advanced diesel engine with electronic control of fuel injection but without EGR or after-treatment (Euro IV).

As with diesel engines, lean-burn natural gas engine technology in developed countries has evolved over time, in response to more stringent emission regulation and market demand. The changes have included evolution of the fuel injection system from mechanically controlled open-loop throttle body injection, to closed-loop electronically controlled, multipoint sequential injection. Other changes have included the introduction of turbo-charging, increased fuel injection pressures, and new combustion chamber and fuel injection nozzle designs.

A modern, closed-loop electronically controlled lean-burn natural gas engine can achieve Euro V emissions levels for both NO_x and PM. For optimal emissions performance these engines should also be equipped with natural gas-optimized oxidation catalyst after-treatment (OC). A properly optimized OC will significantly reduce engine-out emissions of carbon monoxide (CO), methane (CH_4), and toxic exhaust constituents such as formaldehyde. While the total mass of PM emitted by modern lean-burn CNG engines is low (Euro V or lower), testing has shown that the number of ultrafine particles emitted (smaller than 0.1 μm) can be an order of magnitude greater than the number of such particles emitted by a DPF-equipped advanced diesel bus. Testing has shown that the use of OC after-treatment on lean-burn CNG engines can significantly reduce the number of ultrafine particles emitted.

To meet the most stringent US2010 and Euro VI NOx emission standards, natural gas engine manufacturers have found it necessary to switch to stoichiometric combustion combined with exhaust gas recirculation (EGR) and three-way catalyst (TWC) after-treatment. A stoichiometric engine does not have inherently lower engine-out NO_x emissions than a lean-burn engine, but the stoichiometric combustion mixture allows the use of a TWC. A TWC cannot be used on a lean burn engine (either diesel or CNG) because exhaust oxygen levels are too high.

A TWC, similar to the devices used to achieve low NO_x emissions from virtually all modern gasoline engines in developed countries, combines a NO_x reduction catalyst (to lower NO_x) with an oxidation catalyst (to lower CO and HC) . Several studies show that a stoichiometric CNG engine, with EGR, turbocharging, and a properly formulated TWC, can achieve NO_x emission levels on the order of 90% lower than the levels from a lean-burn CNG engine. In the US market commercial heavy-duty CNG engines are available which are certified to US2010 emission standards using these technologies. There are currently no heavy-duty diesel engines available for purchase in the US market that meet the US2010 NO_x emission standard. Several heavy-duty diesel engines engines have been certified at US2010 levels, or are in the process of certification, and are expected to be introduced for new vehicle purchases next year when the regulation comes into effect. Most US heavy-duty diesel engine manufacturers have indicated that they will introduce SCR to achieve the required low NO_x emission levels from their diesel engines.

In contemplating options to further reduce in-use emissions from urban transit buses and other heavy-duty vehicles in India and other developing countries, the following major policy issues must be evaluated:

1. **CNG vs ADVANCED DIESEL:** The relative costs and technology barriers for the introduction of CNG buses compared to the introduction of advanced technology diesel buses must be evaluated, relative to the specific situation in each country/city.

   While the introduction or expansion of CNG vehicle use will require investment in natural gas fueling infrastructure, the introduction of advanced diesel buses meeting US2010/Euro VI emission standards will require diesel fuel sulfur reductions and commercial availability of urea (for SCR). For example, in cities such as Delhi a CNG infrastructure is already in place, but low sulfur diesel fuel is not available; in some other Indian cities there is currently neither CNG infrastructure nor low sulfur diesel fuel in place.

2. **CNG TECHNOLOGY PATH**: When deciding to introduce or expand the use of CNG buses, one must evaluate the appropriate CNG engine technology to use relative to the desired emissions performance. Current lean-burn CNG engine technology can only achieve Euro V emissions levels with the addition of oxidation catalyst. To achieve US2010/Euro VI emissions performance stoichiometric CNG engines with TWC will be required. Continued investment in expanded production capacity for current generation lean-burn CNG engines may be an impediment to future introduction of more stringent emission standards, and early investment to introduce stoichiometric heavy-duty CNG engines may be warranted.

   In cities where CNG infrastructure is in place but where pollution levels are very high relative to WHO recommended guidelines, US2010/Euro VI CNG technology may be a viable option to achieve further reductions in vehicle emissions to improve local air quality.

2. INTRODUCTION

Transit buses are one of the most cost-effective forms of mass transit, and the foundation of public transportation in the developing world. Diesel engines have been the traditional power source for public buses and heavy trucks due to their durability, robustness, reliability, high fuel efficiency and high torque. Because transit buses operate in heavily congested areas under stop-and-go traffic patterns, continuous acceleration and deceleration increases the production of particulate matter (PM), typical of high load during vehicle acceleration periods. Critical public health situations related to exposure to high concentrations of PM have pushed local authorities to take actions favoring low-emitting vehicles and in some extreme cases, banning the use of vintage diesel buses. Health concerns, combined with the constant strengthening of emissions standards have prompted a change in technologies for bus transit solutions, from a uniform fleet of diesel powered buses to a combined fleet of diesel buses with emission reduction technologies, natural gas buses, and hybrid buses in some cases. Data collected in 2005 reports that in the European Union the fleet of urban buses comprised 70,000 vehicles: 90.6% diesel and 5.8% natural gas powered [1]. In the US, natural gas powered vehicles accounted for 7% of a total fleet of 65,000 urban buses in 2007 [2].

Even though the cost of CNG vehicles is higher than diesel vehicles, due to both market size differences and a more complicated fuel storage and delivery system, the CNG solution for mass urban transportation is a technically feasible and economically viable way to comply with the most stringent emission regulations. This report presents a review of CNG technologies and recent studies on emissions of-CNG powered buses, and a comparison with emissions from diesel-powered buses. Based on that review, a summary of technical alternatives for CNG powered buses to achieve Euro IV, V, VI and US2010 emission levels are presented.

2.1 CNG TECHNOLOGIES

Natural gas is a naturally occurring gas composed primarily of methane (typical composition: 87-96% methane, 1.5-5.1% ethane and 0.1-1.5% propane); it is commercially produced from oil fields or from natural gas fields. Natural gas is used widely as a combustion energy source, including for power generation and industrial cogeneration; for these applications it is typically delivered at low to moderate pressure via utility pipeline. Most natural gas vehicles utilize fuel cylinders containing natural gas that has been compressed at high pressure (200-220 bar), reducing its volume by 99% compared to standard atmospheric conditions; this allows significantly greater driving range between fueling events.

Automotive applications use CNG for Otto-cycle engines. The combustion part of the Otto cycle can be accomplished under stoichiometric or lean air-fuel (A/F) conditions. Stoichiometric combustion is defined as the theoretical or ideal combustion process in which fuel and oxygen are completely consumed, with no unburned fuel or oxygen in the exhaust. Lean burn combustion, on the other hand, is accomplished with excess air in the combustion chamber, and the resulting exhaust contains significant oxygen. In a natural gas engines ignition is achieved via a spark plug in both cases, but the configuration of lean combustion engines is more complex. The stoichiometric engine requires a homogenous air-fuel mixture, which is achieved in the intake manifold by throttle-body injection (TBI) or port fuel injection (MPFI). Lean burn engines usually require a stratified mixture, which is achieved through indirect fuel injection or direct injection of fuel with induced turbulence. Indirect and direct fuel injection requires special design of the cylinder heads. Indirect fuel injection also requires a prechamber, where the fuel is injected before reaching the cylinder volume. The prechamber is sized to keep the A/F mixture at stoichiometric conditions during the injection period. The A/F mixture is dragged out of the prechamber by the fuel stream and is passed close to the spark plug for ignition. Each system requires different A/F mixture control strategies to keep the mixture at the right values for ignition and emission control.

Stoichiometric engine A/F control is based on an O_2 sensor in the exhaust stream. The sensor detects the presence of O_2 in the exhaust and sends the signal to the fuel metering system to correct the mixture composition, keeping it at stoichiometric conditions ($\lambda=1$). Lean-burn engines require a linear oxygen sensor that provides a reading of excess oxygen concentration in the exhaust stream. A typical lambda value for a lean-burn engine is around 1.7[1]. It should be noted that the flammability limits of natural gas are far wider than the λ values set by the control systems of both stoichiometric and lean-burn engines. The reason for maintaining tight A/F values is to both control engine-out emissions levels, and to maximize the conversion efficiency of aftertreatment devices.

The effect of A/F mixture on the concentration of CO, HC and NO_x in the exhaust stream is presented in Figure 4. Stoichiometric engines generate engine-out emissions levels higher than lean-burn engines, but the former are suitable for further reductions in NO_x emissions with aftertreatment devices. Aftertreatment for stoichiometric engines is based on three way catalytic converters (TWCs). An efficient application of the three way catalyst (TWC) requires more precise air-fuel control than can be provided by a carburetor because of the required stoichiometric atmosphere, with very low excess oxygen, needed for NO_x reduction. HC and CO are oxidized during lean periods, when O_2 is available. A TWC is capable of conversion efficiencies higher than 95%, provided that the control system keeps the engine under stoichiometric conditions. For a lean-burn engine, the high concentration of O_2 in the exhaust stream does not allow for NO_x reduction, but CO and HC can be oxidized using an oxidation catalyst.

The first generation of CNG powered engines for cars used stoichiometric combustion, and this has remained the most popular choice of engine type for light-duty applications. Most light-duty

[1] Lambda (λ) is defined as the ratio between the current A/F ratio and the stoichiometric A/F ratio. In other words, $\lambda=1$ means that the combustion is stoichiometric, and $\lambda=1.7$ means that the combustion occurs at 70% excess oxygen when compared to stoichiometric conditions.

natural gas engines are based on modified spark ignited gasoline engine designs. For heavy-duty vehicles (trucks, buses) lean-burn natural gas engines became the dominant technology due to their higher fuel efficiency and lower heat rejection compared to stoichiometric engines, and the fact that they can provide power and torque levels equivalent to diesel engines of similar displacement. Fuel systems and ignition systems of this generation of engines were borrowed from stationary application engines [3].

By the mid 90's, a second generation of natural gas engines came on the market in developed countries. These engines utilized electronic controls to reduce the sensitivity to the operating environment, offering an integral design with improved reliability. Throttle body injection (TBI) injection or Single Point Injection (SPI) was used for Euro I and II compliant engines. Multi-port fuel injection (MPFI) engines were introduced for Euro II and III, with lambda sensors to keep stoichiometric conditions for three-way catalyst operation in light-duty applications. Lean-burn engines were introduced for Euro III, with sequential injection operation and with **optional** oxidation catalysts (OC) and Universal Exhaust Gas Oxygen sensors (UEGO), depending on the local emission standard value.

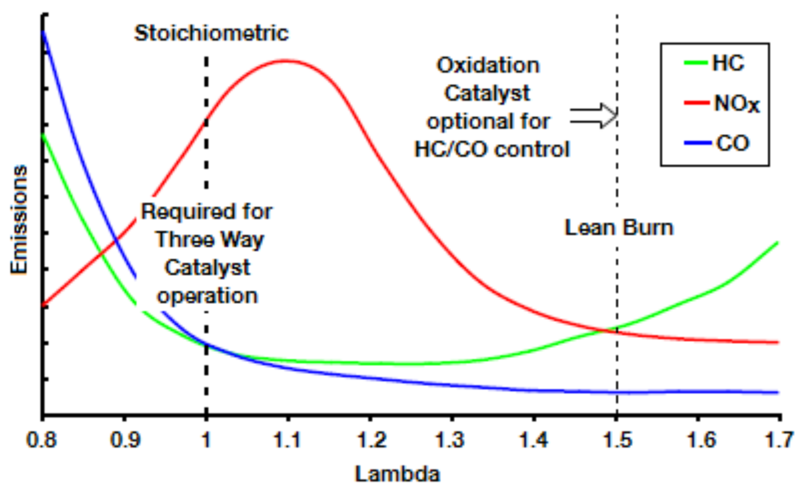

FIGURE 4. Stoichiometric and lean-burn engine out emissions. From Cummins-Westport [3]

More stringent NOx emission limits from US2010 and Euro V forced some manufacturers to choose stoichiometric combustion for heavy-duty CNG engines, to enable the use of the three way catalysts, which is a well known and reliable emission abatement technology [3]. Stoichiometric combustion, as in gasoline vehicles, allows for using three-way catalysts to control NO_x, HC and CO. PM emissions from both stoichiometric and lean-burn CNG engines are very low due to the almost homogeneous combustion of the air-gas mixture, and the absence of large hydrocarbon chains in the fuel.

Numerous papers have been published during the last ten years comparing emissions and performance of available CNG technologies, mostly lean-burn, with clean diesel. The main findings of some selected reports are presented below. In most cases the diesel buses used for comparison in these studies are US1998/Euro III or earlier, both with and without retrofit DPF after-treatment. There is little information available that compares US2002/Euro VI or more advanced diesel buses with CNG buses of a similar model year.

3. COMPARATIVE STUDIES ON EMISSIONS OF DIESEL AND CNG ENGINES

Compressed natural gas engines present an attractive alternative to diesel engines for urban buses because they have been shown to offer lower particulate matter (PM) and nitrogen oxide (NO_x) emissions in terms of grams per mile traveled and in terms of grams per unit energy produced. Although in theory CO_2 emissions per unit of energy produced are also lower compared to gasoline or diesel fuel due to a higher ratio of hydrogen to carbon, the emission studies show a different trend. Some of the most relevant papers on CNG and diesel bus emissions are summarized below.

Studies performed in California for school buses in 1999 show 12% less NO_x and 61% less PM from CNG buses with closed loop fueling management than from similar model and model year buses powered by 8.3 liter diesel engines. Another study comparing diesel and CNG engines in buses of the same model year operated over the Central Business District (CBD) test cycle showed that the CNG powered buses produced an average of 13.0 g/km of NO_x and 0.016 g/km of PM versus 19.7 g/km and 0.41 g/km respectively for a similar diesel-powered bus. Both buses were open loop fuel controlled [4].

A group of three diesel (175 hp) and three CNG buses (195 hp) using the same model year 5.9 liter engine series, were tested over the CBD cycle to compare relative emission levels. Both diesel and CNG buses had OCs installed by the engine manufacturer. Results of this study show that diesel averaged 0.24 g/km of PM, 1.5 g/km CO and 13.2 g/km of NO_x versus 0.025 g/km of PM, 1.9 g/km of CO and 5.4 g/km of NO_x, for CNG powered vehicles (Figure 5)**.** Fuel consumption was 22% higher for CNG buses in terms of energy per mile traveled (Btu/mile) [4]. It should be noted that even though the cycles and bus characteristics (inertia, friction, transmission, fuel and control systems and aftertreatment devices) are not constant through these studies, there is a consistent trend of lower PM and NO_x emissions for CNG buses. PM emissions reductions range from 61% to 80% and NO_x emissions reduction are 12% to 40% lower as compared to their diesel counterparts certified to US98/Euro III emissions levels. CO and THC emissions were considerably higher for CNG buses. Methane accounted for roughly 90% of the measured THC values.

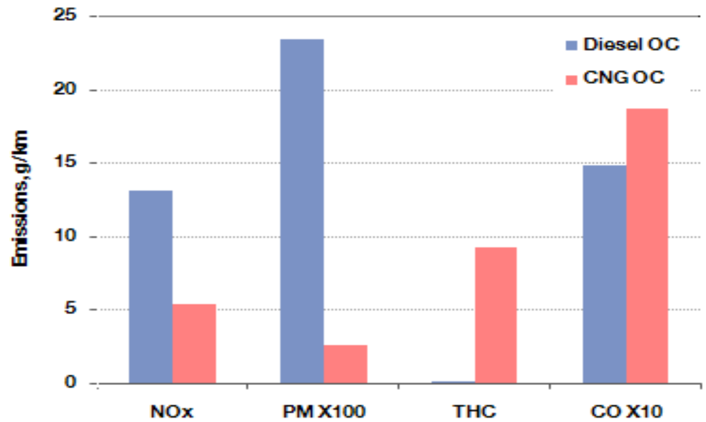

FIGURE 5. **Comparison of average emission rates measured by WVU from diesel and CNG powered buses (Ref. 4)**

As part of a project to compare toxicity between new and clean HD engine technologies in California, a group of diesel buses with aftertreatment devices and a lean-burn CNG bus with no aftertreatment were compared over the CBD, the Urban Dynamometer Driving Schedule (UDDS) and the New York City Bus Cycle (NYBC) [5]. The CNG bus was equipped with a 2000 DDC Series 50G engine; the diesel bus was equipped with a 1998 DDC Series 50 engine and an OC, and the same diesel vehicle retrofitted with a Johnson Matthey Continuously Regenerating Technology (CRT™) diesel particulate filter (DPF) in place of the OC. Results are presented in Table 1.

The CNG bus was tested a second time after changes in the O_2 sensor and ECU upgrade. The advantage of CNG over the catalyzed muffler diesel bus was remarkably lower PM and NO_x emissions for all cycles. High variability was detected for NO_x measurements over all the tested cycles for the CNG engine [5]. Results for the CBD cycle are presented in Figure 6. NO_x emissions were lower for CNG than for diesel over all cycles, while PM emissions from the CNG buses were lower than those from a diesel bus fitted with OC. The diesel bus retrofit with a DPF had higher NOx, but lower PM emissions than the CNG bus.

TABLE 1. **Average emission values for Los Angeles County Metropolitan Area (LAMTA) fleet (Ref. 5)**

Test Cycle	Bus Configuration	PM (mg/mi)	Std. Dev.	THC (g/mi)	Std. Dev.	CO (g/mi)	Std. Dev.	NOX (g/mi)	Std. Dev.	NMHC (g/mi)	Std. Dev.
CBD	CNG	39.88	12.52	10.09	0.79	8.5	0.46	15.42	1.21	1.26	0.09
	Diesel (OEM)	119.03	6.97	0.08	0.01	1.35	0.04	30.21	1.13	N/A	N/A
	CRT	14.15	0.35	0	0	0.17	0	31.14	0.57	N/A	N/A
	CNG-retest	33.45	1.2	13.82	0.09	13.63	0.23	22.66	0.69	2.55	0.19
NYBC	CNG	92.05	19.73	27.39	0.24	24.46	0.28	19.45	0.21	3.27	0.21
	Diesel (OEM)	631	N/A	0.21	N/A	7.16	N/A	51.02	N/A	N/A	N/A
	CRT	95.9	21.57	0	0	0.43	0.03	52.06	1.28	N/A	N/A
	CNG-retest	102.15	21.14	26.88	2.32	36.97	0.26	39.42	0.66	5.44	0.44
UDDS	CNG	23.07	2.81	7.78	0.23	5.99	0.31	11.7	0.66	0.86	0.05
	Diesel (OEM)	90.63	5.43	0.07	0.02	0.99	0.06	24.2	0.8	N/A	N/A
	CRT	16.63	1.96	0.01	0	0.15	0.02	23.14	0.78	N/A	N/A
	CNG-retest	23.67	2.85	7.77	0.3	8.7	0.08	16.96	0.52	1.59	0.06

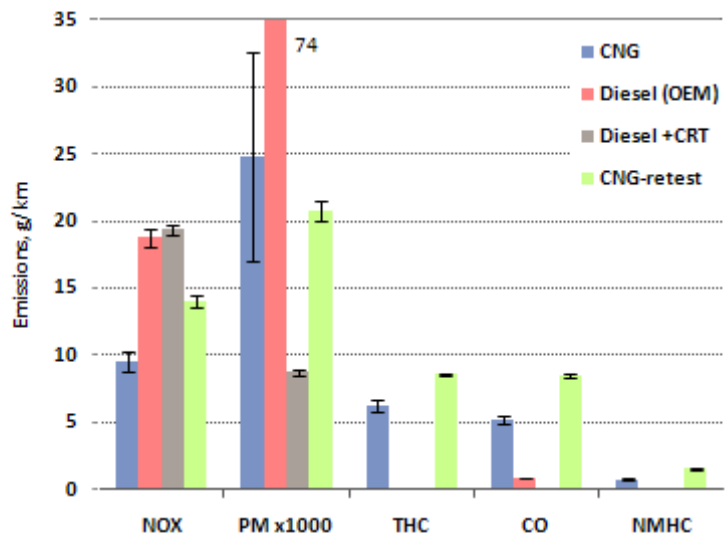

FIGURE 6. Average emission values for Los Angeles County Metropolitan Area (LAMTA) fleet in the CBD cycle (Ref. 5)

In New York, a study comparing different diesel emission control technologies and alternative fuels was performed on three CNG and two diesel buses sharing the same basic engine and rated power [6]. No aftertreatment device was installed in the CNG buses, while the diesel buses were tested with continuously regenerating DPF (CRT). Results show that the CNG buses offer around 70% reduction in PM emission, even without OCs, when compared to the baseline diesel vehicles. The continuously regenerating DPF technology offers PM emission reductions that outperform the low levels obtained by lean-burn CNG engines. The fuel sulfur content required by the DPFs was below 30 ppm. Table 2 shows the results of the emission tests.

As a side note, backfiring during deceleration periods over the two tested cycles for all three CNG buses was detected. This backfiring affected the CO and NO_x measurements and particle size distribution. No further insight was provided for the cause of those misfires [6].

Average emission values for the NYBD cycle are presented in Figure 7. Results show better behavior for diesel-CRT buses due to improvements in the CRT technology for this specific cycle application. Fuel economy was slightly lower for CNG than for diesel in the CBD cycle, but the difference was remarkable in the NYB cycle. This difference can be explained as a result of the low efficiency of spark-ignited engines at low load and low speed, which is characteristic of the NYB cycle due to its low average speed and long idling periods.

TABLE 2. Comparative emission values for CNG and diesel buses (Ref. 6)

Bus ID	Test	Config.	Fuel	NOx (g/mi)	PM (g/mi)	THC (g/mi)	CO (g/mi)	CO_2 (g/mi)	FE (mpg)
A	CBD	OEM	CNG	16.6	0.013	17.9	11.4	2230	3.4
B		OEM	CNG	19.1	0.019	17.9	11.5	2506	3
C		CRDPF	ULSD	25.9	0.035	0.035	0.159	3079	3.2
D		CRDPF	ULSD	21.8	0.047	0.0803	0.107	2672	3.7
A	NYB	OEM	CNG	24.2	0.04	63.3	40.2	5870	1.3
B		OEM	CNG	30.9	0.055	33.7	33.4	5672	1.3
C		CRDPF	ULSD	25.9	0.04	0.04	0.16	3079	3.2
D		CRDPF	ULSD	21.8	0.05	0.08	0.11	2672	3.7

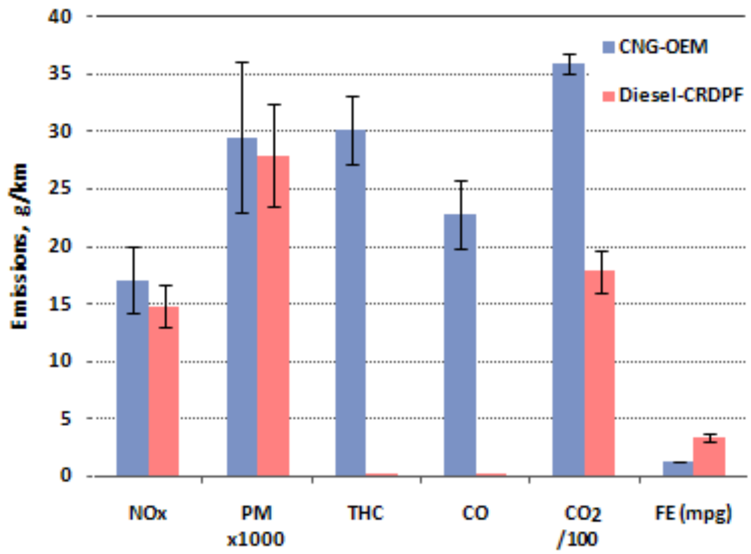

FIGURE 7. Averaged emission values for CNG buses without aftertreatment and diesel buses with continuously regenerating DPFs in the NYBD cycle. NY MTA (Ref. 6)

In most of the reported cases, diesel buses with aftertreatment systems have been compared to CNG buses without aftertreatment devices. This differential approach does not reflect a clear assessment of emissions under best available technology (BAT) conditions, and puts CNG buses at a disadvantage with respect to clean diesels.

A study comparing the BAT for diesel- and CNG-powered buses was performed in Helsinki, Finland, as part of a program to evaluate different options for bus transit operations [7]. The study was performed under the Braunschweig urban bus cycle and the Orange County bus cycle (OCTA). The CNG buses were selected as representative of the newest NG technology, both lean-burn and stoichiometric. Four CNG buses were tested: two lean-burn with OCs, one was stoichiometric with TWC and one with a lean-mix combustion system and TWC. The lean-mix system combines the use of lean burn at high torque and/or speed with stoichiometric combustion at moderate load and speed. All of the CNG engines were turbocharged. The stoichiometric bus had a multipoint injection system and the other three had central injection of natural gas. The natural gas used was of high methane content (98%) and sulfur-free.

Similar new diesel vehicles were selected with and without aftertreatment for reference. One of the three diesel buses had an aftertreatment oxidation catalyst and the other a CRT filter. The fuel system for these engines was an electronic in-line pump. Ultra Low Sulfur Diesel (ULSD) was used on all the tests. The vehicles were tested under half load conditions [7]. Results confirm that PM emissions of CNG buses are extremely low, independent of technology and use mileage. Even though lean-burn is praised as more fuel efficient than stoichiometric CNG, the emission penalty for NO_x emissions makes lean-burn CNG engines very unlikely to pass Euro V and VI regulations. Figure 8 presents a summary of PM and NO_x results under the OCTA cycle. NO_x emissions for the stoichiometric CNG engine with TWC was about half of the lean-burn engines with OCs, which groups lean-burn and lean-mix engines. Total hydrocarbons and fuel consumption varied significantly from bus to bus among the CNG group, according to the report. The positive trend for PM and NO_x emissions in this study follows the trend of previous studies [4, 5].

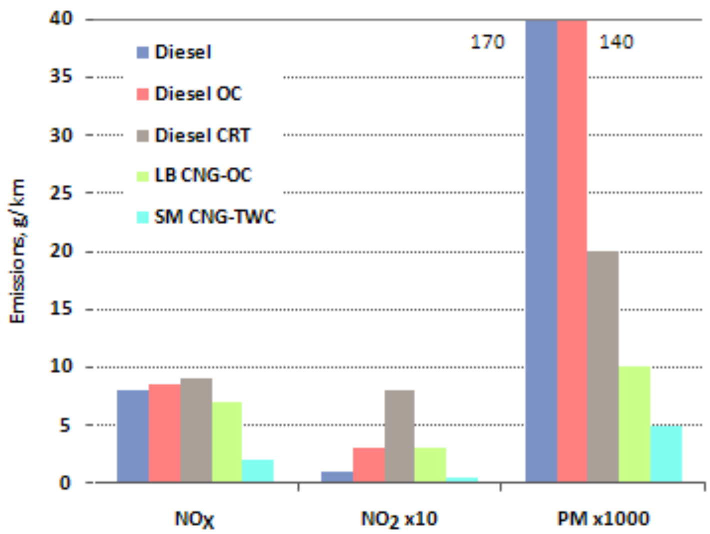

FIGURE 8. PM and NOx emission values under the OCTA cycle for diesel and CNG buses (Ref. 7)

Two of the main drawbacks of natural gas engines are fuel economy and the emission of unburned methane (CH_4). For 1996 technologies, the fuel economy of CNG buses was about 25% lower on an energy basis than diesel in a transit bus application. The fundamental reason is that spark-ignited engines are very inefficient at low speed and low load conditions. Engine idling time at traffic lights and during passenger loading and unloading severely hurts the fuel economy of CNG buses, though this big gap has been reduced thanks to continuous improvements in air/fuel management systems. CNG engines for US2010 emission levels are expected to use 5% more fuel than diesel engines. Due to its greenhouse gas potential, CH_4 has been controlled in Europe since the Euro III regulations (2000). Euro IV regulations require around 60% CH_4 conversion in aftertreatment devices, which implies the use of oxidation catalysts [8].

4. AIR-FUEL MANAGEMENT IN CNG ENGINES: MODELING AND EXPERIMENTS

CNG engines have proven to be a solution in the urban bus fleet operation sector for NO_x and PM emission reduction. CNG technologies have been especially favored in places where the sulfur levels of commercial diesel fuel are not fit for diesel aftertreatment technologies. Although CNG emission levels are lower than those of conventional diesel engines, CNG fuel consumption and CO_2 emissions lag behind diesel. Improvements in this area are focused on the air-fuel management system.

Port fuel injection (TBI or MPFI) is the main air-fuel management technology for CNG vehicles on the market. The main problem is that the volume occupied by the injected natural gas displaces the air required for proper combustion, reducing the volumetric efficiency by up to 10% [9]. In the case of in-cylinder fuel injection (DI), the fuel penetration at the injector nozzle is very poor compared to liquid fuels, causing difficulties in achieving a proper mixture homogenization through the whole cylinder.

To overcome the loss of volumetric efficiency a turbocharger is used. The gaseous fuel mixture problem can be solved with careful design of the combustion chamber, injector type and location and injection strategy [10]. Two different mixture formulations were investigated: homogeneous and stratified. The homogeneous mixture, which can be combined with high dethrottling, can be achieved through single injection at the end of the intake stroke, with lambda values around 1.25 (25% excess oxygen). The stratified case requires additional changes in piston crown design. The modified crown has a recess that should help in creating a stratified mixture near the spark plug. The stratified mixture allows control of the burn rate by injection-induced turbulence, which suggests the possibility of multiple injections during the combustion period. A lambda close to 2.35 can be achieved with this technique [9]. These papers suggest that lean-burn CNG technology allows for more improvements in terms of efficiency and combustion characteristics, translating into fuel consumption competitive with the diesel market. Improving the lean-burn combustion process may induce further engine-out reduction in NO_x emissions due to higher mixture dilution. Euro III engines require a linear range oxygen sensor to compensate for changes in fuel quality. In that case, the fuel system compensates for the lack or excess of desired O_2 concentration in the exhaust gas stream [11].

During the last decade the predominant fuel injection technology for use in CNG engines has been manifold fuel injection. Direct injection of natural gas is often mentioned in the literature, but its commercial application for HD vehicles is limited. Direct-injection CNG engines have been the center of research efforts looking at increasing the power output of a natural gas-fueled engine. Huang et al. [12] found that the combustion behavior of CNG DI engines is affected by the injection timing due to fuel stratification. Injection timing adjustments were found to increase power and improve volumetric efficiency.

For CNG engines, the use of cooled EGR combined with turbocharging has been identified as a promising way to comply with the more stringent US2010 and Euro V and VI standards while being competitive with clean diesel technologies in terms of torque, efficiency and fuel consumption. However, the high pressure and levels of dilution created by this new technology present new challenges for stable combustion along the whole operational range of the engine. Because it is difficult to obtain reliable spark ignition at high pressure and dilution levels, the amount of EGR that can be tolerated for each operating point should be carefully controlled. Conventional open-loop operation based on steady state maps is difficult since there is substantial dynamics both from the turbocharger and the wall heat interaction. Experimental work on a heavy-duty six-cylinder port-injected natural gas engine was performed by Kaiadi et al. [13] to study the EGR interaction. They proposed a method to keep stable combustion at maximum EGR dilution levels. The proposed approach applies standard closed-loop lambda control for controlling the overall A/F ratio, while keeping the load at a constant level when using EGR. In addition, cylinder pressure-based dilution limit control is applied on the EGR in order to keep the combustion coefficient of variation cycle-to-cycle at the desired level of 5%. Pumping losses decrease due to further opening of the throttle, improving volumetric efficiency. Excellent steady-state performance was achieved using closed-loop combustion control to keep the EGR at the highest level with the expected combustion stability [13].

Changes in fuel composition, one of the major problems with natural gas engines, have also been addressed to improve the reliability of CNG vehicles. Heat release timing is a vital parameter to be controlled on any internal combustion engine. On a spark ignited engine, the heat release timing is governed by the spark plug timing, which is expressed in crank angle degrees (CA deg). The spark timing changes according to specific demands of torque and speed, producing the best compromise between fuel consumption and emissions. The spark timing map that is obtained in the engine test bench is developed under controlled conditions and is kept in the engine control unit (ECU) of each engine. In real applications the timing of the spark may deviate from its optimal operation region due to changes in fuel quality, environmental conditions and engine wear, which may lead to losses in engine efficiency. Figure 9 shows the torque reduction with spark timing error [14].

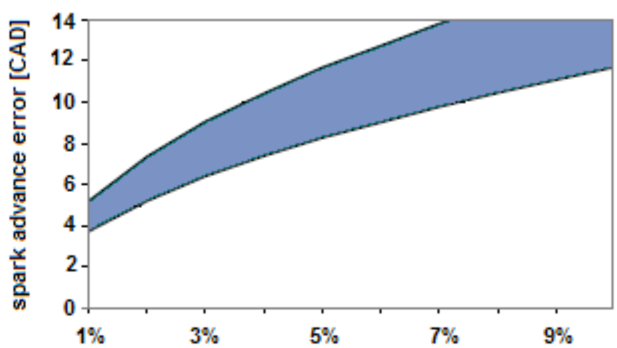

FIGURE 9. Torque loss due to deviation from spark timing at maximum brake torque conditions for a CNG engine (Ref. 14)

Because natural gas composition changes with geographic location and season, some level of control in the spark timing is desired to compensate for such variability. Researchers at Palermo University studied the variability in maximum brake torque (MBT) spark timing under different engine operational conditions and developed a technique based on in-cylinder pressure data collected through a piezoelectric transducer, to perform optimal change in spark timing regardless of fuel composition and operational conditions. A relatively simple analysis of the pressure data provides the information for the closed-loop controller to adjust the spark timing. Results from the study found that after applying the technique, deviations from maximum torque were less than 0.2% [14].

The variability of natural gas composition in an engine tank, which may be caused by seasonal changes or geographic origin, can affect the performance and emission levels of CNG, as has been studied by the California Air Resources Board (CARB) and Petrobras (Brazil) [15]. CARB results show little to no effect on performance and emission for engines with closed loop lambda control. Petrobras concluded that stoichiometric engines without electronic control show increased fuel consumption, CO and HC emissions. Lean-burn engines without electronic control tend to have increased NO_x emissions.

5. CNG EMISSION REDUCTION TECHNOLOGIES FOR EURO III, IV, V AND VI

The combustion process on a CNG engine can be characterized as stoichiometric or lean-burn. Lean-burn heavy-duty engines became popular during the first generation of CNG engines due to their higher fuel efficiency and lower heat rejection compared to stoichiometric engines. CNG engines provide comparable power and torque as compared to conventional diesel engines. The engine-out emission levels from a lean-burn CNG engine without any aftertreatment system are low enough to outperform a conventional diesel engine in terms of PM and NO_x.

5.1 EURO III AND IV LEVELS

Studies performed in the US showed that the lean-burn CNG engines produce around 12-17% lower NO_x and 50%-74% lower PM engine-out emissions than conventional diesel engines. This relative advantage was reduced when low-sulfur and aftertreatment devices were fit to the diesel engine. It can be stated that a lean-burn CNG engine with a proper injection system and a Universal Exhaust Gas Oxygen sensor can achieve Euro III compliance. If the emission target requires further reduction in CO, HC and PM levels, the addition of an oxidation catalyst can provide the coverage required to achieve Euro IV levels. This level of compliance can only be achieved if proper fuel injection system, closed loop control and overall engine tuning is included in the CNG engine development process. Regarding non-regulated species, the addition of an oxidation catalyst also reduces around 90% of the formaldehyde produced by the CNG lean –burn engine.

In 2003, most heavy-duty CNG engines were spark ignited with lean-burn combustion. With high efficiency at low emission levels, exhaust aftertreatment was not required in most cases. Emission reductions from a lean-burn CNG engine were usually achieved by adding an oxidation catalyst (OC).

5.2 EURO V AND VI LEVELS

For achieving the US2010 and Euro V and VI emission limits for HD engines, manufacturers explored the possibility of combining stoichiometric combustion with a TWC. The main problem of stoichiometric combustion for HD applications is the high in-cylinder mixture temperatures during combustion, which leads to high production of NO_x and the excessive amount of heat that must be removed. In addition to higher thermal stress, lower brake efficiency is expected due to the required low compression ratio.

Exhaust gas recirculation (EGR), a technology borrowed from diesel engine emission control technologies, was employed to curb the excessive high temperature and heat production in the stoichiometric CNG engine. The EGR in the stoichiometric engine dilutes the concentration of fuel in the cylinder, which reduces the rate of the combustion reaction and lowers its temperature while keeping the A/F ratio at the stoichiometric value. Because part of the cylinder volume is occupied by inert recirculated gas, there is a reduction in volumetric efficiency that can be corrected by adding a turbocharger. The turbocharger recovers the loss of power that results from dilution with EGR. In most cases the EGR requires an intercooling circuit. Because the exhaust gases from the stoichiometric engine contain negligible O_2, a three way catalyst (TWC) can be applied as the aftertreatment device, which allows for NO_x reduction during rich periods of operation. Several examples of technical development of the CNG stoichiometric engine can be found in the literature, and some examples are summarized below.

Numerical modeling of the effect of EGR in a CNG stoichiometric engine show that using EGR in cooled supercharged inlet conditions (333 K and 250 kPa) can reduce NO_x emissions by about 80% and fuel consumption by 19 to 27% (depending on engine speed) compared to a stoichiometric non-EGR mixture condition. The maximum amount of EGR is limited by the combustion stability and is a function of engine load and speed [16]. However, EGR is not always required to control NOx, as was demonstrated by Middleton et al. [17]. Experimental work show that lean-burn CNG with a compression ratio of 12:1 and bowl-shaped piston crown can achieve Euro III emision levels with an OC, at the same rated power as the original diesel engine. Engine-out emission levels for NO_x were controlled without the use of EGR [17].

A class-eight heavy-duty lean-burn CNG engine was modified to operate as a stoichiometric engine while keeping the same rated power. The original lean-burn CNG engine was rated at 242 kW @ 1950 rpm, with a torque of 1600 N-m @1250 rpm and 2.8 g/kW/h NO_x. According to Chiu et al. [18], the same rated power was achieved after modifications for stoichiometric combustion. Transient emission results after modification for stoichiometric combustion with EGR and TWC are presented in Table 3. PM emissions in this case were above US2010 limits, but can be further reduced with an OC depending on the proportion of soluble organic fraction SOF present in the exhaust, which can be adjusted through engine tuning [18].

TABLE 3. **FTP emission values for a Stoich+EGR+TWC CNG engine. (Ref 18)**

Species	Emissions	FTP results	US 2010	Euro V	Euro VI
CO	(g/kW-hr)	4.8	20.7	4.0	4.0
THC	(g/kW-hr)	2.3	-	-	-
NMHC	(g/kW-hr)	0	0.18	0.55	0.16
CH4	(g/kW-hr)	2.3	-	1.1	0.5
NOx	(g/kW-hr)	0.202	0.270	2.0	0.4
PM	(g/kW-hr)	0.020	0.013	0.030	0.010
NH3	ppm	-	-	-	10
HCHO	(mg/kW-hr)	0.178	-	-	-
CO2	(g/kW-hr)	670.1	-	-	-
BSFC	(g/kW-hr)	256	-	-	-

Comparisons between stoichiometric and lean-burn CNG performed by the Lund Institute of Technology [19] in a commercial six-cylinder CNG engine confirmed that the relative drawbacks of the stoichiometric combustion can be solved by using EGR while controlling emissions with a TWC. The results show that under stoichiometric conditions with EGR and a TWC, NO_x and HC emissions can be reduced by 99% and 90-97% respectively when compared to lean operation. The use of EGR with turbocharging also allowed combustion improvements, leading to a 10% increase in power. Higher CO emissions were reported in stoichiometric-with-EGR operation. A very accurate A/F ratio control is fundamental. The use of high EGR rates required the use of fast combustion chamber design. The ceramic monolith catalyst was designed to offer good oxidation capacity for CH4 under lean and rich conditions [19].

Euro VI and US2010 NOx limits values can be met, even before optimization, by stoichiometric CNG engines with cooled EGR and TWC. Further improvements can be achieved by adding a camless hydraulic valve actuation (HVA) system to improve efficiency. The use of the HVA system was introduced to increase the CNG eficiency by reducing the pumping losses. Pumping losses are associated with the work required to move the gases into and out of the cylinders. The HVA systems allows numerous strategies to reduce this extra work by late intake valve closing during the compression stroke. In addition to lower pumping losses, the HVA allows the engine to change the effective compression ratio (*cr*) according to power demand. In this case, higher *cr* values can be used during low or medium loads, while the higher loads can be run under lower *cr* values. Results from the 13-mode Steady State (SS) test show an improvement in efficiency by 6.1% over a fixed valve timing based system. Emission results show NO_x emission levels of 0.005 g/kW-h, well below the 0.27 g/kw-h or 0.4 g/kw-h for US2010 and Euro VI emission values respectively. CO and THC emission values were 1.166 and 0.536 g/kW-h respectively. PM emission values were not reported [20].

5.3 NON-REGULATED EMISSIONS FROM CNG BUS ENGINES

Besides the regulated emissions, environmental agencies have studied the level of non-regulated emissions from CNG powered buses. For US2004 regulations, the lean-burn CNG engines were able to meet bus emissions standards without any aftreatment device. However, lean-burn CNG buses without aftertreatment may produce formaldehyde, nanoparticles (50nm) and mutagen emissions higher than diesel engines equipped with an oxidation catalyst (OC) or a diesel particulate filter (DPF) and fueled by ultra low sulfur diesel (ULSD).

CARB studied OCs for CNG bus applications for two driving cycles: the central busines district (CBD) and the steady state cruise condition (SS) [21]. The buses tested were lean-burn, closed-loop controlled dedicated CNG engines. The aftertreatment devices were original equipment manufacturer (OEM) OCs, one from Detroit Diesel (DDC) and another by Cummins Westport (CWstprt).The study showed that the OC reduced formaldehyde (HCHO) emissions were by around 95%, in both cycles, and 1,3 butadiene emissions were reduced to below detection levels [21]. Reduction in total PM (28%), total hydrocarbons HC (29%), non-methatme hydrocarbons (NMHC) and carbon monoxide CO (49%) were also reported. Little to no effect was found for CH_4 [21]. Although not expected by the researchers, NO_x emissions were also lower in the CNG-OC bus. Figure 10 shows the average values and standard deviation of two tests for each bus. It may be inferred that an OC can be used effectively to reduce HC, CO and some unregullated pollutants, such as formaldehyde, in lean-burn engines. The reduction achieved may imply that OCs can be effectively used for Euro IV compliance with lean-burn CNG engines.

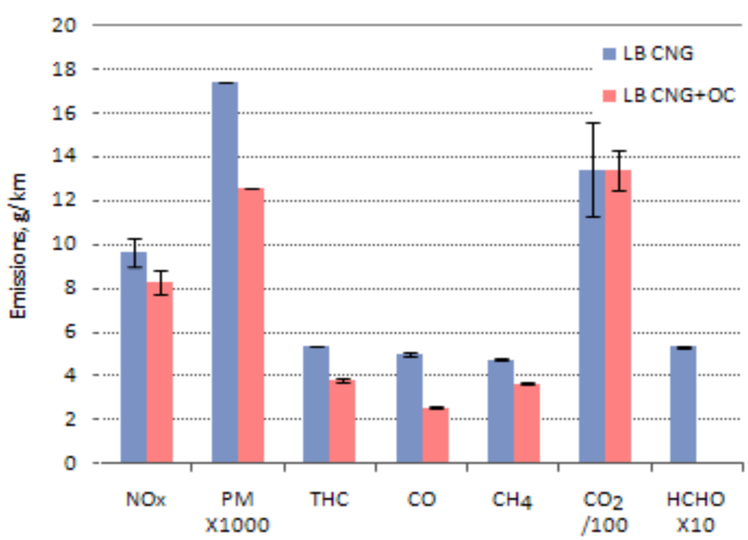

FIGURE 10. Oxidation catalyst emission reduction for CNG engines. California 2003, DDC engine. (Ref. 21)

CO_2 emissions from CNG and diesel buses with different aftertreatment tehcnologies are compared in this report based on information reported from the California Air Resources Board [5], West Virginia University [4] and New York City's Metropolitan Transit Authority [6]. Details for each bus configuration were presented in the section *Comparative studies on emissions of diesel and CNG engines*. Figure 11 shows the summary of CO_2 emissions measurements under different test cycles. Although the emission levels cannot be compared between studies because of differences in bus configuration and load conditions, a trend can be observed. CO_2 emissions from CNG buses were lower than diesel buses within each study under the CBD test cycle. The NYBC cycle showed the largest values but the results were contradictory between the CARB study and the MTA study. The CARB study trend shows lower CO_2 emissions from CNG buses in the NYBC, while the results from MTA show a large difference compared to the CNG buses. Disregarding the data point from MTA on diesel CRT for the NYBC cycle, the general trend shows that CO_2 emissions are 12-17% lower for CNG buses than for diesel buses. This result was contradicted by the VTT study [7], which shows that the CO_2 emissions for CNG lean-burn buses were around 7% higher.

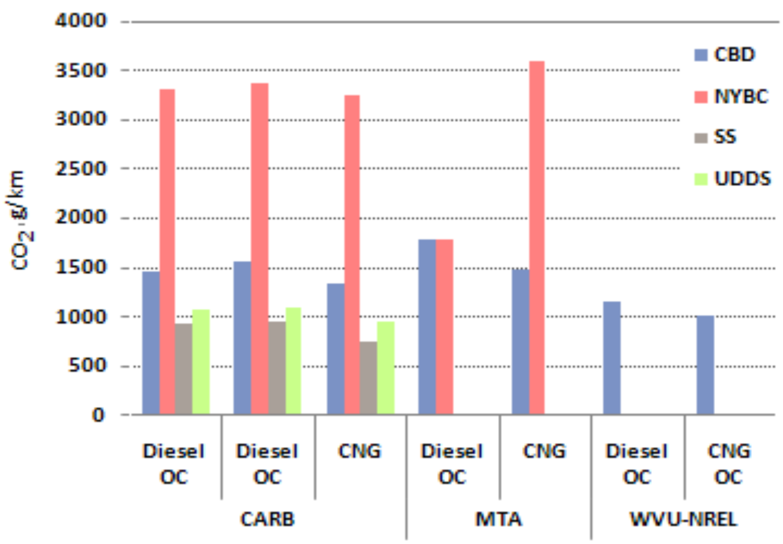

FIGURE 11. Summary of CO_2 emission values measured by CARB (Ref. 5), MTA (Ref. 4) and WVU-NERL (Ref. 6)

The oxidation of alkane hydrocarbons is related to carbon number, with larger chains being more easily oxidated than short ones, making CH_4 the most difficult hydrocarbon to react with O_2. In order to facilitate the oxidation of CH_4, a catalyst is required. Pd is the preferred catalyst choice for both CH_4 and NMHC abatement.

Development of an oxidation catalyst for CNG engines has been studied by Williams et al. [22]. These researchers proposed three different OCs, each of them with an exclusive PGM formulation: Pt 1g/liter, Pd 5 g/liter and Pt/Pd 1/7 g/liter. Results from engine tests show that the Pt/Pd catalyst has relatively better CO, CH_4 and NMHC reduction that the other two catalysts. CO and THC conversion levels were above 98%. CH_4 conversion values were about 20% at 400°C.

Catalyst poisoning with SO_2 was also studied by Williams et al.[22] for all three catalyst formulations. Catalyst poisoning was studied under 100 ppm SO_2 concentration in the exhaust gases. The Pt based catalyst showed a reduction in NO and CO oxidation activity. A significant deactivation in NO, CO and hydrocarbons (methane, ethane, propane) was reported with SO_2 poisoning after 1h in the Pd based catalyst. In the Pt/Pd based catalyst the deactivation was significant for CH_4, increasing the temperature for 50% oxidation (T_{50}) by 130°C more than the non-poisoned catalyst.

CH_4 emission levels have also been detected as a problem in stoichiometric engines using TWCs. A study comparing TWC activity for light-duty vehicles powered with CNG engines was carried out to examine the conversion values for different commercial catalysts in Europe. Results of the study show that CO can be oxidized at low temperatures, usually around 100-170°C. NOx can be reduced around 175-350°C, depending on the reductants available in the exhaust gases: H_2 at low temperature, CO at medium temperature and CH_4 at high temperature. CH_4 is 50% converted at temperatures higher than 375°C [23].

Particle number size distribution was studied by the VTT team from Finland during the CNG bus study, a part of the program "Finnish National Bus Project" [7]. This emissions study, mentioned in previous chapters, was perfomed on buses with different engine and aftertreatment control configuration over two different chassis testing cycles: the Braunschweig urban bus cycle (Br) and the Orange County bus cycle (Or). Three different diesel engines and four different CNG buses were used in these tests. Figure 12 shows the results for particle number size distribution. It is clear that buses with conventional diesel engines and diesel buses fitted with OCs emitted fine particles (PM2.5) with a concentration two orders of magnitude larger than CNG and diesel CRT buses. The oxidation catalyst for CNG buses and the CRT system for diesel buses generated about the same positive effect in particle number size distribution for each system along the spectrum of measured particle sizes. It should be noticed that the result for stoichiometric CNG (SM CNG), which was fitted with a TWC, was not as good as the results for the other CNG buses with OCs. This result is consistent with other studies [7] and was explained by the researchers as being the result of engine behavior or TWC performance. The PM reduction benefits of OCs for CNG engines can be also attributed to the fact that OCs can reduce PM emissions by oxidizing the organic fraction of the PM.

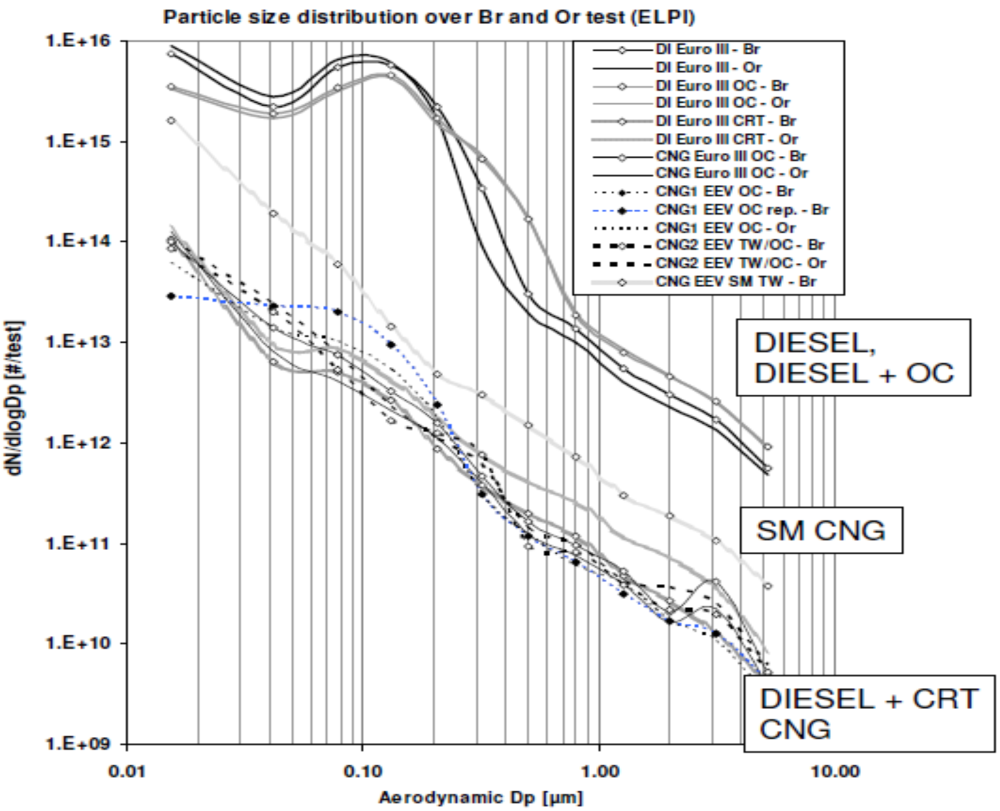

FIGURE 12. Particle number size distribution (Ref. 7)

Similar results were observed by Lanni et al. [6] during tests of CNG buses without OCs and diesel buses fitted with CRT technologies. Details on the tests were provided in previous sections (Table 2). The particle number size distribution behaved similarly to the results reported by VTT in Figure 12. However, for particle size smaller than 0.1 µm (ultrafine particles), the results showed that without OCs, the CNG buses emitted about one order of magnitude more particles than the diesel CRT buses [6].

6. COMMERCIAL STATUS

Cummins Westport is currently offering three main types of CNG engines. The B Gas Plus is a six-cylinder 5.9-liter lean-burn engine, with compression ratio 10.5 and 150-230 hp. It is able to meet Euro III emission limits. An OEM oxidation catalyst is also provided reducing NO_x and PM emissions by 35% and 50% respectively compared to Euro III standards. The C Gas Plus, an 8.3-liter lean-burn engine, is marketed for Euro III. The same engine with an oxidation catalyst is certified as Euro IV. Both engines are turbocharged and use closed loop control, with an A/F ratio sensor (probably UEGO type) and backpressure sensor. These engines require a CNG with methane number 65 minimum. The Euro IV market has different combustion technologies, as explained in previous sections. The ISL-G 8.9 liter engine is a stoichiometric CNG engine that employs cooled EGR, turbocharging and aftertreatment through a TWC to achieve US2010 emission levels of 0.2 g/bhp-hr for NOx and 0.01 g/bhp-hr for PM. This engine is rated at 250-320 hp [24].

IVECO also offers dedicated CNG engines for Euro V regulations. The technology applied to achieve EEV (Environmentally Enhanced Vehicle) certification with a tailpipe NO_x level of ¼ of the level permitted by the EEV standard is based on stoichiometric combustion coupled with a TWC. Figure 13 shows the emission values presented by IVECO. The engines have a four-valve-per-cylinder design. Air/fuel ratio is continuously controlled, making the engine immediately responsive to any changes in natural gas composition [25].

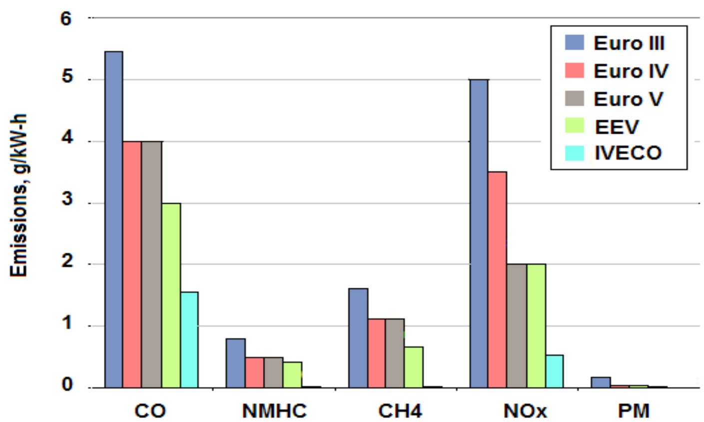

FIGURE 13. Emission levels for IVECO CNG Stoichiometric Engine (Ref. 25)

The vehicles exhibited at the 2007 ENGVA Vehicle Exhibition & Conference were the Daily 65 C 14 CNG and the Irisbus Citelis 12M CNG. The 6.5 t Daily uses the new three-liter dedicated natural gas engine rated at 136 hp and has a CNG storage capacity of 224 liters at 200 bar. The Citelis uses the Cursor 7.8 liter dedicated natural gas engine rated at 272 hp and has a CNG storage capacity of 1232 liters at 200 bar. Multipoint electronic injection is offered in the largest engines, with 12 gas injectors situated in a two by two format at the entrance to the inlet duct of each cylinder achieving an identical mixture in each of them. Closed loop with lambda control is part of the engine control system to compensate for natural gas composition variations [25].

The new Citaro was introduced by Mercedes-Benz and EvoBus in 2006, featuring front independent suspension and a high-performance powertrain. The CNG version of this bus features a 12-liter, six-cylinder in-line M 447 hLAG engine, rated as a Euro4/EEV vehicle. This engine delivers 185 hp at 774.4 lb-ft torque and 1000 rpm. The CNG is stored at 200 bar in the eight tanks on the roof of the vehicle [26].

TEDOM, a bus manufacturer from Czech Republic, offers buses powered by CNG engines able to reach Euro 5 EEV emission standards levels. TEDOM offers naturally aspired or turbocharged 12-liter, six-cylinder in-line stoichiometric natural gas combustion (CNG) engines, ‚water-cooled and electronically controlled with the OBD II implementation. Engines are produced in horizontal or vertical layout with the power range from 180 to 260 kW. The fuel system is composed of three or four cylinders, made of composite materials, with a filling pressure of 200 bar and a volume of 320 liters per tank [27].

6.1 CNG BUS PURCHASE COST

The purchase cost of CNG vehicles is presented and compared with values for diesel buses. Operational costs, including maintenance and fuel costs are out of the scope of this report and may be treated as local values where the bus transit fleet is operating.

The New York transit authority presented a report in 2006 where the purchase cost of diesel, CNG and hybrid buses was disclosed [28]. Orion V high-floor diesel buses are equipped with a DDC series 50 engine and retrofitted with a Johnson Matthey DPF. The diesel bus purchase price was $290,000 each in 1999. Orion VII CNG buses, model year 2003, equipped with DDC Series 50G CNG and no aftertreatment, cost $319,000 each. Orion VII hybrid buses powered by an ISB Cummins engine with the BAE Systems series hybrid propulsion system cost $385,000 each.

A systematic study comparing the life cycle cost of CNG and diesel transit buses was performed by TIAX LLC in 2005 [29]. The study shows that without aftertreatment devices, the purchase cost of a CNG bus is 8.5% more than the diesel bus. The cost of the chassis was assumed as $240,000 in both cases. The CNG powertrain was assumed to be an additional cost of $22.000. Cost figures used by TIAX were obtained from a 2001 report by the California Air Resources Board.

According to the American Public Transportation Association 2007 Transit Vehicle Database, between 2005 and 2007 there were 2,832 12-meter diesel buses ordered by US transit agencies, for which the agency provided information on how much they cost. Prices ranged from $257,000 to $416,000 per bus, with a weighted average cost of $329,500. Over the same time period the database shows 635 12-meter CNG buses purchased. Prices for CNG buses ranged from $329,000 to $410,000 per bus, with a weighted average price of $376,000. On average, over those three years US CNG buses cost $46,000 more than diesel buses, an increase of 14%. Obviously, however, these prices do not fully reflect the increased costs associated with meeting US2010 diesel emission standards.

In Europe, according to the International Association of Public Transport (UITP), in 2006 a CNG powered 12-meter transit bus was about 15-20% more expensive than a diesel powered bus [30].

7. SUMMARY AND FINAL REMARKS

CNG technologies have demonstrated remarkable capability for achieving the most stringent emission standards required by industrialized nations, while improving the air quality in many urban areas around the developing world.

Emissions of two of the most significant pollutants, PM and NO_x, can be dramatically reduced — on the order of 70% and 30% respectively — when compared to conventional diesel buses without aftertreatment. Although comparisons of emissions results between studies cannot be made due to differences in basic test conditions, the trend is generally favorable to CNG buses fitted with some level of aftertreatment. Figure 14 shows the results of two of the studies that compare clean diesel and clean CNG technologies. It should be noted that no direct comparisons can be made between studies, only the trend is significant.

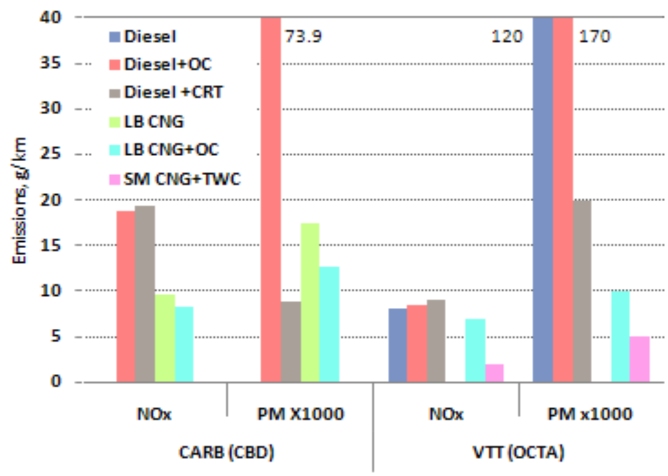

FIGURE 14. Emission levels from CARB (Ref. 19) and the Technical Research Center of Finland VTT (Ref. 7)

When comparing clean diesel and CNG solutions for urban buses, the fuel sulfur level plays an important role in dictating the availability of engine technologies for certain emission levels. In industrialized nations where the fuel sulfur level for on-road diesel engines has been reduced to near-zero levels, the use of aftertreatment devices such as DOCs, DPFs and CRTs can easily be implemented, obtaining emission levels similar or better than CNG technologies. On the other hand, developing nations that do not have low sulfur diesel programs find CNG the most practical technology for bus fleet emission reduction.

The set of technologies required for compliance with each of the European emission standards is presented in Table 4. It should be noted that Euro III and IV emission levels may allow for CNG engine conversion, but Euro V and VI levels can only be achieved by engines designed with the technical features presented in the table. Figure 15 presents the roadmap for CNG bus technologies from Euro III to Euro VI.

The aftertreatment and emission durability column shows the required durability for the whole engine-aftertreatment system for CNG powered buses in the European Union. In the US, model year 2004 and later heavy-duty diesel truck and bus engines are required to have a *useful life* of 450,000 miles/10 years/22,000 hours of operation. Minimum maintenance intervals for the engine-aftertreatment system are defined along *useful life* requirements by environmental regulatory agencies, i.e. the Environmental Protection Agency for the US.

The problem of CNG reliability and fuel economy, although not directly addressed in this report, was noted due to the minimal technical research focused on CNG for mobile applications. Very few technical papers deal with CNG combustion modeling or experimental research, compared to the number that deal with diesel performance and emission control. One of the areas where research in CNG mobility requires more attention is CNG aftertreatment, where naturally low levels of sulfur may allow for even larger reductions of pollutants. The reason may be the small volume of the CNG market in industrialized nations where research funding is available, but conditioned to market forces and specific energy policies.

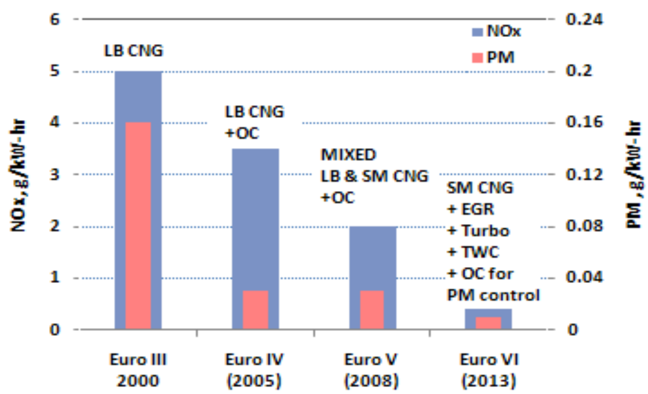

FIGURE 15. The CNG Buses Roadmap: from Euro III to Euro VI

TABLE 4. Summary of CNG technologies required for European emissions compliance stages

Emission level NO_x / PM (g/kWh)	CNG Combustion	Air/Fuel System	Aftertreatment & Emission Durability
Euro III - 2000 **5.0 / 0.016**	Lean-burn	Throttle body, but multipoint injection is preferred. Open loop / lambda sensor	--
Euro IV - 2005 **3.5 / 0.030**	Lean-burn	Closed loop / universal oxygen sensor (wide range oxygen sensor)	Oxidation catalyst Durability: 500.000 km or 7 years
Euro V - 2008 **2.0 / 0.030**	Mixed (lean-burn and stoichiometric) or stoichiometric + EGR and turbocharging	Closed loop / universal oxygen sensor (wide range oxygen sensor)+ Secondary lambda sensor for OBD requirements	TWC for CNG (includes some capability for CH_4 oxidation) Durability: 500.000 km or 7 years
Euro VI - 2013 **0.4 / 0.010 (proposed)**	Stoichiometric + Cooled EGR and turbocharging. Improved design of combustion chamber and overall system (engine+TWC) tuning.	Closed loop / universal oxygen sensor (wide range oxygen sensor)+ Secondary lambda sensor for OBD requirements	TWC for CNG (includes some capability for CH_4 oxidation at temperature below 350°C) Durability: 700.000 km or 7 years

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