Comparison of Clean Diesel Buses to CNG Buses

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ABSTRACT

Using previously published data on regulated and unregulated emissions, this paper will compare the environmental performance of current generation transit buses operated on compressed natural gas (CNG) to current generation transit buses operated on ultra low sulfur diesel fuel (ULSD) and incorporating diesel particulate filters (DPF). Unregulated emissions evaluated include toxic compounds associated with adverse health effects (carbonyl, PAH, NPAH, benzene) as well as PM particle count and size distribution.

For all regulated and unregulated emissions, both technologies are shown to be comparable. DPF-equipped diesel buses and CNG buses have virtually identical levels of PM mass emissions and particle number emissions. DPF-equipped diesel buses have lower HC and CO emissions and lower emissions of toxic substances such as benzene, carbonyls and PAHs than CNG buses. CNG buses have lower NOx emissions than DPF-equipped buses, though CNG bus NOx emissions are shown to be much more variable.

In addition, this paper will compare the capital and operating costs of CNG and DPF-equipped buses. The cost comparison is primarily based on the experience of MTA New York City Transit in operating CNG buses since 1995 and DPF-equipped buses fueled with ULSD since 2001. Published data on the experience of other large transit agencies in operating CNG buses is used to validate the NYCT experience.

The incremental cost (compared to “baseline” diesel) of operating a typical 200-bus depot is shown to be six times higher for CNG buses than for “clean diesel” buses. The contributors to this increased cost for CNG buses are almost equally split between increased capital costs for purchase of buses and installation of fueling infrastructure, and increased operating costs for purchase of fuel, bus maintenance, and fuel station maintenance.

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EXECUTIVE SUMMARY

Since 1988, MTA New York City Transit (NYCT) has worked to reduce harmful exhaust emissions from its fleet of revenue buses, and to date has made significant progress. Based on engine certification data, average emissions of particulate matter from NYCT buses have been reduced by approximately 90% from what they were 15 years ago.

Nonetheless, the Borough of Manhattan is still designated to be in non-attainment with U.S. Environmental Protection Agency (EPA) ambient air quality standards for particulate matter and ozone. Therefore, NYCT recognizes that it must do more to contribute to improving regional air quality by further reducing bus fleet emissions.

This report compares the emissions performance and operating and capital costs of two different technologies that NYCT is currently actively incorporating into the fleet: buses fueled by compressed natural gas (CNG), and diesel buses fueled by ultra-low-sulfur diesel fuel (ULSD) and equipped with diesel particulate filters (DPF).

TECHNOLOGIES COMPARED

NYCT has been operating CNG buses since 1992 and currently has over 240 buses in service at the Jackie Gleason Depot in Brooklyn. A second CNG compatible depot is under construction in the Bronx (West Farms Depot) and is scheduled to open in late 2003. NYCT has 255 additional CNG buses on order. Deliveries of these buses began in March 2003 and are scheduled to be completed in May 2004. The 2000 – 2004 Capital Program also contains funding for the conversion of the Manhattanville Depot in Manhattan to CNG operations, and the purchase of an additional 120 CNG buses. The Manhattanville conversion project is currently in design and is scheduled to be awarded in early 2004.

In February 2000 NYCT began a test program, in conjunction with the New York State Department of Environmental Conservation, to evaluate ULSD and DPFs. The program included a 9-month field demonstration with 25 filter-equipped buses as well as significant emissions testing. Results of the field demonstration indicate that DPFs are durable and effective in NYCT's service environment. During the test, the demonstration fleet accumulated over 750,000 revenue miles without a single failure or problem associated with the filters or the ULSD. As described below, the emissions testing also verified that the combination of filters and ULSD are very effective at reducing diesel emissions.

Based on the success of the demonstration program, NYCT began an aggressive program to incorporate this technology into the bus fleet. In September 2000, NYCT began using ULSD (< 30 ppm sulfur) in buses fleet-wide. The 2000 – 2004 Capital Program contains funding to retrofit DPFs onto over 3,200 diesel buses in the fleet. To date approximately 1,600 units have been installed, with the remainder be completed in 2004. In addition, all new diesel buses are coming from the factory equipped with DPFs. Three hundred and eighty of 885 new diesel buses ordered with filters have already been received.

Emissions Test Results – Regulated Emissions

Emissions testing conducted under the demonstration program has shown that ULSD and filters reduce emissions of hydrocarbons (HC), carbon monoxide (CO) and particulate (PM) by 78 - 98% compared to the baseline emissions from modern, EPA compliant diesel buses that include diesel oxidation catalysts in the exhaust system. The ULSD and filters do not affect the fourth regulated emission component, oxides of nitrogen (NOx). These results are consistent with results of similar testing done in Europe, as well as testing performed on several types of diesel trucks and buses in California.

When this test data is compared to the results of CNG bus emissions tests, one sees that filter-equipped diesels operating on ULSD have significantly lower HC and CO emissions than CNG buses and have PM mass emissions that are virtually identical to those from CNG buses. The data also shows that the CNG buses tested have on average 32% lower NOx emissions than the tested DPF-equipped diesel buses operated on ULSD. A limited amount of data indicates that the use of oxidation catalysts on CNG buses (not typically standard equipment at this time) can reduce HC and CO emissions. Even with an oxidation catalyst, however, HC and CO emissions from CNG buses are still significantly higher than HC and CO emissions from DPF-equipped diesel buses. The use of an oxidation catalyst on CNG buses may also lower CNG NOx emissions slightly.

All of the buses tested were in model years between 1998 and 2001. With respect to NOx emissions, these buses represented the “state of the art” for both diesel and CNG technology at the time that the testing was completed in 2001. Beginning in late 2002, new EPA rules mandated a 40% reduction in NOx from new diesel engines (see Appendix A). Virtually all diesel engine manufacturers have now demonstrated, through EPA certification, that they can meet these requirements. They have also demonstrated a further reduction in NOx emissions from new natural gas engines, but the gap between natural gas and diesel has narrowed. Based on certification data, new CNG buses now have approximately 20% lower NOx emissions than new diesel buses sold after September 2002.

EPA mandates to reduce NOx emissions from heavy-duty vehicles a further 92% starting in 2007 will require new technologies to be applied to both natural gas and diesel engines. It is unclear whether natural gas engines will provide any inherent NOx benefit compared to diesel engines after imposition of these 2007 regulations.

Hybrid diesel-electric propulsion systems, such as those being incorporated into some new buses purchased by NYCT, have also been demonstrated to reduce NOx emissions by 30-60% compared to a standard diesel bus, resulting in NOx emissions equivalent to or lower than those from CNG buses.

Emissions Test Results – Unregulated Emissions

The health community has recently focused attention on aspects of vehicle emissions that are potentially harmful to human health, but that are not currently regulated by the EPA. Their chief concerns are toxic substances present in the exhaust and the number and size of actual PM particles, rather than just their total mass.

The testing done to date has consistently shown that catalyzed filters and ULSD reduce the total toxic constituents of diesel exhaust by 78 – 99%, and reduce many individual toxic substances to levels below detection limits. The filters also reduce the number of particles emitted by over 99% in all particle size ranges.

Recent testing has shown that the exhaust from CNG buses also includes many of the same toxic constituents found in diesel exhaust. In fact, some of these substances, in particular formaldehyde, are present at significantly higher levels in CNG bus exhaust than in diesel bus exhaust. All of the testing performed to date has consistently shown that for the toxic substances measured (benzene, carbonyls, PAH, NPAH) the exhaust from filter-equipped diesel buses has similar or lower levels of toxic constituents than the exhaust from CNG buses.

Recent testing has also shown that the total number of PM particles emitted by CNG buses is significantly lower than the number of PM particles emitted by standard diesel buses, but is comparable to the number of particles emitted by DPF-equipped diesel buses. This is true for all sizes of particle, even the smallest nano-particles.

Capital and Operating Cost Comparison

CNG buses are significantly more expensive to purchase than standard diesel buses. Conversion of a depot to CNG operations also requires installation of fueling infrastructure and depot safety modifications. NYC Transit has found that the total incremental capital costs required to convert a typical 200-bus depot in New York City to CNG operations and to purchase 200 CNG buses is $31 million.

In comparison, the installation of catalyzed particulate filters on 200 new or existing diesel buses costs $1.2 million. There is no new facility investment required since all NYCT depots currently have diesel-fueling infrastructure installed. The cost of installing diesel fueling infrastructure totals approximately

$500,000 per depot, so if this cost is included for comparison, the total capital investment required to use ULSD and filters is $1.7 million per depot.

The use of either CNG buses or catalyzed particulate filters also incurs additional operating costs compared to standard diesel buses. Natural gas is more expensive than diesel fuel on a mile-driven basis, and CNG buses require more maintenance than diesel buses. It is also expensive to maintain the CNG fuel station. The annual incremental costs to operate 200 CNG buses at one depot total approximately $2.5 million compared to the cost to operate 200 standard diesel buses.

ULSD is also more expensive than standard diesel fuel, and catalyzed filters require a marginal amount of annual maintenance. The annual incremental costs to operate 200 buses using ULSD and catalyzed filters total approximately $500,000, including the cost of maintaining the depot's diesel fueling infrastructure.

Assuming a 30-year life for the depot investments required to operate CNG buses, and a 6% discount rate, the net present value of the total incremental costs to operate CNG buses at a typical 200-bus depot for 30 years would be $70 million, or $2.3 million per year (annualized). The net present value of total incremental costs to operate filter-equipped buses at the same depot for 30 years would be $10 million, or $340,000 per year (annualized).

Conclusion

Improvements in diesel engine technology are being driven by more stringent emissions standards. The technology has improved to the point where regulated and unregulated PM emissions and unregulated toxic emissions from the cleanest diesel engines are now equivalent to or lower than those from CNG engines. CNG engines still enjoy a NOx advantage, but at a high cost.

Future EPA standards scheduled to take effect between 2007 and 2010 will force diesel technology to improve further in order to significantly reduce NOx. These standards reduce allowable NOx levels significantly below the inherent NOx level of current CNG engines, so that CNG engines will also have to improve significantly to remain in compliance.

How successful both diesel technology and CNG technology will be in further reducing NOx, and how costly these technology upgrades will be remain to be seen. However, we expect that CNG will remain at a significant cost disadvantage compared to diesel due to its special infrastructure requirements.

BACKGROUND

MTA New York City Transit currently operates approximately 4,500 buses over 227 separate routes throughout the five boroughs of New York City. Traditionally, transit buses have been powered with diesel engines, which are the most efficient and cost-effective power source for heavy-duty applications. Unfortunately, however, all internal combustion engines produce a number of exhaust emissions, some of which have been shown to be harmful to human health and the environment. The most significant of these emissions for diesel engines is soot, or particulate matter (PM), which is sometimes visible as black smoke coming from the tail pipe of a diesel-powered vehicle.

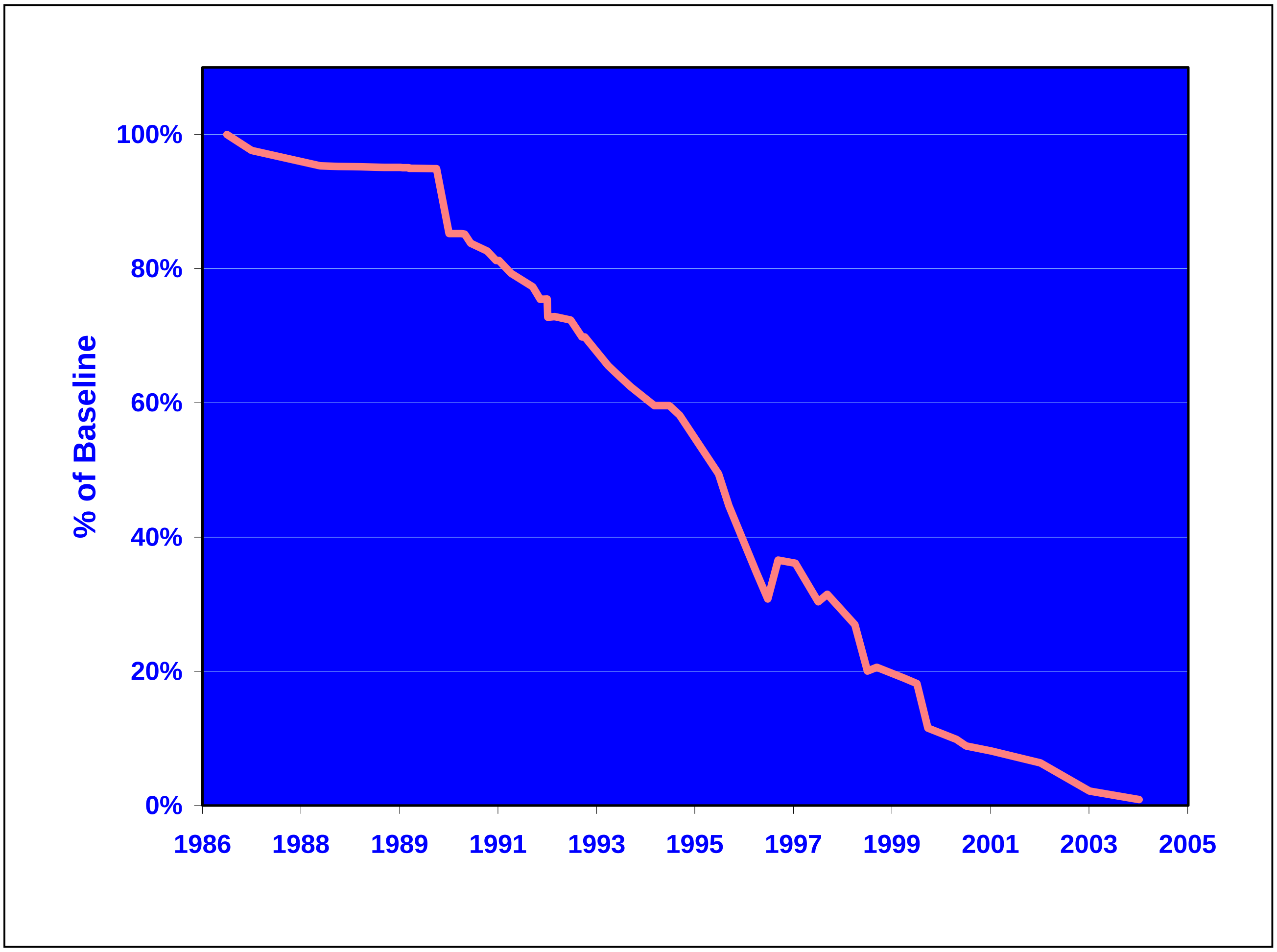


Figure 1 NYCT Average Fleet Emissions of PM (based on engine certification data)

The Borough of Manhattan is currently designated a PM non-attainment area, with respect to the US Environmental Protection Agency's (EPA) national ambient air quality standards. PM non-attainment for all of Manhattan is based on air sampling at one ground-level site on Madison Avenue in mid-town. To be in attainment, the three-year annual average for PM less than 10 microns in diameter (PM 10) at this site must be less than 50 ug/m^3. When Manhattan was designated in non-attainment in the late 1980's, the PM10 readings from this site were in the range of 60 ug/m^3. Data from recent years has indicated reduced levels of PM10, and in fact the average for 1996 through 1999 was 49 ug/m^3, while the average in 2001 was 45.8 ug/m^3 and in 2002 it was 37.8 ug/m^3. Nonetheless, the EPA has not yet lifted the non-attainment status. In addition, EPA has proposed new rules for maximum allowable levels of PM less than 2.5 microns in diameter (PM 2.5). It is not clear exactly how current PM10 levels will correlate to PM 2.5 levels with respect to compliance with the new rules, or how these new rules will affect attainment status. However, it is generally assumed and preliminary evidence indicates that the new rules are more stringent than the old, and that even some areas currently designated as being in attainment will be designated as non-attainment areas once the new rules take full effect.

In 1995, the New York State Department of Environmental Conservation reported to the EPA, in a State Implementation Plan, an estimate that 3.5% of total PM emissions in Manhattan come from vehicle tailpipes. The remaining PM emissions come from stationary sources such as power plants (3.9%) and “area” sources such as home heating equipment (92.5%). At the time, NYSDEC did not characterize what percentage of tailpipe emissions came from NYCT vehicles. Current NYCT calculations, based on engine certification data, estimate that PM emissions from NYCT buses in 1995 constituted less than 15% of all Manhattan tailpipe emissions.

Since 1988, the EPA has regulated a number of diesel emissions, with the major focus on particulate matter (PM) and oxides of nitrogen (NOx). Over the last ten years, the EPA PM and NOx emissions standards have gotten steadily stricter, and the diesel engine industry has responded with fundamental technology improvements that have allowed diesel engines to meet these standards. In addition, the EPA has recently promulgated new standards that will dramatically reduce diesel emissions even further over the next ten years (see Appendix A for a full discussion of emissions regulation and measurement).

As diesel engine technology has improved, NYCT has incorporated the new, cleaner engines into its fleet of revenue buses, to dramatic effect. Based on engine certification data, average emissions of particulate matter from NYCT buses have been reduced by approximately 90% compared to what they were 15 years ago (see Figure 1 above).

HISTORY OF NYCT’S CLEAN FUEL BUS PROGRAMS

Evaluating Various Technologies

NYCT began to evaluate “clean fuel” technologies designed to significantly reduce bus exhaust emissions in 1988. At that time, virtually all transit buses were powered by 2-stroke diesel engines, and the EPA had only recently begun to regulate diesel emissions. The industry was concerned and unsure whether diesel engines would be able to meet the new EPA rules, which reduced the PM emissions standard from 0.6 grams per horsepower-hour in 1988 to 0.1 grams in 1993. The two most promising clean fuel technologies under development at the time were the use of methane (natural gas) and methanol as replacements for diesel fuel. In addition to evaluating these alternative fuels, NYCT also worked with manufacturers to develop a particulate trap system for 2-stroke engines that would filter diesel exhaust and assure that diesel buses would continue to be available for purchase.

Methane is a gas at room temperature and atmospheric pressure, and it can be used to power a vehicle in two different forms: 1) compressed into cylinders at high pressures (CNG) or 2) cooled to approximately minus 163 degrees centigrade at which point it liquefies and can be stored in a tank at low pressure (LNG). Methanol is an alcohol and is liquid at room temperature and atmospheric pressure so it can be stored and used as a vehicle fuel similarly to diesel fuel. Both methane and methanol require significant additional hardware in the bus fuel system, the bus engine, and the facility infrastructure. For example, methane and methanol engines require a spark ignition system (diesel engines use compression ignition).

LNG was, and still is, not readily available in the New York City area so it was judged to be unacceptable as a clean fuel solution. The most significant obstacle to the introduction of either CNG buses or methanol buses was the need to develop a separate fueling infrastructure to accommodate them. For CNG buses, a compressor station is required that can raise the pressure of natural gas from the typical pipeline pressure of 40 to 250 pounds per square inch (psi) to over 3,000 psi in order that enough fuel can be put on the vehicle to provide a full days driving range. Changes are also required in the depot in order to accommodate CNG safely. While methanol is a liquid, and can be handled more easily, there is not a well-developed retail distribution system in New York City. Also, methanol has only about one half of the energy density of diesel fuel. Therefore, you need to carry twice as much fuel on each bus (250 gallons), pump twice as much at the fuel station, and truck twice as much to each depot. To use methanol to power its buses, NYCT would have had to install additional fuel storage capacity at its depots.

Particulate Traps

From 1990 to 1993, NYCT purchased 784 buses, 768 of them were diesels with particulate trap systems. The 1990 purchase included 397 trap-equipped buses, one methanol bus, one dual-fuel diesel-CNG bus, and one dedicated CNG bus. The trap-equipped buses were also the first NYCT buses equipped with electronically controlled, fuel injected engines.

In 1993, the mainstay 2-stroke diesel engine was no longer able to meet EPA emissions regulations without the use of a particulate trap system. NYCT purchased 371 additional trap-equipped buses for a total of 768 such buses. These purchases were made in the context of the limited choices that were available because of the new EPA regulations, and also the fact that 837 1981 model year buses would soon need to be replaced. The trap systems were effective at reducing particulate emissions, but were complex and not as reliable as standard buses. Moreover, the industry began to produce 4-stroke engines with advanced electronic controls and simple, passive diesel oxidation catalysts (DOC), which met the new EPA standards and made the trap systems obsolete only 3 years after their introduction. The trap equipped buses continued to operate until 1995 when the trap systems were removed and replaced with DOCs.

Methanol

The methanol bus purchased in 1990 was delivered and placed in service in 1992. It operated from Casey Stengel Depot and was fueled each day at the Triboro Coach methanol fuel station near LaGuardia Airport. During this period Los Angeles MTA purchased over 300 methanol and ethanol-fueled buses, evaluating the alcohol fuels as the best technology for reducing emissions. The engines failed prematurely on the Los Angeles buses, creating a serious shortfall in buses available for service. NYCT ceased operating the methanol bus in 1995, as we recognized that this was no longer a viable option for future bus purchases.

Compressed Natural Gas (CNG)

The dual-fuel diesel-CNG bus purchased in 1990 also went into revenue service in 1992. It operated from Jackie Gleason Depot and was fueled with CNG each day at Brooklyn Union's Greenpoint facility. The dual-fuel bus was designed to operate on diesel fuel at low speed and on CNG at higher speeds. The results of NYCT's demonstration showed that, because we operate our buses at low average road speed, the emissions benefit from the dual-fuel engine was minimal. The dual-fuel engine in the bus was replaced in 1996 with one of the first new Detroit Diesel Series 50G natural gas engines, which subsequently was qualified as an approved natural gas engine for future bus purchases. The bus remained in service until 2000 when it was removed from service because the bus's fuel system was not compatible with the new high-pressure, fast-fill fuel station at Gleason Depot. The bus was loaned long-term to Command Bus Company.

The third alternative fuel bus from the 1990 purchase was a dedicated CNG bus, which was delivered and placed into service in 1993. It was the first Cummins L-10 CNG engine (the most popular and advanced CNG bus engine at that time) ever installed in an RTS-model bus (NYCT's only qualified bus manufacturer at the time). The bus was plagued with reliability problems, but remained in service until 2000. The bus was also loaned long term to Command Bus.

In 1993, NYCT purchased another dedicated CNG bus, which again remained in service until 2000 and was loaned long-term to Command Bus.

In 1994 NYCT purchased 31 Orion V CNG buses to join the 3 RTS-model CNG buses that we had been operating. In 1995 NYCT leased a small "slow fill" compressor station from Brooklyn Union Gas. The CNG station was installed at the Jackie Gleason depot in Brooklyn. At the same time, changes were made to a small portion of the depot so that work could be done safely on CNG buses in 3 maintenance bays. This significant pilot fleet of CNG buses went into revenue service at the Jackie Gleason Depot in October 1995.

Based on our experience with the pilot CNG bus program at Gleason Depot, in 1996 NYCT forged its first Clean Fuel Bus Plan. The plan included the conversion of Jackie Gleason Depot to full CNG operation, the construction of Coliseum Depot as a CNG-compatible depot, the identification of a depot in Manhattan to be made CNG compatible, a commitment to purchase a total of 500 CNG buses, and a continuing dialogue with interested environmental and regulatory organizations.

The 1995 - 1999 Capital Program was amended to accommodate the commitments made in the Clean Fuel Bus Plan, and the following projects were begun:

- Full facility modifications at Jackie Gleason Depot	$15 million
- Construction of fast-fill CNG fuel station at Jackie Gleason	$5 million
- Construction of new Coliseum Depot as CNG compatible	$10 million (estimated incremental)
- Construction of fast-fill CNG fuel station at Coliseum	$7.3 million
- Purchase of 190 New Flyer low-floor CNG buses	$63 million
- Purchase of 125 Orion low-floor CNG buses	$41 million

The facility modifications and fuel station construction at Jackie Gleason depot were completed in 1999, and the 190 New Flyer low-floor CNG buses were delivered in 1999 and 2000. The first of the 125 Orion low floor CNG buses were delivered in March 2003, and these deliveries are on going. Currently approximately 240 CNG buses operate from Gleason Depot.

Work is currently proceeding on the new Coliseum Depot, which is scheduled to be completed in 4th quarter 2003. In addition, NYCT identified the Manhattanville depot as the third depot to be converted to CNG operations.

In developing the 2000 – 2004 Capital Program Plan, NYCT followed through on the remaining commitments to expand the CNG program that were contained in the original Clean Fuel Bus Plan. The following projects are included in the capital-spending plan that was ultimately approved:

- Purchase of 250 CNG buses	$102 million
- Conversion of Mahattanville Depot to CNG	$ 50 million
- CNG compatibility at 3 new depots and shops	$ 20 million

NYCT has already purchased 130 of the 250 CNG buses in the plan. They will be delivered beginning in early 2004. The Manhattanville CNG conversion project is currently in design, and the construction contract is scheduled to be awarded early in 2004.

Hybrid Electric

In 1992, the MTA Board authorized efforts to develop a new and promising clean fuel bus technology called hybrid diesel-electric propulsion. In 1993, NYCT kicked off a project to design and develop a prototype hybrid-electric bus. A hybrid electric propulsion system combines a small diesel engine with electric drive components and electric energy storage capability to reduce the total energy used to operate the vehicle. A hybrid propulsion system can also reduce total vehicle emissions. This first hybrid project, with Orion Bus Industries and General Electric, resulted in the development of a prototype vehicle for non-revenue testing, which was completed in 1996.

In 1995 NYCT entered into a second hybrid bus program, with the Allison Transmission Division of General Motors, to retrofit a hybrid propulsion system into NYCT's old methanol bus. That bus operated in revenue service in 1999 as a further demonstration of hybrid-electric technology.

Based on the success of the prototype hybrid-electric bus, NYCT proceeded in 1998 to award contracts for a pilot fleet of hybrid-electric buses. We began operating hybrid-electric buses in revenue service in September 1998. Based on our experience with these 10 buses, we proceeded with plans to expand the fleet; and in 1999 we purchased 125 hybrid-electric buses under the 1995-1999 Capital Plan. These buses will be delivered beginning in late 2003.

The 2000 – 2004 Capital Program Plan included funding for 200 additional hybrid-electric buses. These buses were purchased in late 2000, and will be delivered beginning in mid-2004.

Diesel Particulate Filters Redux

In October of 1998, NYCT responded to an RFP from the New York State Department of Environmental Conservation (NYSDEC) asking for "Clean Diesel Demonstration Projects". NYCT was subsequently awarded a grant of NYS Environmental Bond Act funds to complete the proposed demonstration of catalyzed particulate filters, in conjunction with ultra low sulfur diesel fuel. The full project included a 25-bus in-service field test of the CRT™ catalyzed particulate filter made by Johnson Matthey, Inc., as well as significant emission testing. The goals of the project were to verify/demonstrate the CRT's effectiveness at reducing particulate emissions and its durability in the demanding service environment at NYCT.

The CRT (and more generally diesel particulate filters - DPF) are a new emissions control technology applicable to newer four-stroke diesel engines. The CRT contains a precious metal-coated catalyst and a particulate filter that have been engineered as a totally passive emissions control system. The CRT mounts in the bus exhaust system in the same location and general configuration as other typical exhaust after-treatment devices (muffler, oxidation catalyst). It is made up of two chambers. The first contains a matrix of tiny channels made from a ceramic material and coated with a thin layer containing precious metals such as platinum, a highly effective oxidation catalyst. As the exhaust fumes enter the channels, individual molecules land on the coated surface. The catalyst increases the reactions between these molecules and oxygen. Carbon monoxide and hydrocarbons are turned into carbon dioxide and water, respectively. The catalyst also increases the proportion of nitrogen dioxide (NO_2) to nitrogen oxide (NO) in the exhaust. This increase in NO_2 is the key to removing soot (PM) from the exhaust.

In the second chamber, the exhaust encounters another ceramic matrix composed of small diameter tubes that contain blockages. As the exhaust is forced through the second matrix, gaseous components pass through the blockages, but PM is trapped on the walls of the matrix where it is oxidized by reaction with the NO_2 produced in the catalyst chamber, and exits the tail pipe as carbon dioxide (CO_2).

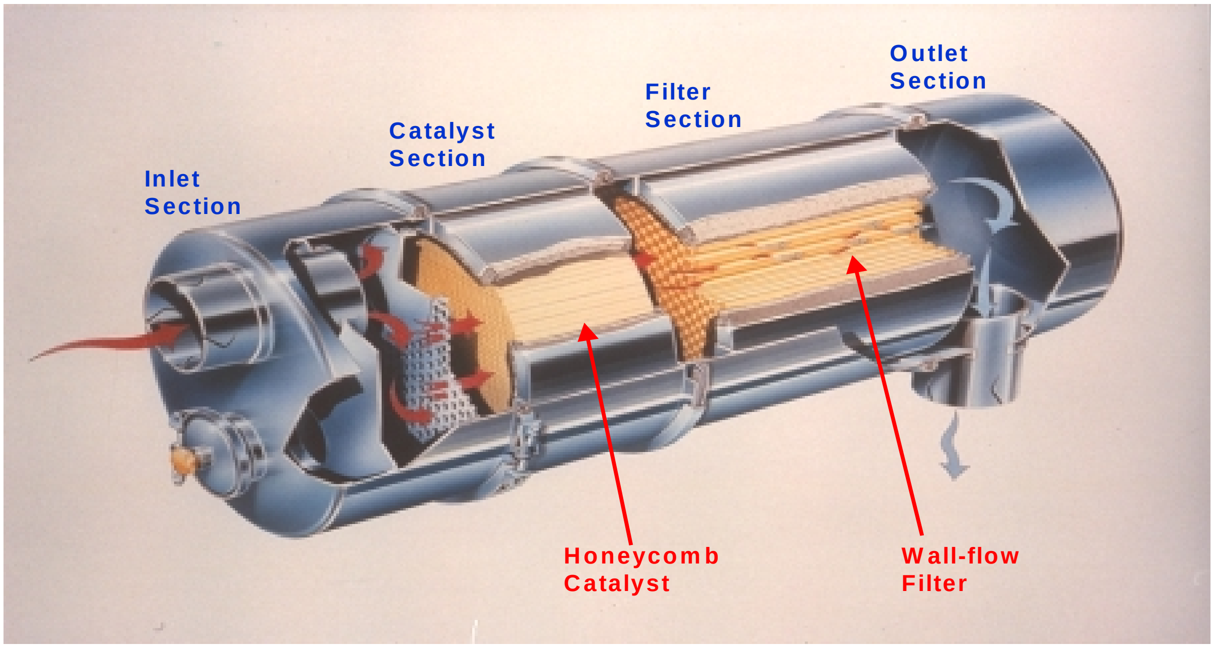


Figure 2 CRT ™ Catalyzed Diesel Particulate Filter (Graphic courtesy of Johnson Matthey)

Unlike the previous generation of exhaust filter systems the CRT and similar devices will not clog through the accumulation of PM particles, because the CRT provides continuous cleaning (regeneration) of the particulate filter. In addition, the CRT can regenerate in temperatures as low as 250^{o}C, much cooler than the 600^{o}C usually required for PM to burn, and easily achievable in a normal diesel exhaust stream without the addition of expensive and maintenance-prone heating equipment. The result is a cost-effective system that significantly reduces CO, HC, and PM from diesel exhaust. See Figures 2 and 3.

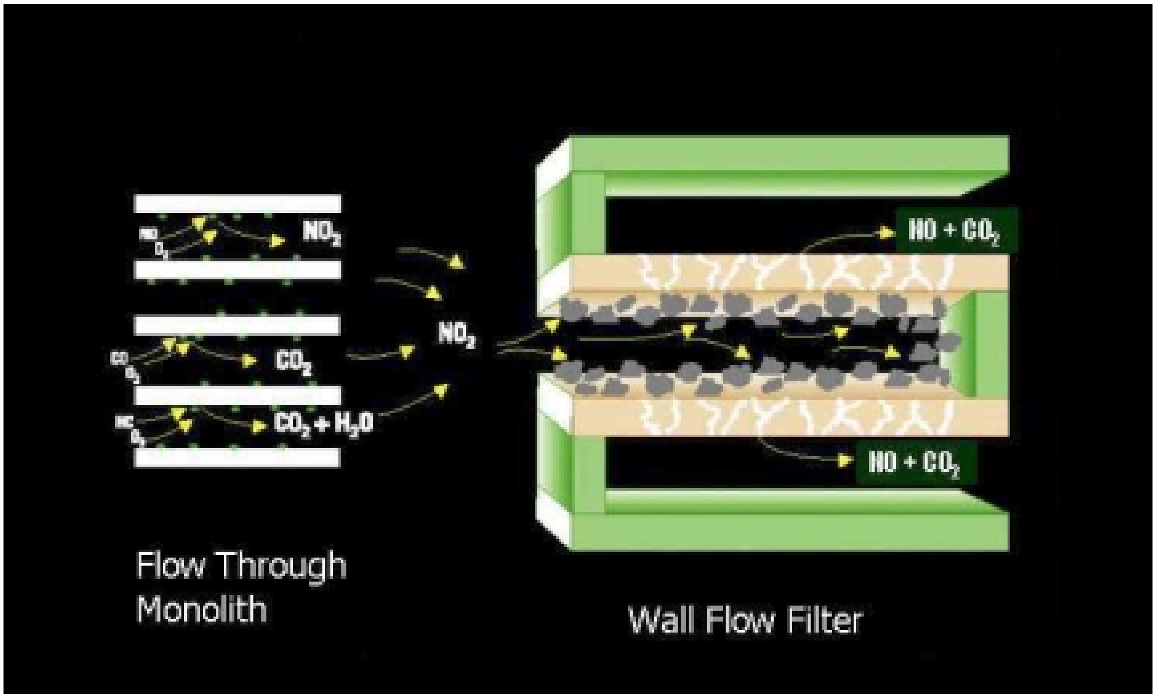


Figure 3 Operation of the CRT^{TM} (Graphic courtesy of Johnson Matthey, Inc.)

The CRT must be used with a special reduced-sulfur fuel. Standard diesel fuel is allowed to have up to 500 parts-per-million (ppm) sulfur. This sulfur ends up in a diesel vehicle's exhaust, and it interferes with the action of the CRT's catalyst. A CRT can not operate effectively if the fuel sulfur level is greater than 50 ppm. Such "ultra-low sulfur" diesel fuel (ULSD) has been used in Europe for over five years, but was not commercially available in the U.S. when NYCT began the CRT demonstration program. In order to begin the program, NYCT had to purchase a special batch of fuel, and arrange logistics for it to be delivered to a depot in New York City.

The CRT demonstration program kicked off in February 2000, when NYCT put 25 buses equipped with CRTs into regular revenue service in Manhattan. At the same time, we began an emissions test program at a test laboratory in Canada.

The test CRTs proved to be very durable in NYCT service. After 9 months the field test officially ended when the original batch of fuel ran out. The 25 buses had accumulated over 750,000 miles in service without a single failure or problem associated with either the ULSD or the CRTs. As noted below, NYCT was able to procure a follow-on supply of ULSD, and 24 of the original 25 CRTs were still in service after over 36 months. One CRT was damaged as the result of an unrelated engine failure after completion of the original field test.

As described further below, the emissions testing has also shown that CRTs and ULSD are very effective at reducing three of the four regulated exhaust emissions.

Based on the success of both the field test and the emissions testing, in late 2000 NYCT began an aggressive program to incorporate this technology into the bus fleet. NYCT was able to find a commercial source of ULSD and signed a 3-year supply contract. In September 2000, NYCT began using ULSD in buses fleet-wide. The 2000 – 2004 Capital Program also contains funding to retrofit filters onto all diesel buses in the fleet (3,200+ units). To date approximately 1,600 units have been installed, with the remainder be completed in 2004. In addition, all new diesel buses are coming from the factory equipped with DPFs. Three hundred and eighty of 885 new diesel buses ordered with filters have already been received.

CLEAN DIESEL & CNG EXHAUST EMISSIONS LEVELS

Regulated Emissions

Figures 4 and 5 below show the results of emissions testing performed as part of NYCT's "Clean Diesel Demonstration Program". The data was collected by Environment Canada (the Canadian equivalent of the US EPA) at their test facility in Ottawa, Ontario. The testing was done in conjunction with the New York State Department of Environmental Conservation, a project partner. Testing was performed on two 1999 Orion buses with DDC Series 50 engines equipped with diesel oxidation catalysts (DOC). As such, the baseline numbers represent emissions from the newest technology diesel engines available at the time, which met all current EPA emissions standards. See Appendix A for a full discussion of emissions test methods and terminology. See Appendix B for a table of all emissions data compared.

As shown, when tested on the CBD cycle the use of ULSD reduces emissions of hydrocarbons (HC), carbon monoxide (CO), and particulates (PM) by 78%, 29%, and 29% respectively, compared to baseline emissions from a diesel bus operating on standard fuel. The addition of a catalyzed filter reduces emissions even further, with HC, CO, and PM reductions of 93%, 94%, and 88% respectively.

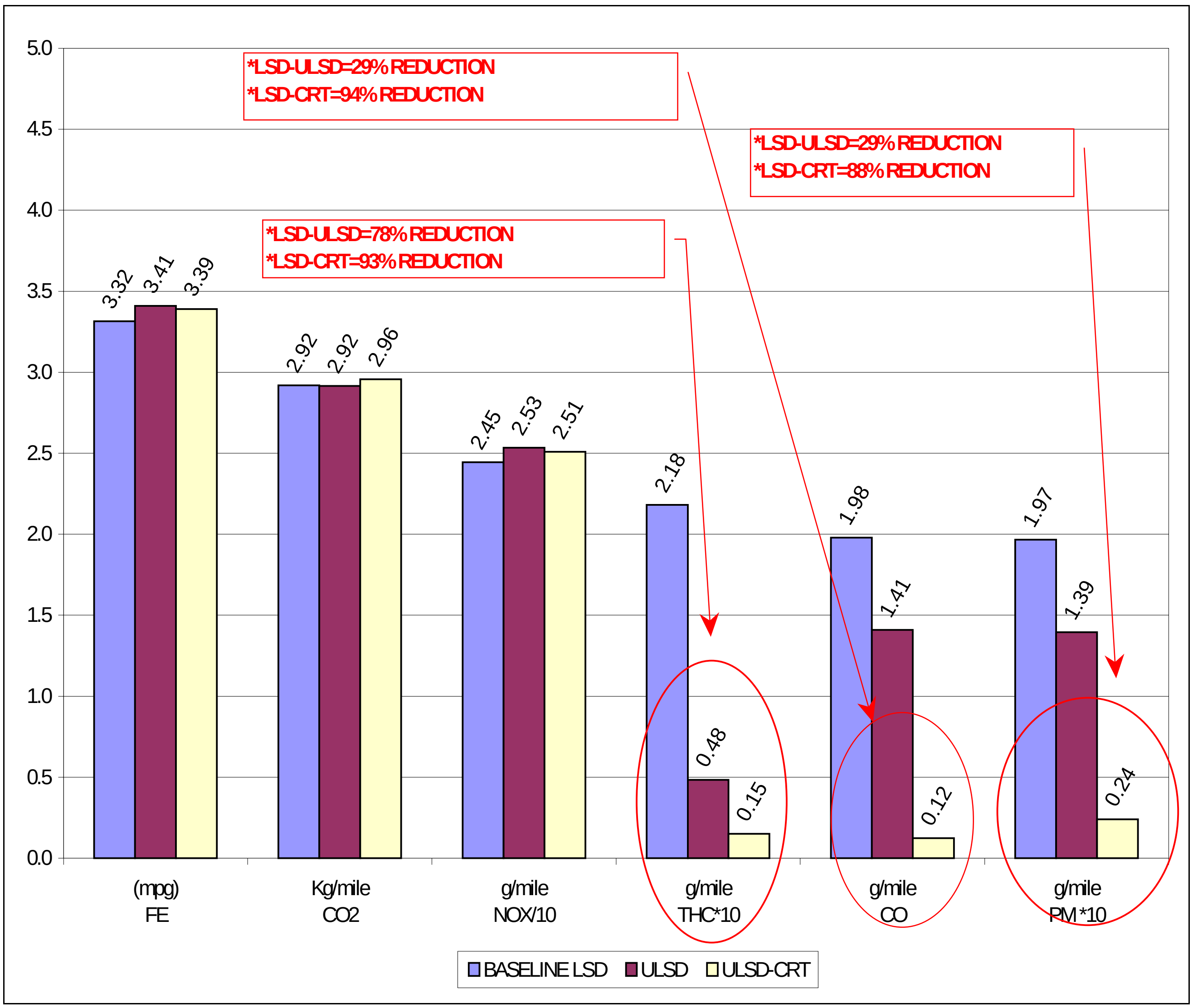


Figure 4 Diesel Emissions with ULSD and CRT^{TM} Diesel Particulate Filter, CBD Cycle

When tested on the NYB cycle, the reductions achieved by the use of a catalyzed filter and ULSD are 93%, 98%, and 93% for HC, CO, and PM respectively.

The use of ULSD and a catalyzed filter do not effect NOx emissions.

These test results are consistent with results reported from testing done on buses and trucks in Europe [1-3], as well as testing conducted on several types of diesel trucks and buses in California, including school buses, garbage trucks, grocery delivery trucks, fuel delivery trucks, and transit buses [4-6]

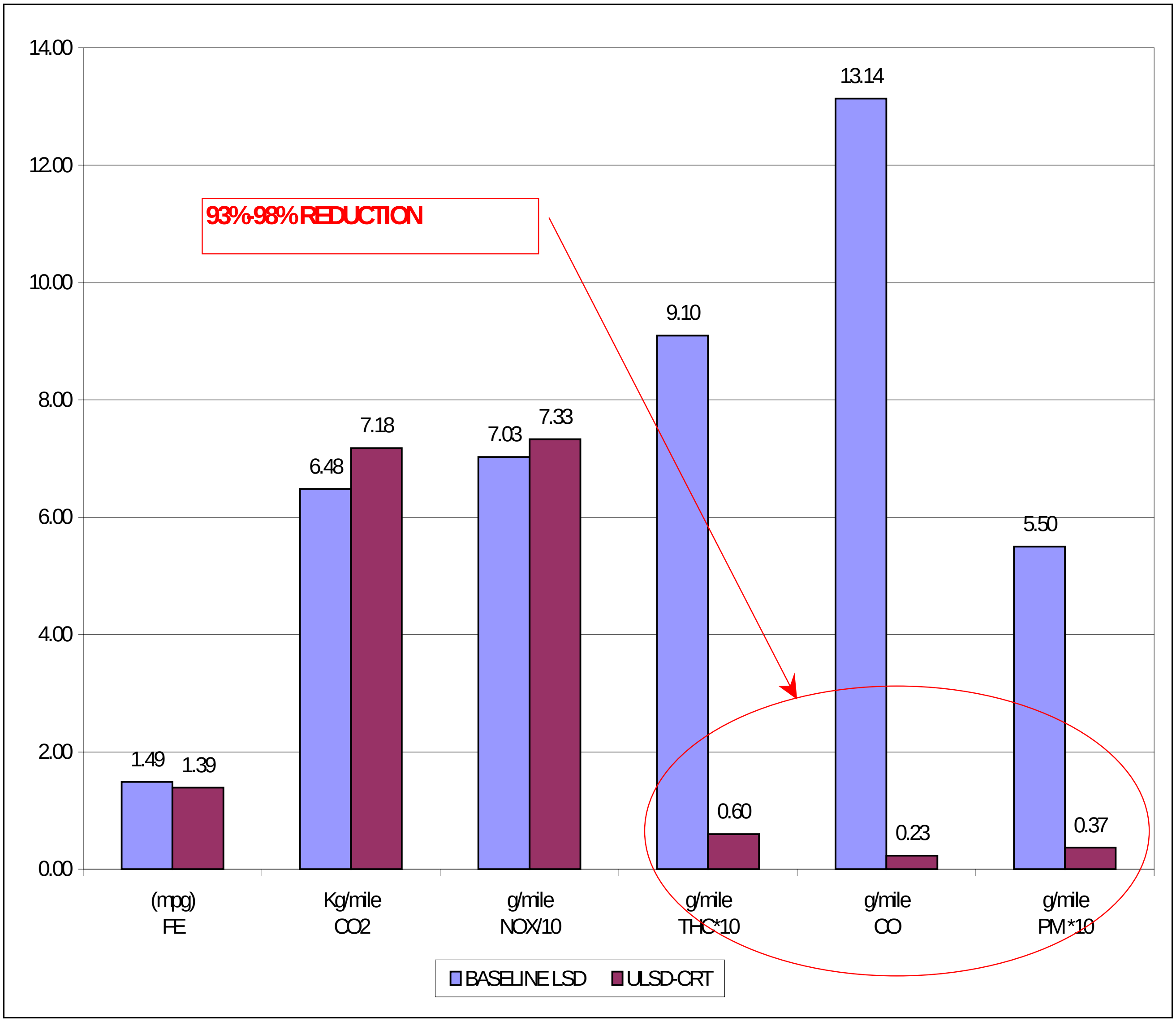
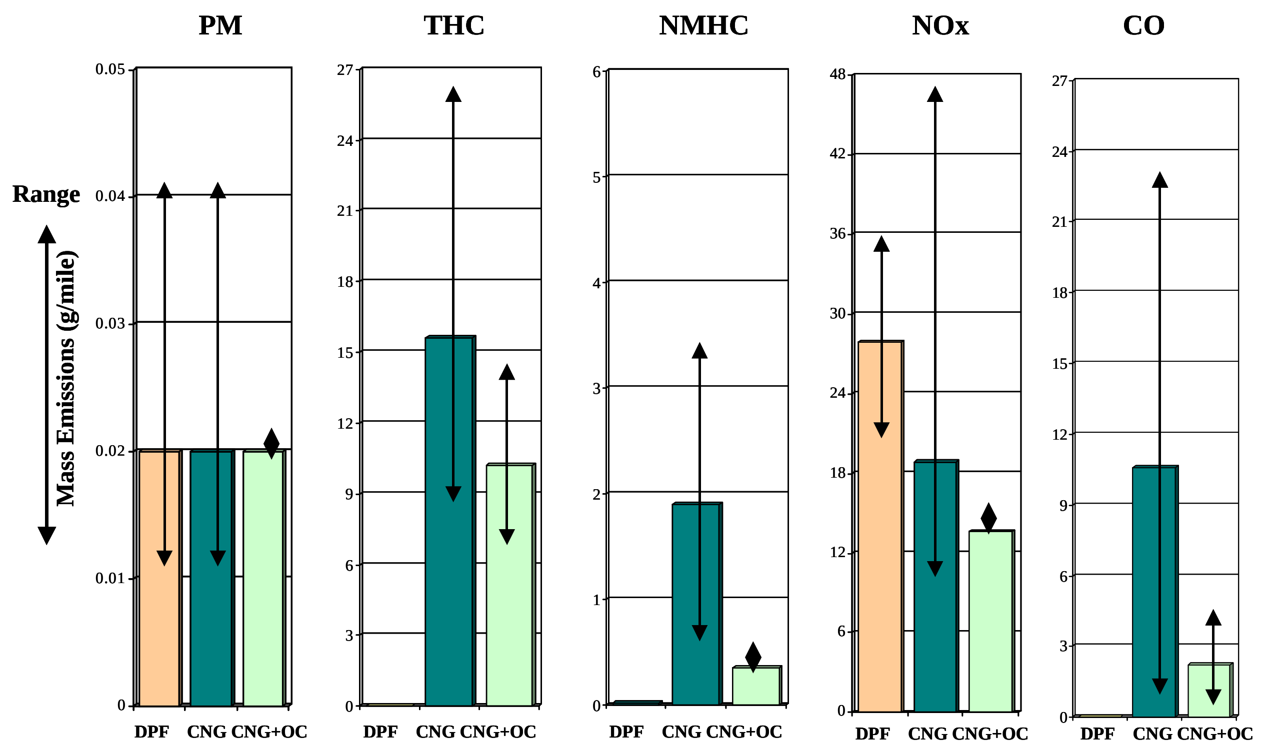


Figure 5 Diesel Emissions with ULSD and CRT^{TM} Diesel Particulate Filter, NYB Cycle

Figures 6 and 7 below compare the emissions from diesel buses operating on ULSD and equipped with a catalyzed filter to the emissions from CNG buses. The data shown comes from the testing mentioned above, plus additional testing done on both CNG and diesel buses by Environment Canada, West Virginia University, and the California Air Resources Board. The data used for comparison includes virtually all U.S. published data on emissions from filter-equipped diesel transit buses, plus a significant portion of the published data on emissions from recent model-year CNG transit buses. The full data set is shown in Appendix B.

In the charts, the bold bars represent the average emissions from each technology. Because actual emissions can vary, sometimes significantly, the range of values represented in the data set is also shown as a line that extends above and below the average value. The average value, high value, low value, and number of data points in each data set are shown in the table below each chart.

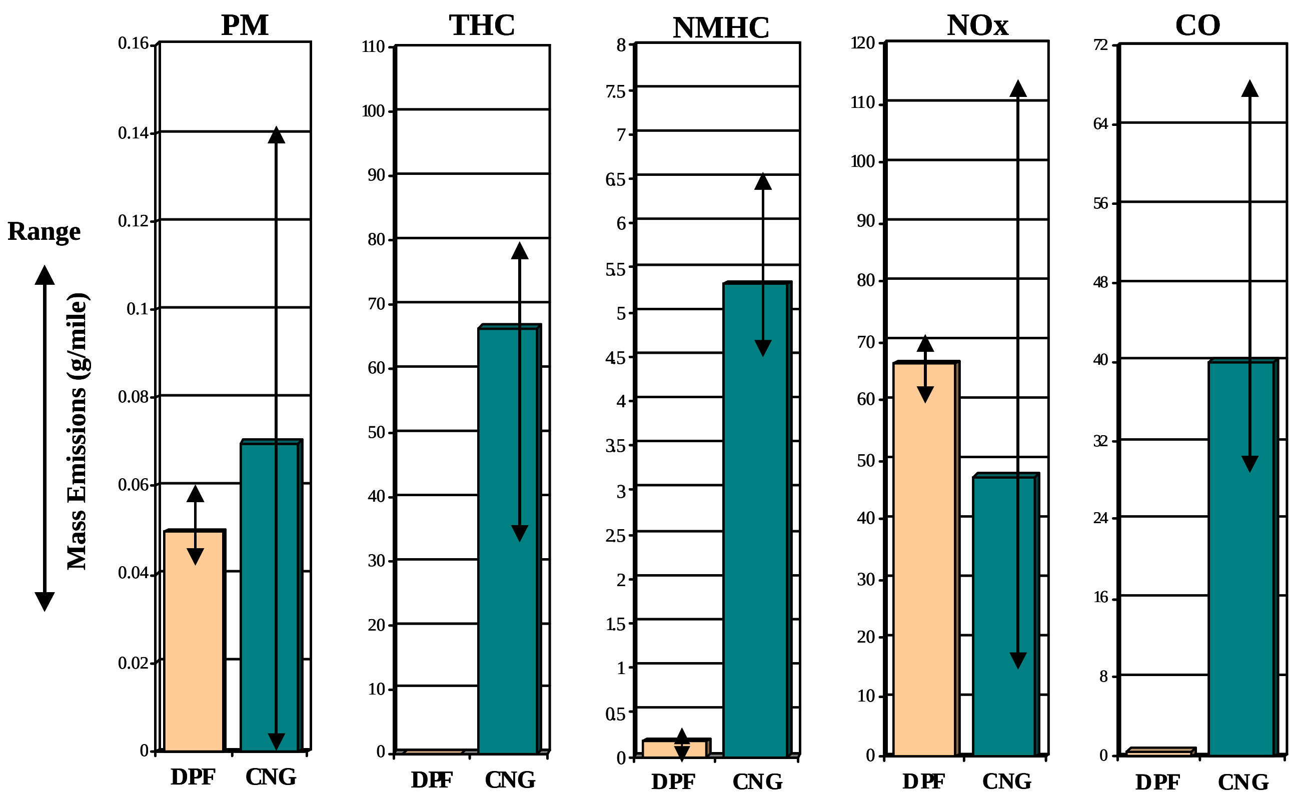
As one can see from the data, emissions of CO and HC (both total hydrocarbons (THC) and non-methane hydrocarbons (NMHC)) from CNG buses are quite variable, and in all cases significantly greater than corresponding emissions from filter-equipped diesel buses. Average PM emissions from the two technologies are virtually identical when measured on the CBD cycle, and slightly lower for filter-equipped diesels when measured on the NYB cycle. In absolute terms, PM emissions from both technologies are very low, and are approaching the limits of what can be measured. In general, the detection limit for most measurements of these regulated emissions is between 0.005 and 0.02 gm/mile, compared to the average measured emissions of 0.02 gm/mi for both technologies on the CBD cycle and 0.05 – 0.07 gm/mile on the NYB cycle.



	PM DPF	PM CNG	PM CNG+OC	THC DPF	THC CNG	THC CNG+OC	NMHC DPF	NMHC CNG	NMHC CNG+OC	NOx DPF	NOx CNG	NOx CNG+OC	CO DPF	CO CNG	CO CNG+OC
Avg.	0.02	0.02	0.02	0.02	15.6	10.2	0.02	1.9	0.4	27.9	18.9	13.6	0.6	10.6	2.2
High	0.04	0.04	0.02	0.06	26.1	14.1	0.06	3.2	0.4	35.2	46.7	13.9	1.7	22.8	4.1
Low	0.01	0.01	0.02	BDL	8.9	6.2	BDL	0.6	0.3	20.5	9.7	13.3	0.1	0.6	0.2
# Samples	8	13	2	8	11	2	8	6	2	8	13	2	8	13	2

Figure 6 Comparison of Emissions: DPF-equipped Diesel, CNG, and CNG with Oxidation Catalyst Buses, CBD Cycle

As shown, the average NOx emissions from CNG buses are lower than the average NOx emissions from filter-equipped diesel buses (approximately 32% lower on the CBD cycle and 29% lower on the NYB cycle), and the best performing CNG buses have significantly lower NOx emissions. However, CNG NOx emissions are also much more variable than diesel NOx emissions, and as shown can be as high or higher than diesel NOx emissions. It is therefore likely that "real world" NOx emissions are well represented by the average figures, and are approximately 30% lower than NOx emissions from diesel buses. Within the data set for CNG buses there is one bus with significantly higher NOx emissions than most of the other buses on the CBD cycle (NYCT 824), and two buses with significantly higher NOx emissions on the NYB cycle (NYCT 824 and Mass PA). It has been confirmed that NYCT 824 experienced backfiring during testing on both cycles, with the backfiring correlated to higher NOx levels. It is not known whether the Mass PA bus exhibited backfiring on either cycle. We believe that the tests for these buses are "valid" and represent real-world in-service behavior. A full discussion of this issue is included at Appendix C. If the results for these buses were excluded from the data set, the average NOx emissions from all CNG buses would change from 18.9 gm/mi to 16.6 gm/mi on the CBD cycle, and from 47.2 gm/mi to 24.2 gm/mi on the NYB cycle.



	PM DPF	PM CNG	THC DPF	THC CNG	NMHC DPF	NMHC CNG	NOx DPF	NOx CNG	CO DPF	CO CNG
Avg.	0.05	0.07	0.2	66.4	0.16	5.30	66.3	47.2	0.5	40.1
High	0.06	0.14	0.3	79.5	0.26	6.60	70.3	113.2	0.9	68.9
Low	0.04	BDL	0.1	33.7	0.06	4.40	60.0	15.3	0.2	29.0
# Samples	3	6	3	6	3	3	3	6	3	6

Figure 7 Comparison of Emissions: DPF-equipped Diesel and CNG Buses, NYB Cycle

All of the buses tested were in model years between 1998 and 2001. With respect to NOx emissions, these buses represented the "state of the art" for both diesel and CNG technology at the time that the testing was completed in 2001. Beginning in late 2002, new EPA rules mandated a 40% reduction in NOx from new diesel engines. No results from buses that meet the new standards were included in the above analysis, as none are available. See discussion below under “Future Technology Developments to Address Diesel NOx”.

Figure 6 also shows data for CNG buses equipped with an oxidation catalyst. In the past, CNG buses have typically not been delivered with oxidation catalysts on the tail pipe. Recent data showing the relatively high CO, HC, and unregulated toxic emissions (discussed below) from CNG buses has sparked interest in applying this technology to CNG buses in order to reduce these emissions. The California Air Resources Board has collected and published a limited amount of data (tests on two buses) showing the effect of an oxidation catalyst applied to CNG buses, and this data is included in Figure 6. As shown, the oxidation catalyst can significantly reduce CO, THC, and NMHC emissions from CNG buses. However even with an oxidation catalyst in place, emissions of these substances are still significantly higher than emissions of the same substances from filter-equipped diesel buses. As shown, addition of an oxidation catalyst may also reduce CNG NOx emissions slightly.

Non-regulated Emissions

Toxicity

In addition to the regulated emissions detailed above, there is increasing concern in the health and environmental communities about the toxic constituents of diesel exhaust. In order to determine whether ULSD and catalyzed filters can reduce diesel exhaust toxicity, the testing under NYCT’s Clean Diesel Demonstration Program included analysis of this issue. The testing program focused on the collection of data on three types of toxic compounds: carbonyl hydrocarbon species, polycyclic aromatic hydrocarbons (PAH) and nitrated polycyclic aromatic hydrocarbons (NO2PAH).

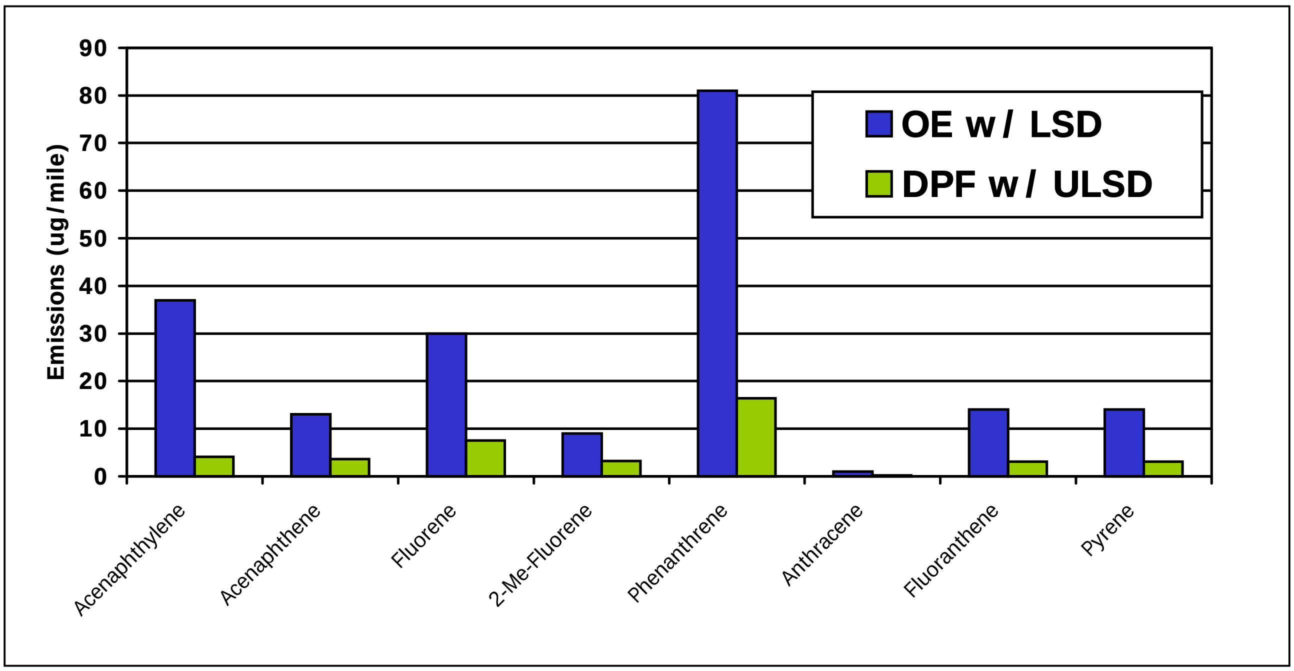


Figure 8 Toxic Constituents of Diesel Exhaust (PAH Emissions), NYB Cycle

When tested on the CBD cycle, use of ULSD and a DPF was shown to reduce average carbonyl, PAH, and NO2PAH emissions by 99%, 78%, and 79% respectively compared to baseline diesel emissions. On the NYB cycle, the reductions were >99%, 79%, and 94% for carbonyl, PAH, and NO2PAH emissions respectively. Some of this data is shown in Figures 8 and 9 and is included in Appendix B.

Until recently, many people assumed that the exhaust of CNG buses did not include appreciable amounts of toxic compounds. Recent testing conducted on NYC Transit buses as well as buses in California has shown that this is not true [7-9]. Figure 10 below shows toxicity data from the New York test program and Figure 11 shows comparable data from the California Test program, all taken on the CBD cycle. In addition to total Carbonyl, PAH compounds and NPAH compounds, these figures also show emissions of benzene, one of the most significant carcinogens found in diesel and CNG exhaust. The data used to create these charts includes virtually all U.S. published data on unregulated toxic emissions from CNG buses, and is included in Appendix B.

As shown in Figure 10, benzene and carbonyl emissions from CNG buses are significantly higher than emissions of these substances from diesel buses, with or without a filter installed. In fact, carbonyl emissions from CNG buses are almost 20 times as high as carbonyl emissions from standard diesel buses. Most of these carbonyl emissions from CNG buses are formaldehyde. PAH emissions from CNG buses are comparable to those from diesel buses without a filter, and approximately 4 times higher than PAH emissions from filter-equipped diesel buses. NO2PAH emissions from CNG buses are lower than NO2PAH emissions from standard diesel buses and comparable to NO2PAH emissions from filter-equipped diesel buses.

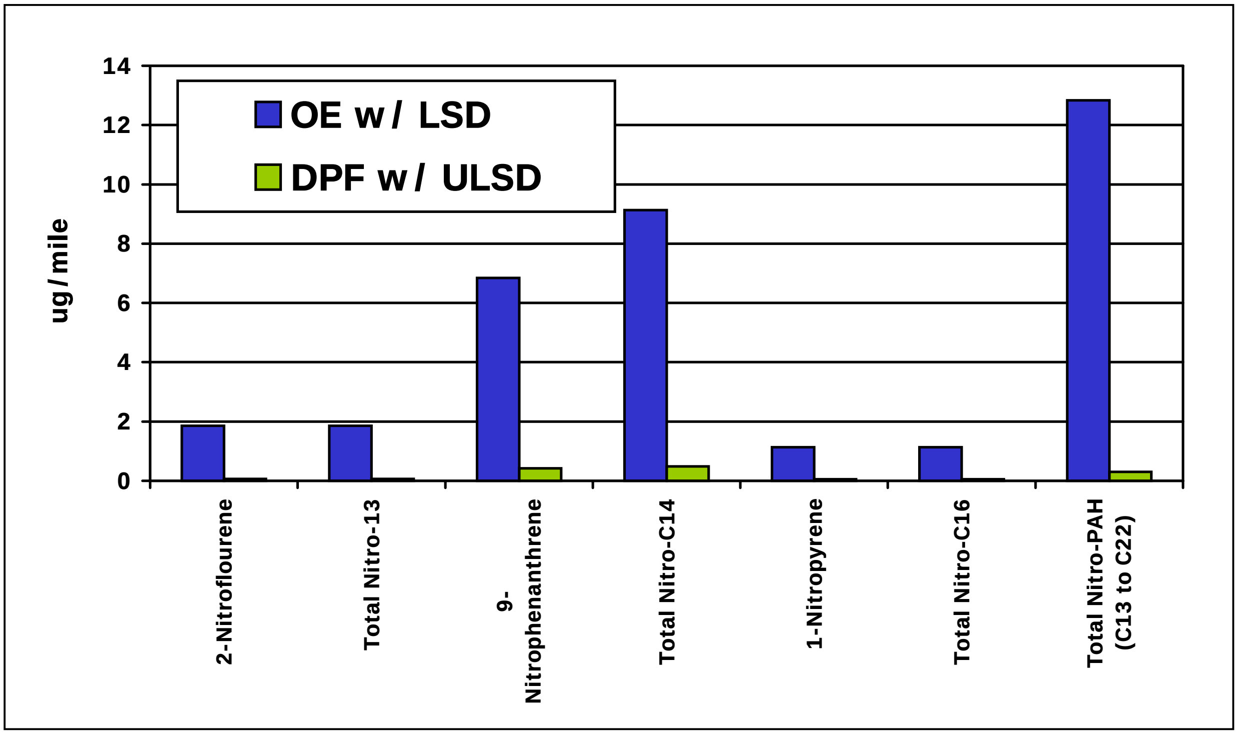
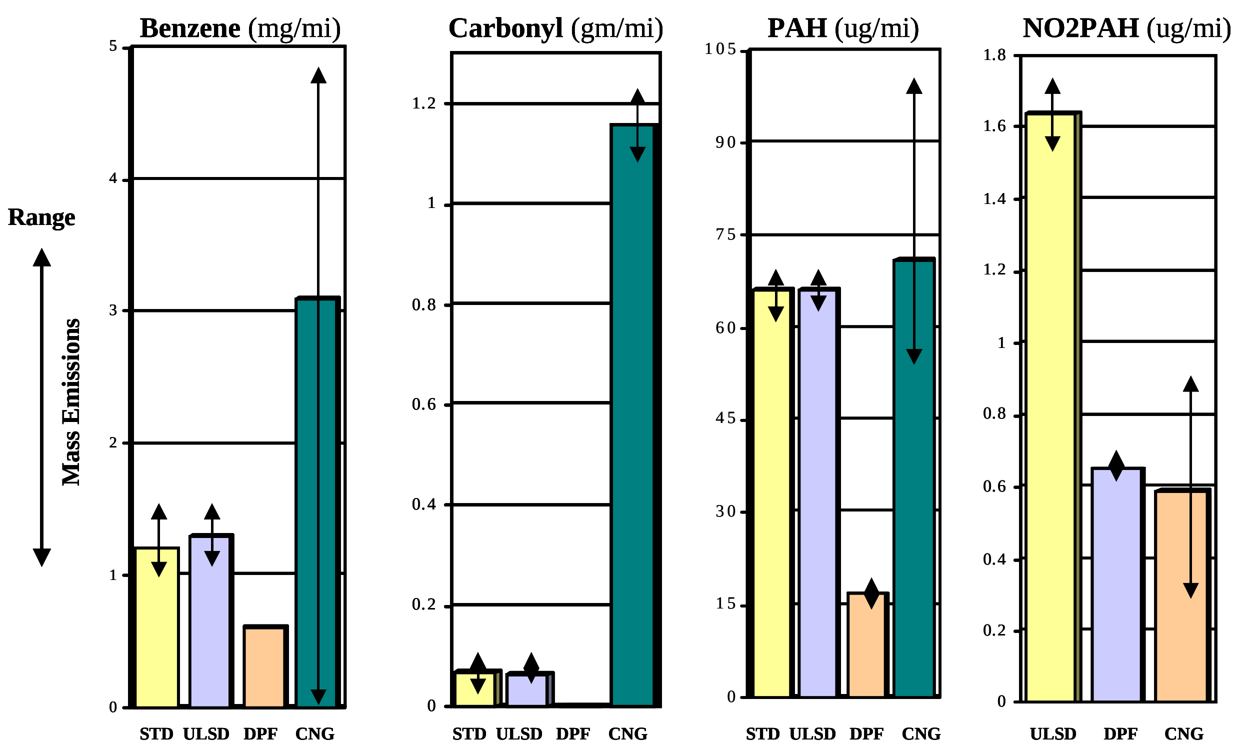


Figure 9 Toxic Constituents of Diesel Exhaust (NO2PAH Emissions), NYB Cycle

As shown in Figure 11, the data collected in the California program is consistent with that collected in the New York program. The measured benzene and carbonyl emissions are very comparable between the two programs for all three technologies (standard diesel, filter-equipped diesel, CNG). The magnitude of PAH and NO2PAH emissions reported in the California data is significantly higher than that reported in the New York data, however the relative level of emissions when comparing one technology to another is consistent between the two data sets. The discrepancy between the reported levels of PAH and NO2PAH in the two data sets can probably be explained by differences in how the samples were collected and analyzed in each of the labs which did the analysis since there are no standardized methods for collecting and analyzing this data, as there are for regulated emissions. PAH and NPAH are a class of substances containing hundreds of different aromatic hydrocarbons with more than two fused benzene rings. Most studies only measure the 16 primary PAHs designated by US EPA, while others may include additional PAHs. In addition, the amounts of these substances that are emitted are generally three to six orders of magnitude less than the regulated emissions components. As such, small changes in the method of collection and analysis will have a much larger impact on the reported results. The fact that the reported values from each lab are internally consistent gives a high confidence level that all of this data can be used to make comparisons between technologies.

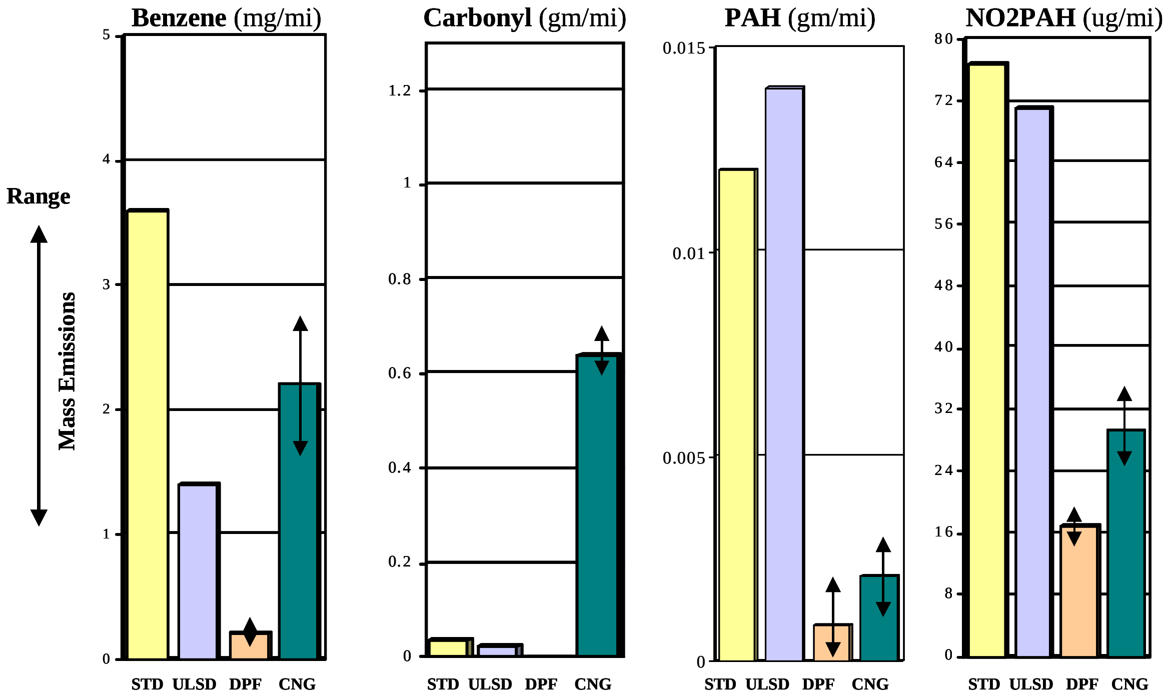
The New York program also collected data on the NYB cycle. This data is consistent with all of the CBD data shown above. This data is included in Appendix B.

There is very little published data showing the level of toxic emissions from CNG buses equipped with an oxidation catalyst. However, these toxic substances are present in vehicle exhaust either as part of the gaseous hydrocarbons (NMHC) or adsorbed onto solid particles (PM). As such, the addition of an oxidation catalyst to a CNG bus should reduce the level of toxic compounds proportionally to the reduction in NMHC and PM provided by the catalyst. Based on the limited data published by the California Air Resources Board [9, 22] it appears that toxic emissions from catalyst-equipped CNG and DPF-equipped diesel buses are comparable. A DPF-equipped diesel bus may have slightly lower carbonyl emissions, while a catalyst-equipped CNG bus may have slightly lower PAH emissions. Additional data is required to make more definitive conclusions.



	Benzene STD	Benzene ULSD	Benzene DPF	Benzene CNG	Carbonyl STD	Carbonyl ULSD	Carbonyl DPF	Carbonyl CNG	PAH STD	PAH ULSD	PAH DPF	PAH CNG	NO2PAH ULSD	NO2PAH DPF	NO2PAH CNG
Avg.	1.2	1.3	0.6	3.1	0.07	0.06	0	1.16	66	66	17	71	1.64	0.65	0.59
High	1.4	1.4	0.6	4.8	0.08	0.07	BDL	1.24	69	69	17	102	1.72	0.67	0.91
Low	1.0	1.1	0.6	BDL	0.05	0.06	BDL	1.09	62	63	16	54	1.55	0.62	0.27
# Samples	2	2	2	3	3	2	2	3	3	2	2	3	2	2	2

Figure 10 Toxic Constituents of Exhaust: Comparison of Diesel, Diesel with ULSD, Diesel with DPF, and CNG Buses, CBD Cycle (New York data)



	Benzene STD	Benzene ULSD	Benzene DPF	Benzene CNG	Carbonyl STD	Carbonyl ULSD	Carbonyl DPF	Carbonyl CNG	PAH STD	PAH ULSD	PAH DPF	PAH CNG	NO2PAH STD	NO2PAH ULSD	NO2PAH DPF	NO2PAH CNG
Avg.	3.6	1.4	0.2	2.2	0.038	0.023	0.000	0.641	0.012	0.014	0.001	0.002	76.7	71.1	17.0	29.2
High	3.6	1.4	0.2	2.7	0.038	0.023	0.000	0.675	0.012	0.014	0.002	0.003	76.7	71.1	18.9	33.8
Low	3.6	1.4	0.2	1.7	0.038	0.023	0.000	0.607	0.012	0.014	0.000	0.001	76.7	71.1	15.0	24.5
# Samples	1	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2

Figure 11 Toxic Constituents of Exhaust: Comparison of Diesel, Diesel with ULSD, Diesel with DPF, and CNG Buses, CBD Cycle (California data)

Particle Number and Size

A second area of concern with respect to the health effects from vehicle emissions is the number and size of PM particles emitted. It has been hypothesized that the number of particles emitted is much more important than the total mass of particles emitted and that smaller particles have a greater adverse impact on human health than larger particles.

While the total mass of PM emissions from diesel engines has been significantly reduced in recent years, some have worried that the average size of emitted particles may have decreased, and that the total number of particles emitted may have actually increased. As noted above, catalyzed particulate filters are very effective at reducing the total mass of PM emitted by diesel engines, but it is also important to understand how they effect particle size distribution and number count.

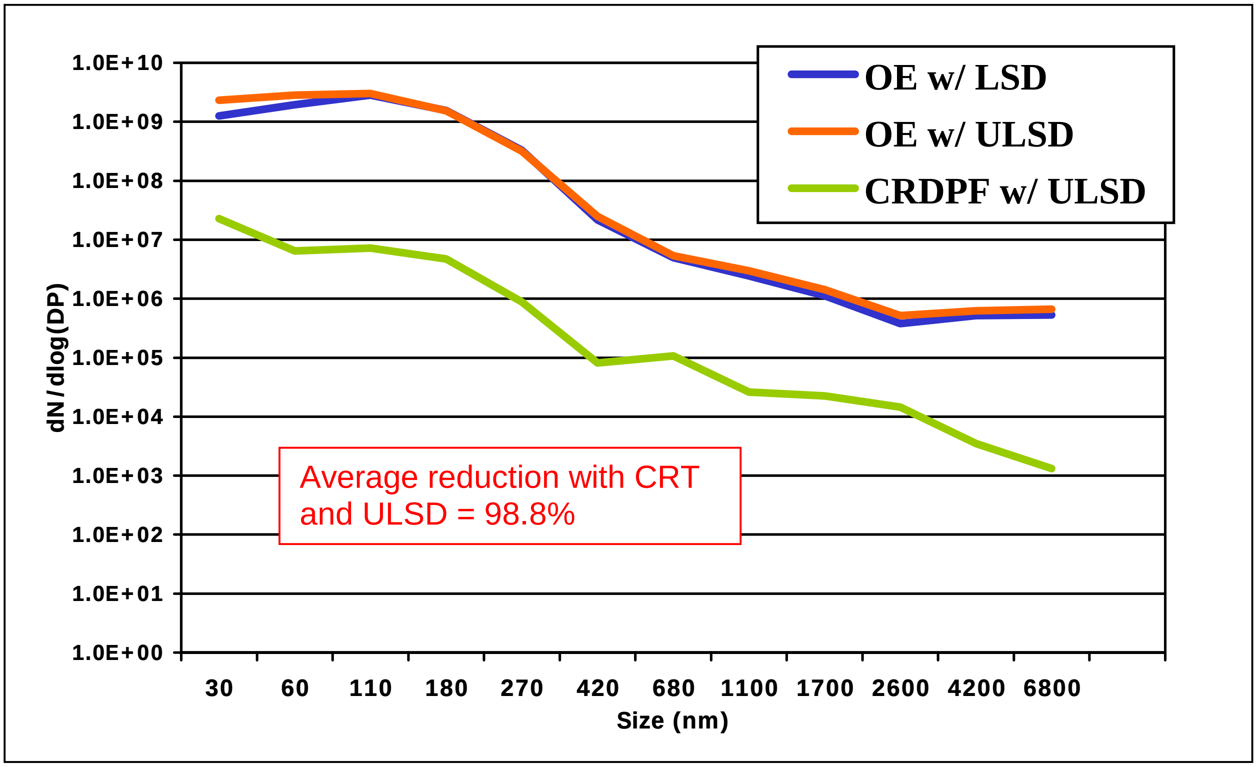


Figure 12 Particle Size Distribution Over CBD Cycle (ELPI data)

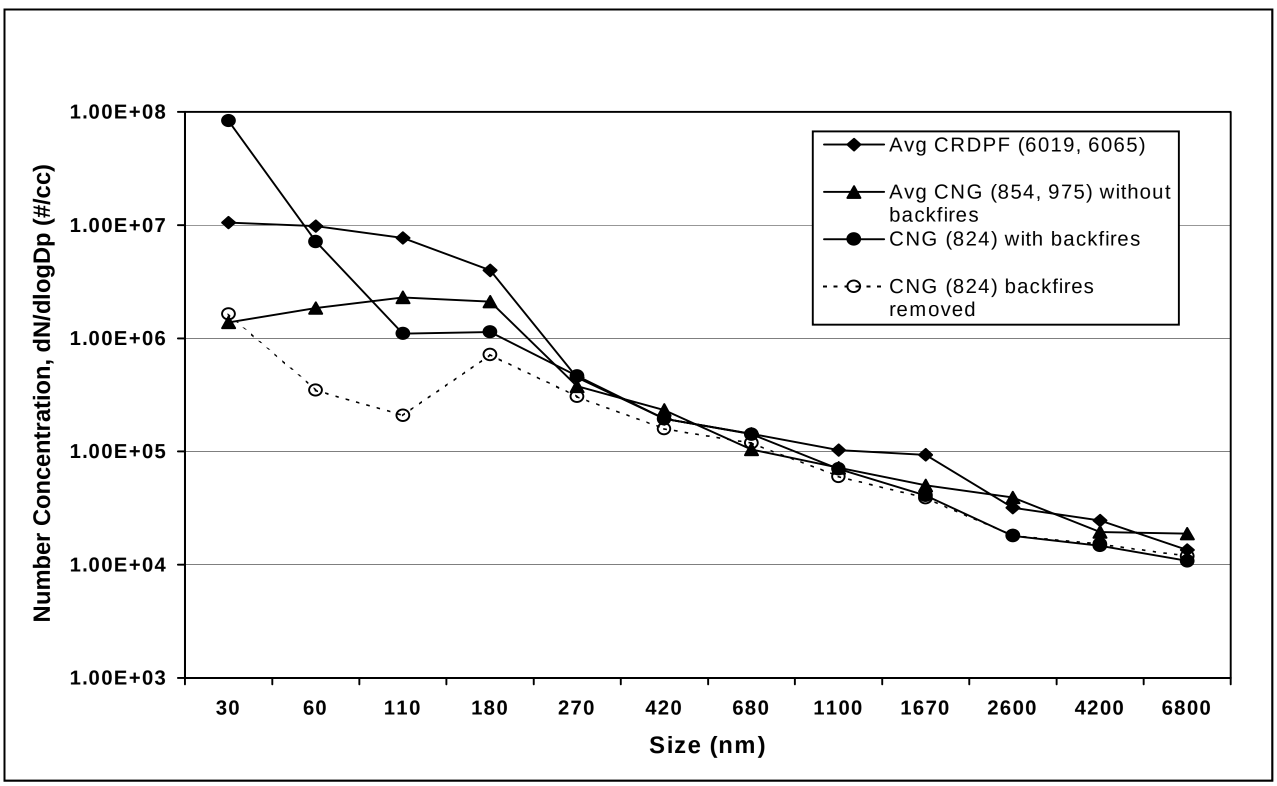


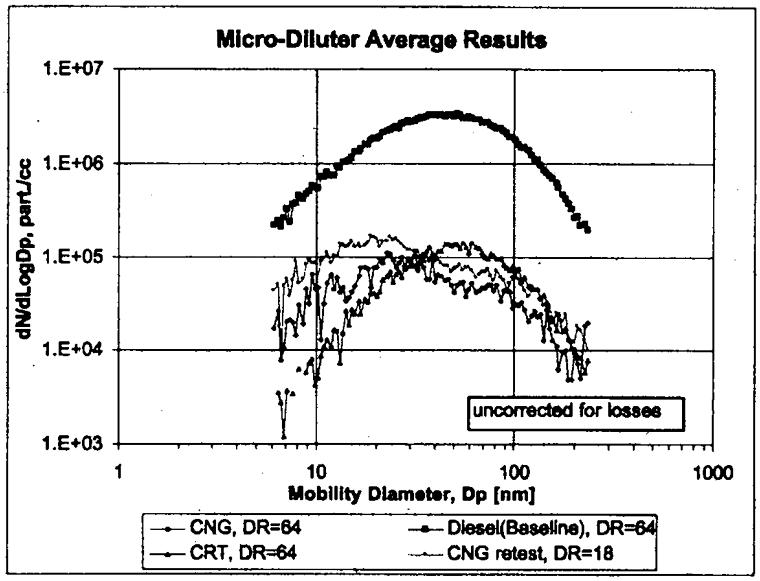
Figure 13 Particle Size Distribution Comparison: Standard Diesel, DPF-equipped Diesel and CNG buses (New York Data)

Particle size testing conducted by the New York State Department of Environmental Conservation as part of NYCT's Clean Diesel Demonstration Program has shown that the use of a catalyzed filter is very effective at reducing PM particle counts. In fact, the filter was shown to reduce the number of emitted particles by at least 99% across all size ranges, compared to baseline emissions. In addition, the use of the filter did not skew the distribution of particles toward a greater production of smaller particles. This data is presented in Figures 12.

Until recently, no data was available on the number of particles emitted by CNG buses and their size distribution. Recent testing conducted on NYC Transit buses as well as buses in California has included this particle size evaluation [7, 10]. Figures 13 and 14 compare the total number of particles of various sizes emitted by standard diesel buses, diesel buses with DPF and CNG buses. Figure 13 includes data on CNG buses with and without backfiring. CNG bus backfiring is discussed in detail in Appendix C.

As shown, both CNG buses and DPF-equipped buses emit significantly fewer particles than standard diesel buses in all size ranges. Over all, the number of very small particles emitted by CNG buses and DPF-equipped buses are comparable.

Particle Size Distributions - Steady State Tests



Note: Diluted exhaust temp. ranged approx. from 80 to 90 F

Source: 1) Holmén, B.A., and A. Ayala, "Ultrafine PM Emissions from Natural Gas, Oxidation-Catalyst Diesel and Particulate-Trap Diesel Heavy-Duty Transit Buses," *Environ. Sci. Technol.*, 2002, submitted.

2) Holmén, B., A. Ayala, N. Kado, and R. Okamoto (2001). "ARB's Study of Emissions from "Late-model" Diesel and CNG Heavy-duty Transit Buses: Preliminary Nanoparticle Measurement Results," 5th International ETH Conference on Nanoparticle Measurements, Zürich.

Figure 14 Particle Size Distribution Comparison: Standard Diesel, DPF-equipped Diesel and CNG buses (California Data)

Future Technology Developments to Address Diesel NOx

As noted above, the tested CNG buses have on average 32% lower NOx emissions than the tested diesel buses, even when diesels are operated on ULSD and outfitted with catalyzed filters. All of the buses tested were in model years between 1998 and 2001. With respect to NOx emissions, these buses represented the “state of the art” for both diesel and CNG technology at the time that the testing was completed in 2001.

Beginning in late 2002, new EPA rules mandated a 40% reduction in NOx from new diesel engines (see Appendix A). Virtually all diesel engine manufacturers have now demonstrated, through EPA certification, that they can meet these requirements. Most, including NYCT’s major supplier the Detroit Diesel Corporation, will meet the requirements by adding exhaust gas re-circulation (EGR) to their engines. At least one supplier, the Caterpillar Corporation, will avoid the use of EGR by using a combination of technologies, including more sophisticated fuel control, compound turbo-charging, and changes in the combustion chamber.

Detroit Diesel has also demonstrated a further reduction in NOx emissions from new natural engines, but in post-2002 engines the gap between CNG and diesel has narrowed. Based on certification data, as shown below in Figure 12, new natural gas engines now have approximately 20% lower NOx emissions than new diesel engines (compared to 40% lower for pre-October 2002 engines, based on certification engine testing and 32% lower based on chassis testing, as discussed above). There is virtually no chassis test data available to show the actual “on-road” emissions from either post-October 2002 CNG buses or post-October 2002 diesel buses with EGR. However, it is likely that these buses will exhibit similar behavior to previous generations of diesel and CNG buses, with fairly high variability of actual in-use NOx emissions from CNG buses.

As shown in Figure 15, Detroit Diesel has also demonstrated an even greater reduction in NOx emissions from new natural gas engines with the addition of an oxidation catalyst in the exhaust system. As discussed previously, these catalysts are standard equipment on new diesel engines, but typically have not been applied to natural gas engines in the past. With a catalyst installed, new natural gas engines have been certified to have 50% lower NOx emissions than new EGR-equipped diesel engines.

Engine Type	NOx Emissions (gm/bhp-hr)
2000 DDC Series 50 Diesel Engine	3.91
2000 DDC Series 50G Natural Gas Engine	2.20
2003 DDC Series 50 EGR Diesel Engine	2.40
2003 DDC Series 50G Natural Gas Engine	1.90
2003 DDC Series 50G Natural Gas Engine, w/ catalyst	1.20
All results taken from test data submitted to EPA for certification of the engine	

Figure 15 Certified NOx Emissions Levels from Diesel and NG Engines

EPA mandates to reduce NOx emissions from heavy-duty vehicles a further 92% starting in 2007 (down to 0.2 gm/bhp-hr) will require new technologies to be applied to both natural gas and diesel engines. It is unclear whether natural gas engines will provide any inherent NOx benefit compared to diesel engines after the new rules take full effect. It is also unclear how much these new technologies will cost, and whether the incremental cost of meeting the new standards will be different for natural gas and diesel engines.

In addition, as noted previously, NYCT is also purchasing hybrid diesel-electric buses. These buses include catalyzed particulate filters as part of the emissions control system on their diesel engines, and like all diesel buses in the NYCT fleet will use ULSD.

The hybrid propulsion system uses an electric drive motor and an energy storage (battery) system to recapture energy normally wasted in braking, which can then be re-used to accelerate the bus. The result is a significant improvement in fuel economy, averaging 10 - 30% better than a standard diesel bus in revenue service in NYC. The improvement in fuel economy, along with less transient engine operation, also results in lower NOx emissions. Testing done by West Virginia University [11, 23] and the California Air Resources Board [12] has shown that hybrid buses with pre-2002 diesel engines have 30 – 60% lower NOx emissions than standard diesel buses, and generally have NOx emissions equivalent to or better than pre-2002 CNG buses. Future hybrid buses with post-2002 diesel engines will have even lower NOx emissions, which are likely to be as low or lower than NOx emissions from post-2002 CNG buses.

CLEAN DIESEL & CNG CAPITAL COST COMPARISON

All of the costs noted in this section are based on the experience of NYC Transit in operating CNG buses since 1995, and in operating DPF-equipped diesel buses since 2001. Where possible, the experience of NYC Transit has been put into context by referencing the experiences of other large transit agencies in operating CNG buses, including the Los Angeles County Metropolitan Transportation Authority (LACMTA), the Greater Cleveland Regional Transit Authority (GCRTA), and Coast Mountain Bus Company of Vancouver, British Columbia (CMB). Data on the experiences of these agencies was taken from published documents from these agencies, which are referenced in Appendix D. NYC Transit is the only large transit agency in the U.S with significant experience operating DPF-equipped diesel buses.

Filter-Equipped Diesel Buses

To date, NYCT has performed approximately 1,600 retrofit installations of diesel particulate filters on buses. The cost of these retrofits (purchase and installation) has ranged from $5,000 to $7,000 per bus, with an average of $5,900. This cost includes $4,200 - $6,100 to purchase the DPF and installation kit, and between $200 and $1,200 for the installation (4 hours – 21 hours). Approximately 5% spare filters must be purchased to provide a “float” for annual cleaning, at an average cost of $4,000 per unit.

All NYCT depots currently have diesel-fueling infrastructure installed, and there is no additional infrastructure investment required to use ULSD, or to use the filters. However, for comparison purposes the cost to install diesel fuel tanks, dispensers, and related safety/monitoring equipment at a new 200-bus depot totals $495,000. This cost includes storage for approximately 3 days worth of fuel in order to guard against supply disruptions. It also includes overfill and leak detection systems integrated with a central monitoring/alarm system.

No special tools or facility investments are required to use diesel particulate filters. DPFs do require annual cleaning using a specialized cleaning machine and a test bench, to remove ash accumulation. It is expected that the required devices could cost up to $25,000, but they could be used to clean as many as 2,000 filters per year. NYCT will contract with a third party for a filter cleaning service. The cost of the cleaning and test machines, which will be borne by the third party, is included in the operating costs noted in the next section, as part of the cleaning fee.

CNG Buses

LACMTA, GCRTA, and CMB have reported that it currently costs between $35,000 and $70,000 more to purchase a CNG bus than to purchase an equivalent diesel bus [13-15]. LACMTA reported in 2002 that the actual price differential on their most recent bid opening was $46,000 [13]. Most of this incremental cost is due to the complicated high-pressure fuel storage system required with CNG buses. Some of the incremental cost is due to higher costs for CNG engines than for diesel engines.

NYCT does not have any recent experience in which we bid CNG and diesel buses at the same time for comparison, but historically our experiences were similar to those of these other large transit agencies. For the purposes of this analysis, we will use $30,000 as the incremental cost of a CNG bus. This is a conservative figure which takes in to account possible price reductions as the number of CNG bus deliveries increases, as well as a recent increase in the cost of diesel engines which meet post-2002 EPA emission standards.

The use of CNG fuel also requires significant infrastructure to compress the gas into the fuel cylinders on the bus. The fast-fill CNG fuel station at the Jackie Gleason Depot cost $5 million to install. The fast-fill CNG fuel station at the Coliseum depot cost $7.3 million to install. Both of these stations are sized to provide equivalent fueling capacity to existing diesel fueling systems, and can handle up to 30 buses/hour. LACMTA and GCRTA have both reported similar costs for CNG fuel station installations [13,14].

In addition, unlike diesel fuel vapors, natural gas is lighter than air. Therefore, natural gas that leaks from a bus can potentially accumulate at the ceiling level of a depot, creating an explosion hazard. In order to mitigate this hazard, significant modifications must be made to the maintenance and storage areas of any depot that will operate CNG buses.

These modifications include the removal of the ceiling-hung open-flame heaters typically used in depots, installation of additional ducts to increase fresh airflow, installation of emergency purge fans in the roof, and installation of a methane detection system. This work will have a large impact on NYCT, since the majority of our buses are stored inside.

Based on the work already performed at Jackie Gleason Depot and the new West Farms Depot, NYCT estimates that the incremental capital cost to outfit an entire depot with inside bus storage for CNG operations will be between $6 million and $50 million. The large range in costs is dependent on whether the project is a retrofit (more expensive) or new construction (less expensive), and whether the facility is a single-story building (less expensive), or a multiple story building (much more expensive). The current estimate for conversion of Manhattanville depot (an existing multi-story facility) to CNG operations is $50 million. For the purposes of this analysis, we will use a figure of $20 million to convert a “typical” 200-bus depot to CNG operations.

This is the one area of CNG bus operation in which the NYCT experience varies significantly from the experience of other transit agencies. LACMTA, GCRTA, and CMB have all reported that the cost to convert one of their depots to CNG operations is approximately $1 million [13-15]. The largest factor in the cost of NYC Transit’s CNG depot modifications has been the need to replace ceiling-hung open-flame heaters (typical in depots built in the last 50 years) with roof-mounted fresh-air fed heating units throughout the maintenance and in-door parking areas, including the installation of significant additional duct work. Some of the other factors that certainly influence the costs include: 1) the general cost of construction in NYC is 3-4 times higher than in other cities such as Cleveland, 2) the use of multi-level bus depots due to the lack of available outdoor space, particularly in Manhattan, 3) other agencies, especially in California, park a much greater percentage of their buses outdoors, which results in much smaller depot facilities, especially when depots are located in densely populated areas, and 4) some of the codes and standards related to safe operation of natural gas vehicles in buildings are not uniform across the country; NYCT has chosen to follow very strict guidelines with respect to CNG depot conversions in order to ensure the highest level of safety for our employees and neighbors.

Future Technologies Designed to Reduce Diesel and CNG NOx

As previously discussed, diesel buses sold since October 2002 include new technology (primarily exhaust gas re-circulation) in order to meet new EPA standards that mandate a 40% NOx reduction. This technology has added between $ 4,000 and $6,000 to the cost of a diesel bus, compared to one sold prior to October 2002. This incremental cost was not included in Figure 16, because it is now part of the baseline cost of diesel buses. The incremental cost of CNG buses in comparison to diesel buses was adjusted to account for this recent increase in diesel bus capital costs.

Also as previously discussed, additional technologies will be required for both diesel and CNG vehicles to meet even stricter NOx emission standards that will come into effect between 2007 and 2010. The cost of these technologies was not included in Figure 16 for two reasons: 1) no commercial systems are available, so it is not clear what the cost will be, and 2) it is highly likely that the same technologies will be required for both diesel and CNG engines, so the effect on the incremental cost analysis will be off-setting.

Total Capital Cost Comparison

The total capital costs discussed above for conversion of a typical 200-bus depot to clean fuel operations with either CNG or filter-equipped diesel buses are summarized below in Figure 16.

Cost Element	**CNG**		**DPF-equipped Diesel**	
	Per Bus	**Total**	**Per Bus**	**Total**
Incremental Bus Cost	$30,000	$6,000,000		
CNG Fuel Station	NA	$5,000,000		
Depot Modifications	NA	$20,000,000		
Catalyzed Filter (incl spares for cleaning float)			$5,900	$1,230,000
Diesel Fuel Station			NA	$495,000
TOTAL		$31,000,000		$1,725,000

Figure 16 Comparison of Capital Costs: CNG vs DPF-equipped Diesels for Typical 200-bus Depot

CLEAN DIESEL & CNG OPERATING COST COMPARISON

All of the operating costs noted in this section are based on the experience of NYC Transit in operating CNG buses since 1995, and in operating DPF-equipped diesel buses since 2001. Where possible, the experience of NYC Transit has been put into context by referencing the experiences of other large transit agencies in operating CNG buses, including the Los Angeles County Metropolitan Transportation Authority (LACMTA), the Greater Cleveland Regional Transit Authority (GCRTA), and Coast Mountain Bus Company of Vancouver, British Columbia (CMB). Data on the experiences of these agencies was taken from published documents from these agencies, which are referenced in Appendix D. NYC Transit is the only large transit agency in the U.S with significant experience operating DPF-equipped diesel buses.

Filter-Equipped Diesel Buses

As noted above, NYCT has operated its diesel fleet on ULSD for almost three years. The original contract for the fuel set the price $0.12 per gallon higher than the price of the standard diesel fuel we had been using. In July 2003, NYCT bid a new five-year fuel supply contract and the winning bid reduced the differential price by $0.02 per gallon, to $0.10 per gallon. NYCT's fleet-wide average diesel fuel economy between January 2002 and June 2003 was 2.6 miles/gallon. Therefore, in the future the use of ULSD will cost $0.04/mile more than the use of standard diesel, or $1,040/bus /year (with an average mileage of 26,000 miles/bus/year).

As noted above, the filters will also need to be cleaned annually to remove accumulated ash build-up. The cleaning service will cost approximately $190 per filter from a third party, including transportation and handling. In addition, removal and replacement of the filter will take on average 8 hours per bus at $60/hour. Altogether, annual cleaning will result in additional scheduled maintenance costs of $670/bus/year.

After three years of operation, DPFs have proven to be very reliable in the NYC Transit duty cycle. However, success requires that the diesel engine operate within normal parameters. Engine upset conditions that increase engine-out particulate emissions can overwhelm the ability of the filter to regenerate, resulting in filter "plugging". When this happens, the filter can usually be "reconditioned" using a heat treatment that oxidizes the accumulated carbon out of the filter. This reconditioning process will cost approximately $280 per filter for the reconditioning service, plus the cost to remove and replace the filter as above, for a total of $760 per event. We also expect that up to 25% of filters which become plugged may not be salvageable and will have to be replaced at an average cost of $4,000 per filter.

To date, NYC Transit has experienced a "plugging rate" of approximately 5% per year on non-EGR engines. EGR engines have exhibited a higher problem rate, based on premature failures of components used in this relatively new technology. While we expect that these pre-mature failures will be reduced as the technology matures, it is reasonable to expect a continued higher rate of failures on EGR engines than on non-EGR engines due to the greater complexity of the engine and engine controls. Over time, buses with EGR engines will comprise an increasing percentage of the diesel fleet. NYC Transit therefore projects an annual plugging rate of 7.5% for DPF-equipped buses in the long-term.

Given the above assumptions about plugging rates and reconditioning and filter replacement costs, the projected cost of plugging incidents will be on average $137 per year per DPF-equipped bus.

NYCT currently spends approximately $92,000 per year maintaining the existing diesel fueling infrastructure at each depot. This includes scheduled and unscheduled maintenance on the tanks, piping, and dispensers, as well as the cost of emergency spill containment kits and third party central monitoring of all overfill and leak detection alarms.

CNG Buses

NYCT's contract for the purchase of natural gas at Jackie Gleason depot in Brooklyn sets the price per therm at $0.6165 x (price per gallon for standard diesel fuel). Between January 2002 and June 2003, the actual average price that NYCT paid for natural gas at this depot was $0.57 per therm. During the same time period, the 221 CNG buses at Jackie Gleason used an average of 0.77 therms/mile in service, so that the average cost of fuel for CNG buses has been $0.44/mile. This includes the natural gas used to operate the compressors at the CNG fueling station, which in recent months has averaged approximately 4.8% of the total (0.04 therms/mile). During this time period, the fuel economy of our diesel buses averaged 2.6 miles per gallon, and the average price of standard diesel fuel was $0.85/gallon so that the average cost of standard diesel fuel was $0.33/mile. Therefore, the use of natural gas at Jackie Gleason depot has cost $0.11/mile more than the use of standard diesel fuel, or $2,860/bus/year (with an average mileage of 26,000 miles/bus/year).

When NYCT opened the CNG fuel station at the West Farms depot in the Bronx, the same pricing mechanism for CNG fuel as used in Brooklyn was not available (this area is served by a different natural gas utility). For this depot, the price of natural gas will be based on a standard tariff rate for natural gas used as a transportation fuel. This tariff uses a fixed price per therm for the cost of local distribution through the utility's system, plus a variable price per therm for the natural gas commodity, which is based on the utility's actual cost. Between May 2002 and March 2003, natural gas pricing under this tariff would have averaged $0.60/therm, comparable to that experienced at the Jackie Gleason depot.

NYCT's contract for installation of the CNG fuel station at Coliseum Depot includes third party maintenance of the station for a period of ten years. The cost of maintenance is based on the natural gas throughput at the station, and will vary between $900,000 and $1,000,000 per year given the expected natural gas usage for fueling 200 buses. The award of this contract was the result of a competitive process, and the contract was awarded to the low bidder. After awarding this contract, we subsequently negotiated a similar contract with the same company to cover maintenance of the fuel station at the Jackie Gleason depot. Over the last 18 months, the actual cost of this contract has averaged $72,000 per month, or $864,000 per year.

NYCT's experience over the past 8 years of operating CNG buses has shown that they are not as reliable as diesel buses, and that they require more maintenance, both scheduled and unscheduled. We project that total incremental maintenance costs are $0.20/mile compared to diesel buses, or $5,200/bus/year.

The above figures for increased operating costs of CNG buses are consistent with published reports of CNG bus operating costs at other large transit agencies, including LACMTA, GCRTA, and CMB. All of these agencies have reported significantly increased costs to operate CNG buses compared to diesel buses, including increased fuel costs, increased maintenance costs, and significant costs to maintain and operate CNG fuel stations. LACMTA, the largest operator of CNG buses in North America with 1,450 CNG buses, reports that CNG bus costs for fuel and maintenance average 15-20% greater than for diesel buses [13]. GCRTA reports that their CNG buses cost $0.26/mile more to operate than diesel buses [14]. Coast Mountain projects that CNG buses will cost at least 30% more to operate in the long term [15].

Future Fuel Costs

In the last several years the price of both diesel fuel and natural gas has become much more volatile than long-term historical experience. In the mid-to-late 1990's NYCT generally paid between $0.70 and $0.80 per gallon for standard diesel fuel (this price does not include federal and state road user taxes applied to diesel fuel purchased by private users, which can add up to $0.50 per gallon). In early 1999 the price began to drop, going as low as $0.40 per gallon. In late 1999 it spiked to over $1.50 per gallon briefly, and then dropped into the $1.00 per gallon range. As noted above, over the last 18 months NYCT's cost of standard diesel fuel has averaged $0.85/gallon, with price excursions as low as $0.70 per gallon and as high as $1.31 per gallon. Generally, diesel fuel prices peak in late fall to early winter as refiners stockpile heating fuel, and then drop in the summer. In the winter of 2002 - 2003, diesel fuel prices stayed generally high throughout the winter and peaked in March 2003, but have since dropped to average levels.

We expect this volatility to continue. Supply disruptions caused by refiners' efforts to reduce fuel sulfur levels in response to EPA mandates may increase short-term volatility as we approach 2006, and there will probably continue to be slight upward pressure on average pricing as well.

As shown in Figure 17, movements in natural gas prices historically tend to mirror movements in diesel and gasoline prices, at least in terms of direction and general scale. In fact, as shown in Figure 17, natural gas prices have become even more volatile than diesel fuel prices in the last few years, probably due to increasing deregulation of the market. The year 2000 saw natural gas prices double in most of the country. In California the increases were even greater. The price increases in 2000 were driven by two factors: 1) increased demand for natural gas to fuel electric generating plants, and 2) localized shortages in pipeline capacity to move the gas to end users. One of the areas of the country that has been most effected by shortages in pipeline capacity has been the Northeast.

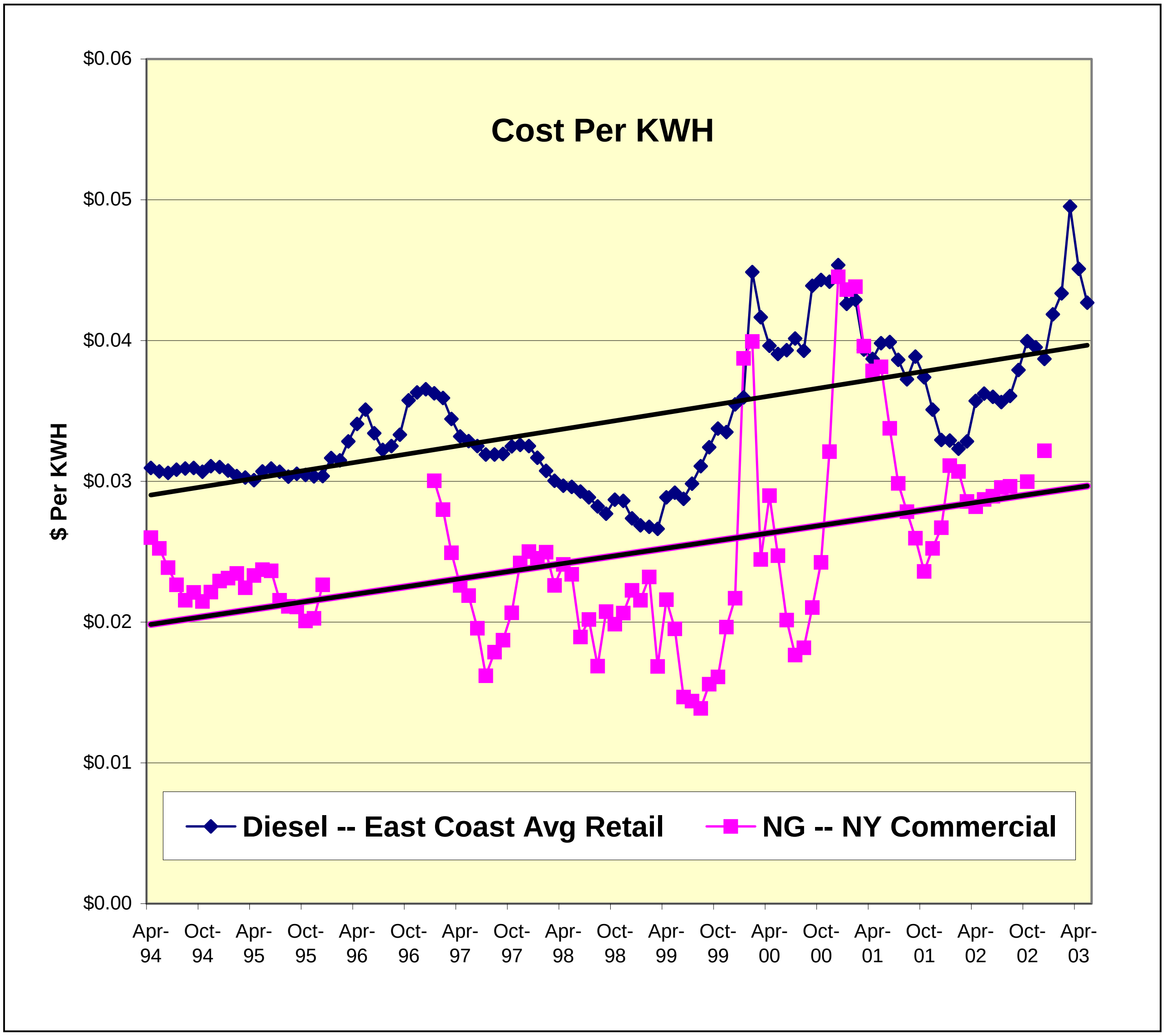


Figure 17 Historical Comparison of Diesel and Natural Gas Prices in New York (data from US Department of Energy, Energy Information Administration)

While the severe capacity problems experienced in 2000 eased somewhat in the following two years, natural gas prices have again doubled in the first half of 2003, compared to prices at the end of 2002. In fact, the price for natural gas used at the Jackie Gleason depot went from $0.77/therm in February 2003 to $1.23/therm in March 2003 (As noted above, the basic pricing mechanism indexes the price of natural gas to the price of diesel fuel, which did not rise as dramatically, however the contract also sets the floor price at the utility's cost to purchase the natural gas commodity. In effect NYCT's price for natural gas almost doubled in March 2003 even though the utility was in effect providing local distribution for free).

These price increases were caused by low stockpiles of natural gas following the unusually cold winter of 2002 - 2003 plus continuing high demand for natural gas for electricity generation [16]. There is no reason to believe that the basic situation will change in the future. As with diesel fuel, we expect continued volatility and upward pressure on natural gas pricing in the short and medium term.

In this situation, we expect the relationship between fuel costs for diesel and CNG buses that was outlined and summarized above to remain generally constant for the foreseeable future.

Total Cost Comparison

The total incremental operating costs discussed above for conversion of a typical 200-bus depot to clean fuel operations with either CNG or filter-equipped diesel buses are summarized below in Figure 18.

Cost Element	CNG		DPF-equipped Diesel	
	Per Bus	Total	Per Bus	Total
Incremental CNG Fuel	$2,860	$572,000		
CNG Fuel Station Maintenance	NA	$900,000		
Incremental Bus Maintenance	$5,200	$1,040,000		
Incremental ULSD			$1,040	$208,000
Diesel Fuel Station Maintenance			NA	$92,000
Filter Replacements/Reconditioning			$137	$27,400
Annual Filter Cleaning			$670	$134,000
TOTAL	$8,060	$2,512,000	$1,847	$461,400

Figure 18 Comparison of Incremental Annual Operating Costs: CNG vs DPF-equipped Diesels for Typical 200-bus Depot

CLEAN DIESEL & CNG TOTAL LIFE-CYCLE COST COMPARISON

The net present value of total incremental life cycle costs for conversion of a typical 200-bus depot to clean fuel operations with either CNG or filter-equipped diesel buses are summarized below in Figure 19.

The following assumptions were used for this life cycle cost analysis:

- The discount rate is 6%
- The incremental capital and operating costs for each technology are as described in detail in the preceding sections.
- The time frame for the analysis is 30 years, assuming that the capital investments for facility modifications and incremental bus purchase costs (as discussed above) are made in year 1 and the incremental operating costs discussed above are expended every year. As discussed below, since the facility investments have a longer life cycle than the bus investments, the incremental bus purchase costs are repeated during the 30-year time frame.
- Facility investments (ie for diesel fuel or CNG infrastructure) have an effective life of 30 years. These investments are only made once during the analysis time frame, in year 1.
- Transit buses have an effective life of 15 years, so that incremental purchase costs for CNG buses will have to be made in year 1 and year 15.
- Diesel particulate filters have an effective life of 7 ½ years, so that the purchase of DPFs will have to be made in year 1, year 8, year 15, and year 22.
- It is typical for transit agencies to invest in “overhauls” of transit buses throughout their life, including an overhaul or replacement of the engine some time between the 7th and 10th years of life. These investments were excluded from the analysis since they apply equally to CNG and diesel buses, and would generally be offsetting. This is a conservative assumption, since based on current experience the overhaul or replacement of a CNG engine would be expected to be more expensive that the overhaul or replacement of a diesel engine.

	CNG	**DPF-Equipped Diesel**
NPV of Incremental Capital Costs	$33,653,806	$3,448,862
NPV of Incremental Operating Costs	$36,651,891	$6,732,158
NPV of TOTAL INCREMENTAL COSTS	$70,305,697	$10,181,020
Annualized NPV of Total Incremental Costs	$2,343,523	$339,367

Figure 19 Comparison of Net Present Value of Total Incremental Costs: CNG vs DPF-equipped Diesels for Typical 200-bus Depot (30 years of operation; 6% discount rate)

As shown, over 30 years of operation (the life of the original facility investments required for CNG operation) the use of filter-equipped diesel buses at one 200-bus depot will cost $10.2 million in net present value terms more than the cost of operating today’s “baseline” diesel buses, or $339,000 more per year. Alternately, the use of CNG buses at the same depot would cost $70.3 million more in net present value terms, or $2.3 million more per year than the cost of operating today’s “baseline” diesel buses.

The cost of operating 200 CNG buses for 30 years would be $60.1 million more than the cost of operating 200 filter-equipped buses, or $2 million more per year.

As discussed in the previous section on capital costs, the only area where the experience of NYC Transit in operating CNG buses has differed significantly from the experience of other large transit agencies is in the cost of upgrading facilities to safely operate CNG vehicles. The above analysis includes a one-time investment of $20 million to upgrade a 200-bus depot, in line with actual NYC Transit experience. Other transit agencies have reported facility upgrade costs on the order of $1 million per depot. If this figure is included in the analysis instead of the higher NYC Transit number, the incremental cost of operating 200 CNG buses falls to $1.7 million more per year compared to baseline diesel buses, or $1.4 million more per year compared to filter-equipped diesel buses.

APPENDIX A

EXHAUST EMISSIONS: STANDARDS & MEASUREMENT

Exhaust Emissions Standards

All internal combustion engines produce gaseous and solid compounds that are released into the atmosphere through the exhaust system (tailpipe). These compounds include water (H_2O), carbon dioxide (CO_2), carbon monoxide (CO), various oxides of nitrogen (NOx), various hydrocarbon compounds (HC), and particulate matter, or "soot" (PM). Many of these compounds have been proven to be harmful to human health, either directly (as is the case with CO and PM) or indirectly, by contributing to the production of atmospheric pollution (for example, HC and NOx combine in the atmosphere to produce ground level ozone, or "smog", and CO_2 is the primary "greenhouse gas" that contributes to global warming).

In order to improve air quality nationwide, the U.S. Environmental Protection Agency (EPA) began to regulate vehicle exhaust emissions in the 1970's. Since 1988 the EPA has promulgated increasingly more stringent standards for maximum allowable emissions from heavy-duty diesel and CNG engines. There are four emissions components that are currently regulated: CO, HC, NOx, and PM. Diesel engines produce relatively little CO and HC – these exhaust components are more important in vehicles powered by gasoline engines, and to a lesser extent CNG engines. However, both diesel and CNG engines produce comparably larger amounts of PM and NOx, and these two components have been the focus of regulation for heavy-duty engines.

The EPA does not currently regulate CO_2 from vehicles. However, with the recent increased emphasis on the issue of global warming there is increased focus on CO_2 emission sources. It is expected that vehicle CO_2 emissions will be regulated in some form in the future. More likely in the short and medium term are voluntary incentives designed to reduce vehicle CO_2 emissions and increasing pressure for more aggressive action by environmental groups.

For the purposes of regulation, heavy-duty engine emissions are measured in units of grams per brake horsepower-hour (gm/bhp-hr). Brake horsepower-hours are a unit measure of work performed, so expressing emissions in this way allows easy comparison of engines of different sizes.

As shown in Figure 1 below, PM and NOx emissions standards have gotten steadily stricter over the last ten years. The diesel engine industry has responded with fundamental technology improvements that have allowed diesel engines to meet these standards. These changes have included the adoption of the "4-cycle" diesel engine to replace the standard "2-cycle" engine, the use of sophisticated electronic fuel controls, and the incorporation of catalytic exhaust after-treatment.

It is also important to note that for the last six years, the PM standards for urban transit buses have been stricter than the standards for other similar sized trucks and inter-city buses. Currently, diesel transit bus engines are allowed to produce only one half as much PM as the diesel engines used in these other large vehicles.

As shown in the table, the NOx standards were reduced by 40% in 2002. CNG engines sold prior to 2002 already met these stricter NOx standards, but diesel engines required additional technology. Most diesel engine manufacturers have elected to use exhaust gas re-circulation to meet the new standards, and virtually all manufacturers have already demonstrated, by virtue of certification testing submitted to the EPA, that the new NOx standards are met for new diesel engines currently being sold.

In 2001, the EPA finalized a rule that calls for a further 80% reduction in PM and a further 92% reduction in NOx emissions from all heavy-duty engines by 2010. New technologies will be required, for both diesel and CNG engines, to meet these standards. For diesels these technologies will include reduced sulfur diesel fuels, catalyzed particulate filters, and some form of NOx reduction device. CNG engines will also require a NOx reduction device, and may require filters as well.

APPENDIX A

Natural gas engines for buses are required to meet the same heavy-duty emissions standards set for diesel engines, except that only non-methane hydrocarbons are regulated. Methane is the major component of natural gas. While methane is a hydrocarbon (CH_4) it is relatively non-reactive, and does not contribute to ozone formation in the atmosphere. It is therefore "exempt" from current emissions regulations. Methane is, along with carbon dioxide (CO_2), a powerful "greenhouse gas" which contributes to global warming. Current CNG buses emit a fairly large amount of methane into the atmosphere, both through the exhaust and through leakage in the fuel delivery system. If CO_2 emissions are regulated in the future methane emissions may be as well.

	EPA Emissions Standards For Transit Buses (gm/bhp-hr)			
YEAR	**PM**	**NOx**	**HC[1]**	**CO**
1988	0.60	10.7	1.3	15.5
1990	0.60	6.0	1.3	15.5
1991	0.25	5.0	1.3	15.5
1993	0.10	5.0	1.3	15.5
1994	0.07	5.0	1.3	15.5
1996	0.05	5.0	1.3	15.5
1998	0.05	4.0	1.3	15.5
2004[2]	0.05	Option 1: 2.4 NOx + NMHC		15.5
		Option 2: 2.5 NOx + NMHC and 0.5 NMHC		
2007	0.01	0.2[3]	0.14 NMHC[3]	15.5
2010	0.01	0.2[3]	0.14 NMHC[3]	15.5

***Notes**:*

1. *Non-methane HC for natural gas engines: 1.2 gm/bhp-hr*
2. *Several engine manufacturers have signed a consent decree with the EPA agreeing to meet the 2004 requirements by October, 2002*
3. *NOx and NMHC standards would have to be met by 50% of engines sold during 2007 – 2009, and by 100% of engines sold beginning in 2010*

Appendix A Figure 1: EPA Emissions Standards for Transit Bus Engines

Exhaust Emissions Measurement

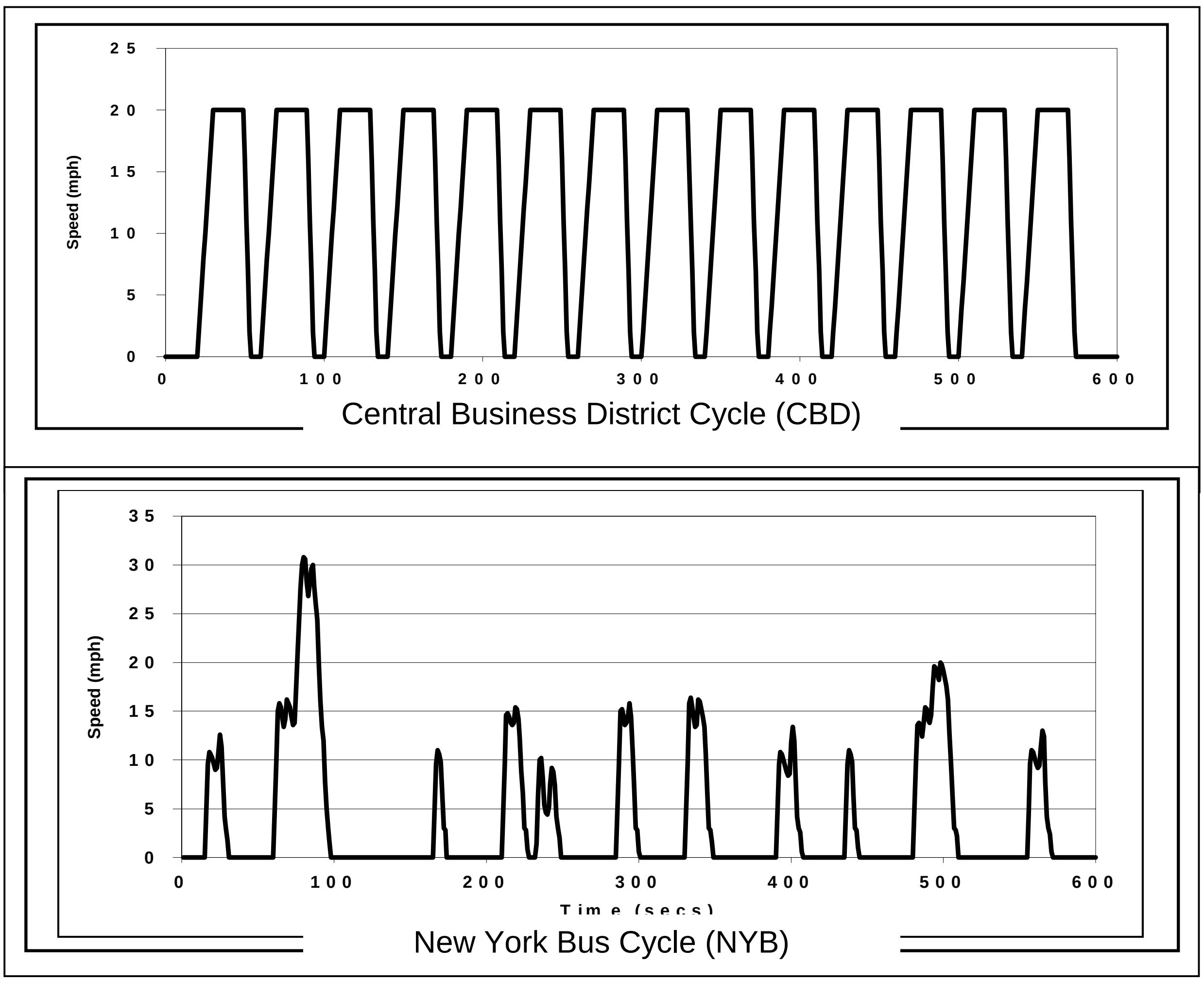
Before a manufacturer can sell diesel or CNG engines of a new design, they must certify that the design meets the applicable emission standards, by submitting test data to the EPA. For the purposes of regulation, diesel (and CNG) engine emissions are measured in grams per brake horsepower-hour (gm/bhp-hr). Brake horsepower-hours are a unit measure of work performed, so expressing emissions in this way allows easy comparison of engines of different sizes.

The testing is done using an engine dynamometer which simulates what would be required of the engine if it were installed in a typical vehicle. The testing is done using a standard test cycle called the Federal

Transient Procedure (FTP). The FTP was developed by the EPA to mimic the driving cycle that a “typical” diesel vehicle would see during its life. The cycle includes both “stop-and-go” urban driving and higher speed highway operation.

Exhaust emissions from heavy-duty vehicles can also be measured using a full-vehicle “chassis dynamometer”, and test cycles such as the Central Business District cycle (CBD) and/or the New York Bus Cycle (NYB). The CBD is an idealized cycle that is meant to simulate stop-and-go driving in an urban setting (accelerate to 20 mph, cruise at 20 mph, decelerate to a stop, idle, then repeat). The NYB cycle is a test cycle that is based on actual driving data collected on a bus route in New York City. The NYB cycle is not uniform like the CBD, it operates over a much wider range of bus speeds, and it includes a much higher percentage of idle time. Both of these cycles have been used for a number of years to collect further information on in-use transit bus emissions to supplement the certification engine testing. Various organizations have published test results for diesel and CNG buses using both the CBD and NYB cycles.

Chassis dynomometer results are not reported in gm/bhp-hr as are certification data; they are reported in grams/mile. It is impossible to directly compare gm/mile results to gm/bhp-hr results. However, results stated in one unit can be “converted” to the other unit. These conversions are based on various assumptions, and are approximations only.



Appendix A Figure 2 Emissions Test Cycles

APPENDIX A

It is important to recognize that while chassis testing is intended to provide information about "real world" emissions, no single test cycle can really describe all of the conditions that any bus or group of buses would experience during actual service. Based on comparisons of measured fuel economy on these test cycles and actual fuel economy experienced in service, NYCT believes that the CBD and NYB cycles "bracket" the actual emissions produced by our buses. Results on the CBD cycle probably understate actual emissions, and results on the NYB cycle overstate actual emissions. Both cycles are useful in comparing emissions from different engine technologies because either cycle can provide a true "apples-to-apples" comparison.

Future Regulatory Directions

As noted, PM emissions from heavy-duty engines are currently regulated on a mass basis (ie. only the mass of PM emitted per unit of work is measured). Recent work on the potential health effects of ambient PM in the environment indicates that other factors besides the total mass of emitted particles may be important. Emphasis is now being placed on the size and number of emitted particles, with smaller particles hypothesized to have a greater adverse impact on human health than larger particles. Some members of the health and environmental communities have begun pushing for regulatory schemes that limit not only the mass of PM emitted by vehicles, but also the total number of PM particles, especially in the smallest size ranges.

Proper evaluation of this issue has been hampered by a lack of information. Until recently, it has been virtually impossible to count individual particles during emissions testing, so there is very little real data available to compare the number and size of particles produced by different engine technologies (for example CNG as compared to diesel). In the last several years, instruments have been developed that can effectively collect this data and they are starting to be employed in emissions measurement projects. This report cites most of the available data on PM emission particle size for both CNG and diesel buses.

In addition to particle number/size, increased emphasis is also now being placed on the toxic hydrocarbon species that are present in diesel (and CNG) exhaust. Again, proper evaluation of this issue has been hampered by a lack of information. While there are available instruments that can collect and analyze data on exhaust toxicity, this testing is time consuming and expensive. In the last two years, a limited amount of information has been published on exhaust toxicity for both diesel and CNG buses. This report cites most of this available data.

Test Data Used for Comparison, Regulated Emissions

Results from CBD Test Cycle

Bus	Engine	Fuel	Emissions (gm/mi)					MPG	Notes
			PM	THC	NMHC	NOx	CO		
NYCT 6019	Diesel	STD	0.22	0.18	0.18	25.6	1.8	3.3	1
NYCT 6065	Diesel	STD	0.21	0.26	0.26	23.3	2.1	3.3	1
NYCT 6065	Diesel	STD	0.23	0.22	0.22	23.0	2.5	3.8	4
OCTA 5347	Diesel	STD	0.39	0.36	0.36	24.5	3.7	5.9	6
LACMTA 3005	Diesel	STD	0.65	0.20	0.20	40.1	10.0	3.3	8
LACMTA 3007	Diesel	STD	0.12	0.08	0.08	30.2	1.4	UNK	9
Average Baseline Diesel			*0.30*	*0.22*	*0.22*	*27.8*	*3.6*	*3.9*	
NYCT 6019	Diesel	ULSD	0.19	0.06	0.06	25.6	1.2	3.4	1
NYCT 6019	Diesel	ULSD	0.22	0.08	0.08	27.7	1.0	3.2	4
NYCT 6065	Diesel	ULSD	0.14	0.04	0.04	25.1	1.6	3.5	1
NYCT 6065	Diesel	ULSD	0.11	0.17	0.17	23.0	0.9	3.8	4
LACMTA 3005	Diesel	ULSD	0.37	0.24	0.24	37.8	6.9	3.7	8
Average Diesel Using ULSD			*0.21*	*0.12*	*0.12*	*27.8*	*2.3*	*3.5*	
NYCT 6019	Diesel W/ DPF	ULSD	0.04	0.03	0.03	26.4	0.2	3.1	1
NYCT 6019	Diesel W/ DPF	ULSD	0.03	0.04	0.04	25.3	0.2	3.3	4
NYCT 6065	Diesel W/ DPF	ULSD	0.01	BDL	BDL	23.8	0.1	3.7	1
NYCT 6065	Diesel W/ DPF	ULSD	0.01	0.06	0.06	20.5	0.1	3.9	4
LACMTA 3007	Diesel W/ DPF	ULSD	0.01	BDL	BDL	31.5	0.2	4.0	5
LACMTA 3005	Diesel W/ DPF	ULSD	0.01	0.01	0.01	29.1	1.7	3.6	8

APPENDIX B

Bus	Engine	Fuel	Emissions (gm/mi)					MPG	Notes
			PM	THC	NMHC	NOx	CO		
LACMTA 3005	Diesel W/ DPF	ULSD	0.01	0.02	0.02	35.2	1.7	3.8	8
LACMTA 3007	Diesel W/ DPF	ULSD	0.01	BDL	BDL	31.1	0.2	UNK	9
Average Diesel w/ DPF & ULSD			*0.02*	*0.02*	*0.02*	*27.9*	*0.6*	*3.6*	
NYCT	NG	CNG	0.02	20.6	3.2	14.9	12.7	3.1	2
NYDOT	NG	CNG	0.02	26.1	2.4	9.7	10.8	2.6	2
Mass PA	NG	CNG	0.02	15.2	0.6	25.0	0.6	3.1	2
LACMTA 5300	NG	CNG	0.03	8.9	UNK	14.3	8.7	4.7	5
OCTA 2201	NG	LNG	0.04	14.4	UNK	15.7	5.7	3.8	6
NYCT 824	NG	CNG	0.02	17.5	UNK	46.7	22.8	3.5	7
NYCT 854	NG	CNG	0.01	17.9	UNK	16.6	11.4	3.4	7
NYCT 975	NG	CNG	0.02	17.9	UNK	19.1	11.5	3.0	7
LACMTA 5300	NG	CNG	0.01	11.2	UNK	16.5	11.3	3.2	8
LACMTA 5301	NG	CNG	0.01	12.8	UNK	13.9	12.2	3.2	8
LACMTA 5300	NG	CNG	0.04	UNK	1.3	15.4	8.5	UNK	9
LACMTA 5300	NG	CNG	0.03	UNK	2.6	22.7	13.6	UNK	9
DDC CNG3	NG	CNG	0.03	8.7	1.0	15.6	8.0	UNK	10
Average CNG			*0.02*	*15.6*	*1.9*	*18.9*	*10.6*	*3.4*	
Cummins Westport	NG	CNG w/ DOC	0.02	14.1	0.4	13.9	0.2	UNK	10
DDC CNG-3	NG	CNG w/ DOC	0.02	6.2	0.3	13.3	4.1	UNK	10
Average CNG w/ DOC			*0.02*	*10.2*	*0.4*	*13.6*	*2.2*	*UNK*	

APPENDIX B

Test data Used for Comparison, Regulated Emissions

Results from NYB Test Cycle

Bus	Engine	Fuel	Emissions (gm/mi)					MPG	Notes
			PM	THC	NMHC	NOx	CO		
NYCT 6019	Diesel	STD	0.65	0.91	0.91	70.3	13.0	1.5	1
		Average Baseline Diesel	*0.65*	*0.91*	*0.91*	*70.3*	*13.0*	*1.5*	
NYCT 6019	Diesel W/ DPF	ULSD	0.04	0.06	0.06	70.3	0.2	1.4	1
NYCT 6019	Diesel W/ DPF	ULSD	0.05	0.16	0.16	68.6	0.9	1.4	4
NYCT 6065	Diesel W/ DPF	ULSD	0.06	0.26	0.26	60.0	0.5	1.6	4
		Average Diesel w/ DPF & ULSD	*0.05*	*0.16*	*0.16*	*66.3*	*0.5*	*1.5*	
NYCT	NG	CNG	BDL	79.5	4.4	26.2	37.2	1.3	2
NYDOT	NG	CNG	0.11	73.3	6.6	15.3	31.7	1.1	2
Mass PA	NG	CNG	0.14	70.2	4.8	113.2	29.0	1.2	2
NYCT 824	NG	CNG	0.07	78.1	UNK	73.3	68.9	1.4	7
NYCT 854	NG	CNG	0.04	63.3	UNK	24.2	40.2	1.3	7
NYCT975	NG	CNG	0.06	33.7	UNK	30.9	33.4	1.3	7
		Average CNG	*0.07*	*66.4*	*5.3*	*47.2*	*40.1*	*1.3*	

APPENDIX B

NOTES (for both CBD and NYB regulated emissions test data):

1. Testing done under NYCT's Clean Diesel Vehicle Air Quality Project, by Environment Canada Environmental Technology Center, Ottawa, Ontario. Reported in SAE 2002-01-0430, pre-durability tests. Also reported in SAE 2001-01-0511.
2. Testing done under Hybrid-Electric Drive Heavy-Duty Vehicle Testing Project, by West Virginia University and M.J. Bradley Associates, published in "Final Test Report" by Northeast Advanced Vehicle Consortium.
4. Testing done under Clean Diesel Vehicle Air Quality Project, by Environment Canada Environmental Technology Center, Ottawa, Ontario. Reported in SAE 2002-01-0430, post-durability tests.
5. Testing done by the California Air Resources Board, Heavy-Duty Emissions Laboratory, Los Angeles, CA. Data reported in CARB Report No. 01-01
6. Testing done by West Virginia University, for Orange County Transit Authority, CA. Reported in "A Comparison of Emissions from Hybrid Electric & Conventional Drive Transit Buses", July 2002
7. Testing done by Environment Canada Environmental Technology Center, Ottawa, Ontario, as an extension of NYCT's Clean Diesel Vehicle Air Quality Project. Results reported in SAE 2003-01-0300
8. Testing done under California EC-Diesel technology validation program, by West Virginia University. Results reported in SAE 2002-01-0433
9. Testing done by California Air Resources Board. Results reported in "ARB's Study of Emissions from Late model Diesel and CNG Heavy-duty Transit Buses", 5th International Conference on Nanoparticle Measurements
10. Testing done by California Air Resources Board. Results reported in SAE 2003-01-1900

BDL = Below detection limit of emissions analysis equipment

UNK = data was not reported

Test data Used for Comparison, Unregulated Emissions

Results from CBD Cycle, New York Test Program

Bus	Engine	Fuel	Benzene (mg/mi)	Carbonyl (gm/mi)	PAH (ug/mi)	NO2PAH (ug/mi)	Note
NYCT 6019	Diesel	STD	UNK	0.073	62	UNK	2
NYCT 6065	Diesel	STD	1.4	0.077	66	UNK	2
NYCT 6065	Diesel	STD	1.0	0.054	69	UNK	2
Average Baseline Diesel			*1.2*	*0.068*	*66*	*UNK*	
NYCT 6019	Diesel	ULSD	1.1	0.058	63	1.55	1
NYCT 6065	Diesel	ULSD	1.4	0.065	69	1.72	1
Avg Diesel Using ULSD			*1.3*	*0.062*	*66*	*1.64*	
NYCT 6019	Diesel w/ CRT	ULSD	0.6	BDL	17.3	0.67	1
NYCT 6065	Diesel w/ CRT	ULSD	0.6	0.000001	16.1	0.62	1
Avg Diesel w/ DPF & ULSD			*0.6*	*0.000001*	*16.7*	*0.65*	
NYCT 824	NG	CNG	4.5	1.09	57	0.91	1
NYCT 854	NG	CNG	4.8	1.15	54	0.27	1
NYCT 975	NG	CNG	BDL	1.24	102	UNK	1
Average CNG			*3.1*	*1.16*	*71*	*0.59*	

NOTES:

1. Testing done by Environment Canada Environmental Technology Center, Ottawa, Ontario, as an extension of NYCT's Clean Diesel Vehicle Air Quality Project. Results reported in SAE 2003-01-0300
2. Testing done under NYCT's Clean Diesel Vehicle Air Quality Project, by Environment Canada Environmental Technology Center, Ottawa, Ontario. Reported in SAE 2002-01-0430

BDL = below detection limits

UNK = data not collected or reported

APPENDIX B

Test data Used for Comparison, Unregulated Emissions

Results from CBD Cycle, California Test Program

Bus	Engine	Fuel	Benzene (mg/mi)	Carbonyl (gm/mi)	PAH (gm/mi)	NO2PAH (ug/mi)	Note
CARB	Diesel	STD	3.6	0.038	0.012	76.7	1
ECD-1	Diesel	ULSD	1.4	0.023	0.014	71.1	1
ECD+ CRT	Diesel w/ CRT	ULSD	0.2	0.0003	0.0016	15.0	1
ECD1+ CRT	Diesel w/ CRT	ULSD	0.2	0.0004	0.0002	18.9	1
Avg Diesel w/ DPF & ULSD			*0.2*	*0.0004*	*0.0009*	*17.0*	
CNG1	NG	CNG	2.7	0.607	0.0027	24.5	1
CNG2	NG	CNG	1.7	0.675	0.0014	33.8	1
Average CNG			*2.2*	*0.641*	*0.0021*	*29.2*	

NOTES:

1. Testing done under California EC-Diesel technology validation program, by West Virginia University. Results reported in SAE 2002-01-2873. Results for benzene reported in SAE 2002-01-0432

BDL = below detection limits

UNK = data not collected or reported

APPENDIX B

Test data Used for Comparison, Unregulated Emissions

Results from NYB Cycle, New York Test Program

Bus	Engine	Fuel	Benzene (mg/mi)	Carbonyl (gm/mi)	PAH (ug/mi)	NO2PAH (ug/mi)	Note
NYCT 6019	Diesel	STD	4.8	0.287	201	12.3	1
NYCT 6019	Diesel w/ CRT	ULSD	1.2	BDL	42	0.65	1
NYCT 824	NG	CNG	26.2	2.61	210	2.88	1
NYCT 854	NG	CNG	16.8	3.14	146	1.18	1
NYCT 975	NG	CNG	BDL	2.68	291	UNK	1
Average CNG			*14.3*	*2.81*	*216*	*2.03*	

NOTES:

1. Testing done by Environment Canada Environmental Technology Center, Ottawa, Ontario, as an extension of NYCT's Clean Diesel Vehicle Air Quality Project. Results reported in SAE 2003-01-0300

BDL = below detection limits

UNK = data not collected or reported

APPENDIX C

Discussion of Outlier CNG Test Results

During testing done as an extension of NYC Transit's Clean Diesel Vehicle Air Quality Project [7], one of NYC Transit's CNG buses (Number 824) exhibited significant "back-firing" during testing on the dynamometer. The emissions results from this bus showed normal levels of PM, THC, and NMHC, but high levels of CO and very high levels of NOx on both the CBD and NYB cycles. In fact, the NOx emissions from this bus were twice the CNG average, and were in fact higher than the highest diesel bus. NYCT Bus 824 had been previously tested under a different program at which time it did not exhibit back-firing and the NOx result was significantly lower than the average for all CNG buses.

While clearly an outlier, the authors decided to include the results from the second test of NYCT Bus 824 in the CNG data set because it was judged to be representative of sub-optimal, but none-the-less "real world" behavior for CNG buses in service. This assessment was based on a demonstrated history of CNG bus backfiring during revenue service at NYC Transit, as discussed below.

CNG BUS BACKFIRING

All buses tested under the Clean Diesel Vehicle Air Quality Project, both CNG and Diesel and including bus 824, were in service just prior to testing, and were checked by qualified technicians to assure proper operation prior to shipping the vehicles to the test facility. Furthermore, upon return to NYCT the vehicles were immediately put back into service without additional maintenance. We are therefore confident that none of the buses, including bus 824, had engine problems at the time of testing that would significantly affect in-service bus performance, or would be representative of "poor" maintenance practice.

Many of NYCT's buses in the fleet from which the CNG test buses were drawn had previously experienced "backfiring" to some degree. This behavior did not significantly affect their performance, could not be traced to a verifiable defect or mis-adjustment, and was generally accepted by bus operators as normal for these buses.

At the time of testing, buses 975 and 854 had been retrofit with new components as part of an upgrade campaign described below, which was apparently at least partially successful in reducing "backfiring." Bus 824 had not been retrofit. When interpreting the results of this testing, the results from bus 824 should therefore be seen as typical of buses in service prior to the product upgrade and the results from buses 975 and 854 as typical of buses in service after the upgrade. As such, the entire data set is representative of the range of results expected from buses in "real world" service.

A brief discussion of the operation of the CNG fuel system is necessary to better understand the backfiring phenomenon.

In the CNG fuel system, fuel is stored under high pressure (~3600 PSIA) in fuel cylinders. Between these cylinders and the engine, the fuel is filtered and then passes through a shut off valve, first stage regulator, heat exchanger and a second coalescing filter. The fuel then passes through a second shut off valve controlled by the engine's electronic fuel management system (DDEC) before arriving at the engine. On the engine are a fuel pressure sensor, Impco regulator, Pulse width modulated Stepper motor Valve (PSV) and a venturi gas mixer.

The most likely cause of the "backfiring" described herein is an over-fueling event resulting in post-combustion ignition of excess fuel downstream of the combustion chamber. This over fueling event is most likely caused by fuel governing components that are not working in an optimal way. The components likely to contribute to these observed phenomena are the control solenoid, low-pressure regulator, engine control module and related sensors, Impco fuel regulator, PSV, and fuel mixing assembly.

APPENDIX C

After numerous reports of poor performance from the field, including incidents of backfiring, Detroit Diesel developed upgraded fuel system components, which were installed on previously fielded engines as a retrofit campaign. DDC refers to this campaign as the Series 50G/60G Natural Gas Product Update. The campaign included replacing the PSV with a new assembly that included mechanical improvements and was more resistant to moisture and high temperatures. They also added a factory calibration check to their production process for this component. The low-pressure fuel control solenoid was redesigned to include pilot operation to overcome sticking and a viton diaphragm to better withstand compressor oils. An improved coalescing filtration system was designed to eliminate oil bypass. The low-pressure regulator was redesigned to eliminate pulsation, which often lead to a rich running condition, and to include increased internal flow area that eliminated fuel starvation in some situations. Other improvements included new engine software to better control the fuel regulator and waste gate turbo-charger, an oxygen sensor with improved durability and less drift, and an improved turbo charger.

At the time of testing, NYCT's CNG bus fleet was undergoing the upgrade campaign mentioned above. Anecdotal evidence after completion of the campaign on the entire fleet indicates that the product update did virtually eliminate the previously experienced "backfiring" condition during on-road driving. In addition, the fuel economy of the CNG fleet improved by approximately 5% after completion of the campaign (average usage of natural gas went from 0.81 therms/mile to 0.77 therms/mile).

Two of the buses tested (975 and 854) had been retrofit with the new components prior to the testing, while bus 824 had not been retrofit. During testing, bus 824 experienced severe backfiring on both CBD and NYB cycles. Buses 975 and 854 did not experience backfiring on the CBD cycle, but did experience mild backfiring on the NYB cycle. However, even during these backfiring events during testing for buses 975 and 854, the observed PM spike was significantly smaller than that observed for bus 824, and neither of these buses exhibited high NOx levels.

When interpreting the results of this testing, the results from bus 824 should be seen as typical of buses in service prior to the product upgrade and the results from buses 975 and 854 as typical of buses in service after the upgrade. As such, the entire data set is representative of the range of results expected from buses in "real world" service.

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