Environmental Benefits of Alternative Fuels and Advanced Technology in Transit

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13. ABSTRACT (Maximum 200 words)

This report evaluates potential reductions in pollutant emissions and fuel consumption that could be achieved through greater adoption of alternative fuels including CNG, LNG and biodiesel, and advanced vehicle technologies such as hybrid electric drive systems in the national transit bus fleet. According with the analysis results, ongoing and planned procurements by transit agencies of new technology diesel, alternative fuel and hybrid-electric buses will result in reductions in emissions of CO, NMHC, NO_x and PM with modest increases in CO_2 emissions and fuel consumption over the next 3 years.

Increased adoption above and beyond that occurring through the transit agencies own initiatives can further capitalize emissions and fuel economy benefits of new technologies. Hypothetical scenarios in which new "clean-diesel" (post-2007 model year), CNG, diesel-electric hybrid, gasoline electric hybrid and biodiesel fuel use were each individually increased to 15% of the U.S. fleet were considered. Potential changes in annual emissions and fuel consumption are presented. Benefits from the different technologies are discussed. Diesel-electric hybrid buses appear to offer the best overall environmental benefits and is the only technology to result in a reduction in fossil fuel consumption. The relative emissions and efficiency impacts benefits of the various technologies are presented for comparison.

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FOREWORD

This report was prepared as part of an alternative fuels study required by Section 3016(C) of the Safe, Accountable, Flexible, and Efficient Transportation Act: A Legacy for Users (SAFETEA-LU). That section directed the Secretary of Transportation to conduct a study of the actions necessary to increase the use of alternative fuels in public transportation vehicles. The study considered potential environmental and other benefits expected from increased use of alternative fuels as well as incentives and opportunities to encourage greater implementation of alternative fuels and technologies within the transit industry. The product of that earlier study was the *Alternative Fuels Study: A Report to Congress on Policy Options for Increasing the Use of Alternative Fuels in Transit Vehicles,* published December 2006 [1].

This analysis, *Environmental Benefits of Alternative Fuels and Advanced Technology in Transit,* summarizes the findings of work done to estimate the level of pollutant emissions produced by the current national transit bus fleet and to evaluate the potential reductions that could be achieved by greater adoption of alternative fuels including CNG, LNG and biodiesel, and advanced vehicle technologies such as hybrid electric drive systems. The report estimates the total annual emissions from the U.S. transit bus fleet as it existed in 2003, the emission impact of planned bus procurements, and considers hypothetical scenarios in which “clean-diesel”, CNG, diesel/electric hybrid, gasoline/electric hybrid, and biodiesel use are individually increased to 15% of the total fleet.

This report is of interest to transit property managers, transit vehicle manufactures, and federal state and local environmental regulatory agencies and policy makers.

DISCLAIMER

EXECUTIVE SUMMARY

In light of increasing pressure to reduce emissions of harmful pollutants and greenhouse gases as well as improve fuel efficiency of heavy duty on-road vehicles the U.S. Congress directed the Federal Transit Administration (FTA) to conduct a study and develop a report on the potential environmental and other impacts of increasing the utilization of alternative fuels in public transit. In response to this directive, the FTA directed West Virginia University to evaluate the effects of increased use of alternative fuels and hybrid electric technology on the tailpipe emissions and fuel consumption of the U.S. transit bus fleet.

Cumulative tailpipe emissions from the existing transit bus fleet were estimated by considering the emissions from conventional diesel buses, compressed natural gas buses, liquefied natural gas buses and diesel-electric hybrid buses using 2003 fleet statistics data reported by the American Public Transportation Association (APTA) and measured transit bus emissions data from transit buses tested by West Virginia University and other organizations. Diesel, natural gas and diesel-electric hybrid buses comprised nearly 99% of the vehicle miles traveled by transit buses in the United States [5] in 2003. Other types of buses did not exist in significant numbers to significantly impact the national transit bus emissions total. Buses powered by electric catenary were not considered in this analysis because they produce no tailpipe emissions. Although it is acknowledged that emissions are produced by the electric power plant supplying the electricity, consideration of power plant emissions was beyond the current scope of this analysis. Considering the demographics of the 2003 transit bus fleet, the total estimated emissions are listed in Table E. 1.

Table E. 1: Estimated total emissions from the existing national transit bus fleet in 2003

	Number of Buses	**CO** tons[1]	**NMHC** tons	**CH_4** tons	**NO_x** tons	**PM** tons	**CO_2** tons	**Fuel Consumed** Thousands of Gallons [2]
Total Emissions								
Diesel	49,938	15,886	2,611		65,669	1,494	6,497,649	589,135
CNG/LNG	7,609	1,194	308	5,879	6,318	7	796,630	100,393
Diesel Hybrid	489	5	0.6		220	0.5	35,865	3,364
Total	**58,036**	**17,085**	**2,920**	**5,879**	**72,207**	**1,502**	**7,330,143**	**692,892**

Many transit agencies have already made substantial commitments to environmentally friendly fuels and vehicle technologies. Information about bus procurements that were in progress or planned at the time this report was written in the summer of 2006 was available through APTA. Table E. 2 shows the expected changes in tons of emissions emitted annually given the anticipated new bus procurements over the next three years.

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[1] Total emissions are reported in short tons throughout this report.

[2] Natural gas fuel consumption is reported in terms of energy equivalent diesel gallons.

Table E. 2: Expected changes in annual transit bus emissions in 2009 based on current procurement trends and estimated growth in vehicle miles traveled

Number of Buses	**CO** tons	**NMHC** tons	**CH_4** tons	**NO_x** tons	**PM** tons	**CO_2** tons	**Fuel Consumed** Thousands of Gallons
Relative Change Compared to 2003 Fleet							
↑ 3,556	↓ 6,165	↓ 887	↑ 1,022	↓ 10,508	↓ 649	↑ 70,738	↑ 16,723

The predictions show reductions in emissions of CO, NMHC, NO_x and PM with modest increases in CO_2 emissions and fuel consumption. The increase in CO_2 emission and fuel consumed may be attributed to the anticipated growth in the number of buses partially offset by the increase in the number of fuel efficient hybrid-electric transit buses. Methane emissions, which are not regulated by the EPA but are considered a greenhouse gas, will increase due to the greater number of natural gas buses.

Incentives that accelerate the adoption of alternative fuels and new technologies could further improve air quality in metropolitan areas and reduce the emissions of transit buses nationally. In order to assess the potential environmental impact of greater use of alternative fuels and hybrid-electric buses, hypothetical scenarios in which new “clean-diesel” (post-2007 model year), CNG, diesel-electric hybrid, gasoline electric hybrid and biodiesel fuel use were each individually increased to 15% of the U.S. fleet. Table E. 3 shows the changes in annual emissions and fuel consumption in addition to those shown in Table E. 2 that could be achieved.

Table E. 3 Impact of increasing alternative fuels and technologies to 15% of the transit bus fleet

	CO tons	**NMHC** tons	**CH_4** tons	**NO_x** tons	**PM** tons	**CO_2** tons	**Fuel Consumed** Thousands of Gallons
Incremental Change Relative to Anticipated 2009 Fleet Levels							
Clean Diesel	↓ 1,723	↓ **377**	-	↓ 3,291	↓ 201	↑ 35,251	↑ 2,664
CNG	↓ 689	↓ 341	↑ 422	↓ 4,239	↓ **205**	↓ 220,758	↑ 2,154
Diesel Hybrid	↓ **1,776**	↓ 366	-	↓ 4,418	↓ 202	↓ **491,352**	↓ **50,658**
Gasoline Hybrid	↑ 6,178	↓ 211	-	↓ **5,963**	↓ 199	↓ 74,114	↑ 2,833
Biodiesel (B20) (a)	↓ 384	↓ 166	-	↑ 369	↓ 38	↑ 25,087	↑ 3,876

(a) Implemented in the older diesel buses of the fleet

New technology conventional diesel and diesel-electric hybrid buses offer similar reductions in CO, NMHC, NO_x and PM emissions because both benefit from the most recent clean-diesel technology engines. Increased implementation of CNG buses offer similar reductions in NMHC, NO_x and PM compared to diesel and diesel-electric hybrids. CNG buses appear superior to conventional clean-diesel buses in terms of CO_2 emissions. Gasoline-electric hybrid buses also offer similar reductions in NMHC, and PM to conventional diesel, diesel-electric hybrid and CNG and are superior to all technologies in terms of NO_x reductions. Diesel-electric hybrid buses appear to offer the best overall environmental benefits and is the only technology to result in a reduction in fossil fuel consumption.

1.0 INTRODUCTION

1.1 Background

This report, *Environmental Benefits of Alternative Fuels and Advanced Technology in Transit* estimates the environmental effects that could be brought about through increased use of alternative fuels and advanced powertrain technologies in the U.S. transit bus industry. The analysis was undertaken as part of an Alternative Fuels Study required under Section 3016(C) of the Safe, Accountable, Flexible, and Efficient Transportation Act: A Legacy for Users (SAFETEA-LU). The product of that earlier study was the *Alternative Fuels Study: A Report to Congress on Policy Options for Increasing the Use of Alternative Fuels in Transit Vehicles* [1], published December 2006 and available on the FTA website [http://www.fta.dot.gov].

1.2 Objectives

This report addresses the environmental impacts that could be realized through increased use of alternative fuels and advanced powertrain technologies in the national transit bus fleet. The objectives of this report are as follows:

1. Predict the emissions of the existing (2003) U.S. transit bus fleet using statistical fleet data reported by the American Public Transportation Association (APTA) and measured transit bus emissions data from transit buses tested by West Virginia University and other organizations.
2. Predict the emissions reductions that will be achieved through the completion of alternative fuel and advanced technology bus procurements that are already underway or that are planned by major U.S. transit agencies through 2009.
3. Predict the emissions reductions that could be achieved if a percentage of the existing diesel bus fleet were replaced with alternative fuels and/or advanced technologies including:
    - Clean-diesel technology with ultra-low sulfur diesel fuel (i.e. 2007 technology)
    - Stoichiometric compressed natural gas technology (CNG)
    - Diesel-electric hybrid drive systems
    - Gasoline-electric hybrid drive systems
    - Biodiesel fuel B20 (80% diesel, 20% biodiesel blend)

Emissions from the 2003 national bus fleet were determined and compared with estimated 2009 emissions; where the 2009 bus fleet was anticipated from APTA procurements [5, 6]. Then the impact of greater use of alternative fuels and technologies was evaluated, considering 15% penetration of clean-diesel, stoichiometric CNG, diesel-electric hybrid, gasoline-electric hybrid and biodiesel into the 2009 bus fleet.

1.3 Organization of the Report

The body of the report is organized as follows:

- Section 2.0: Emissions of the Current National Bus Fleet – The total emissions produced nationally by the existing transit bus fleet were estimated using fleet data published by APTA and existing emissions test data.
  - Section 2.1: Methodology – The methodology for estimating the emissions based on the existing body of emissions test data is explained.
  - Section 2.2: Fleet Composition – The make-up of the 2003 U.S. transit bus fleet is presented and organized based on fuel, engine/vehicle technology and model year.
  - Section 2.3: Diesel Bus Emissions – Emissions from the diesel-powered buses in the current fleet are estimated.
  - Section 2.4: Validation – The computational methodology is validated against fuel consumption data compiled by APTA and compared to the EPA National Emissions Inventory computed using the EPA's Mobile 6.2 emissions inventory model.
  - Section 2.5: Emissions from CNG/LNG – The emissions contribution of existing CNG and LNG buses is estimated.
  - Section 2.6: Diesel Hybrid Buses – The emissions contribution of existing diesel-hybrid buses is estimated.
  - Section 2.7: Current Fleet Totals – The total emissions from the national bus fleet are computed in tons/year.
- Section 3.0: Emissions Impacts of Ongoing Procurements – This section considers bus procurements that were ongoing or planned at the time the study was conducted based on data from APTA. The analysis estimates the emissions that will be produced by the national bus fleet in 2009. The methodology and order of presentation follow that of Section 2.0.
- Section 4.0: Greater Use of Alternative Fuels and Technology – This section considers five hypothetical procurement strategies that increase the adoption of clean-diesel, stoichiometric CNG, diesel-electric hybrid, gasoline-electric hybrid and biodiesel to 15% of the national fleet. Emissions from each scenario are estimated and compared with the predicted emissions computed in Section 3.0.
- Section 5.0: Conclusions – The findings of the study are summarized briefly with some closing remarks.
- Section 6.0: Recommendations – Some recommendations for further study are discussed.
- Appendix A: Global Warming Potential Estimates - Contributions to global warming are estimated in terms of Global Warming Potentials (GWPs).

- Appendix B: Conversion of All Diesel Buses to Biodiesel – Considers the hypothetical case of using biodiesel in all diesel buses of the 2009 bus fleet.

2.0 EXHAUST EMISSIONS FROM THE CURRENT U.S. TRANSIT BUS FLEET

The first step in this analysis was to establish the contribution of the existing national bus fleet to the national atmospheric pollution inventory. The emissions of interest for transit buses are carbon monoxide (CO), nitrogen oxides (NO_x), non-methane hydrocarbons (NMHC), methane (CH_4), total particulate matter (PM) and carbon dioxide (CO_2). Potential reductions in fuel consumption are also of interest particularly reduction of the U.S. dependence on imported petroleum through the introduction and extension of alternative and sustainable fuels.

2.1 Methodology

Emissions data are typically acquired from buses using a chassis dynamometer, on which the bus is driven through a speed-time trace (representative of the bus operation) known as a cycle. Exhaust emissions are measured while the bus is driven through the cycle and are reported as mass of pollutant emitted per distance traveled usually in units of g/mile. In theory, the total mass of emission constituents released into the atmosphere by diesel transit buses could be calculated by multiplying the distance-specific emission by the total vehicle miles traveled (VMT) by the diesel transit bus fleet.

A difficulty arises because the same cycle has not been used for all bus testing. Early bus testing was conducted using the Central Business District (CBD) cycle of SAE J1376 [2], although the CBD has some undesirable characteristics. Other cycles used have been the Heavy-Duty Urban Dynamometer Driving Schedule (UDDS) of the Code of Federal Regulations Title 40 [3], the Orange County Transit Authority (OCTA) cycle of SAE J2711 [4], and the Washington Metropolitan Area Transit Authority (WMATA) cycle. Other cycles such as the New York Bus Cycle or the Manhattan Cycle of SAE J2711 have been used, but represent slower bus operation than is the norm nationally.

National fuel economy data and bus age distributions were available from the 2005 American APTA Transit Vehicle Database [6]. These data indicate that diesel buses dominated the fleet and that the average fuel economy of diesel buses was 3.47 miles per gallon. Most of the buses in the fleet could be expected to have similar fuel economy, although early buses with two stroke engines and as few as three gears may have poorer economy and newer buses employing exhaust gas recirculation (EGR) and other emission controls may have poorer economy as well. Buses in the model year range from 1994 to 2002, which represent the greatest population of diesel buses would be expected to achieve a fuel economy of around 4.0 mpg. A survey of data from emissions testing suggested that the OCTA cycle yielded fuel economy that was sufficiently close to the fuel economy of the largest percentage of active buses.

The OCTA cycle was therefore chosen as the key cycle for this evaluation. It was assumed that mass emissions from buses would scale reasonably with the quantity of fuel consumed; while this may not be true when extremes in vehicle behavior are compared, the assumption is defensible for translation of CBD, WMATA, and UDDS data to OCTA data.

Emissions and fuel economy data, shown in Table 1, were available from a 2000 model year (MY) diesel bus – equipped with DOC – tested on a wide variety of cycles. Emissions values and fuel economy of this bus are inline with other buses from the same MY and emissions controls. These data were used to develop the cycle translation factors, defined by equation 1 as:

$$Conversion\ Factor = C.F. = \frac{Fuel\ Economy_{k}}{Fuel\ Economy_{OCTA}} \tag{1}$$

where *k* represents the given cycle. OCTA equivalent emissions and fuel economy are determined by equation 2:

$$\begin{gathered} OCTA\ equivalent\ \ Emissions = Emissions_{k} \cdot C.F. \\ OCTA\ equivalent\ Fuel\ Economy = \frac{Fuel\ Economy_{k}}{C.F} \end{gathered} \tag{2}$$

Table 1: Emissions results from 2000 MY diesel transit bus on multiple driving cycles

Cycle	CO g/mile	NO_x g/mile	HC g/mile	PM g/mile	CO_2 g/mile	Fuel Economy mile/gal
OCTA	3.20	20.00	0.10	0.23	2,405	4.01
CBD	3.28	18.80	0.18	0.20	2,265	4.25
WMATA	3.87	26.90	0.19	0.22	2,820	3.42
UDDS	2.29	18.40	0.10	0.28	2,053	4.69
BEELINE	2.60	20.70	0.12	0.23	2,456	3.92
NYBUS	20.10	53.00	0.32	1.36	6,197	1.55

Table 2 shows the OCTA-equivalent emissions data (in units of g/mile) and the conversion factors. Fuel economy results are divided by the conversion factor to get fuel economy equivalence. Examination of translated emissions data on the same 2000 MY bus verifies that the translation is reasonable and represents the best available approach.

Table 2: OCTA equivalent emissions from the 2000 MY diesel transit bus

Cycle	Conversion Factor	CO g/mile	NO_x g/mile	HC g/mile	PM g/mile	CO_2 g/mile	Fuel Economy mile/gal
OCTA	1.000	3.20	20.00	0.10	0.23	2,405	4.01
CBD	1.060	3.48	19.93	0.19	0.21	2,401	4.01
WMATA	0.853	3.30	22.94	0.16	0.19	2,405	4.01
UDDS	1.170	2.68	21.52	0.12	0.33	2,401	4.01
BEELINE	0.978	2.54	20.24	0.12	0.23	2,401	4.01
NYBUS	0.387	7.77	20.49	0.12	0.53	2,395	4.01

As seen from the data in Table 2, translated CO_2 emissions correlated extremely well with the measured value for the OCTA Cycle. This is to be expected as CO_2 emissions are representative of the amount of fuel consumed. The translation also worked well for NO_x emissions; NO_x emissions typically vary in sympathy with CO_2 emissions and generally correlate with fuel consumed. The translation worked reasonably well for PM emissions with the exception of the UDDS and NYBUS cycles. While not as well correlated as CO_2 and NO_x emissions, the translation of CO and HC emissions are acceptable, especially considering that HC and CO emissions from diesel engines are typically low. For the purposes of this analysis OCTA, WMATA, and CBD cycle results will primarily be used.

In the following subsections, the composition of the 2003 bus fleet is determined and emissions from diesel, CNG, LNG and diesel-electric hybrid are presented as a function of the vehicle model year (VMY); using this information, the total national transit bus emissions are evaluated.

2.2 Composition of the Existing U.S. Transit Bus Fleet by Power Source

Information about the number and types of vehicles that made up the 2003 U.S. transit bus fleet was acquired from the American Public Transportation Association 2005 Public Transportation Fact Book [5] and the 2005 APTA Transit Vehicle Database [6]. Data reported in the 2005 Fact Book and 2005 Transit Vehicle Database were acquired from a survey of approximately 300 transit agencies which represents 15% of the nation’s nearly 2,000 bus agencies, but represents an estimated 70% of all buses and approximately 90% of buses between 35 feet and 45 feet and nearly all 60-foot articulated buses. Most of the vehicles not represented in this survey are operated by small-city and rural agencies and would be 30 feet or less in length. The comprehensive data available in the 2005 APTA Transit Vehicle Database was generated from the survey conducted as of January 2005 [6], depicting the 2003 fleet characteristics. Data from subsequent years was not complete when this study was executed. Figure 1 shows the distribution of active transit buses by power source.

The data used for this analysis include active transit buses and non-electric trolleybuses (i.e. trolleys powered with internal combustion engines) that are generally 30 feet or greater in length. Vans and minibuses of less than 30 feet in length, used primarily in demand response and paratransit service were excluded from this analysis due to the relatively low number of vehicles, wide variety of vehicle configurations and lack of sufficient emissions data for this type of vehicles.

Excluded from this analysis were buses powered by methanol and ethanol as they comprise a very small number of full size transit buses. Electric buses and trolley buses powered by third rail or catenary, or powered exclusively by electric battery are also excluded from the analysis since they do not include an internal combustion engine and do not directly produce pollutant emissions. It is acknowledged that the power plant generating the electricity to power the trolleybuses would be a pollution source. Although the FTA considers electric-powered trolley buses to be alternative fueled vehicles, the scope of this analysis only concerned tailpipe emissions. Estimation of power plant emissions was beyond the scope of this study.

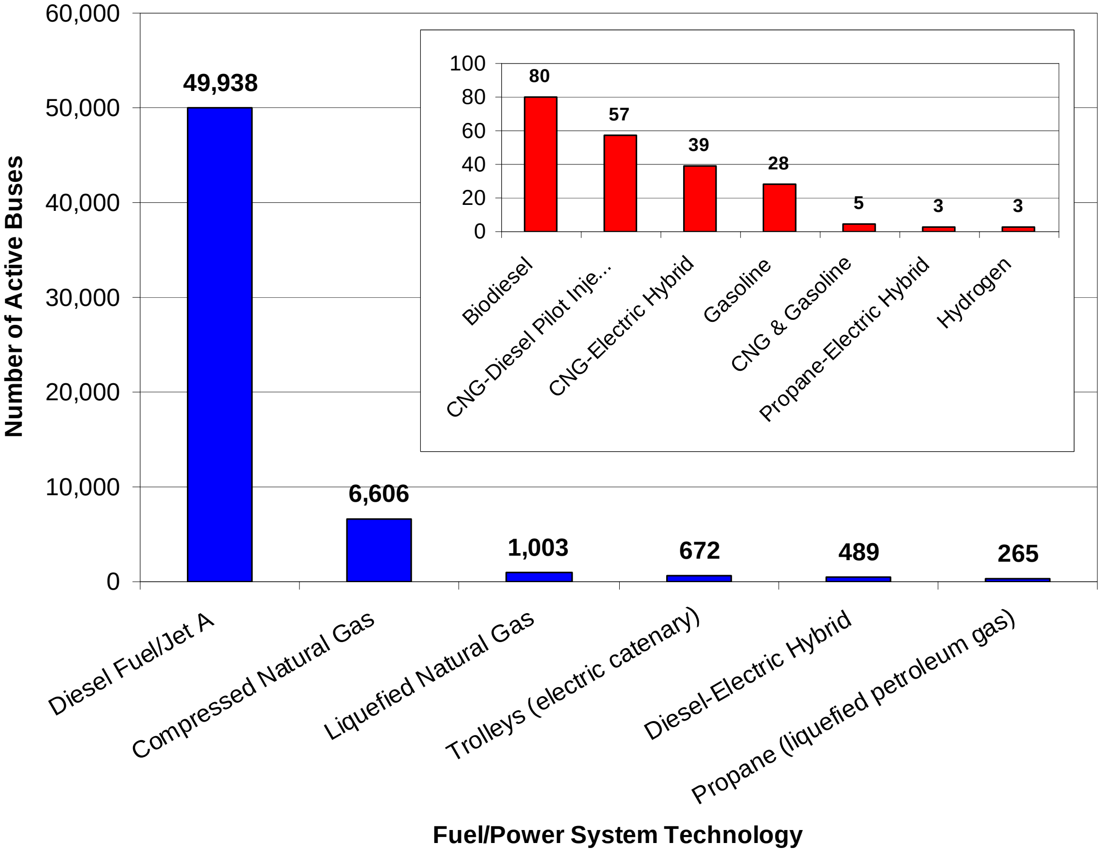


Figure 1: Active transit buses categorized by power source in 2003 [6]

Table 3 presents national fuel consumption by transit buses in 2003 reported by APTA [5]. It should be noted that diesel, LNG and CNG comprise over 99% of the total fuel consumed, and that the use of biodiesel is insignificant in comparison. Gaseous fuel data are presented in diesel equivalent gallons. Biodiesel fuel consumption was estimated from Figure 1 data and fuel economy (Section 4.5) assuming that such buses operate with B20 fuel.

Table 3: Transit bus fuel consumption in 2003 [5]

Fuel Type	**Fuel Consumed** thousands of gallons	Percentage
Diesel	535,963	82.47%
Compressed Natural Gas	94,881	14.60%
Gasoline	1,119	0.17%
Liquefied Natural Gas	14,231	2.19%
Propane	1,843	0.28%
B100 [a]	197	0.03%
Other	1,670	0.26%
Total	**649,904**	**100.00%**

[a] Estimated

2.3 Emissions from Conventional Diesel Fueled Buses

Buses fueled on conventional petroleum-derived diesel fuel make up the vast majority (85%) of buses currently in service in the U.S. numbering 49,938. Included in this total are buses fueled with federal specification No. 1 and No. 2 diesel fuel, California Air Resources Board specification diesel fuel, Jet A fuel and ultra-low sulfur (generally <30 ppm S) fuel. Diesel-electric hybrid buses were considered separately and are not included in this subset.

Figure 2 shows a break down of active diesel-powered transit buses by vehicle model year. Six model year bins were selected that correspond to the years in which emissions regulations were promulgated by the U.S. Environmental Protection Agency (EPA). Although engine model year is more relevant to emissions than VMY, these data are not reported by APTA. Therefore, in the absence of any other data, it must be assumed that the engine model year corresponds to the vehicle model year.

The annual vehicle miles traveled by diesel buses, 2,065.9 million miles, is estimated proportionally from the total annual vehicle miles traveled (VMT), the total number of buses and the number of diesel buses in 2003. Neither the distributions of VMT by vehicle model year nor by power-source were available from the APTA data. It was also assumed that VMT is proportional to the number of active buses in each model year bin. Based on this assumption the VMT for each model year bin was computed and is shown in Figure 3.

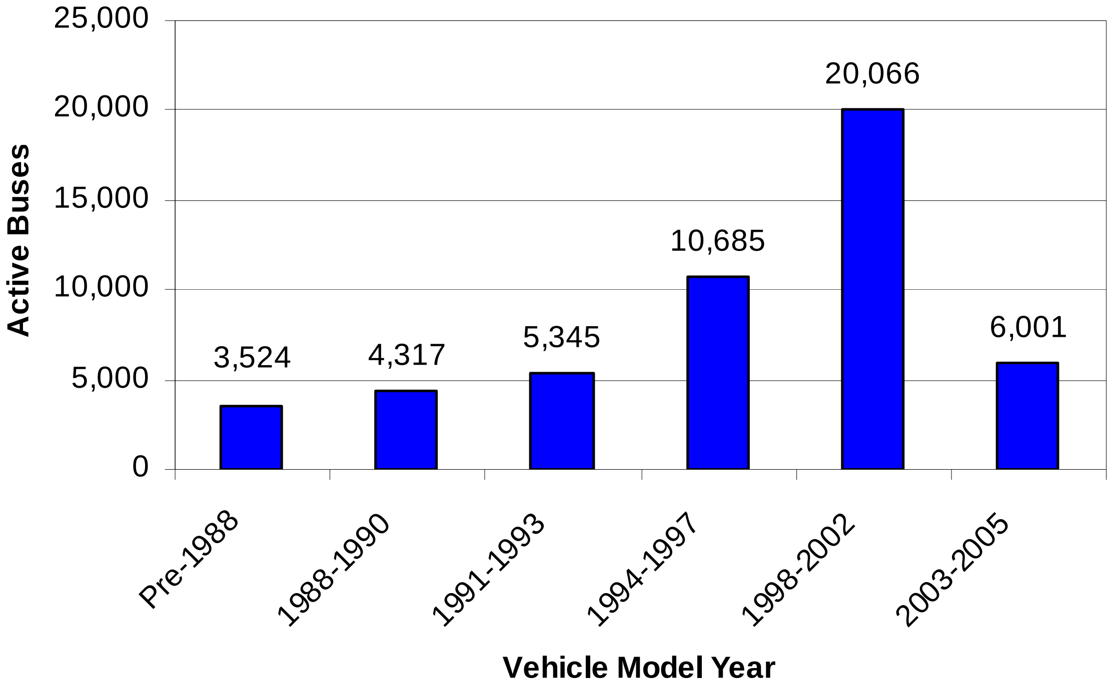


Figure 2: Distribution of diesel-powered transit buses by vehicle model year in 2003 [6]

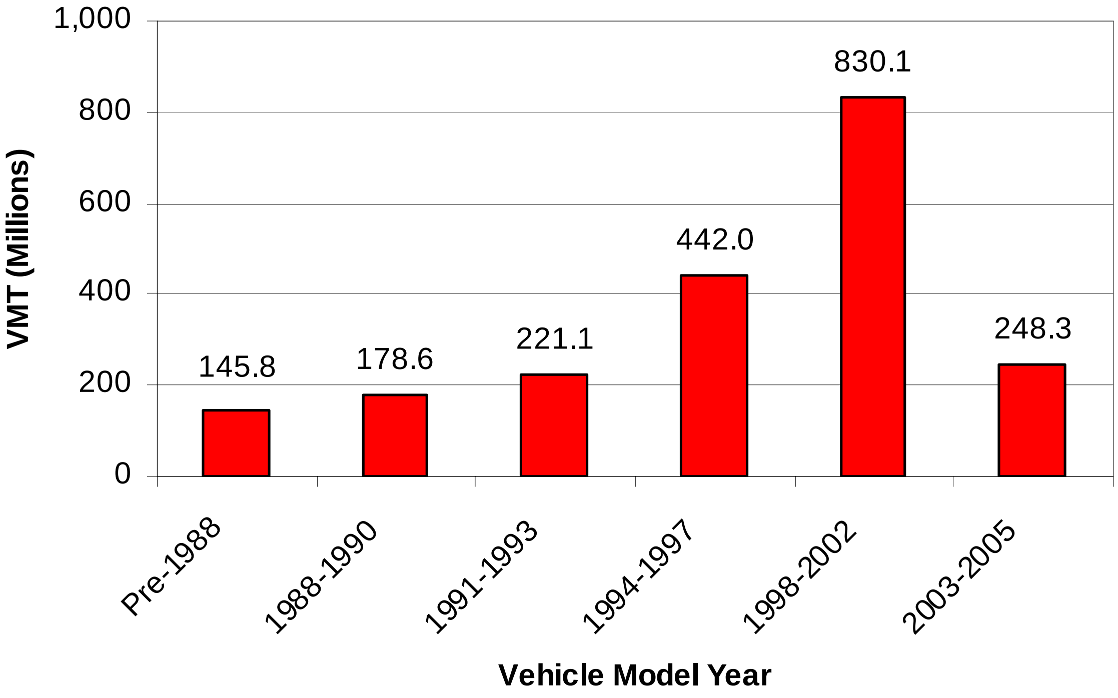


Figure 3: Total vehicle miles traveled by diesel buses as a function of vehicle model year in 2003

Emissions data that best represents each model year group was extracted from the West Virginia University Heavy Duty Vehicle Emissions Database [7] and from the technical literature. Where available, data from multiple buses with similar engine technologies and representing different engine manufacturers were averaged to yield representative emissions values. These data were then translated to OCTA equivalent emissions, as described above. Table 4 shows representative distance specific emissions as a function of vehicle model year for vehicles making up the present day diesel transit bus fleet.

Table 4: Representative distance specific emissions for the existing diesel transit bus fleet

MY Group	Data Source	CO g/mile	HC g/mile	NO_x g/mile	PM g/mile	CO_2 g/mile	Fuel Economy mile/gal
2003-2006	2003-04 MY DDC S50 Engines with EGR and DOC	3.22	0.22	15.22	0.21	2,854	3.38
1998-2002	1998-00 MY DDC S50 and Cummins M11 with DOC	2.79	0.46	28.88	0.25	2,927	3.37
1994-1997	1994-1997 MY DDC S50, Cummins M11 & L10 with and without DOC	6.74	1.31	27.95	0.45	2,455	4.22
1991-1993	1991-1993 MY DDC 6V92TA, Cummins L10, No Aftertreatment	11.45	2.64	32.03	1.50	3,243	3.20
1988-1990	1988-1990 DDC 6V92TA, Cummins L10, No Aftertreatment	20.28	2.12	31.84	1.95	2,964	3.38
Pre 1988	1986-1987 DDC 6V92TA, No Aftertreatment	14.82	2.69	45.96	1.49	2,912	3.40

Annual emissions of the national diesel bus fleet (Table 5) were evaluated from the total annual vehicle miles traveled (2,065.9 million miles [5]), the number of diesel active buses (Figure 1), their distribution by vehicle model year (Figure 2), and the OCTA equivalent emissions from each model year (Table 4). Table 5 and Figure 4 show estimated total mass emissions emitted into the atmosphere annually by the existing national diesel transit bus fleet.

Table 5: Annual mass emissions and fuel consumption of the national diesel transit bus fleet

MY Group	CO tons	HC tons	NO_x tons	PM tons	CO_2 tons	Fuel Consumed thousands of gallons
2003-2006	880	61	4,165	58	780,989	73,354
1998-2002	2,556	419	26,425	229	2,678,277	246,353
1994-1997	3,285	637	13,617	219	1,196,354	104,744
1991-1993	2,790	644	7,807	366	790,532	69,046
1988-1990	3,992	418	6,269	384	583,573	52,817
Pre 1988	2,382	432	7,385	239	467,924	42,821
Total	**15,886**	**2,611**	**65,669**	**1,494**	**6,497,649**	**589,135**

2.4 Validation of the Emissions Prediction Methodology

The annual diesel fuel consumption computed using the estimation method is 589,135,000 gallons. APTA data reported total consumption of 535,963,000 gallons of diesel fuel in 2003. The predicted fuel consumption is within 10% of the value reported by APTA [5]. Given that diesel buses traveled 2,065.9 million miles annually a diesel fleet-average fuel economy of 3.51 miles per gallon was estimated. This predicted average fuel economy agrees well with the value of 3.47 reported in the 2005 APTA Fact Book [5]. This validates the assumption that national bus operation is well approximated by the OCTA chassis dynamometer cycle.

As a second check of the validity of the methodology, CO_2 emissions can be estimated directly from gallons of fuel consumed. Combustion of one gallon of diesel fuel produces 22.2 pounds of CO_2 [8]. Therefore, combustion of 589,135,000 gallons of fuel would produce 6,539,398 tons of CO_2 based on fuel consumed compared to 6,497,563 calculated using the prediction method, giving a difference of less than 1% between the two calculations.

For comparison, the U.S. EPA computes national-level (50-state) mobile source emissions inventories using trends from the National Emissions Inventory [9] and the MOBILE 6.2 Vehicle Emissions Modeling Software [10]. The EPA projections include all types of bus applications such as school buses, motor coaches and airport shuttle buses and therefore result in much larger VMT of 6,673 million miles. Table 6 shows the EPA predicted annual emissions from buses. While it is recognized that the EPA predictions include other types of buses, the data reported by EPA is of the same order of magnitude as that predicted by the methodology used in this report when the ratio of VMT is considered.

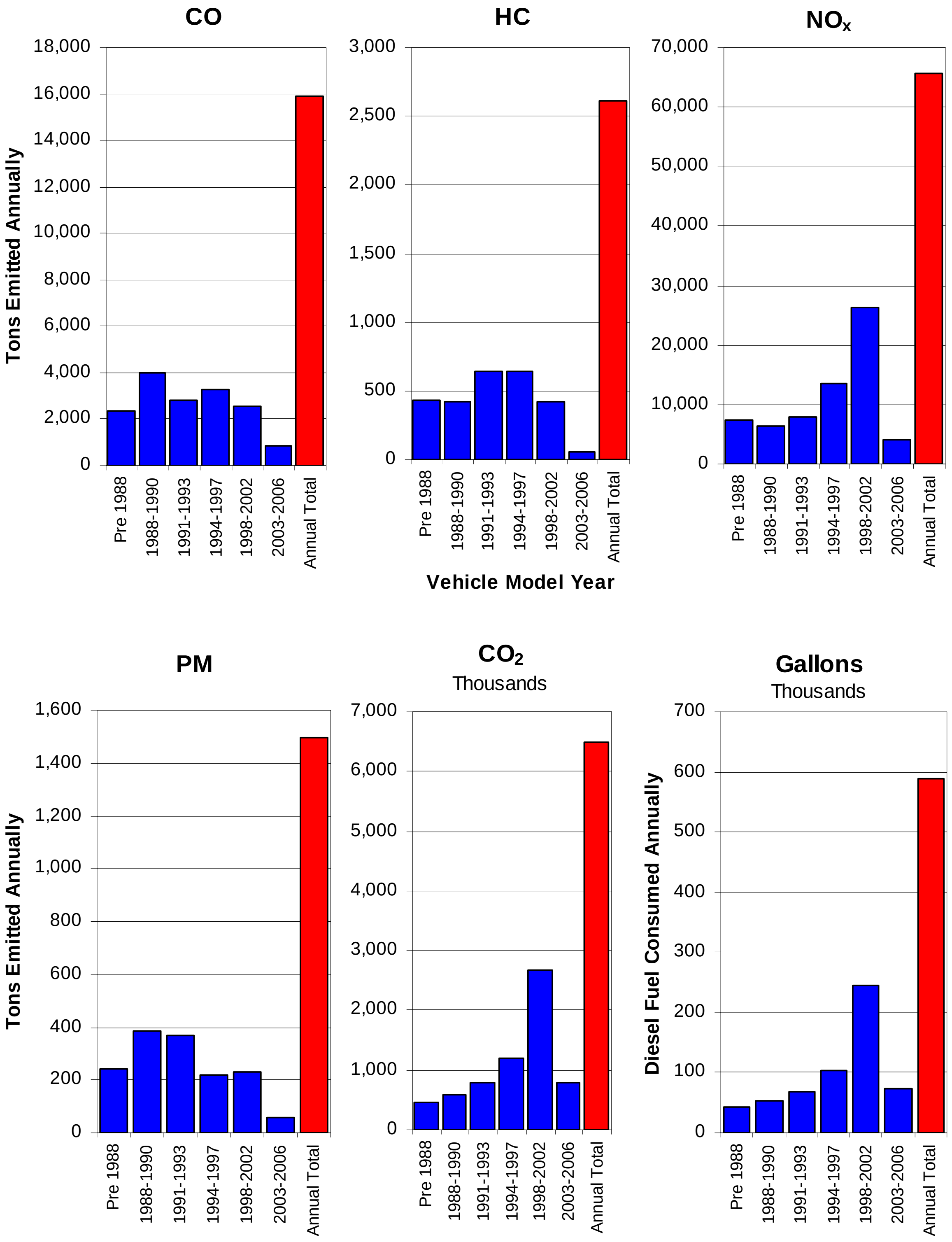


Figure 4: Annual contribution to national emissions inventories from diesel transit buses

Table 6: EPA projected annual emissions from heavy-duty diesel buses

Pollutant	Tons Emitted Annually
CO	32,464
NO_x	102,729
VOC	6,903
PM	6,943

These comparisons indicate that the emissions prediction method produces a reasonably accurate estimation of transit bus emissions to accomplish the objectives of this study.

2.5 Emissions from Compressed and Liquefied Natural Gas Buses

Buses fueled with compressed and liquefied natural gas make up the largest category (94%) of alternatively-fueled transit buses. Emissions from vehicles employing compressed or liquefied natural gas are similar and are therefore considered together. The same analysis and assumptions are applied to CNG and LNG buses as were applied to the diesel buses. Figure 5 shows the distribution of CNG and LNG powered buses by vehicle model year [5]. Total VMT as a function of vehicle model year bins, corresponding to changes in emissions regulations, is plotted in Figure 6. Table 7 shows representative distance specific emissions as a function of vehicle model year for vehicles making up the 2003 CNG and LNG transit bus fleet. Table 8 and Figure 7 show estimated total mass emissions emitted into the atmosphere annually by the existing national CNG and LNG transit bus fleet.

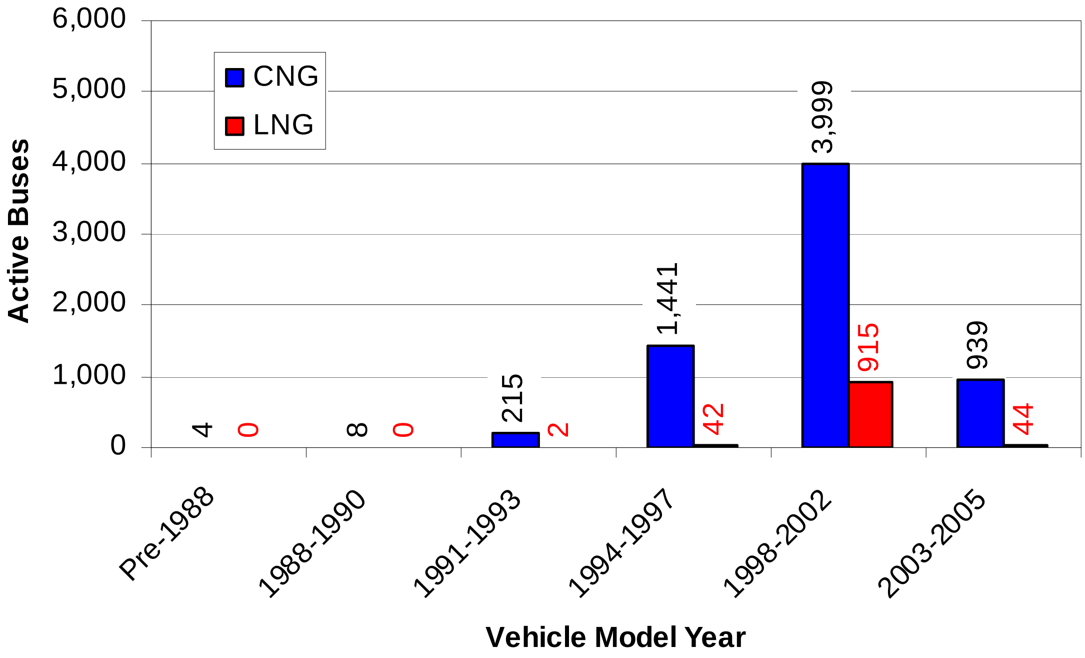


Figure 5: Distribution of CNG and LNG powered transit buses by VMY in 2003 [5, 6]

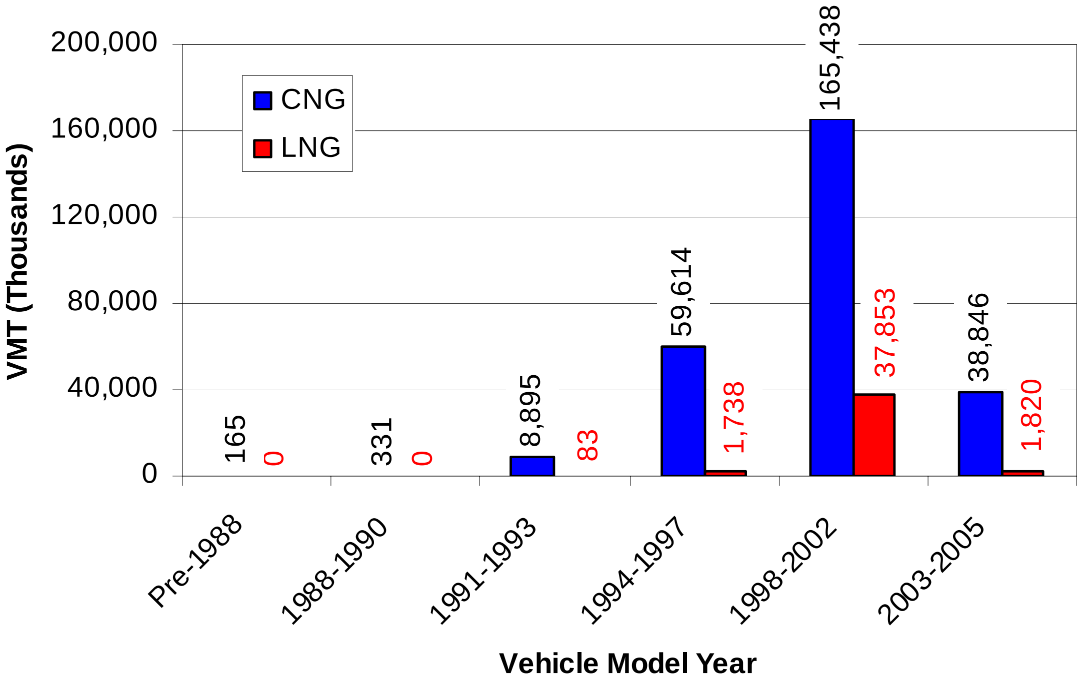


Figure 6: Total vehicle miles traveled by CNG and LNG buses as a function of VMY in 2003

Table 7: Representative distance specific emissions for the existing CNG/LNG transit bus fleet

MY Group	**Data Source**	**CO** g/mile	**HC** g/mile	**NMHC** g/mile	**NO$_x$** g/mile	**PM** g/mile	**CO$_2$** g/mile	**Fuel Economy** mile/gal
2003-2006	2004-2005 MY John Deere 6081H and Cummins CG-280	0.31	21.13	1.09	14.82	0.01	1,937	3.65
1998-2002	1998-01 MY DDC S50G, Cummins L-10G & C8.3G	3.09	16.48	0.79	17.84	0.02	2,284	3.10
1994-1997	1996-1997 MY DDC Series 50G, Cummins L10G and B5.9G	6.10	19.97	1.05	20.90	0.03	2,515	3.01
1991-1993	1991-1993 MY Cummins L-10G	7.38	19.28	1.21	23.38	0.04	2,662	2.79
1988-1990	1989-1990 MY Cummins L-10G	2.06	6.36	0.32	19.89	0.07	2,586	2.88
Pre 1988	1987 MY Cummins L-10G	3.46	20.84	1.04	17.16	0.11	2,630	2.80

Table 8: Annual mass emissions and fuel consumption of the national CNG/LNG transit bus fleet

MY Group	**CO** tons	**HC** tons	**NMHC** tons	**NO$_x$** tons	**PM** tons	**CO$_2$** tons	**Fuel Consumed** thousands of gallons
2003-2006	14	947	49	664	1	86,853	11,132
1998-2002	693	3,693	176	3,998	4	511,931	65,494
1994-1997	412	1,350	71	1,414	2	170,080	20,377
1991-1993	73	191	12	231	0.40	26,343	3,216
1988-1990	1	2	0.1	7	0.02	943	115
Pre 1988	1	4	0.2	3	0.02	480	59
Total	**1,194**	**6,187**	**308**	**6,318**	**7**	**796,630**	**100,393**

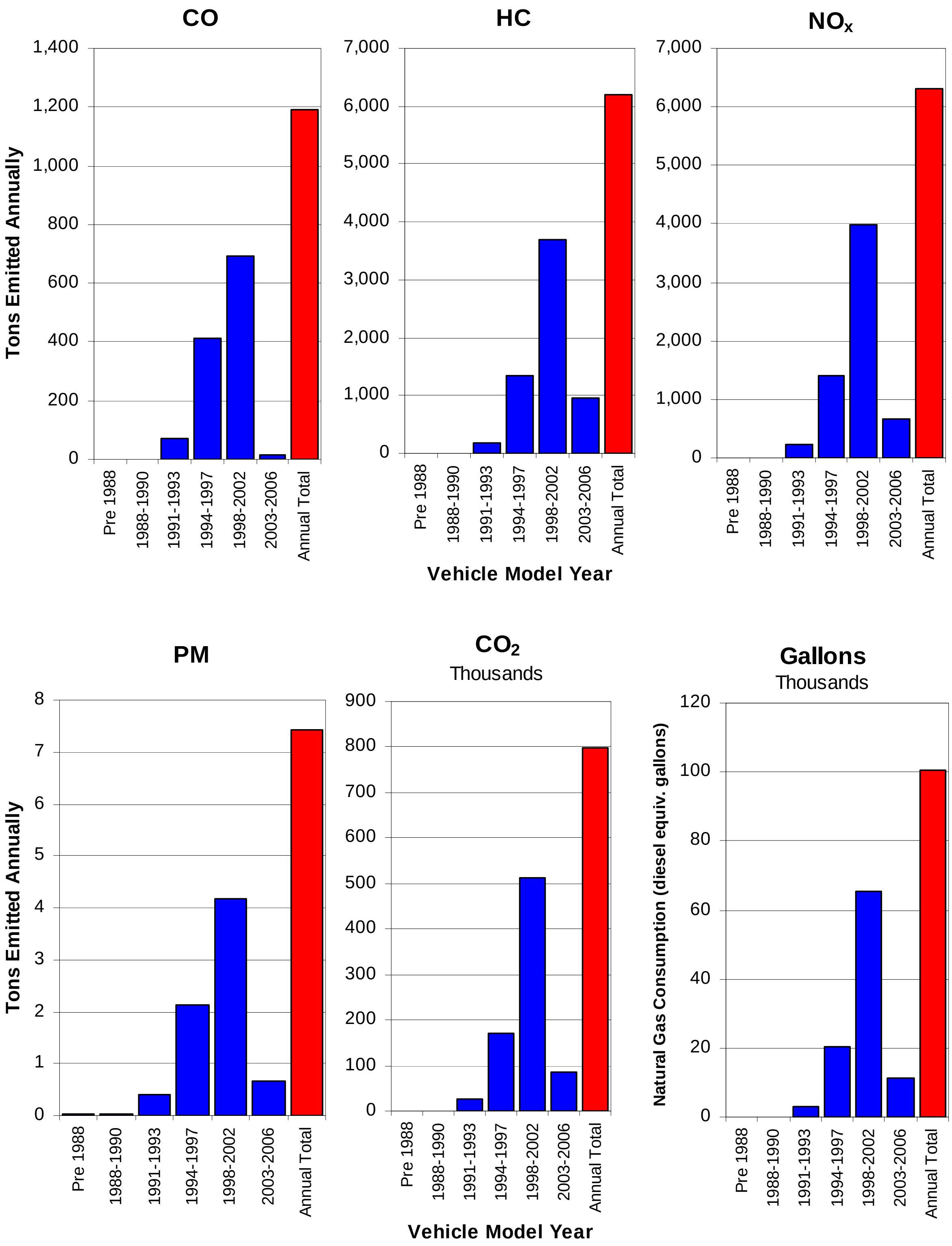


Figure 7: Annual contribution to national emissions inventories from CNG/LNG transit buses

Natural gas fuel consumption is reported in terms of energy equivalent diesel gallons – that is the number of gallons of diesel fuel having the same energy content of the natural gas consumed. The annual natural gas (CNG + LNG) consumption (reported as equivalent diesel gallons) computed using the estimation method is 100,393,000 gallons. APTA [5] data reported total consumption of 115,868,000 equivalent diesel gallons in 2003. The predicted CNG/LNG consumption is within 13% of the value reported by APTA lending confidence to the accuracy of the predictive model. The average fuel economy of CNG/LNG buses was estimated to be 3.13 miles/diesel-equivalent-gallon which compares reasonably well with the 2.71 miles/diesel-equivalent-gallon cited in the 2005 APTA Fact Book [5].

2.6 Emissions for Diesel-Electric Hybrid Buses

Diesel-electric hybrid buses are the third largest type of bus in service (0.8%) and their numbers are increasing. Figure 8 shows the number of diesel-electric hybrid buses in service according to the 2003 APTA Transit Vehicle Database [6] and the vehicle miles traveled by those buses.

Table 9 shows distance-specific emissions data for existing hybrid buses; it is important to note that all of the diesel-electric hybrid buses are equipped with catalyzed diesel particulate filters (DPF) which are highly effective at oxidizing PM, CO and HC emissions. Reductions in CO, HC and PM compared to conventional-drive diesel buses not equipped with DPFs are primarily attributed to the presence of the DPF and not to the hybrid-drive system, and conventional-drive diesel buses equipped with DPF would achieve similar reductions in CO, HC and PM. Estimated annual emissions and fuel consumed by diesel-electric hybrid buses are shown in Table 10 and Figure 9.

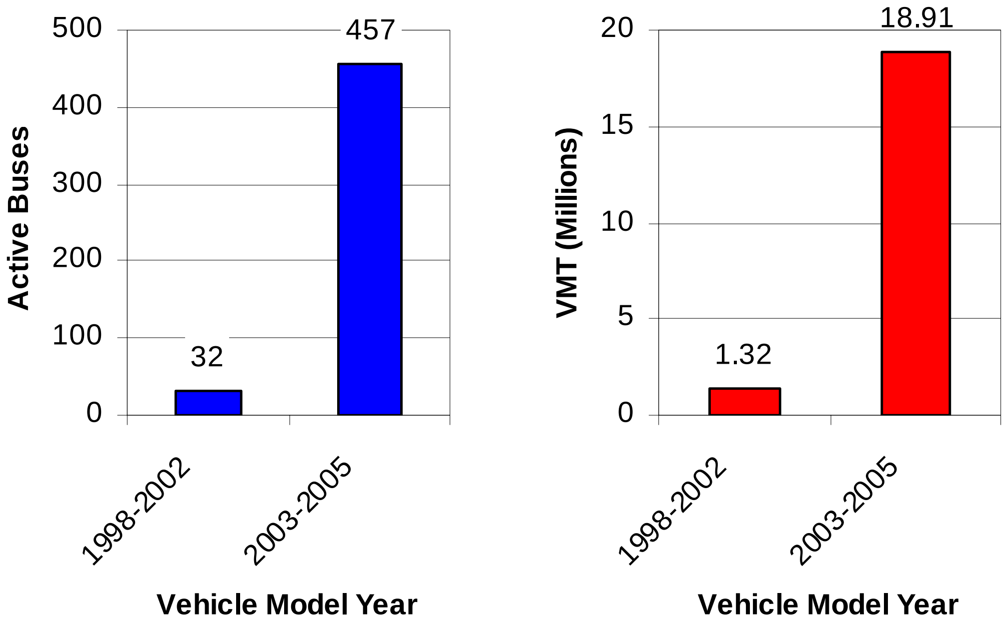


Figure 8: Diesel-electric hybrid buses [5, 6] and VMT in 2003

Table 9: Distance-specific emissions from diesel-electric hybrid buses

MY Group	Data Source	CO g/mile	HC g/mile	NO_x g/mile	PM g/mile	CO_2 g/mile	Fuel Economy mile/gal
2003-2006	2004 MY BAE Series with DPF and EGR	0.16	0.03	9.57	0.02	1,585	6.11
1998-2002	1998 Allison Series, 1998 BAE Series, 2002 Allison Parallel, 2002 BAE Series, all with DPFs	1.03	0.03	14.09	0.02	1,946	4.95

Table 10: Annual mass emissions and fuel consumption of the national diesel hybrid transit buses

MY Group	CO tons	HC tons	NO_x tons	PM tons	CO_2 tons	Fuel Consumed thousands of gallons
2003-2006	3.43	0.53	199.49	0.45	33,025	3,094
1998-2002	1.50	0.04	20.56	0.03	2,839	268
Total	**4.93**	**0.58**	**220.05**	**0.48**	**35,865**	**3,361**

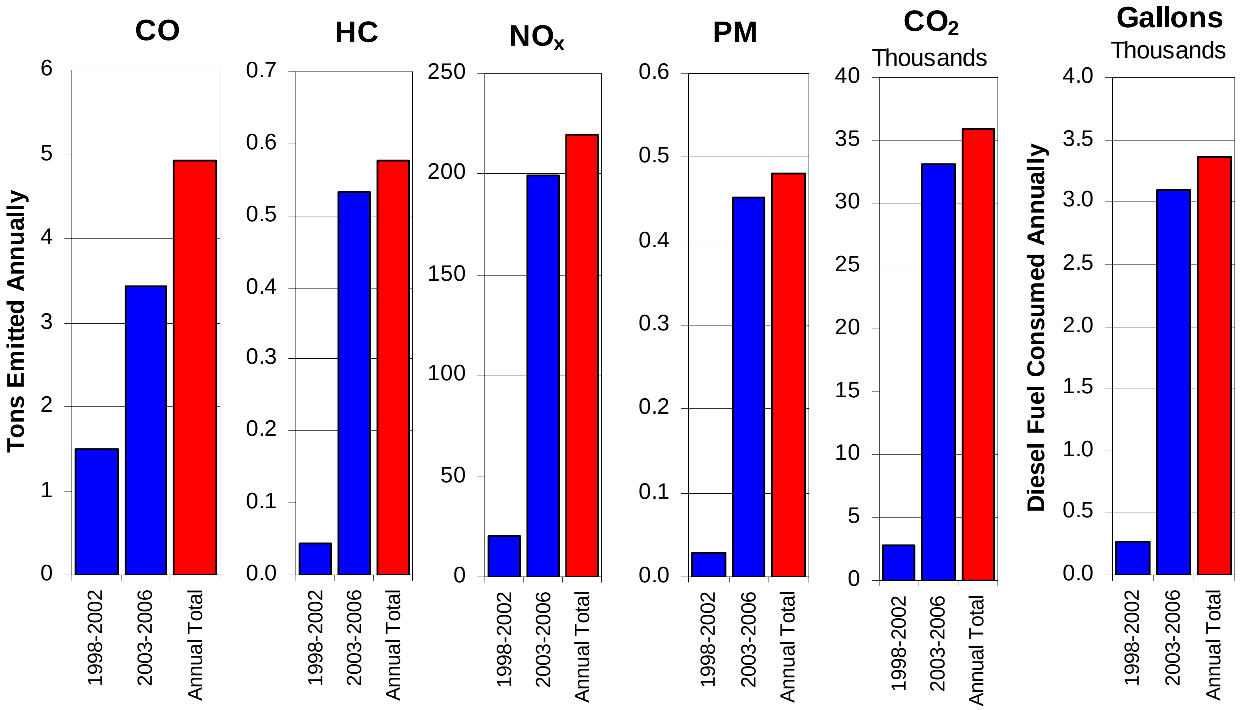


Figure 9: Annual contribution to national emissions levels from diesel hybrid transit buses in 2003

2.7 Current National Transit Bus Emissions Totals

Cumulative emissions from the existing transit bus fleet were estimated by considering the emissions from conventional diesel buses, compressed natural gas buses, liquefied natural gas buses and diesel-electric hybrid buses. Other types of buses did not exist in significant numbers to impact the national transit bus emissions total.

Total annual emissions are reported in Table 11; average emissions per bus are determined from the annual emissions, the number of active buses, and VMT data.

Table 11: Estimated total emissions from the existing national transit bus fleet in 2003

	Number of Buses	**CO** tons	**NMHC** tons	**CH_4** tons	**NO_x** tons	**PM** tons	**CO_2** tons	**Fuel Consumed** thousands of gallons
Total Emissions								
Diesel	49,938	15,886	2,611		65,669	1,494	6,497,649	589,135
CNG/LNG	7,609	1,194	308	5,879	6,318	7	796,630	100,393
Diesel Hybrid	489	5	0.6		220	0.5	35,865	3,361
Total	**58,036**	**17,085**	**2,920**	**5,879**	**72,207**	**1,502**	**7,330,143**	**692,889**
Average Emissions Levels per Bus								
		CO g/mile	**NMHC** g/mile	**CH_4** g/mile	**NO_x** g/mile	**PM** g/mile	**CO_2** g/mile	**Fuel Economy** mile/gal
Diesel		6.98	1.15		28.84	0.66	2,853	3.51
CNG/LNG		3.44	0.89	16.94	18.21	0.02	2,296	3.14
Diesel Hybrid		0.22	0.03		9.87	0.02	1,608	6.02

3.0 EMISSIONS IMPACTS OF ONGOING TRANSIT BUS PROCUREMENTS

The 2005 APTA Public Transportation Fact Book [5] and Transit Vehicle Database [6] report statistics on the number and types of buses that have been ordered as of January 2005 and on future purchases that are planned but not yet underway [6]. Figure 10 shows planned new bus procurements through the year 2009 by power source.

The majority of new buses purchase will be used to replace aging buses. However, it is expected that the national transit bus fleet will grow modestly over the next several years. Figure 11 shows the number of transit buses in active service over the last decade [6]. Based on this trend, it is expected that the number of buses will increase by approximately 6.5% by year 2009; therefore, according to current procurements, nearly 70% of the buses purchased will replace existing buses.

APTA data does not indicate which buses will be replaced. For the purpose of this analysis it was assumed that new buses purchased will replace existing diesel buses and that the oldest diesel buses will be replaced first. Figure 12 shows the anticipated composition of the national bus fleet in year 2009 based on available data from APTA and the assumptions mentioned above. The increasing demand for public transit is also manifested in an increase in vehicle miles traveled. Based on the recent historical trend, VMT by transit buses will increase by approximately 4% to 2510.4 million miles by 2009 as shown in Figure 13.

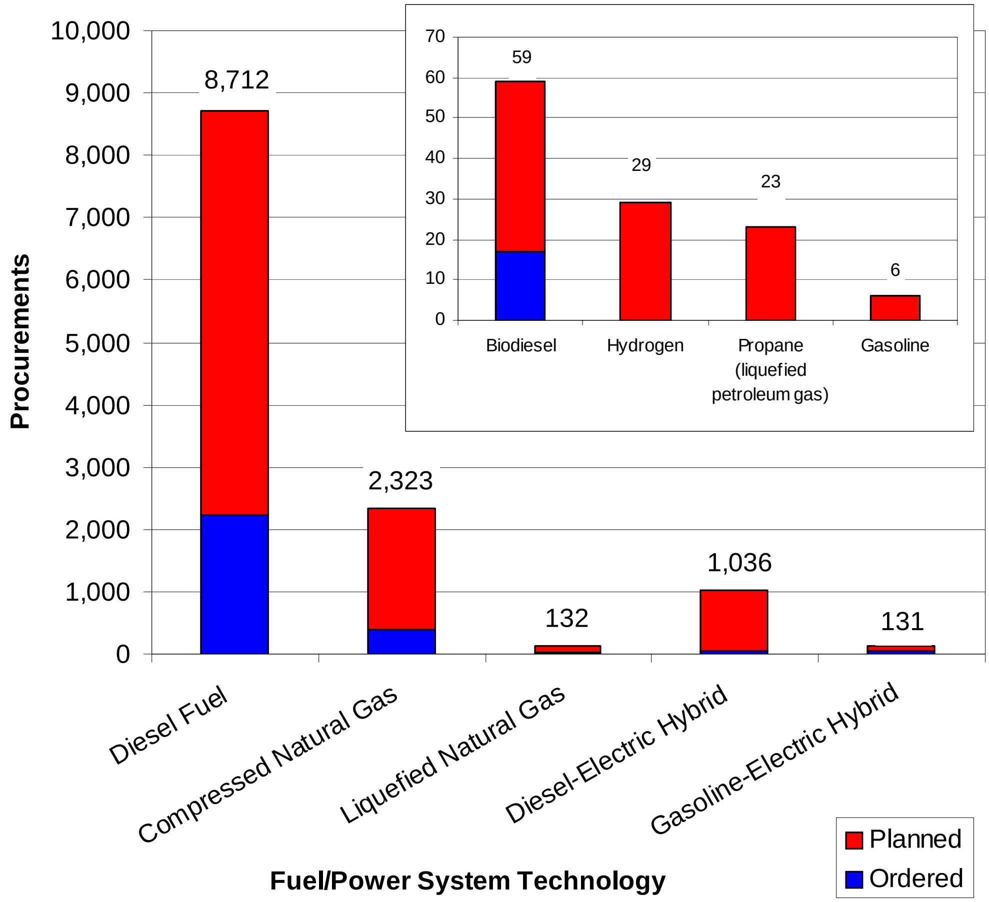


Figure 10: 2004 – 2009 transit bus procurements

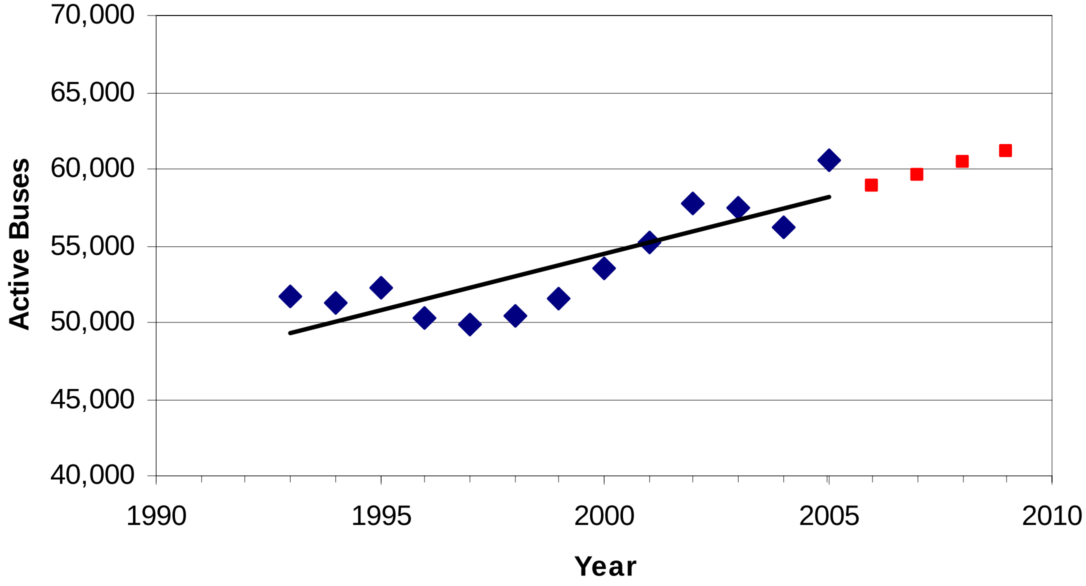


Figure 11: Historical national transit bus fleet size [5]

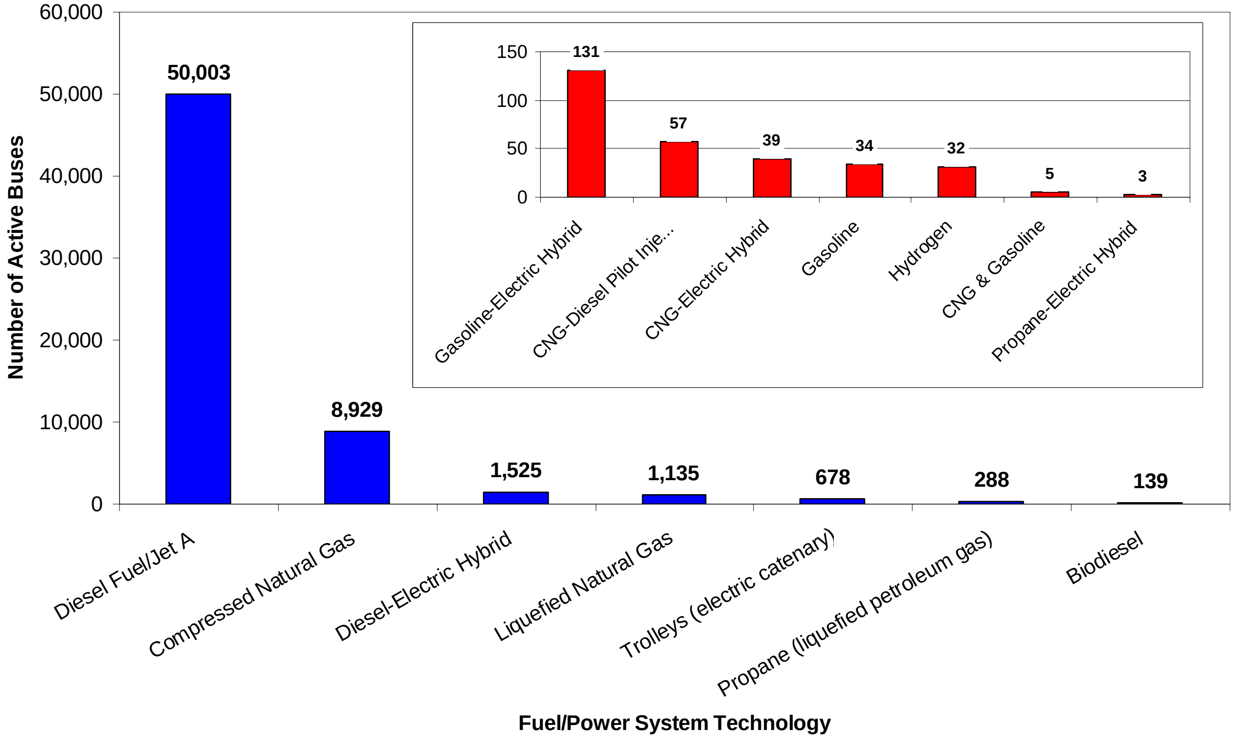


Figure 12: Anticipated 2009 national transit bus fleet by power source

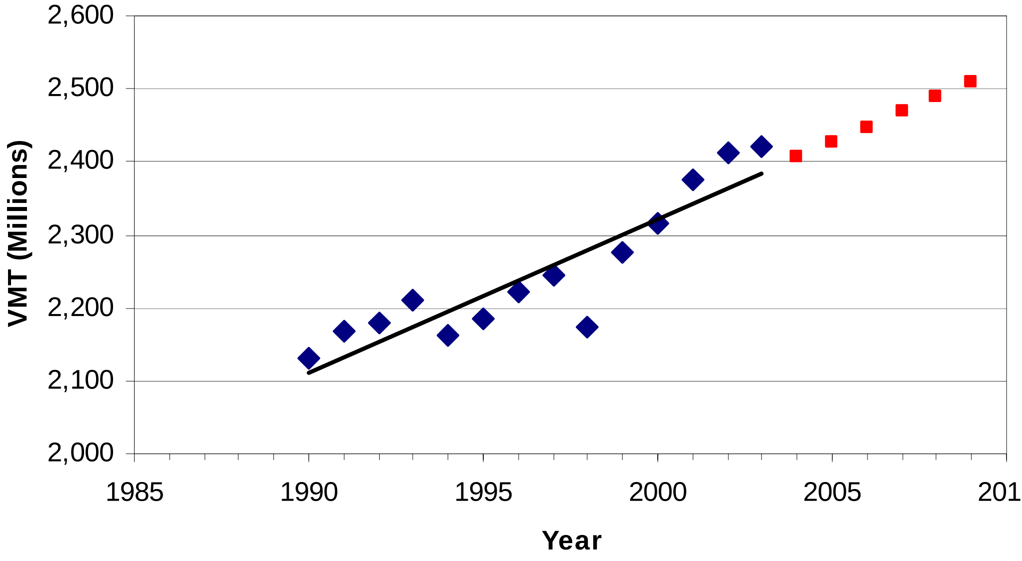


Figure 13: Historical trend in vehicle miles traveled by transit buses [5]

3.1 Contribution of Diesel Transit Buses in Year 2009

Based on currently available information on planned and ongoing bus procurements and growth trend in public transit, the number of diesel buses is expected to grow to approximately 51,000 by year 2009. However, it is assumed that some older diesel transit buses will be replaced by purchases of new technology diesel buses and by buses employing alternative fuels and hybrid drive systems. Figure 14 and Figure 15 show anticipated distributions in the number of active diesel buses and vehicle miles traveled as a function of vehicle model year in 2009.

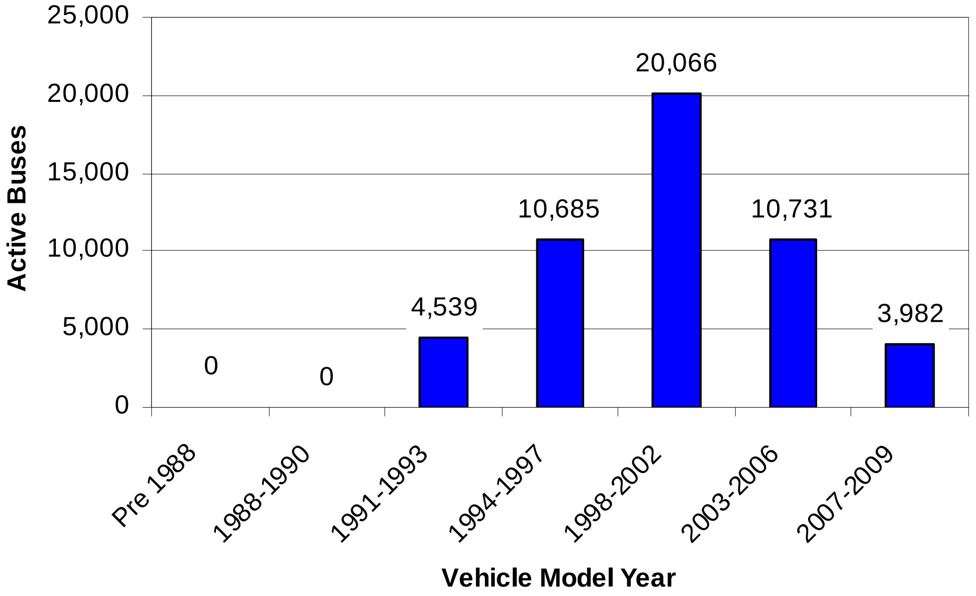


Figure 14: Model year distribution of diesel transit buses in 2009

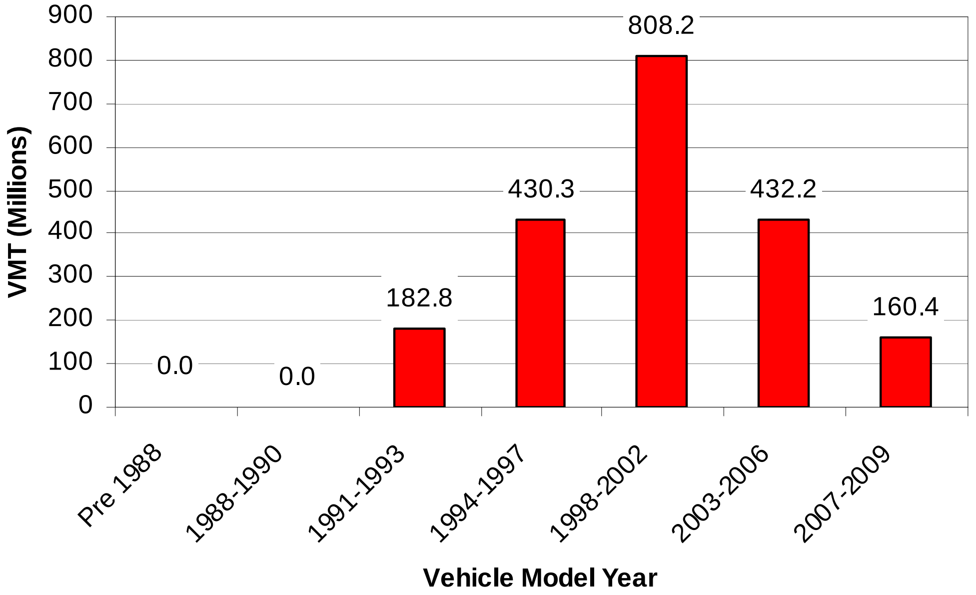


Figure 15: Estimated mileage distribution by model year of diesel buses in year 2009

Chassis dynamometer emissions data are not yet available for 2007 and newer model year buses. Therefore, it is necessary to estimate these emissions levels. Beginning in 2007 the PM standard for heavy-duty highway engines drops from 0.05 g/bhp-hr to 0.01 g/bhp-hr; in order to meet this PM standard all heavy-duty diesel vehicles will be equipped with diesel particulate filters. PM emissions data from 2004 model year buses equipped with DPFs as a retrofit option are available in the literature. Particulate matter levels from 2007 and newer buses will be nearly equivalent to PM levels of these existing DPF equipped buses. DPFs are also highly effective at oxidizing hydrocarbons and carbon monoxide. Therefore, HC and CO emissions from 2007 and newer buses will be equivalent to existing DPF equipped buses.

No experimental data on NO_x levels from 2007 compliant engines is yet available. Therefore it is necessary to estimate the NO_x emissions: for this analysis NO_x emissions from 2007 and newer engines is approximated by multiplying the 2004 level shown in Table 4 by the ratio of the 2007 to 2004 EPA NO_x certification limits. The EPA NO_x emissions limit for 2004–2006 model year heavy-duty diesel engines is 2.5 g/bhp-hr measured on an engine dynamometer over the Federal Transient (FTP) Cycle. Engines manufactured after January 2007 will meet a fleet average NO_x level of 1.2 g/bhp-hr. Therefore, NO_x levels for 2007 and newer engines are approximated as:

$$NO_x^{2007} = \frac{1.2(g/bhp-hr)}{2.5(g/bhp-hr)} * 15.22(g/mile) = 7.31\ g/mile$$

Approximated emissions levels for MY 2007-2009 buses are shown in Table 12.

Table 12: Assumed OCTA equivalent emissions levels for MY 2007-2009 diesel transit buses

MY Group	**Data Source**	**CO** g/mile	**HC** g/mile	**NO_x** g/mile	**PM** g/mile	**CO_2** g/mile	**Fuel Economy** mile/gal
2007-2009	Estimated	0.29	0.002	7.31	0.022	2,854	3.38

Using the data shown in Table 4, Table 12 and Figure 15, the estimated emissions contribution from diesel transit buses in the 2009 vehicle fleet are shown in Table 13 and Figure 16. These predicted emissions results indicate reductions of approximately 6,300 tons of CO, 900 tons of HC, 11,600 tons of NO_x, 650 tons of PM and 207,000 tons of CO_2 annually and savings of 15 million gallons of diesel fuel. These reductions result from replacement of older model buses with modern technology diesel buses.

Table 13: Estimated annual emissions from the 2009 diesel bus fleet

MY Group	**CO** tons	**HC** tons	**NO_x** tons	**PM** tons	**CO_2** tons	**Fuel Consumed** thousands of gallons
1991-1993	2,307	532	6,454	302	653,572	57,084
1994-1997	3,198	620	13,257	213	1,164,720	101,974
1998-2002	2,488	408	25,727	223	2,607,459	239,839
2003-2006	1,533	106	7,252	101	1,359,639	127,704
2007-2009	51	0	1,292	4	504,527	47,388
Total	**9,577**	**1,667**	**53,981**	**843**	**6,289,918**	**573,989**

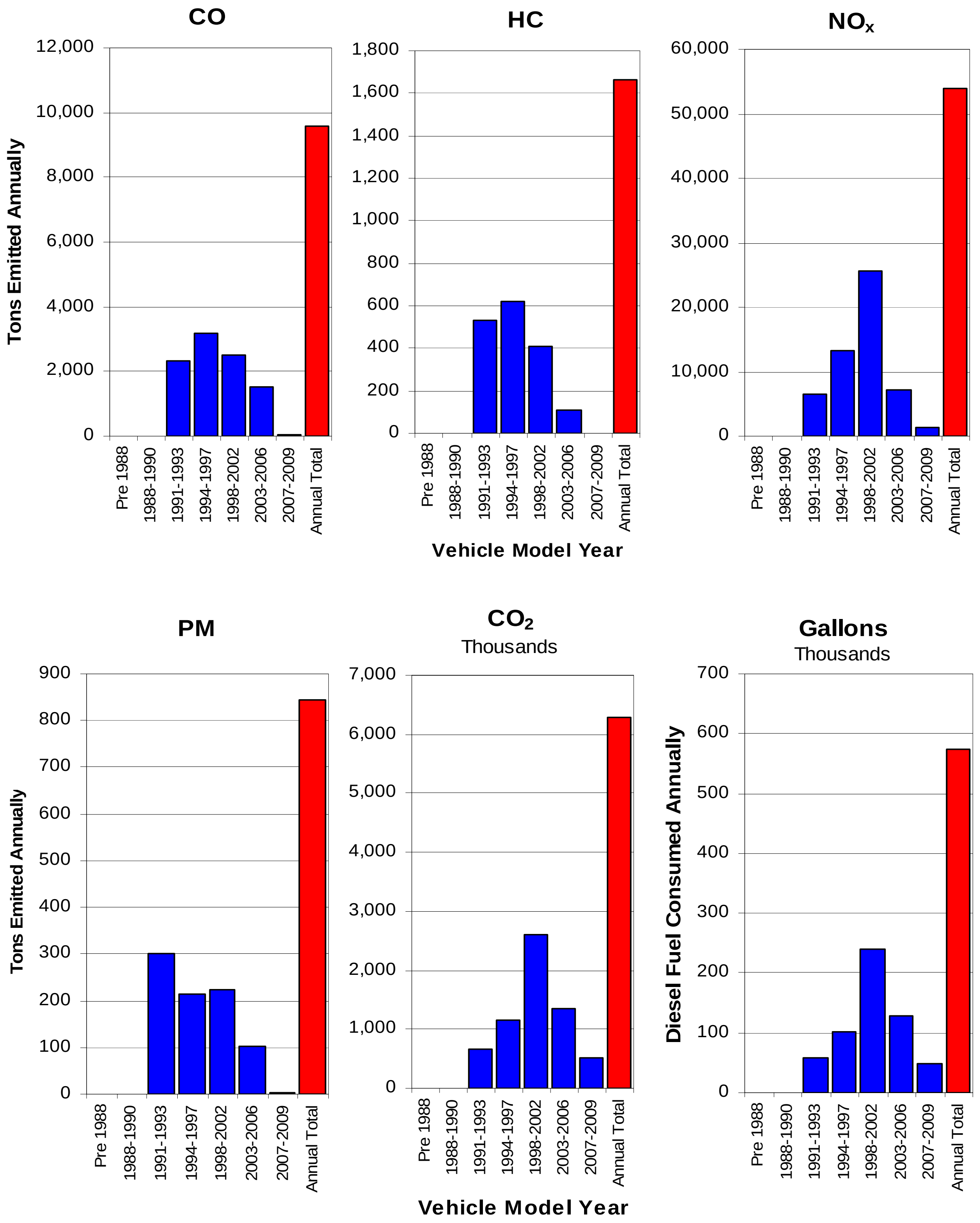


Figure 16: Predicted annual emissions from the 2009 diesel bus fleet

3.2 Contribution of Natural Gas Transit Buses in Year 2009

The number of CNG buses is expected to increase over the next 3 years while purchases of LNG buses are declining. For the purposes of this analysis it was assumed that no existing CNG or LNG buses will be replaced and that all new CNG/LNG purchases will contribute to increasing the number of these buses in the national fleet. Figure 17 and Figure 18 show anticipated distributions in the number of active CNG and LNG buses and vehicle miles traveled as a function of vehicle model year in 2009.

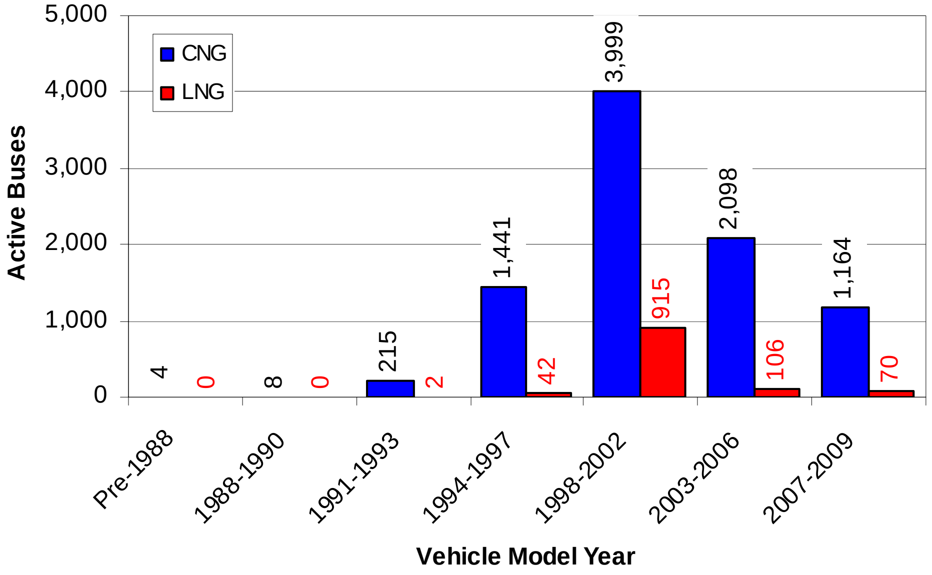


Figure 17: Model year distribution of CNG and LNG transit buses in 2009

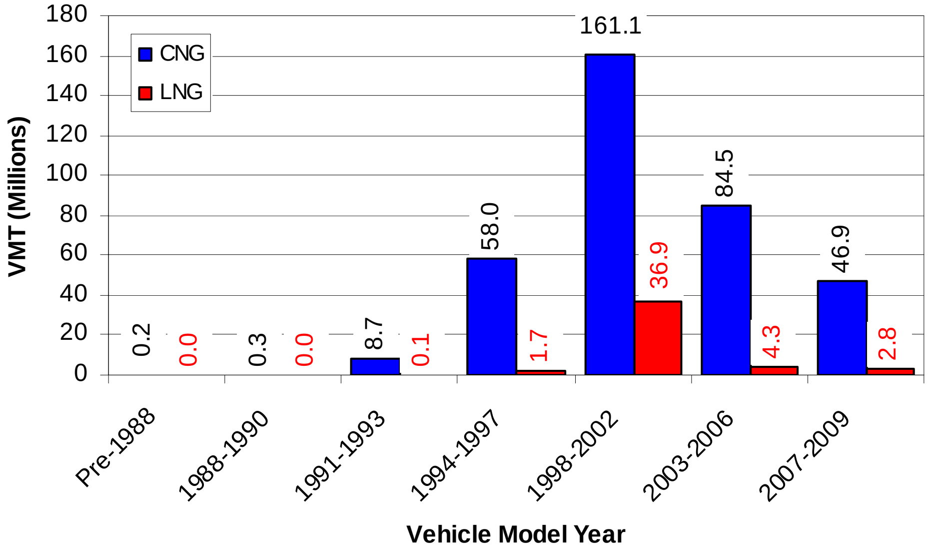


Figure 18: Estimated mileage distribution by model year of CNG and LNG buses in year 2009

The current generation of natural gas engines for transit buses in the United States uses lean-burn, spark-ignited engine technology. Lean-burn engines are built on diesel engine technology as a base and offer the best potential fuel economy. HC, CO and toxic HC emissions can be effectively reduced with catalyst-based technologies and the inherently low PM emissions from lean-burn natural gas engines can be further reduced with catalyzed filter technologies. However, the current lean-burn natural gas engine technology is not expected to meet the 2007 NO_x emissions limits.

Natural gas engine manufacturers will turn to stoichiometric combustion and three-way catalysts to meet 2007 emissions certification requirements [11]. Cummins Westport Innovations Inc. will employ stoichiometric combustion with cooled EGR and three-way catalyst to comply with 2007 NO_x limits [12]. Stoichiometric natural gas engines are common in Europe. Emissions levels of 2007 compliant natural gas transit buses are approximated from recent studies of emissions from European stoichiometric natural gas transit buses [13, 14]. The data from the VTT study was collected in the Braunschweig cycle on smaller buses at a lower test weight; thus, the emissions results were translated to the OCTA cycle using the ratio of CO_2 emissions for the same bus tested in both driving cycles [13], a procedure similar to that presented in Section 2.1 above. The results were also corrected for differences in bus weight using a linear relationship between fuel consumption vs. weight found by Erkkilä K. and Nylund [14]. Table 14 shows the adjusted emissions values that are believed to reasonably represent the emissions of 2007-2009 natural gas transit buses.

Table 14: Assumed emissions levels for MY 2007-2009 natural gas transit buses

MY Group	Data Source	CO g/mile	HC g/mile	NMHC g/mile	NO_x g/mile	PM g/mile	CO_2 g/mile	Fuel Economy mile/gal
2007-2009	Estimated	2.78	1.76	0.09	5.02	0.013	2,237	3.40

The estimated emissions contribution from CNG and LNG transit buses in the 2009 vehicle fleet was computed using data from Table 7, Table 14 and Figure 18. The results are shown in Table 15 and Figure 19. The predicted total annual emissions from natural gas buses are higher than current levels but this increase is due to growth in the number of natural gas buses.

Table 15: Estimated annual emissions from the 2009 natural gas bus fleet

MY Group	CO tons	HC tons	NMHC tons	NO_x tons	PM tons	CO_2 tons	Fuel Consumed thousands of gallons
Pre 1988	1	4	0	3	0	467	58
1988-1990	1	2	0	7	0	918	112
1991-1993	71	186	12	225	0	25,647	3,131
1994-1997	401	1,315	69	1,376	2	165,583	19,838
1998-2002	675	3,595	172	3,892	4	498,394	63,762
2003-2006	30	2,067	106	1,450	1	189,585	24,299
2007-2009	152	96	5	275	1	122,555	14,618
Total	**1,331**	**7,265**	**364**	**7,229**	**9**	**1,003,149**	**125,818**

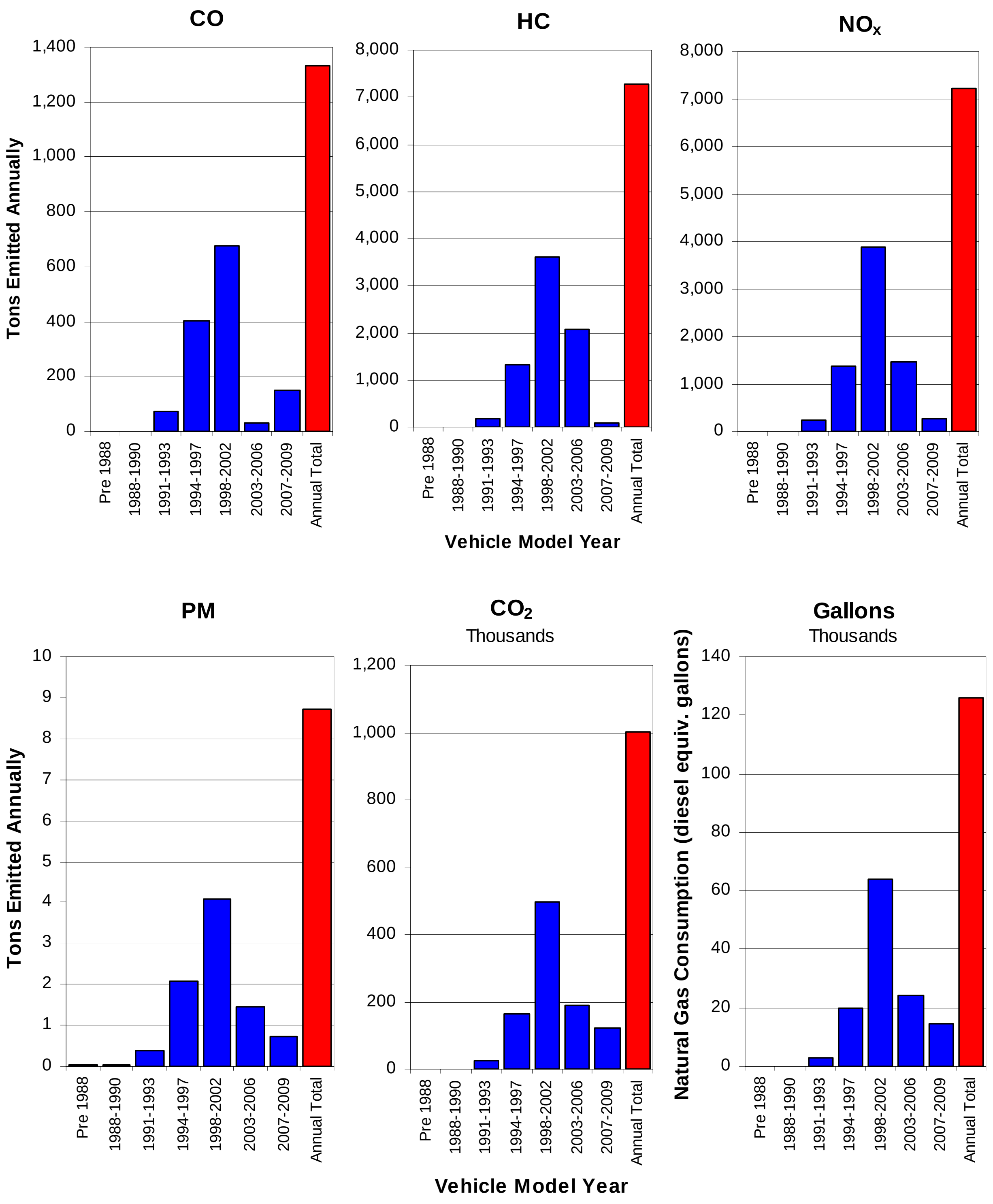


Figure 19: Predicted annual emissions from the 2009 natural gas bus fleet

3.3 Contribution of Diesel-Electric Hybrid Transit Buses in Year 2009

The number of diesel-electric hybrid powered transit buses will rise substantially as a result of hybrid bus procurements at several major transit agencies. By year 2009 the number of diesel-electric hybrid buses in service is expected to rise to over 1,500 units. Figure 20 shows the diesel-electric hybrid active buses distribution and VMT as a function of vehicle model year.

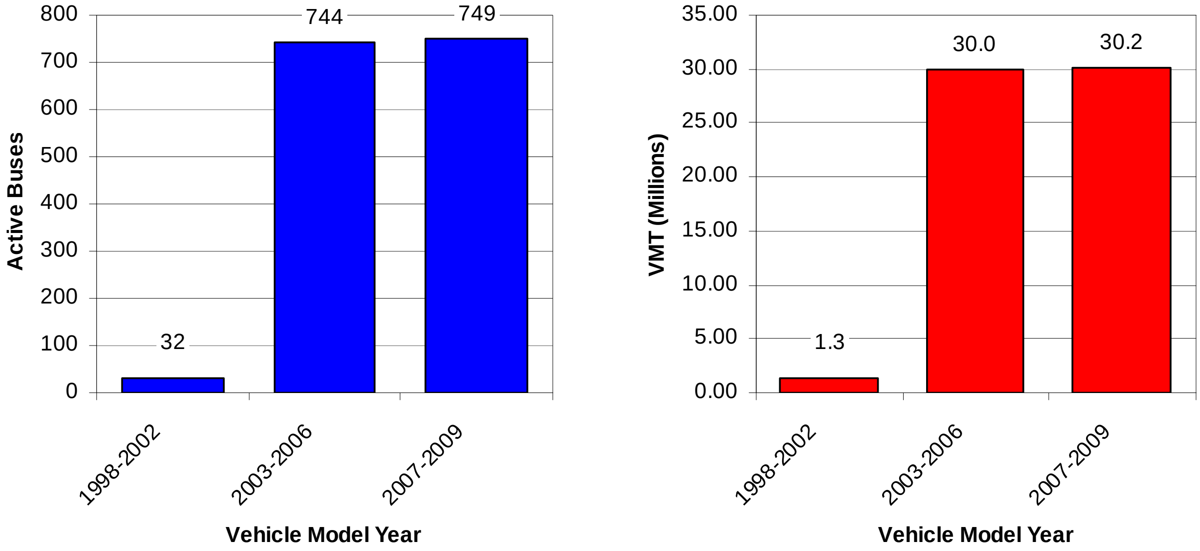


Figure 20: Number and VMT of diesel-electric buses in 2009

New model diesel-hybrid electric transit buses will be equipped with 2007 compliant diesel engines and will benefit from the lower NO_x emissions. The method described in Section 3.1 was used to estimate the NO_x emissions expected from 2007-2009 diesel-electric hybrid buses; expected emissions levels of new model diesel-electric hybrid buses are shown in Table 16. Predicted annual emissions from diesel-electric hybrid buses are shown in Table 17 and Figure 21.

Table 16: Assumed emissions levels for MY 2007-2009 diesel-electric hybrid transit buses

MY Group	Data Source	CO g/mile	HC g/mile	NO_x g/mile	PM g/mile	CO_2 g/mile	Fuel Economy mile/gal
2007-2009	Estimated	0.16	0.03	4.59	0.02	1,585	6.50

Table 17: Estimated annual emissions from the 2009 diesel-electric hybrid bus fleet

MY Group	CO tons	HC tons	NO_x tons	PM tons	CO_2 tons	Fuel Consumed thousands of gallons
1998-2002	1.46	0.04	20.01	0.03	2,764	260
2003-2006	5.43	0.85	316.18	0.72	52,344	4,904
2007-2009	5.32	1.00	152.63	0.67	52,706	4,641
Total	**12**	**2.0**	**488**	**1**	**107,814**	**9,805**

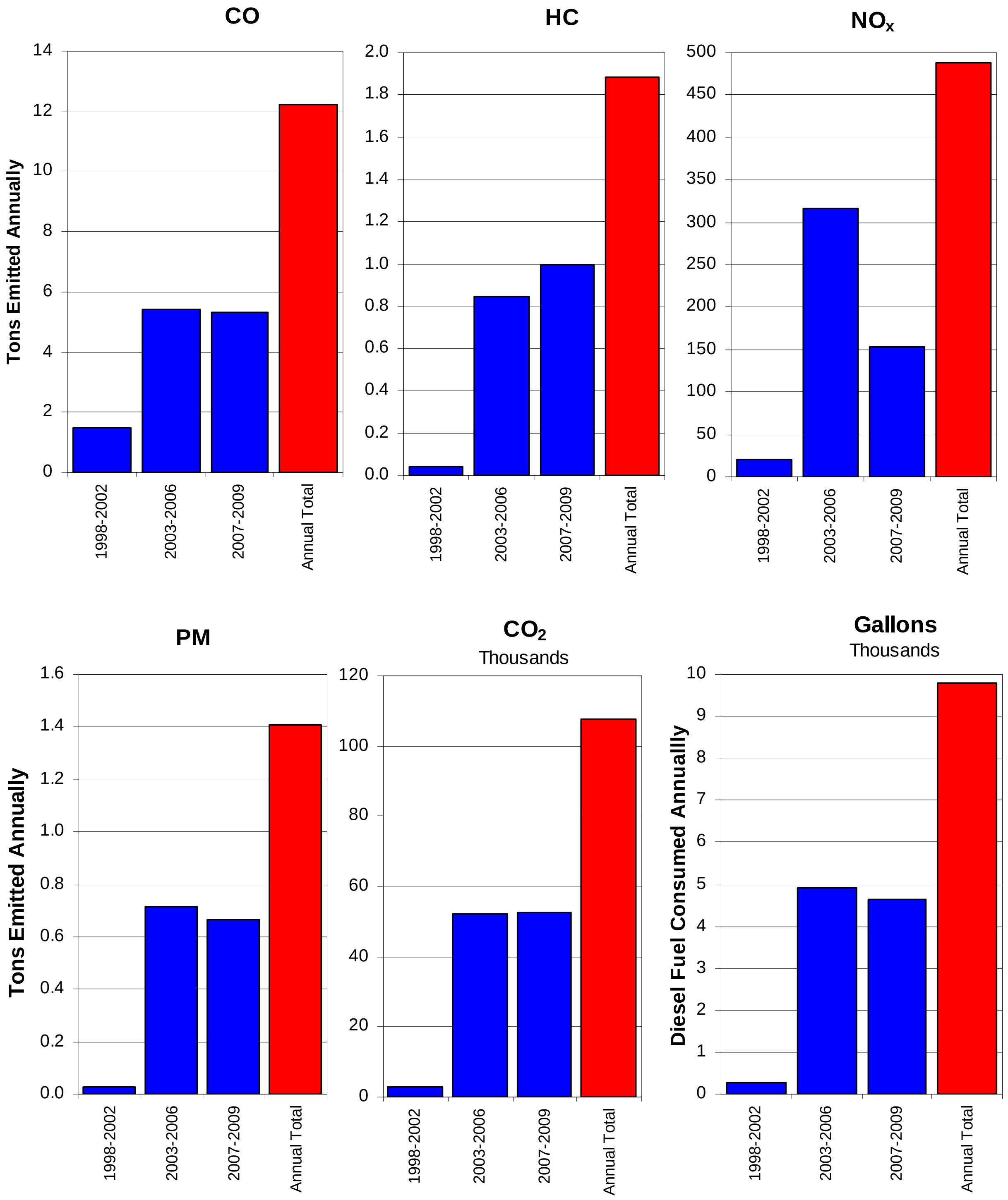


Figure 21: Predicted annual emissions from the 2009 diesel-electric hybrid bus fleet

3.4 Predicted Transit Bus Emissions Based on Current Procurement Trends

Available data from APTA indicates that conventional diesel, CNG/LNG and diesel-electric hybrid buses will still account for around 99% of vehicle miles traveled in year 2009. Other niche market fuels and bus technologies, including biodiesel fuel, propane (LPG), gasoline-electric hybrids, CNG-electric hybrids and propane-electric hybrids still will not have achieved adequate market penetration to have an impact on the national transit bus emissions inventory. Projected total annual emissions from transit buses in year 2009 given present bus procurement trends is shown in Table 18.

Table 18: Projected annual emissions from the national transit bus fleet in 2009

	Number of Buses	**CO** tons	**NMHC** tons	**CH_4** tons	**NO_x** tons	**PM** tons	**CO_2** tons	**Fuel Consumed** thousands of gallons
Total Annual Emissions								
Diesel	50,003	9,577	1,667		53,981	843	6,289,918	573,989
CNG/LNG	10,064	1,331	364	6,902	7,229	9	1,003,149	125,818
Diesel Hybrid	1,525	12	2		489	1	107,814	9,805
Total	**61,592**	**10,920**	**2,032**	**6,902**	**61,699**	**853**	**7,400,881**	**709,612**
Average Emissions Levels per Bus								
		CO g/mile	**NMHC** g/mile	**CH_4** g/mile	**NO_x** g/mile	**PM** g/mile	**CO_2** g/mile	**Fuel Economy** mile/gal
Diesel		4.31	0.75		24.32	0.38	2,833	3.51
CNG/LNG		2.98	0.81	15.45	16.18	0.02	2,245	3.22
Diesel Hybrid		0.18	0.03		7.22	0.02	1,592	6.26

Table 19 shows the anticipated change in emissions in year 2009 relative to the current (2003) transit bus fleet (Table 11 vs. Table 18) assuming that transit agencies continue to execute their current bus procurement strategies, as described in the 2005 APTA Transit Vehicle Database [6]. Based on the emissions model and assumptions described above, the replacement of older model diesel buses with the latest technology diesel buses, and increased deployment of CNG and diesel-electric hybrid buses will bring about reductions in emissions of CO, NMHC, NO_x and PM emissions despite growth in the number of transit buses. Methane (CH_4) emissions will increase due to growth in the number of natural gas transit buses. While methane does not contribute to the formation of smog and is not regulated by the EPA, it is a powerful greenhouse gas and may contribute to global warming. The predictions show modest increases in CO_2 emissions and fuel consumption in approximate proportion to the growth in the national bus fleet.

Table 19: Relative change (2003-2009) in emissions considering current bus procurement trends

Number of Buses	**CO** tons	**NMHC** tons	**CH_4** tons	**NO_x** tons	**PM** tons	**CO_2** tons	**Fuel Consumed** thousands of gallons
↑ 3,556	↓ 6,165	↓ 887	↑ 1,022	↓ 10,508	↓ 649	↑ 70,738	↑ 16,723
↑ 6%	↓ 36%	↓ 30%	↑ 17%	↓ 15%	↓ 43%	↑ 1%	↑ 2%

In the next section a much larger introduction of buses with alternative fuels and technologies into the 2009 bus fleet is evaluated.

4.0 GREATER USE OF ALTERNATIVE FUELS AND TECHNOLOGIES

The purpose of this report is to assess the potential benefits of greater use of alternative fuels and technologies in the transit industry.

While conventional diesel fueled vehicles comprise the majority of transit buses currently in active service as well as the majority of new bus purchases planned by transit agencies over the next several years, several transit agencies have invested in significant numbers of compressed natural gas powered buses, as on going commitments to improving local air quality or due to pressures from regulatory agencies, transit boards and local environmental advocates. As a result CNG accounts for approximately 11% of the present transit bus fleet [5] and is expected to grow modestly to approximately 14% of the fleet by 2009.

Also, diesel-electric hybrid transit buses are an emerging technology that is gaining acceptance. The number of diesel-electric hybrid buses is expected to exceed 1,500 buses nationally by 2009 if current purchase trends continue.

Section 3.0 of this report explored the impacts of new bus procurements that are in progress or planned over the next several years. This section considers the potential benefits of much greater adoption of new clean-diesel (i.e. 2007 or newer diesel engine technology), CNG, hybrid-electric drive technologies and biodiesel fuels that might arise through stronger incentives that encourage use of alternative fuels and technologies. The following scenarios consider the national emissions impact of replacement of 15% of the existing fleet with new clean-diesel, CNG, diesel-electric hybrid, gasoline-electric hybrid and biodiesel powered buses respectively. APTA data shows that approximately 3,000 new transit buses are manufactured each year. In a 3 year period from 2007 to 2009 approximately 9,000 new transit buses will be put into service, which represents about 15% of the 2009 bus fleet. Therefore 15% replacement of existing buses represents a realistic procurement rate.

4.1 Increased Utilization of Clean Diesel Transit Buses

The first hypothetical scenario considers procurement of 9,348 (15%) clean-diesel buses. Based on APTA data, 4,730 diesel buses were purchased between 2004 and 2006 bringing the total diesel bus purchases between 2004 and 2009 to 14,078 and resulting in the hypothetical distribution shown in Table 20. The predicted total emissions resulting from this hypothetical procurement strategy are presented in Table 21. The last two rows in Table 21 show the changes in emissions above and beyond those shown in Table 19 as a result of accelerated procurement of clean-diesel technology buses. Additional reductions of 16%, 19%, 5% and 24% in CO, NMHC, NO_x and PM emissions respectively could be achieved. Emissions of CO_2 and fuel consumption would not be significantly affected.

Table 20: Hypothetical 2009 bus Fleet with 15% clean diesel fleet penetration

Power Type	2003 Fleet	Purchases	Replacements	2009 Fleet	
Clean-Diesel Technology	**49,938**	**14,078**	**11,719**	**52,297**	**83.9%**
Compressed Natural Gas	6,606	1,159	227	7,538	12.1%
Liquefied Natural Gas	1,003	62	2	1,063	1.7%
Diesel-Electric Hybrid	489	287	0	776	1.2%
Gasoline-Electric Hybrid	0	85	0	85	0.1%
Propane (liquefied petroleum gas)	265	19	0	284	0.5%
Biodiesel	80	32	0	112	0.2%
CNG-Diesel Pilot Injection	57	0	0	57	0.1%
CNG-Electric Hybrid	39	0	0	39	0.1%
Gasoline	28	5	0	33	0.1%
CNG & Gasoline	5	0	0	5	0.0%
Propane-Electric Hybrid	3	0	0	3	0.0%
Hydrogen	3	25	0	28	0.0%
Total	**58,516**	**15,752**	**11,948**	**62,320**	**100%**

Table 21: Annual Emissions from hypothetical fleet consisting of 15% new diesel buses

	Number of Buses	**CO** tons	**NMHC** tons	**CH$_4$** tons	**NO$_x$** tons	**PM** tons	**CO$_2$** tons	**Fuel Consumed** thousands of gallons
Total Annual Emissions								
Diesel	52,297	8,084	1,307		51,354	643	6,527,462	599,212
CNG/LNG	8,601	1,106	347	6,630	6,719	8	853,562	107,900
Diesel Hybrid	776	7	1		336	1	55,108	5,164
Total		**9,197**	**1,655**	**6,630**	**58,408**	**652**	**7,436,132**	**712,276**
Relative Change Compared to Current Procurement Trends								
Change		↓ 1,723	↓ 377	-	↓ 3,291	↓ 201	↑ 35,251	↑ 2,664
Percent Change		↓ 16%	↓ 19%	-	↓ 5%	↓ 24%	0%	0%

4.2 Increased Utilization of CNG Transit Buses

The second hypothetical scenario that will be considered is a 15% penetration of stoichiometric CNG buses into the national fleet by year 2009. Based on estimates of transit fleet growth, the total number of buses was estimated to reach 62,320 units by year 2009. Based in the 2005 APTA Transit Vehicle Survey, 12,451 new buses are expected to be purchased during that period. There were 7,609 CNG/LNG buses in the 2003 national fleet and 1,221 CNG/LNG buses were purchased between 2004 and 2006. In order for new stoichiometric CNG buses to reach 15% of the total fleet, 9,348 of such buses must be added to the fleet. It is assumed in this scenario that 229 existing CNG/LNG buses older than 12 years will be replaced. Based on these assumptions, a hypothetical transit bus fleet consisting of 15% new stoichiometric CNG buses might resemble the distribution shown in Table 22.

Table 22: Hypothetical 2009 bus Fleet with 15% CNG fleet penetration

Power Type	2003 Fleet	Purchases	Replacements	2009 Fleet	
Diesel Fuel/Jet A	49,938	4,730	11,719	42,949	68.9%
Compressed Natural Gas	**6,606**	**10,507**	**227**	**16,886**	**27.1%**
Liquefied Natural Gas	1,003	62	2	1,063	1.7%
Diesel-Electric Hybrid	489	287	0	776	1.2%
Gasoline-Electric Hybrid	0	85	0	85	0.1%
Propane (liquefied petroleum gas)	265	19	0	284	0.5%
Biodiesel	80	32	0	112	0.2%
CNG-Diesel Pilot Injection	57	0	0	57	0.1%
CNG-Electric Hybrid	39	0	0	39	0.1%
Gasoline	28	5	0	33	0.1%
CNG & Gasoline	5	0	0	5	0.0%
Propane-Electric Hybrid	3	0	0	3	0.0%
Hydrogen	3	25	0	28	0.0%
Total	**58,516**	**15,752**	**11,948**	**62,320**	**100%**

Based on this hypothetical procurement scenario, the predicted annual emissions in tons/year are shown in Table 23. Changes in emissions above and beyond those resulting from current known procurement trends (Table 19) are also shown. Fuel consumption would rise modestly due to the lower efficiency of CNG engines compared to diesel engines. Accelerated procurement of new stoichiometric CNG buses would result in additional reductions in CO, NMHC, NO_x, PM and CO_2 of 6%, 17%, 7%, 24% respectively. Fuel consumption in terms of energy equivalent diesel gallons would not be significantly affected. There would be a slight additional increase in methane emissions.

Table 23: Annual emissions from hypothetical fleet consisting of 15% CNG buses

	Number of Buses	CO tons	NMHC tons	CH_4 tons	NO_x tons	PM tons	CO_2 tons	Fuel Consumed thousands of gallons
Total Annual Emissions								
Diesel	42,949	7,964	1,306		48,321	634	5,343,052	487,967
CNG/LNG	17,949	2,260	384	7,323	8,802	13	1,781,963	218,635
Diesel Hybrid	776	7	1		336	1	55,108	5,164
Total		**10,231**	**1,691**	**7,323**	**57,460**	**648**	**7,180,123**	**711,766**
Relative Change Compared to Current Procurement Trends								
Change		↓ 689	↓ 341	↑ 422	↓ 4,239	↓ 205	↓ 220,758	↑ 2,154
Percent Change		↓ 6%	↓ 17%	↑ 6%	↓ 7%	↓ 24%	↓ 3%	0%

4.3 Increased Utilization of Diesel-Electric Hybrid Transit Buses

Diesel-electric hybrid drive transit buses are gaining significant momentum within the transit bus market. Several large U.S. transit agencies are procuring or planning to purchase significant numbers of diesel-electric hybrid transit buses. This scenario considered 15% penetration of new diesel-hybrid transit buses into the national fleet. Growth of the transit fleet was assumed to be the same as in previous scenario with the fleet reaching 62,320 full size transit buses by 2009.

As in the previous case, 9,348 (15%) 2007 model year or newer diesel-electric hybrid transit buses would need to be purchased in addition to the 287 diesel hybrids purchased between 2004 and 2006. Table 24 shows the demographics of a hypothetical bus fleet consisting of 15% new diesel-electric hybrid buses.

Table 24: Hypothetical 2009 bus fleet with 15% diesel hybrid fleet penetration

Power Type	2003 Fleet	Purchases	Replacements	2009 Fleet	
Diesel Fuel/Jet A	49,938	4,730	11,719	42,949	68.9%
Compressed Natural Gas	6,606	1,159	227	7,538	12.1%
Liquefied Natural Gas	1,003	62	2	1,063	1.7%
Diesel-Electric Hybrid	**489**	**9,635**	**0**	**10,124**	**16.2%**
Gasoline-Electric Hybrid	0	85	0	85	0.1%
Propane (liquefied petroleum gas)	265	19	0	284	0.5%
Biodiesel	80	32	0	112	0.2%
CNG-Diesel Pilot Injection	57	0	0	57	0.1%
CNG-Electric Hybrid	39	0	0	39	0.1%
Gasoline	28	5	0	33	0.1%
CNG & Gasoline	5	0	0	5	0.0%
Propane-Electric Hybrid	3	0	0	3	0.0%
Hydrogen	3	25	0	28	0.0%
Total	**58,516**	**15,752**	**11,948**	**62,320**	**100%**

Estimates of annual emissions from this hypothetical transit bus fleet are shown in Table 25 along with estimated reductions relative to the 2009 procurements trend level. Additional reductions of 16%, 18%, 7% and 24% in CO, NMHC, NO_x and PM emissions respectively could be achieved through accelerated procurement of diesel hybrid buses. CO, NMHC, NO_x and PM reductions are similar to those of 2007 model year conventional diesel buses because the hybrid buses benefit from the same engine technology improvements and diesel particulate filter technologies. The hybrid drive system yields additional reductions in NO_x compared to conventional diesel buses. Additional reductions in CO_2 and fuel consumption of 7% would be achieved through accelerated procurement of diesel-electric hybrid buses.

Table 25: Annual emissions from hypothetical fleet consisting of 15% diesel hybrid buses

	Number of Buses	**CO** tons	**NMHC** tons	**CH_4** tons	**NO_x** tons	**PM** tons	**CO_2** tons	**Fuel Consumed** thousands of gallons
Total Annual Emissions								
Diesel	42,949	7,964	1,306		48,321	634	5,343,052	487,967
CNG/LNG	8,601	1,106	347	6,630	6,719	8	853,562	107,900
Diesel Hybrid	10,124	73	13		2,241	9	712,916	63,087
Total		**9,144**	**1,666**	**6,630**	**57,281**	**651**	**6,909,529**	**658,954**
Relative Change Compared to Current Procurement Trends								
Change		↓ 1,776	↓ 366	-	↓ 4,418	↓ 202	↓ 491,352	↓ 50,658
Percent Change		↓ 16%	↓ 18%	-	↓ 7%	↓ 24%	↓ 7%	↓ 7%

4.4 Increased Utilization of Gasoline-Electric Hybrid Transit Buses

Electric hybrid drive systems can utilize anyone of a number of power sources including internal combustion engines fueled with diesel, gasoline, natural gas, propane or in the future by hydrogen fuel cells. Also, new hybrid drive systems currently integrate gasoline-electric hybrid drive systems into transit buses, and according to the 2005 APTA Transit Vehicle Database [6] 131 gasoline-electric hybrid buses are expected to be in service by 2009.

The following hypothetical scenario considers 15% adoption of new gasoline-electric hybrid buses into the U.S. bus fleet. In order to reach 15% of the national fleet, a total of 9,433 gasoline hybrid buses would need to be purchased (of which, 85 were purchased between 2004 and 2006). The resulting fleet demographics may resemble that shown in Table 26.

Table 26: Hypothetical 2009 bus fleet with 15% gasoline hybrid fleet penetration

Power Type	**2003 Fleet**	**Purchases**	**Replacements**	**2009 Fleet**	
Diesel Fuel/Jet A	49,938	4,730	11,719	42,949	68.9%
Compressed Natural Gas	6,606	1,159	227	7,538	12.1%
Liquefied Natural Gas	1,003	62	2	1,063	1.7%
Diesel-Electric Hybrid	489	287	0	776	1.2%
Gasoline-Electric Hybrid	**0**	**9,433**	**0**	**9,433**	**15.1%**
Propane (liquefied petroleum gas)	265	19	0	284	0.5%
Biodiesel	80	32	0	112	0.2%
CNG-Diesel Pilot Injection	57	0	0	57	0.1%
CNG-Electric Hybrid	39	0	0	39	0.1%
Gasoline	28	5	0	33	0.1%
CNG & Gasoline	5	0	0	5	0.0%
Propane-Electric Hybrid	3	0	0	3	0.0%
Hydrogen	3	25	0	28	0.0%
Total	**58,516**	**15,752**	**11,948**	**62,320**	**100%**

Limited emissions data exists in the technical literature for gasoline-electric hybrid buses. WVU measured the emissions of a 1998 MY New Flyer 40-foot transit bus equipped with a Ford Triton V-10 gasoline engine and an ISE ThunderVolt^{TM} TB40-H hybrid electric drive system. This same vehicle was also tested at the California Air Resources Board chassis dynamometer facility. The current generation of gasoline hybrid transit buses is a descendent of this technology. Estimated distance-specific emissions of gasoline-electric hybrid buses are shown in Table 27.

Table 27: Assumed OCTA equivalent emissions levels of gasoline-electric hybrid transit buses

MY Group	**Data Source**	**CO** g/mile	**HC** g/mile	**NO_x** g/mile	**PM** g/mile	**CO_2** g/mile	**Fuel Economy** mile/gal
1998-2009	1998 MY New Flyer ISE Hybrid Bus	19.15	0.40	0.86	0.027	2,567	3.41

Estimates of annual emissions from this hypothetical transit bus fleet are shown in Table 28 along with estimated reductions relative to the predicted 2009 fleet. Gasoline engines equipped with three-way catalysts produce very low NO_x and PM emissions resulting in substantial potential reductions. Potential reductions in NO_x emissions through substantial investment in gasoline-hybrid technology exceed the reductions possible with diesel-electric hybrid buses. Emissions of HC and CO from gasoline engines are typically higher than from diesel engines. Therefore, reductions of HC and CO are lower than achievable with diesel-electric hybrid buses. Throttled gasoline engines are less efficient than diesel engines resulting in somewhat higher fuel consumption.

Table 28: Annual emissions from hypothetical fleet consisting of 15% gasoline hybrid buses

	Number of Buses	**CO** tons	**NMHC** tons	**CH_4** tons	**NO_x** tons	**PM** tons	**CO_2** tons	**Fuel Consumed** thousands of gallons
Total Annual Emissions								
Diesel	42,949	7,964	1,306		48,321	634	5,343,052	487,967
CNG/LNG	8,601	1,106	347	6,630	6,719	8	853,562	107,900
Diesel Hybrid	776	7	0.9		336	0.7	55,108	5,164
Gasoline Hybrid	9,433	8,020	168		360	11	1,075,045	111,415
Total		**17,098**	**1,821**	**6,630**	**55,736**	**654**	**7,326,767**	**712,445**
Relative Change Compared to Current Procurement Trends								
Change		↑ 6,178	↓ 211	-	↓ 5,963	↓ 199	↓ 74,114	↑ 2,833
Percent Change		↑ 57%	↓ 10%	-	↓ 10%	↓ 23%	↓ 1%	0%

4.5 Increased Utilization of Biodiesel in Transit Buses

More widespread implementation of biodiesel fuel into the transit bus fleet is somewhat different than implementation of CNG and hybrid buses in that biodiesel fuel can be implemented in existing buses as well as new buses. Reaching 15% penetration of biodiesel into the national fleet does not necessarily require purchasing new buses.

Biodiesel is a class of fuels that can be produced from a variety of vegetable oils or animal fats. Although, it is often associated with being a soy-based fuel, biodiesel can be derived from other sources. Consequently, there is great potential for significant variation in product quality and specification for products generically described as biodiesel. Research has shown that there are fuel quality, handling, storage and vehicle operability requirements which need to be addressed when biodiesel is used in diesel vehicle fleets. Performance concerns also exist, particularly, the combustion of biodiesel and biodiesel blends is known to form deposits and corrosive material that may lead to fouling of injectors and fuel system components, deterioration of certain seals and gaskets and wear of engine components. Some engine manufactures do not cover biodiesel fuel under warranties and certain warranties may be voided by use of biodiesel fuel.

The impact of biodiesel fuel on emissions is also not well understood and little data exist in the technical literature. Emissions impacts may depend on the source the biodiesel fuel, the quality of the refining process used to produce the fuel, the quality and properties of the biodiesel fuel itself, the blend level of biodiesel, and the quality and properties of the conventional diesel fuel with which the biodiesel is blended. For example, if biodiesel is blended with a poorer quality conventional diesel fuel, emissions improvements may be achieved but if the biodiesel is blended with a particularly high quality diesel fuel emissions may be negatively impacted.

There are insufficient data, and insufficiently representative data, to draw any conclusions regarding the average effect of biodiesel on NO_x emissions even to determine whether biodiesel, on average, causes NO_x emissions improvements [15]. Vehicle (chassis dynamometer) data presented by NREL [15] show that for a blend of 20% biodiesel and conventional diesel (B20, the most common blend for which data exist) NO_x emissions varied from a decrease of 12% to and increase of 15% with an average of approximately 2% increase compared to conventional diesel fuel. The use of neat biodiesel fuel (B100) is not considered in this scenario since B100 is not in regular use by transit agencies due to warranty restrictions from engine manufactures and maintenance and performance concerns. Also the effect on emissions from B100 needs to be further investigated.

There is a broad consensus that biodiesel and biodiesel blends produce significant reductions in PM emissions and increase in NO_x emissions for engines up to about 1997 model year. For newer engines there are very little data available but ongoing research exists. Data indicate that biodiesel increases the reactivity of PM in a diesel particulate filter thereby improving regeneration of DOCs and diesel particulate filters (DPFs) [17].

Analysis of biodiesel impacts on emissions have been presented by the U.S. EPA in 2002 [16], and by the National Renewable Energy Laboratory (NREL) in 2006 [17]. Using data from the above sources, the change in emissions of 20% biodiesel blend (B20) compared to average diesel base fuel is shown in Table 29. These data were used to predict the impact of widespread implementation of biodiesel. NREL reported changes in break specific fuel consumption (BSFC, g/bhp-hr) which were translated to changes in fuel economy (mpg) considering that the power required to travel a specified distance is not affected by the change of fuel. Such consideration is valid in this case since the fuel-energy-content variation is not extreme and the engine is expected not to operate at maximum power and to follow the driving cycle trace equally with both diesel and B20 fuels.

Table 29: Emissions impact of 20% biodiesel added to an average diesel base fuel (B20 blend)

Fuel	**Data Source**		**After treatment**	**CO g/bhp-hr**	**HC g/bhp-hr**	**NO_x g/bhp-hr**	**PM g/bhp-hr**	**BSFC g/bhp-hr**
Diesel	2002 MY 5.9L 300 hp Cummins ISB [(a)], NREL [17]		Without DPF	1.53	0.25	2.16	0.1329	189.7
B20				1.2	0.126	2.26	0.1009	194.8
Diesel			With DPF	0.04	0.002	2.16	0.0014	191.6
B20				0.03	0.001	2.25	0.001	196.5
After treatment	**MY**	**Source**	**CO**	**HC**	**NO_x**	**PM**	**CO_2**	**Fuel Economy**
w/o DOC	1997 and older	EPA [16]	-11.0%	-21.1%	2.0%	-10.1%	0.6%	-2.1%
DOC and w/o DOC	2004 and newer	NREL [17]	-22%	-50%	4%	-24%	0.7% [(b)]	-2.6%
DPF	2004 and newer	NREL [17]	N.D. [(c)]	-74%	4%	-27%	0.5% [(b)]	-2.5%

[(a)] Cooled high-pressure EGR, variable geometry turbocharger, calibrated to meet 2004 U.S. emissions standards.

[(b)] The effects of B20 in CO_2 emissions were evaluated by carbon balance, from fuel consumption, HC and CO emissions, and fuel properties data.

[(c)] Non detectable differences with 95% confidence

4.5.1. Use of Biodiesel in the Older Buses

Diesel buses manufactured after January 1st 2007 will be equipped with DPFs and will have very low PM emissions levels (less than one third of DOC levels). Given such low emissions levels of DPF equipped buses and that biodiesel fuel should be utilized in buses where it offers the highest benefit in PM, HC and CO reductions, this scenario considers the 2009 bus fleet described in Section 3.0 but contemplates converting the oldest diesel buses to biodiesel fuel, thus giving the best emissions impact. It should be noted that once the oldest buses are retired from the fleet, the highest benefit from biodiesel fuel will be transferred to its use in newer buses. A hypothetical fleet comprised of 15% B20 usage in older model buses is shown in Table 30. Figure 22 presents the vehicle model year distributions from the diesel and B20 biodiesel hypothetical fleets. Emissions of these buses when fueled with B20 biodiesel were estimated based on the data from Table 29. Table 31 shows the estimated total annual emissions from the U.S. transit bus fleet considering 15% implementation of B20 in the older model buses.

Table 30: Hypothetical 2009 bus fleet with 15% B20 biodiesel

Power Type	2003 Fleet	Purchases	Replacements	2009 Fleet	
Diesel Fuel/Jet A	49,938	8,712	17,856	40,794	65.5%
Compressed Natural Gas	6,606	2,323	0	8,929	14.3%
Liquefied Natural Gas	1,003	132	0	1,135	1.8%
Diesel-Electric Hybrid	489	1,036	0	1,525	2.4%
Gasoline-Electric Hybrid	0	131	0	131	0.2%
Propane (liquefied petroleum gas)	265	23	0	288	0.5%
Biodiesel	**80**	**9,285**	**17**	**9,348**	**15.0%**
CNG-Diesel Pilot Injection	57	0	0	57	0.1%
CNG-Electric Hybrid	39	0	0	39	0.1%
Gasoline	28	6	0	34	0.1%
CNG & Gasoline	5	0	0	5	0.0%
Propane-Electric Hybrid	3	0	0	3	0.0%
Hydrogen	3	29	0	32	0.1%
Total	**58,516**	**21,677**	**17,873**	**62,320**	**100%**

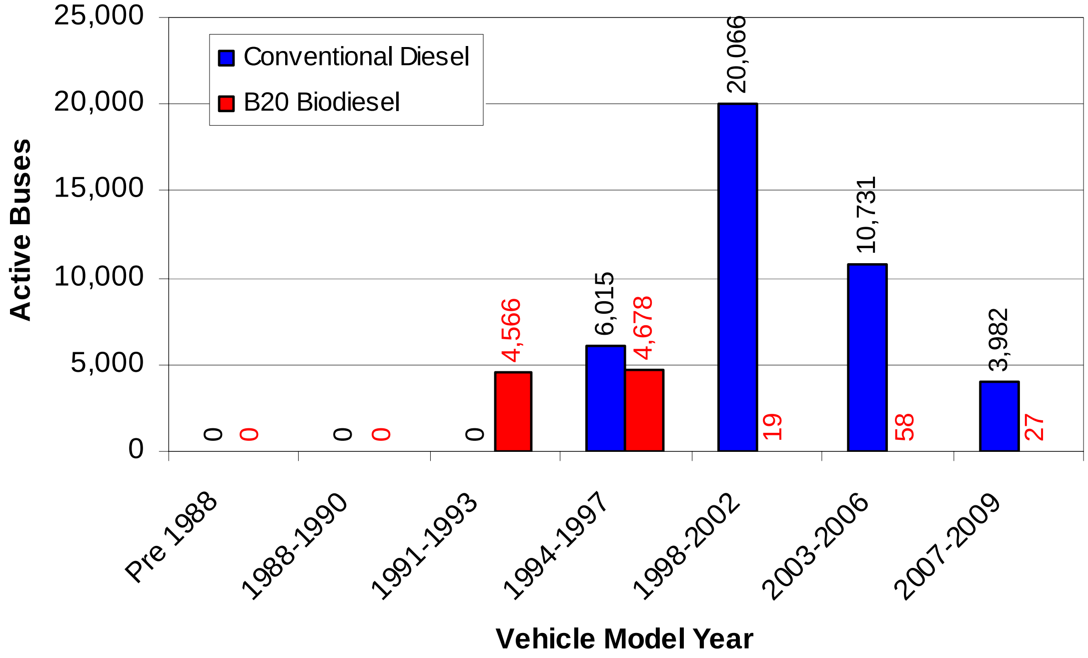


Figure 22: Distribution of diesel and biodiesel transit buses by VMY from hypothetical fleet consisting of 15% B20 biodiesel fueled older model year buses

Table 31: Annual emissions from hypothetical fleet consisting of 15% B20 biodiesel usage in older model buses

	Number of Buses	**CO** tons	**NMHC** tons	**CH$_4$** tons	**NO$_x$** tons	**PM** tons	**CO$_2$** tons	**Fuel Consumed** thousands of gallons
Total Annual Emissions								
Diesel	40,794	5,872	863		41,733	447	5,127,291	472,336
CNG/LNG	10,064	1,331	364	6,902	7,229	9	1,003,149	125,818
Diesel Hybrid	1,525	12	2		489	1	107,814	9,805
Biodiesel	9,348	3,320	637		12,618	358	1,187,714	105,529
Total		**10,536**	**1,866**	**6,902**	**62,068**	**815**	**7,425,969**	**713,488**
Relative Change Compared to Current Procurement Trends								
Change		↓ 384	↓ 166	-	↑ 369	↓ 38	↑ 25,087	↑ 3,876
Percent Change		↓ 4%	↓ 8%	-	↑ 1%	↓ 4%	0%	↑ 1%

Conversion to B20 of 15% of the fleet (the oldest diesel buses in the 2009 fleet) would result in a modest decrease in CO, HC and PM emissions, and a small increase in NO$_x$ emissions, CO$_2$ emissions and fuel consumed. It should be noted that introduction of B20 in 15% of the bus fleet would reduce the end use of petroleum diesel fuel by 3.0% and the total end use fossil fuel consumption (diesel equivalent for CNG/LNG consumption) by 2.4%.

End use values for emissions and fuel consumption are given since a life cycle analysis is beyond the scope of this report. Emissions and fuel consumed during biodiesel production are not considered. Hill et al. [18] conducted a life cycle analysis in soybean based biodiesel (B100) and determined that its production and use releases 59% of the net greenhouse gas emissions of an energetically equivalent amount of petroleum diesel; that is, biodiesel can reduce net greenhouse gas emissions by 41%. Hill et al. [18] also determined that, when by-products are accounted for, biodiesel yields 93% more energy than the energy invested in its production. As a contrast, an earlier work [19] determined that B100 would reduce life cycle consumption of petroleum by 95% and yield 3.2 units of fuel product energy for every unit of fossil fuel energy consumed. The differences in the results from both studies may be attributed primarily to the larger system boundaries established by Hill et al.

4.5.2. Use of Biodiesel in the Newer Buses

Biodiesel could also be implemented in the newer model diesel buses within the fleet. A hypothetical fleet using B20 in 15% of the newer buses is considered here. The fleet distribution is the same as Table 30, but in this case biodiesel is implemented in the newer buses. The vehicle model year distributions from the diesel and B20 biodiesel hypothetical fleets are presented in Figure 23 and the predicted emissions are shown in Table 32. Implementation of B20 fuel in 15% of the newer buses within the fleet will have a lower impact on CO, NMHC and PM emissions compared to conversion of the older model buses.

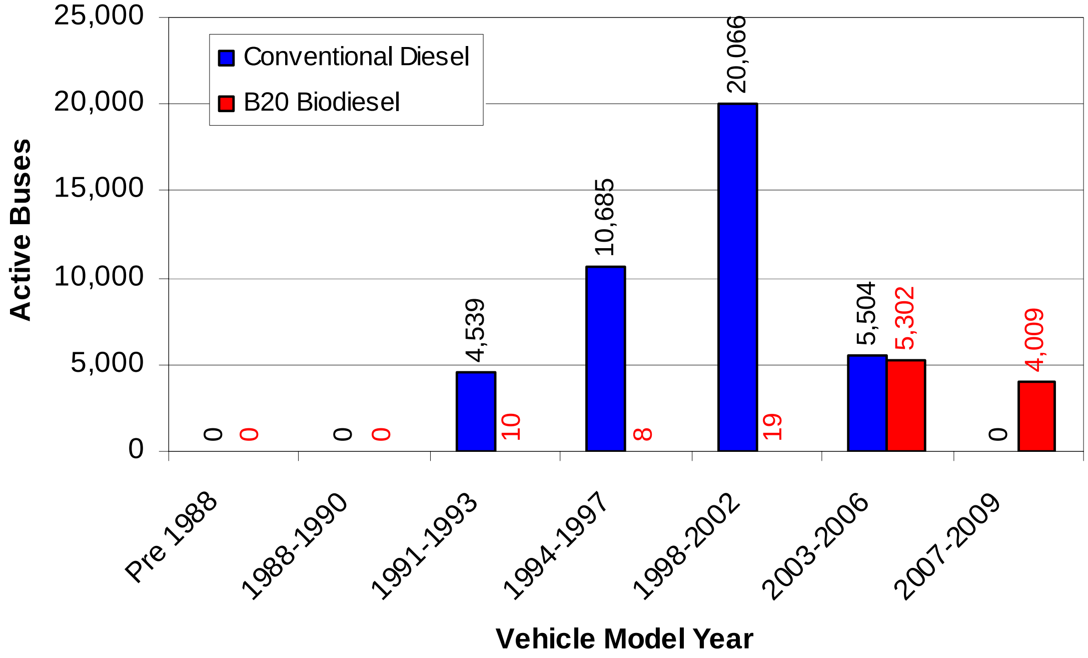


Figure 23: Distribution of diesel and biodiesel transit buses by VMY from hypothetical fleet consisting of 15% B20 biodiesel fueled newer buses

Table 32: Annual emissions from hypothetical fleet consisting of 15% B20 biodiesel usage in newer model buses

	Number of Buses	**CO** tons	**NMHC** tons	**CH_4** tons	**NO_x** tons	**PM** tons	**CO_2** tons	**Fuel Consumed** Thousands of Gallons
Total Annual Emissions								
Diesel	40,794	8,779	1,615		49,157	790	5,123,119	464,398
CNG/LNG	10,064	1,331	364	6,902	7,229	9	1,003,149	125,818
Diesel Hybrid	1,525	12	2		489	1	107,814	9,805
Biodiesel	9,348	651	28		5,128	42	1,191,775	114,152
Total		**10,773**	**2,008**	**6,902**	**62,004**	**842**	**7,425,858**	**714,172**
Relative Change Compared to Current Procurement Trends								
Change		↓ 147	↓ 24	-	↑ 304	↓ 11	↑ 24,977	↑ 4,560
Percent Change		↓ 1%	↓ 1%	-	0%	↓ 1%	0%	↑ 1%

Finally, considering conversion of all diesel buses to B20 would represent an 18% reduction in final use petroleum diesel fuel and 14% reduction in final use fossil fuel consumption, and additional reductions in CO, HC and PM emissions. Such special scenario is presented in Appendix B.

4.6 Benefits of 15% Implementation of Alternative Fuels and Technologies

Section 3.0 of this report predicted the emissions and fuel consumption impacts that can be anticipated if transit agencies continue to execute their ongoing and planned new bus procurements as reported in the 2005 APTA Fact Book [5]. Table 19 showed predicted emissions changes as a result of the anticipated 2009 transit bus fleet relative to the 2003 fleet (Table 11). Section 4.0 considers the potential additional benefits that could be achieved through accelerated replacement of older model buses with new technology buses:

1. New diesel buses meeting the 2007 emissions standards,
2. New CNG buses with stoichiometric natural gas engines which meet or exceed the 2007 EPA standards,
3. Diesel-electric hybrid buses with 2007 compliant engines,
4. Gasoline-electric hybrid buses,
5. Increased utilization of B20 biodiesel fuel existing buses (both older model and newer model buses were evaluated).

Table 33 shows the incremental additional reductions above and beyond those for the 2009 predicted bus fleet which could be achieved by accelerating the implementation of the five most probable alternatives to conventional diesel buses.

Table 33: Impact of implementing alternative fuels and technologies in 15% of the 2009 transit bus fleet

	CO tons	**NMHC** tons	**CH_4** tons	**NO_x** tons	**PM** tons	**CO_2** tons	**Fuel Consumed** thousands of gallons
Clean Diesel	↓ 1,723	↓ **377**	-	↓ 3,291	↓ 201	↑ 35,251	↑ 2,664
CNG	↓ 689	↓ 341	↑ 422	↓ 4,239	↓ **205**	↓ 220,758	↑ 2,154
Diesel Hybrid	↓ **1,776**	↓ 366	-	↓ 4,418	↓ 202	↓ **491,352**	↓ **50,658**
Gasoline Hybrid	↑ 6,178	↓ 211	-	↓ **5,963**	↓ 199	↓ 74,114	↑ 2,833
Biodiesel (B20) [(a)]	↓ 384	↓ 166	-	↑ 369	↓ 38	↑ 25,087	↑ 3,876
	Percent Incremental Change						
Clean Diesel	↓ 16%	↓ 19%	-	↓ 5%	↓ 24%	0%	0%
CNG	↓ 6%	↓ 17%	↑ 6%	↓ 7%	↓ 24%	↓ 3%	0%
Diesel Hybrid	↓ 16%	↓ 18%	-	↓ 7%	↓ 24%	↓ 7%	↓ 7%
Gasoline Hybrid	↑ 57%	↓ 10%	-	↓ 10%	↓ 23%	↓ 1%	0%
Biodiesel (B20) [(a)]	↓ 4%	↓ 8%	-	↑ 1%	↓ 4%	0%	↑ 1%

[(a)] Implemented in the older diesel buses of the fleet

The first scenario considered accelerated acquisition of conventional diesel buses with 2007 emissions compliant engines. Emissions reductions arise through more rapid replacement of older model diesel buses with lower emitting diesel buses equipped with advanced NO_x control technologies and catalyzed diesel particulate filters. The second scenario considered procurement of an equal number of CNG buses equipped with the newest technology stoichiometric natural gas engines. Reductions of NMHC and PM emissions are similar to those achieved by clean-diesel technology buses. NO_x reductions are slightly better than predicted for clean-diesel buses. According to the emissions data available and the prediction method, CNG buses offer superior reductions in CO_2 emissions compared to clean-diesel buses. CNG buses offer less advantage in terms of CO emissions and produce methane emissions. Increasing the number of diesel-electric hybrid buses to 15% of the fleet results in similar reductions in CO, NMHC, and PM emissions as conventional diesel buses because both bus types benefit from the same improvements in diesel engine technology and diesel particular filters.

The diesel-electric hybrid buses offer additional NO_x reductions as a result of the hybrid drive system. Diesel hybrid buses yield the largest reductions in CO_2 emissions and are the only technology to show a reduction in fuel consumption based on the available data for the predictive model. Gasoline-electric hybrid buses offer the highest NO_x emissions reductions due to the vanishingly low NO_x levels of gasoline engines with 3-way catalysts. Reductions in PM emissions are similar to conventional diesel and diesel hybrids. Gasoline hybrids also reduce NMHC and CO_2 emissions but not to the degree of conventional diesel, diesel-electric hybrid and CNG buses. It should be noted that the emissions data available for gasoline hybrid buses were measured from a very early version of this technology. Emissions test results for more recent gasoline-electric hybrid buses do not exist in the literature. Emissions testing of the latest versions of gasoline hybrid buses should be conducted to provide more accurate data for transit agencies and emission inventory prediction models such as this.

Little emissions data exists in the literature for biodiesel fueled buses. Given the lack of adequate data, the best effort was made to predict the impact of increased use of biodiesel in transit buses. The results of this best effort indicate that the maximum benefit of B20 biodiesel usage would be achieved by converting the oldest buses in the fleet to biodiesel rather than newer buses. The predictions indicate slight additional reductions in CO, NMHC and PM emissions compared to anticipated 2009 levels could be achieved through conversion of 15% of the oldest model diesel buses to biodiesel with less than a 1% increase in NO_x, CO_2 and fuel consumption.

Considering the predictions shown in Table 33, diesel-electric hybrid buses appear to offer the best overall environmental benefits.

5.0 CONCLUSIONS

The objective of this report was to estimate the impacts that could be associated with an increased rate of implementation of alternative fuels and new technologies into the U.S. transit bus industry if incentives were put in place to encourage the adoption of alternative fuels and technology. The analysis considered accelerated implementation of (1) 2007 clean-diesel technology buses running on ultra-low sulfur diesel fuel; (2) stoichiometric natural gas buses; (3) diesel-electric hybrid buses utilizing 2007 technology diesel engines; (4) gasoline-electric hybrid buses; and (5) conversion of existing buses to B20 biodiesel fuel. Replacement of 15% of the oldest existing transit buses with each of the above technologies between 2006 and 2009 was considered. A

15% replacement rate was determined to be feasible in a three year period based on APTA data [5] on the number of new buses manufactured per year.

The study specifically examines environmental benefits and does not include life cycle costs of the vehicles or capital improvements, which are beyond the scope of this analysis. Emissions life-cycle analysis is also excluded from this study. The cost structure of different alternative fueled vehicles and advanced technology vehicles is addressed in a separate study [27].

In order to establish a baseline, cumulative emissions (in tons/year) produced nationally by the U.S. transit fleet in 2003 were estimated based on fleet statistics data published by APTA and measured emissions test results for transit buses. Based on the methodology used, the predicted emissions of the U.S. transit bus fleet are shown in Table 34.

Table 34: Summary of emissions from the 2003 U.S. transit bus fleet

Number of Buses	**CO** tons	**NMHC** tons	**CH$_4$** tons	**NO$_x$** tons	**PM** tons	**CO$_2$** tons	**Fuel Consumed** thousands of gallons
58,036	**17,085**	**2,920**	**5,879**	**72,207**	**1,502**	**7,330,143**	**692,889**

The emissions that could be expected in the year 2009 if the U.S. transit agencies implemented their current procurement strategies were then estimated. Information about ongoing and planned procurements was taken from the 2005 APTA Fact Book [5] and Transit Vehicle Database [6]. It was assumed that new bus procurements replaced the oldest model diesel transit buses in the U.S. fleet. The predicted 2009 levels and the relative change with respect to the 2003 levels are shown in Table 35. The predictions indicated that ongoing and planned procurements of the latest technology diesel buses and increased deployment of CNG and diesel-electric hybrid buses will reduce emissions of CO, NMHC, NO$_x$ and PM emissions despite growth in the number of transit buses and annual vehicle miles traveled. Modest increases in CO$_2$ emissions and fuel consumption are expected due to growth in the number of transit buses. Methane emissions are also expected to increase due to growth in the number of CNG buses.

Table 35: Summary of emissions from the 2009 U.S. transit bus fleet

Number of Buses	**CO** tons	**NMHC** tons	**CH$_4$** tons	**NO$_x$** tons	**PM** tons	**CO$_2$** tons	**Fuel Consumed** thousands of gallons
61,592	**10,920**	**2,032**	**6,902**	**61,699**	**853**	**7,400,881**	**709,612**
↑ 3,556	↓ 6,165	↓ 887	↑ 1,022	↓ 10,508	↓ 649	↑ 70,738	↑ 16,723

Four hypothetical scenarios were considered in which, the latest technology diesel buses, CNG buses, diesel-electric hybrid buses, gasoline electric hybrid buses were individually increased to 15% of the fleet. A fifth hypothetical scenario considered conversion of 15% of the existing transit buses to B20 biodiesel; it was determined that conversion of the oldest buses offered the highest emissions advantage rather than converting to biodiesel the newer model buses. The additional incremental change in emissions and fuel consumption above and beyond those anticipated based on current procurement trends were predicted for each case and are shown in Table 36.

Table 36: Relative potential changes in emissions due to 15% implementation of alternative fuels and new technologies compared to the anticipate 2009 fleet emissions

	CO tons	**NMHC** tons	**CH_4** tons	**NO_x** tons	**PM** tons	**CO_2** tons	**Fuel Consumed** thousands of gallons
Clean Diesel	↓ 1,723	↓ **377**	-	↓ 3,291	↓ 201	↑ 35,251	↑ 2,664
CNG	↓ 689	↓ 341	↑ 422	↓ 4,239	↓ **205**	↓ 220,758	↑ 2,154
Diesel Hybrid	↓ **1,776**	↓ 366	-	↓ 4,418	↓ 202	↓ **491,352**	↓ **50,658**
Gasoline Hybrid	↑ 6,178	↓ 211	-	↓ **5,963**	↓ 199	↓ 74,114	↑ 2,833
Biodiesel (B20) (a)	↓ 384	↓ 166	-	↑ 369	↓ 38	↑ 25,087	↑ 3,876

(a) Implemented in the older diesel buses of the fleet

Accelerated implementation of all of the technologies considered offer some benefits over current procurement trends. New technology conventional diesel and diesel-electric hybrid buses offer similar reductions in CO, NMHC, NO_x and PM emissions because both benefit from the most recent clean-diesel technology engines. Increased implementation of CNG buses offer similar reductions in NMHC, NO_x and PM compared to diesel and diesel-electric hybrids. CNG buses appear superior to conventional clean-diesel buses in terms of CO_2 emissions. Gasoline-electric hybrid buses also offer similar reductions in NMHC, and PM to conventional diesel, diesel-electric hybrid and CNG and are superior to all technologies in terms of NO_x reductions. In terms of emissions, the technologies considered are closely grouped due to fuel neutral EPA emissions regulations of 2007. Based on the predicted impacts on emissions shown in Table 36 and Figure A 1 (global warming potential estimates), diesel-electric hybrid buses appear to offer the best overall environmental benefits and is the only technology to result in a reduction in fossil fuel consumption.

6.0 RECOMMENDATIONS

- This analysis considered the 2003 U.S. Transit fleet as the baseline for comparison. It is recommended that a second analysis be conducted using the most recent APTA data from the 2007 editions of the Public Transportation Fact Book and Transit Vehicle Database.
- It is recommended that this analysis be repeated and extended at a later date to include the impacts of new technology buses manufactured after the EPA 2010 emissions regulation come into force. At present insufficient data on new bus procurements and the anticipated emissions levels exist for such analysis to be performed. However, the analysis will be possible in the near future.
- The impact of biodiesel fuel on emissions is not well understood and little data exist in the technical literature. Emissions impacts may depend on the source the biodiesel fuel, the quality of the refining process used to produce the fuel, the quality and properties of the biodiesel fuel itself, the blend level of biodiesel, and the quality and properties of the conventional diesel fuel with which the biodiesel

is blended. Further emissions testing needs to be conducted to better quantify and understand the impact of biodiesel fuels on emissions of both legacy and new technology diesel engines and vehicles.

- The emissions and fuel economy of hybrid transit buses is highly affected by driving conditions (i.e. route duty cycles) and power train configuration. Further study is needed to better understand and quantify these effects in order to enable that hybrid buses are utilized in applications which maximize their benefits.

APPENDIX A: GLOBAL WARMING POTENTIAL ESTIMATES

The greenhouse effect is caused by the absorption of terrestrial radiation leaving the surface of the Earth. Under normal conditions, the energy content of the Earth would be balanced between solar –low wavelength– incoming radiation and terrestrial –long wavelength– outgoing radiation. On the other hand, under greenhouse conditions, the energy content of the Earth is not balanced and energy is stored continuously thus increasing the Earth's temperature, i.e. causing global warming.

The greenhouse effect is produced by the atmospheric concentration of water vapor, carbon dioxide, and other trace gases [25]. Increasing the atmospheric concentrations of these greenhouse gases alters the balance of the Earth's energy transfers (e.g. atmosphere, space, land, and the oceans [20]). A gauge of these changes is called radiative forcing, which is a measure of changes in the energy available to the Earth-atmosphere system (i.e. a change in the net absorption of energy by the Earth) [25].

Greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). Numerous alogenated substances containing fluorine, chlorine or, bromine are also greenhouse gases. Other gases that do not have a direct radiative forcing effect are also considered greenhouse gases since they influence the global radiation budget by atmospheric reactions that alter the atmosphere's composition. Such tropospheric gases or pollutants include carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and tropospheric (ground level) ozone (O_3) [20, 24]. The Intergovernmental Panel on Climate Change (IPCC) [24] recognizes that tropospheric ozone is formed by photochemical reactions with two precursor pollutants, namely volatile organic compounds (VOCs) and nitrogen oxides (NO_x), and that VOCs and NO_x not only affect ozone concentrations but also influence lifetimes (residence times) of other greenhouse gases. Finally, aerosols, i.e. microscopic airborne particles (such as PM emissions or liquid droplets), may also affect the absorptive characteristics of the atmosphere [20, 24].

A quantitative measure of the globally averaged relative radiative forcing impacts of a particular greenhouse gas is provided by its Global Warming Potential (GWP). The GWP of a greenhouse gas is defined as the ratio of the time-integrated radiative forcing (both direct and indirect effects) from the instantaneous release of 1 unit mass of a trace substance relative to that of 1 unit mass of a reference gas [24]. The reference gas used is CO_2, and therefore GWP weighted emissions are measured in mass of CO_2 equivalent emissions. The reference mass units are teragrams (Tg) and GWPs are reported in Tg CO_2 Eq. Although other time horizon values are available, the IPCC and the United Nations Framework Convention on Climate Change (UNFCCC) [26] have agreed to use GWPs based upon a 100-year time horizon.

GWPs and atmospheric lifetimes of selected gases are presented in Table A 1 [IPCC 1996, 25]. Global warming potentials are not provided for CO, NO_x, non-methane volatile organic compounds (NMVOCs, which include NMHC), SO_2, and aerosols (including PM) because there is no agreed-upon method to estimate the contribution of gases that are short-lived in the atmosphere, spatially variable, or have only indirect effects on radiative forcing [22, 25].

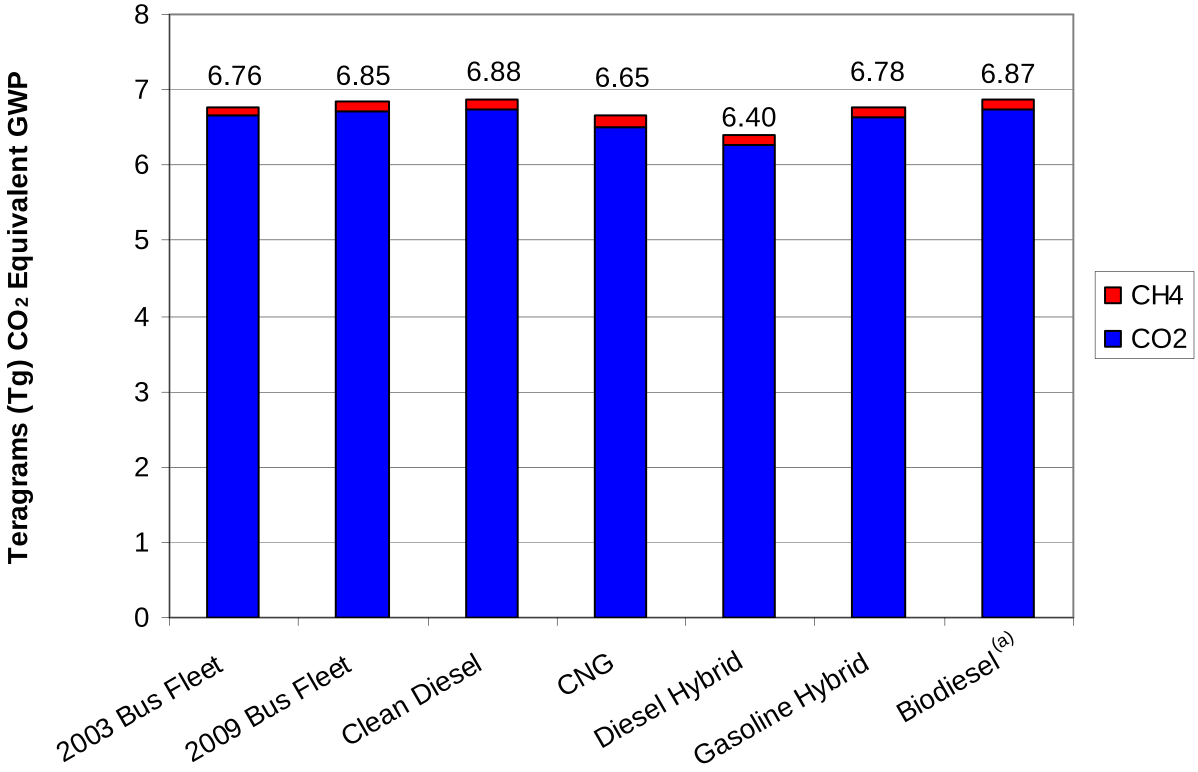
Table A 1: Global warming potentials and atmospheric lifetimes of selected greenhouse gases

Gas	Atmospheric Lifetime years	GWP [(a)]
Carbon dioxide (CO_2)	50 - 200	1
Methane (CH_4) [(b)]	12 ± 3	21
Nitrous oxide (N_2O)	120	310

Source: IPCC 1996 [25]
[(a)] 100-year time horizon
[(b)] The GWP of CH_4 includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO_2 is not included.

Even though scarce data exist on nitrous oxide (N_2O) emissions from heavy-duty vehicles, U.S. EPA developed emission factors [21] (as a function of emissions control technology) and used them to estimate the 1990-2005 national emissions inventory [22]. Mobile sources-N_2O emissions values [22, section 3.4] and studies on NO_x/N_2O ratios [23] reveal that the N_2O contribution of highway heavy-duty vehicles to the overall mobile sources emissions and GWPs is very small (less than 3%) and it is safe to neglect N_2O GWPs from transit buses. Nevertheless, further research and understanding of N_2O emissions from transit buses and other mobile sources is needed.

CO_2 and CH_4 emissions estimates –in Tg CO_2 Eq.– for the U.S. transit bus fleet are presented in Figure A 1; global warming potentials are shown for 2003 and 2009 U.S. bus fleets, and for the different alternative fuels and technologies implementation scenarios considered. Since CO, NMHC, NO_x and PM do not participate so far in global warming calculations and the CH_4 contribution is minor, the conclusions from GWP calculations are similar to those drawn from CO_2 mass-emissions (tons) and fuel consumed alone.



[a] Implemented in the older diesel buses of the fleet

Figure A 1: CO_2 and CH_4 emissions from the U.S. transit bus fleet (Tg CO_2 Eq.)

APPENDIX B: CONVERSION OF ALL DIESEL BUSES TO BIODIESEL

Continuing the analysis presented in Section 4.0, a hypothetical fleet where all diesel fuel buses are converted to B20 is shown in Table B 1. Figure B 1 presents the vehicle model year distributions from the hypothetical fleet; Table B 2 presents the annual emissions and fuel consumed, and compares them with the 2009 baseline bus fleet.

Table B 1: Hypothetical 2009 bus fleet with biodiesel implemented in all diesel buses

Power Type	2003 Fleet	Purchases	Replacements	2009 Fleet	
Diesel Fuel/Jet A	49,938	8,712	58,650	0	0.0%
Compressed Natural Gas	6,606	2,323	0	8,929	14.3%
Liquefied Natural Gas	1,003	132	0	1,135	1.8%
Diesel-Electric Hybrid	489	1,036	0	1,525	2.4%
Gasoline-Electric Hybrid	0	131	0	131	0.2%
Propane (liquified petroleum gas)	265	23	0	288	0.5%
Biodiesel	**80**	**50,079**	**17**	**50,142**	**80.5%**
CNG-Diesel Pilot Injection	57	0	0	57	0.1%
CNG-Electric Hybrid	39	0	0	39	0.1%
Gasoline	28	6	0	34	0.1%
CNG & Gasoline	5	0	0	5	0.0%
Propane-Electric Hybrid	3	0	0	3	0.0%
Hydrogen	3	29	0	32	0.1%
Total	**58,516**	**62,471**	**58,667**	**62,320**	**100%**

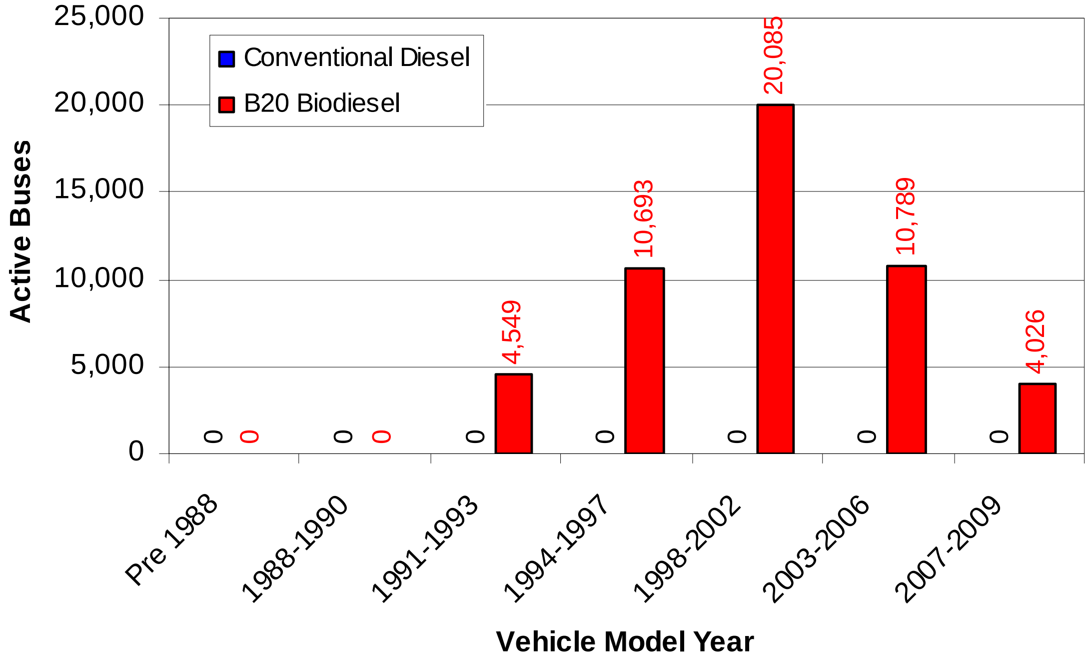


Figure B 1: Distribution of diesel and biodiesel transit buses by VMY from hypothetical fleet with biodiesel implemented in all diesel buses

Table B 2: 2009 Annual emissions from hypothetical fleet consisting of B20 biodiesel implemented in all diesel buses

	Number of Buses	**CO** tons	**NMHC** tons	**CH$_4$** tons	**NO$_x$** tons	**PM** tons	**CO$_2$** tons	**Fuel Consumed** thousands of gallons
Total Annual Emissions								
Diesel	0	0	0		0	0	0	0
CNG/LNG	10,064	1,331	364	6,902	7,229	9	1,003,149	125,818
Diesel Hybrid	1,525	12	2		489	1	107,814	9,805
Biodiesel	50,142	8,239	1,227		55,594	729	6,347,630	589,481
Total		**9,582**	**1,593**	**6,902**	**63,312**	**739**	**7,458,593**	**725,104**
Relative Change Compared to Current Procurement Trends								
Change		↓ 1,338	↓ 440	-	↑ 1,613	↓ 114	↑ 57,712	↑ 15,492
Percent Change		↓ 12%	↓ 22%	-	↑ 3%	↓ 13%	↑ 1%	↑ 2%

Conversion to B20 of all the diesel buses in the fleet would result in a moderate decrease in CO, HC and PM emissions, and a small increase in NO$_x$ emissions, CO$_2$ emissions and fuel consumed. Introduction of B20 in all diesel buses of the fleet would reduce the end use of petroleum diesel fuel by 18% and the total end use fossil fuel consumption (diesel equivalent for CNG/LNG consumption) by 14%.

NOMENCLATURE

APTA	American Public Transportation Association
B20	Fuel blend with 20% Biodiesel and 80% conventional diesel fuels
B100	Neat biodiesel fuel
CBD	Central Business District Test Cycle
CH_4	Methane emissions
CNG	Compressed natural gas
CO	Carbon monoxide emissions
CO_2	Carbon dioxide emissions
DDC	Detroit Diesel Corporation
DOC	Diesel oxidation catalyst
DPF	Catalyzed diesel particulate filter
EGR	Exhaust gas recirculation
EPA	U.S. Environmental Protection Agency
FTA	Federal Transit Administration
g/mile	Grams of pollutant emitted per mile traveled
GWP	Global Warming Potential
HC	Total hydrocarbons emissions
mpg	Miles per gallon
NMHC	Non-methane hydrocarbons emissions
NO_x	Oxides of nitrogen emissions
N_2O	Nitrous Oxide
OCTA	Orange County Transit Authority Test Cycle
PM	Total particulate matter emissions
Ppm	Parts per million
SAE	Society of Automotive Engineers International
SO_2	Sulfur Dioxide
Tg	Teragrams
UDDS	Heavy-Duty Urban Dynamometer Driving Schedule
VMT	Vehicle miles traveled
VMY	Vehicle model year
VOC	Volatile Organic Compounds
WMATA	Washington Metropolitan Area Transit Authority Test Cycle

REFERENCES

1. "Alternative Fuels Study: A Report to Congress on Policy Options for Increasing the Use of Alternative Fuels in Transit Vehicles", United States Department of Transportation, Federal Transit Administration, December 2006. http://www.fta.dot.gov/documents/Alternative_Fuels_Study_Report_to_Congress.pdf.
2. "Fuel Economy Measurement Test (Engineering Type) for Trucks and Buses", SAE Document Number J1376, Society of Automotive Engineers International, Warrendale PA, 1997.
3. Code of Federal Regulations, Title 40, Part 86, "Protection of Environment – Control of Emissions from New and In-Use Highway Vehicles and Engines", U.S. Government Printing Office, Washington DC, 2005.
4. "Recommended Practice for Measuring Fuel Economy and Emissions of Hybrid-Electric and Conventional Heavy-Duty Vehicles", SAE Document Number J2711 Society of Automotive Engineers International, Warrendale PA, 2002.
5. "2005 Public Transportation Fact Book, 56th Edition", American Public Transportation Association, Washington DC. ISBN 1-931594-14-7, March 2005. www.apta.com
6. "2005 APTA Transit Vehicle Database", American Public Transportation Association, Washington DC. ISBN 1-931594-17-1, May 2005. www.apta.com
7. Clark N.N., Prucz J.C., Gautam M., and Lyons D.W., "The West Virginia University Heavy Duty Vehicle Emissions Database as a Resource for Inventory and Comparative Studies", Society of Automotive Engineers, 2000-01-2854, 2000.
8. "Emissions Facts: Average Carbon Dioxide Emissions Resulting from Gasoline and Diesel Fuel", U.S. Environmental Protection Agency, EPA420-F-05-001, February 2005. http://www.epa.gov/otaq/climate/420f05001.htm
9. "2002 National Emissions Inventory Data & Documentation", U.S. Environmental Protection Agency, February, 2006. http://www.epa.gov/ttn/chief/net/2002inventory.html
10. "MOBILE6 Vehicle Emission Modeling Software", U.S. Environmental Protection Agency, March 2006. http://www.epa.gov/otaq/m6.htm
11. Kubsh J., "Advanced Emissions Controls for Natural Gas Vehicles", DOE Natural Gas Vehicle Technology Forum, Manufacturers of Emissions Control Association, May 2006. http://www.nrel.gov/vehiclesandfuels/ngvtf/pdfs/adv_emission_controls_kubsh.pdf
12. Ouellette P., "Emissions from HD Natural Gas Vehicles", BC Lung Air Quality and Health Workshop, March 2006. http://www.bc.lung.ca/services/OuelletteEmissions.pdf

13. Nylund N., Erkkilä K., Lappi M., and Ikonen M., “Transit Bus Emissions Study: Comparison of Emissions from Diesel and Natural Gas Buses”, Research Report, VTT Technical Research Centre of Finland, October 2004. http://www.vtt.fi/inf/pdf/jurelinkit/VTTNylund.pdf
14. Erkkilä K. and Nylund N., “Transit Bus Emissions Study: 2006 Annual Report”, VTT Technical Research Centre of Finland, April 2007, In Finnish. http://www.vtt.fi/inf/julkaisut/muut/2007/RakeBus2006.pdf.
15. McCormick B., Alleman T., Barnitt R., Clark W., Hayes B., Ireland J., Proc K., Ratcliff M., Thornton M., Whitacre S., and Williams A., “Biodiesel R&D at NREL”, National Biodiesel Conference & Expo February 5-8, 2006 San Diego CA. http://www.nrel.gov/vehiclesandfuels/npbf/pdfs/39538.pdf
16. “A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions”, Draft Technical Report, EPA420-P-02-001, U.S. Environmental Protection Agency, Assessment and Standards Division, Office of Transportation and Air Quality, October 2002. http://www.epa.gov/otaq/models/analysis/biodsl/p02001.pdf
17. Williams A., McCormick R.L., Hayes R.R., Ireland J., and Fang H.L., “Effect of Biodiesel Blends on Diesel Particulate Filter Performance”, Powertrain and Fluid Systems Conference and Exhibition, October 2006, Toronto, Canada, SAE paper. NREL/CP-540-40015. http://www.nrel.gov/vehiclesandfuels/npbf/pdfs/40015.pdf
18. Hill J., Nelson E., Tilman D, Polasky S., and Tiffany D., “Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels”, Proceedings of the National Academy of Sciences USA, 103:11206-11210.
19. Sheehan J., Cacombreco V., Duffield J., Graboski M., and Shapouri H., “Life cycle inventory of biodiesel and petroleum diesel for use in an urban bus”, National Renewable Energy Laboratory, May 1998, NREL/SR-580-24089. www.nrel.gov/docs/legosti/fy98/24089.pdf
20. “Greenhouse gases and global warming potential values”, Excerpt from *Inventory of U.S. greenhouse gas emissions and sinks: 1990-2000*, U.S. Environmental Protection Agency, Office of Atmospheric Programs, April 2002. http://www.epa.gov/climatechange/emissions/downloads/ghg_gwp.pdf
21. “Update of Methane and Nitrous Oxide Emission Factors for On-Highway Vehicles”, U.S. Environmental Protection Agency, Office of Transportation and Air Quality, EPA 420-P-04-016, November 2002. http://www.epa.gov/otaq/models/ngm/420p04016.pdf
22. “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2005”, U.S. Environmental Protection Agency, EPA 430-R-07-002, April 2007. http://www.epa.gov/globalwarming/publications/emissions
23. Lipman T.E. and Delucchi M.A., “Emissions of Nitrous Oxide and Methane from Conventional and Alternative Fuel Motor Vehicles”, Climatic Change 53 (4), 477 – 516, 2002.

24. "Climate Change 2001: The Scientific Basis", Intergovernmental Panel on Climate Change (IPCC), J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, C.A. Johnson, and K. Maskell, eds.; Cambridge University Press., Cambridge, 2001. http://www.grida.no/climate/ipcc_tar/
25. "Climate Change 1995: The Science of Climate Change", Intergovernmental Panel on Climate Change, J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell, eds. Cambridge University Press, Cambridge, 1996.
26. Framework Convention on Climate Change; November 1, 2002; Report of the Conference of the Parties at its eighth session; held at New Delhi from 23 October to 1 November 2002; Addendum; Part One: Action taken by the Conference of the Parties at its eighth session; Decision -/CP.8; Communications from Parties included in Annex I to the Convention: Guidelines for the Preparation of National Communications by Parties Included in Annex I to the Convention, Part 1: UNFCCC reporting guidelines on annual inventories; p. 7, http://unfccc.int/resource/docs/cop8/08.pdf
27. "Transit Bus Life Cycle Cost and Year 2007 Emissions Estimations", United States Department of Transportation, Federal Transit Administration, July 2007. http://www.fta.dot.gov/documents/WVU_FTA_LCC_Final_Report_07-23-2007.pdf