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Source: *Journal of the Transportation Research Forum*, Vol. 47, No. 3 (Public Transit Special Issue 2008), pp. 127-148
Published by: Transportation Research Forum
Stable URL: http://www.trforum.org/journal

Emissions Reduction in Transit Buses: Westchester County's Proactive Approach

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Transit agencies are subject to both nationwide and local emissions regulations. The Westchester County Department of Transportation (WCDOT) is required to bring its older buses into compliance with county regulations. This paper quantifies emissions reductions resulting from actions taken by WCDOT through an emissions reduction program starting in 2005, with projections up to 2009. Selected buses were tested by the West Virginia University (WVU) Transportable Chassis-Dynamometer Emissions Laboratory over the OCTA cycle and a custom WCDOT driving schedule, the Bee-Line cycle. Based on measured results, future fleet-wide emissions were estimated for two scenarios: a baseline scenario in which the county requirements are met just in time, and a proactive scenario which reflects early actions taken by WCDOT. The proactive approach of WCDOT towards emissions reduction was shown to save, over the five-year period, 112.5 tons (53%) of carbon monoxide (CO), 23.3 tons (1%) of nitrogen oxides (NO_x), 11.3 tons (30%) of hydrocarbons (HC), 7.3 tons (44%) of particulate matter (PM), 1,119 tons (1%) of carbon dioxide (CO_2), and 114,000 gallons (1%) of diesel fuel.

INTRODUCTION

Besides national emissions regulations, some transit agencies face local and state regulations. Westchester County Department of Transportation (WCDOT) provides transit service via the Bee-Line System, which serves almost 30 million riders annually over a 450-square-mile area. All Bee-Line vehicles are owned by the county and operated by three contracted vendors, including Liberty Lines Transit (LLT), its largest contractor. WCDOT is under jurisdiction of the Westchester, New York, County Board of Legislators, which, in turn, is required by the U.S. Environmental Protection Agency (EPA) to promote actions that assure compliance with national ambient air quality standards. The Board of Legislators requires transit agencies to retrofit their older buses in a phase-in period that started in 2007 with 35% of the fleet, and ends in 2009 with 100% of the fleet. Considering these requirements, WCDOT started retrofits back in 2005 and has complied in advance with the county ordinance.

The EPA has defined a diesel engine retrofit program as any technology in which the overall effect, when applied to an existing diesel engine, is the reduction on emissions beyond that currently required by EPA regulations at the time of its certification (EPA 2006). On the retrofit program undertaken by WCDOT, the relevant technology that was employed to accomplish the emissions reduction is the Diesel Particulate Filter (DPF), which is an EPA verified diesel retrofit technology (EPA 2008). Selective catalytic reduction (SCR) for oxides of nitrogen (NO_x) emissions was also considered, but its implementation is still under consideration by the transit agency.

Retrofit technologies have been proven successful in reducing carbon monoxide (CO), HC and particulate matter (PM) emissions in specific fleet applications. Melendez et al. (2005) evaluated the impact of using the Engelhard Catalyzed Diesel Particulate Filter (DPX) and the Johnson-Matthey Continuously Regenerating Technology Particulate Filter (CRT) onto existing transit buses of vintage 1990 to 1999 and different engine models used by the Washington Metropolitan Area Transit Authority. When compared to non-aftertreatment equipped buses, the catalyzed filter technologies reported 83%-99% in PM reductions; CO emissions were reduced in the 65%-94% range and HC emissions were reduced by 75%-99%. Similar results were also found by Chatterjee and Frank (2002) after testing 25 NY City Transit buses, which were retrofitted with CRT technology. The buses, equipped with DDC Series 50 engines, exhibited around 90% reduction in PM and CO emissions and 70% for HC. Hearne et al. (2005) tested the CRT from Johnson-Matthey and Diesel Oxidation Catalyst (DOC) from Nett Technologies on school buses equipped with 1996 and 1997 engines. PM and CO emissions were reduced 48%-79%, and HC was reduced by 88%-95% using the CRT. The DOC reduced CO by 74%-85%.

Reduction on NO_x emissions has been based mostly on exhaust gas recirculation (EGR) systems. A combined DPF system with a low pressure EGR retrofit kit was tested by Blomquist et al. (2003) in several field trial programs, with results, based on chassis dynamometer, of 50%-60% NO_x reductions and near 90% reduction in PM, CO, and HC emissions.

In California, the Metropolitan Transportation Commission Urban Bus Diesel Retrofit Program was implemented in Oakland/Bay Area, California, in order to accelerate the achievement of the region's air quality attainment standards. Based on the California Air Resources Board (CARB) public transit fleet rule emissions regulations, a Cleaire Longview™ device that integrates a NO_x reducing catalyst (NRC) and a catalyzed active diesel particulate filter was installed, reporting 25% in NO_x reduction and 85% in PM reduction (Metropolitan Transportation Commission 2006).

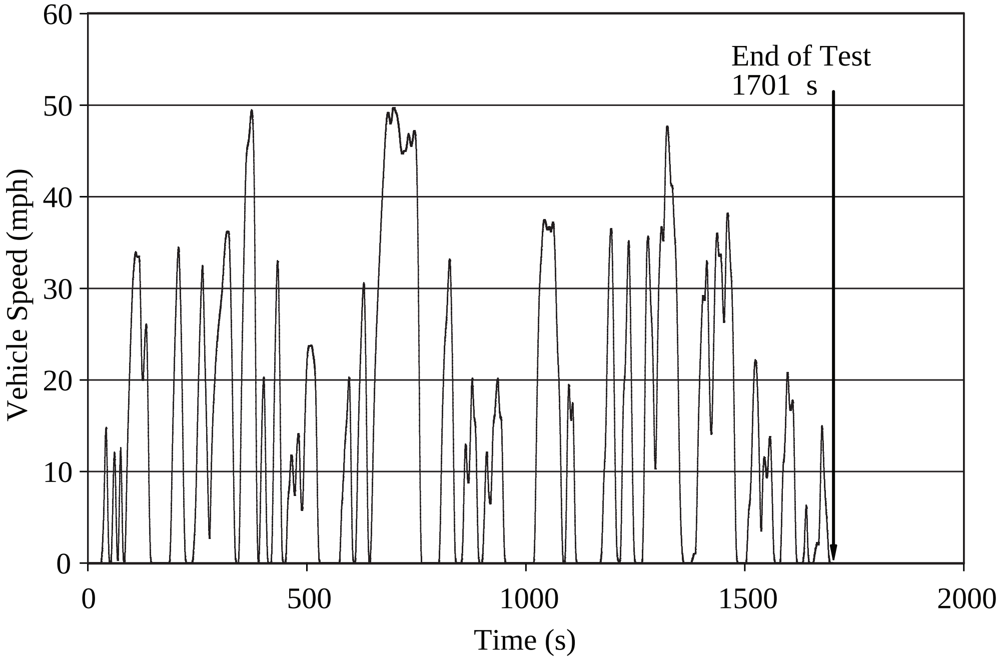
The objective of the work presented in this paper was to quantify emissions reductions resulting from actions taken by WCDOT and LLT through its emissions reduction program between 2005 and 2009. This paper presents the major findings of a report prepared for LLT and WCDOT by Transit Resource Center (TRC) and West Virginia University (WVU) (WCDOT and LLT 2007). The approach used was also employed in a transit bus emissions inventory study conducted by WVU for the Federal Transit Administration (FTA) (US DOT 2007).

EMISSIONS CHARACTERIZATION

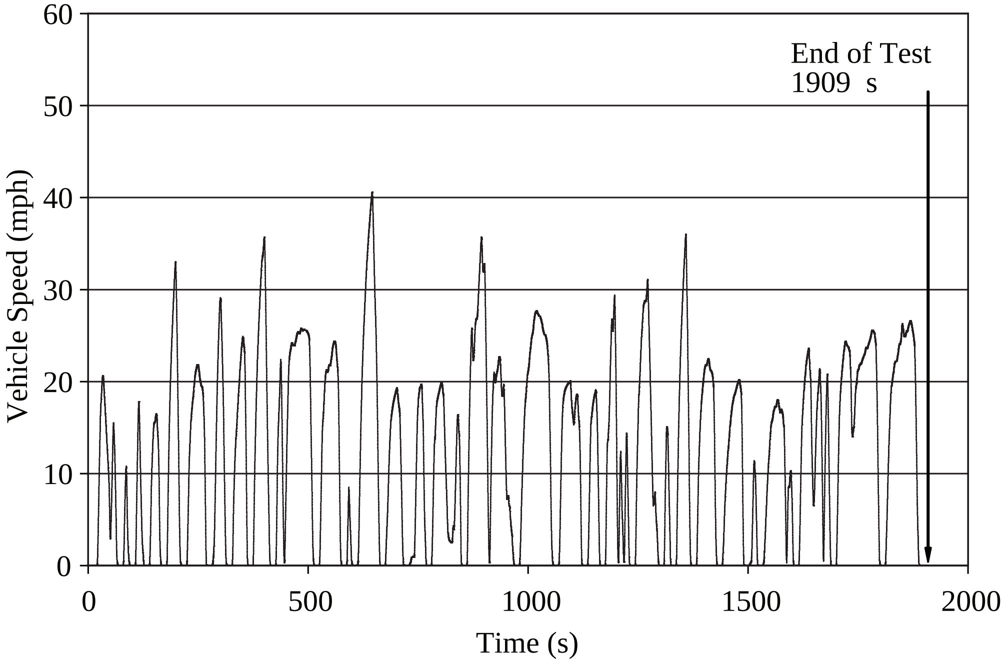
The TRC/WVU team collected emissions, fuel consumption, and performance data from 10 representative Liberty Lines buses. The cumulative data generated from the testing served to quantify the emissions reduction achieved by WCDOT due to their retrofit efforts and to assist with the development of future emissions-reduction strategies. The emissions measurements were conducted by the West Virginia University Transportable Emissions Testing Laboratory (TransLab), which is designed to measure the emissions from heavy-duty vehicles operating on conventional and alternative fuels (Clark et al. 1995, Gautam et al. 1991). The heavy-duty chassis dynamometer is capable of testing vehicles at weights ranging from approximately 20,000 lb. to 65,000 lb. The test weight for the buses tested in this study was set to simulate a load of half passenger capacity plus the driver at 150 lb./passenger.

During testing, a human driver, prompted by a driver's interface monitor, operated the test vehicle through a prescribed dynamometer driving schedule. Each bus was tested over two different driving cycles: the Beeline Cycle and the Orange County Bus Cycle (OCTA) as shown in Figure 1. The Beeline Cycle was developed by WVU and TRC in 2002 and represents the operating duty cycle of the WCDOT transit bus fleet (Schiavone et al. 2003). The Orange County Bus Cycle is one of the recommended cycles in the SAE J2711 recommended practice for fuel economy and emissions measurement (SAE International 2002). The OCTA cycle was chosen as an additional test cycle in order to facilitate comparison with emissions test results of similar buses from other studies. Table 1 presents several test cycle statistics.

Figure 1: Beeline and OCTA Test Cycles



(a) Beeline



(b) OCTA

Table 1: Test Cycle Statistics

Test Cycle	Beeline	OCTA
Average Speed (mph)	14.36	12.33
Std. Dev. Speed (mph)	14.75	10.28
Max. Speed (mph)	49.70	40.60
Max. Acceleration (ft/s^2)	7.33	5.87
Max. Deceleration (ft/s^2)	10.27	8.80
Total Distance (mi)	6.79	6.54
Total Time (s)	1,701	1,909
Idle Time (%)	25.6	20.5
Stops per mile	3.54	4.74

The whole exhaust gas flow of the test vehicle was ducted to a full-scale dilution tunnel and mixed with HEPA filtered dilution air. Hydrocarbon emissions were measured using a heated flame ionization detector (HFID). Non-methane hydrocarbon (NMHC) emissions were sampled in Tedlar bags and analyzed at WVU by gas chromatography methods. Wet chemiluminescent analyzers measured NO_x emissions. Two separate chemiluminescent analyzers allowed the NO and NO_2 fractions to be determined. Carbon monoxide and carbon dioxide (CO_2) were measured using non-dispersive infrared analyzers. Particulate emissions were measured gravimetrically. A proportional sample of diluted exhaust was extracted from the main dilution tunnel into a secondary dilution tunnel. The sample passed through a primary and a secondary Pallflex 70-mm fluorocarbon coated glass fiber filter, with a filtration efficiency of 98% for particles larger than 0.1 micron. The exhaust sample conditioning systems and gaseous emissions analyzers conformed to CFR 40 Parts 86 (US GPO 2006) where applicable for chassis dynamometer emissions testing.

Emissions from a total of 10 transit buses were measured in order to establish the emissions levels of buses representing those comprising the WCDOT transit bus fleet. Table 2 summarizes the make/model and emissions related equipment of each of the test buses. Emissions were measured from each bus over the Beeline Cycle and the Orange County Bus Cycle. Three repeats of each test cycle were conducted. Table 3 presents the average of the three repeat test runs conducted on each bus over the Beeline driving cycle. Table 4 presents the results over the OCTA cycle.

A diesel oxidation catalyst (DOC) is a flow-through device consisting of a honeycomb-like substrate, which has a large surface area that is coated with an active catalyst layer. The catalyst layer contains a small, well dispersed amount of precious metals, such as platinum or palladium. Carbon monoxide, gaseous hydrocarbons, and liquid hydrocarbon particles are oxidized as the exhaust gases traverse the catalyst substrate. About 30% of the total particulate matter mass of diesel exhaust is attributed to liquid hydrocarbons or soluble organic fractions (SOF). DOCs can achieve SOF removal efficiencies of 80%-90%, resulting in reductions in overall PM emissions of 20%-50%, according to the EPA Heavy-Duty Diesel Emissions Reduction Project (EPA 1999). Diesel particulate filters (DPF) capture and oxidize diesel particulate in the exhaust gas stream. The DPF employed in this study were passive devices. The Engelhard DPX and Johnson-Matthey CRT diesel particulate filters employed by WCDOT are both cordierite wall flow filter devices. The DPX filter is a catalyzed ceramic wall-flow filter that utilizes a dual function platinum precious metal catalyst in combination with a base metal oxide catalyst. The catalyst coating is impregnated into the porous filter walls (LeVatec et al. 2003). The CRT filter is a two-stage system that incorporates a platinum-loaded oxidation catalyst followed by an uncoated ceramic wall flow filter. The catalyst is used to continuously oxidize NO emitted from the engine to NO_2. The NO_2 is adsorbed onto the particles, lowering the exhaust gas temperature needed for regeneration (LeVatec et al. 2003). In many cases, DPF reduce PM emissions by greater than 95% (Alleman et al. 2006, Melendez et al.

Table 2: Summary of WCDOT Buses Tested

Bus	Make / Model	Rated Power (hp)	Emissions Equipment Description
A*	2006 Orion VII – 40' Series Drive Diesel-Electric Hybrid	260	Standard MY 2006 EPA certification; Cummins ISB 206H diesel engine with catalyst and DPF. Also includes variable geometry turbo, EGR, and high pressure common rail fuel injection.
B	2006 Orion V – 40'	280	Standard MY 2006 EPA certification; Cummins ISM 280 diesel engine with catalyst. Also includes variable vane turbo, EGR and crankcase recovery.
C	2005 Orion V – 30'	275	Standard MY 2005 EPA certification; DDC S50 engine with second-generation EGR (2.5 g/bhp-hr NO_x + NMHC) and catalyst.
D	2002 Orion V – 30'	275	Standard MY 2002 EPA certification; DDC S50 engine with first-generation EGR (4.0 g/bhp-hr NO_x) and catalyst.
E*	1996 Orion V – 40'	275	DDC S50 engine exchanged in 2006 and retrofitted with DPF.
F	2002/03 Neoplan Artic – 60'	370	DOC
G*	2002/03 Neoplan Artic – 60'	370	DDC S60 engine retrofitted with DPF.
H	1990 Flxible Metro – 40'	277	DDC 6V92 DDEC 2 stroke engine (with electronic fuel delivery control) exchanged in 2006; retrofitted with DOC and crankcase recovery system.
I	1986 MCI 102 A2 – 40'	277	DDC 6V92 engine (with mechanical fuel delivery control) exchanged in 2006; retrofitted with DOC.
J	1987 MCI 102 A2 – 40'	277	DDC 6V92 DDEC 1 engine (with electronic fuel delivery control) exchanged in 2006; retrofitted with DOC.

***** Denotes proactive steps taken by WCDOT to reduce emissions.

2005). Periodic maintenance is required to remove accumulated ash (inorganic calcium sulfate and zinc phosphate originating from engine lubricating oil), which is not combustible. DPFs are also highly effective at reducing HC and CO emissions, often to levels that are below the detection limits of emissions measurement equipment. Emissions reductions vary as a result of engine type, size age, duty cycle, condition, maintenance history, and fuel sulfur level. Catalyzed DPFs convert NO in the exhaust stream to NO_2 in order to promote the oxidation of PM. Previous studies (Alleman et al. 2006, LeVatec et al. 2003) have shown that NO_2 can comprise up to 50% of the total NO_x emissions depending on engine parameters and fuel properties. DPFs generally have little effect on the total NO_x ($NO+NO_2$) emissions, although some studies have observed very modest conversion of NO_2 to N_2 over the DPF (Alleman et al. 2006).

Methane emissions are generally low for diesel fueled vehicles. The results in Table 3 and Table 4 show measured methane emissions of the same order of magnitude as the non-methane hydrocarbon emissions (NMHC). The buses tested in this study were equipped with aftertreatment devices that reduce HC emissions. Methane is difficult to reduce catalytically, therefore, the DOC and DPF devices are much more active at reducing the NHMC portion than the methane. The methane portion of the HC emissions were likely affected little by the aftertreatment devices, while substantial reductions in the non-methane component were affected by the DOC and DPF.

Table 3: Emissions Results – Beeline Cycle

Bus	Model / Make	Engine	After-treatment	CO (g/mile)	NO_x (g/mile)	NMHC (g/mile)	CH_4 (g/mile)	PM (g/mile)	CO_2 (g/mile)	Fuel Econ. (mpg)
A	2006 Orion VII Hybrid	Cummins ISB-260	DPF	0.05	9.37	0.016	0.027	0.009	1,998	4.832
B	2006 Orion V	Cummins ISM-280	DOC	2.27	7.98	0.397	0.233	0.151	2,544	3.788
C	2005 Orion V	DDC S50 DDEC 4	DOC	0.91	10.34	0.098	0.011	0.186	2,185	4.416
D	2002 Orion V	DDC S50 DDEC 4	DOC	0.43	16.58	0.011*	-	0.299	2,422	3.986
E	1996 Orion V	DDC S50 DDEC 4	DPF	0.33	41.74	0.061	0.025	0.009	2,692	3.586
F	2002 Neoplan AN 460 Artic	DDC S60 DDEC 4	DOC	1.63	31.39	0.212*	-	0.221	3,487	2.890
G	2002 Neoplan AN 460 Artic	DDC S60 DDEC 4	DPF	0.10	30.72	0.024	BDL	0.009	3,940	2.451
H	1990 Flxible – 870	DDC V92 DDEC 4	DOC	0.50	20.62	0.403	0.364	0.374	2,990	3.226
I	1986 MCI-102A2	DDC V92 Mech.	DOC	4.66	44.24	1.124	0.800	0.575	2,970	3.236
J	1987 MCI-102A2	DDC V92 DDEC I	DOC	4.44	38.47	0.194	0.214	1.234	2,745	3.507

Notes: BDL = Below detection limit; * = THC; - = No data

LOCAL EMISSIONS REGULATIONS

In addition to federal EPA regulations, WCDOT must comply with Westchester County Board of Legislators (WCBOL) Act 19 of 2006 (WCBOL 2006). Act 19 requires that all diesel-powered vehicles leased and/or operated by or on behalf of Westchester County be powered by ultra low sulfur diesel (ULSD) fuel no later than September 1, 2006, and utilize the best available technology (BAT), as defined below, to reduce the emission of pollutants. The act requires 35% of the fleet to meet BAT requirements in 2007, 65% in 2008, and 100% in 2009. The WCBOL Committee on Environment intends that DPFs (or technologies with similar benefits) be used to the maximum extent possible as part of the emissions-reduction system.

Act 19 recognizes that in 2004, the EPA classified Westchester County as a non-attainment area for ground-level ozone and fine particulate matter (PM 2.5). The EPA will re-evaluate attainment no later than June 2010. The Board of Legislators finds that there is credible evidence that diesel emissions pose environmental and health risks, and that requiring the use of emission-control technologies and ULSD fuel can help in minimizing these risks and attract the best PM 2.5 and NO_x, reducing technologies to the Westchester County market.

Table 4: Emissions Measured Over the OCTA Cycle

Bus	Model / Make	Engine	After-treatment	CO (g/mile)	NO_x (g/mile)	NMHC (g/mile)	CH_4 (g/mile)	PM (g/mile)	CO_2 (g/mile)	Fuel Econ. (mpg)
A	2006 Orion VII Hybrid	Cummins ISB-260	DPF	0.05	9.84	0.007	0.032	0.004	1,849	5.221
B	2006 Orion V	Cummins ISM-280	DOC	3.40	8.97	0.544	0.439	0.137	2,423	3.971
C	2005 Orion V	DDC S50 DDEC 4	DOC	1.95	11.3	0.067	0.086	0.243	2,137	4.511
D	2002 Orion V	DDC S50 DDEC 4	DOC	0.43	18.2	0.052	BDL	0.208	2,378	4.059
E	1996 Orion V	DDC S50 DDEC 4	DPF	0.37	42.21	0.031	0.069	0.007	2,635	3.664
F	2002 Neoplan AN 460 Artic	DDC S60 DDEC 4	DOC	2.23	28.11	0.096	0.181	0.221	3,337	2.890
G	2002 Neoplan AN 460 Artic	DDC S60 DDEC 4	DPF	0.08	30.72	0.023	BDL	0.009	3,558	2.715
H	1990 Flxible – 870	DDC 6V92 DDEC 4	DOC	0.61	19.35	0.406	0.428	0.600	2,841	3.394
I	1986 MCI-102A2	DDC 6V92 Mech.	DOC	3.91	40.50	1.326	0.909	0.553	2,734	3.515
J	1987 MCI-102A2	DDC 6V92 DDEC I	DOC	12.35	36.07	0.305	0.237	1.277	2,600	3.684

BAT is defined in Act 19 as a system for reducing the emission of pollutants, which is based on technology verified by the EPA or CARB or has been identified pursuant to New York City's Department of Environmental Protection that

a. Reduces diesel particulate matter emissions by at least 85%, as compared to a similar engine operating on traditional diesel fuel, or reduces engine emissions to 0.01 grams diesel particulate matter per brake horsepower hour or less; and

b. Achieves the greatest reduction in emissions of NO_x at a reasonable cost and in no case produces a net increase in NO_x in excess of 10%. Reasonable cost in this case means that the cost to purchase and install the system with technologies to reduce both PM and NO_x does not exceed the cost of the system without Nitrogen Oxides control by more than 30%.

A "grandfathering" provision is included in Act 19 that allows the use of any installed BAT system for at least three years. This "grandfathering" provision is significant because WCDOT already retrofitted several buses with DPF beginning in 2005. Since DPF qualified as BAT when first installed, WCDOT would not be required to replace these units until 2008.

EMISSIONS REDUCTION PROGRAM

In 2003, TRC, in partnership with WVU, estimated the amount of exhaust emissions reduction possible from the use of ULSD fuel in combination with exhaust aftertreatment devices in the WCDOT transit bus fleet. Based on this evaluation, WCDOT installed DPF on selected buses, which became an integral part of the agency's efforts to reduce emissions from the diesel fleet. WCDOT began operating with ULSD in 2001.

The WCDOT transit bus fleet is listed in Table 5. The table depicts the fleet at the time this study was carried out, i.e., 2006-2007. Eleven Flxible buses, represented by bus *H* above, were retired and not replaced in 2007; therefore, the number of buses considered for compliance with Act 19 is 334.

Table 5: Westchester County Transit Bus Fleet in 2006

Group Characteristics	Emissions Equipment	Number
1986 MCI 40' Mechanical	DOC	25
1986 MCI 40' DDEC-1	DOC	7
1995/1996 Orion 40' DDC-S50	DPF	84
1990 Flxible 40' DDEC-2	DOC + Crankcase Recirculation	11
2002/2003 Neoplan 60' DDC-S60	DPF	78
2002 Orion 30' DDC-S50	DOC + EGR	15
2005 Orion 30' DDC-S50	DOC + EGR	17
2006 Orion 40' Cummins ISM280	DOC + VVT + Crankcase Recirculation	104
2006 Orion 40' Diesel-Hybrid	DPF + VVT + EGR + Common Rail Fuel Injection	4
Total		**345**

WCDOT started to implement an emissions reduction program to improve air quality in their influence area in 2005. To date, WCDOT has exceeded the Act 19 implementation schedule regarding the use of BAT. Act 19 implementation requirements, listed in Table 6, did not begin until 2007. However, according to WCDOT retrofit dates, 84 buses were converted in 2005 and 78 in 2006. Four Diesel-Electric Hybrid buses were acquired in 2006. As will be shown later, these proactive retrofits have resulted in substantial emissions savings. With 334 buses in the WCDOT fleet having a gross vehicle weight rating (GVWR) of more than 14,000 lb., 117 buses (35% of the total fleet) were affected by Act 19 and had to comply by September 1, 2007.

Given that 162 buses were already converted by WCDOT with DPF prior to 2007 and the four 2006 hybrids are equipped with DPF and are, therefore, considered BAT, WCDOT exceeded county requirements by 49 buses. Starting in 2005 when DPFs were installed, this particular retrofit technology met the criteria for BAT for PM and no verified retrofit meeting the BAT criteria existed for NO_x reduction at that time. After WCDOT had completed its DPF retrofits, two manufacturers have since introduced retrofit technology that also reduces NO_x. However, as mentioned earlier, the Act has a provision that "grandfathers" the existing retrofit DPF equipment for three years to protect the investment made in the initial retrofit technology. At the end of the three-year period, however, WCDOT will be required to upgrade buses previously retrofitted with DPF with NO_x-reduction equipment (assuming it meets BAT "reasonable cost" requirements). An ideal scenario would be one where the original DPF equipment is retained and new NO_x-reduction equipment is added to complement the original equipment investment.

Table 6: Act 19 BAT Implementation Requirements

Deadline	Percentage	Number of WCDOT buses
9/1/07	35%	117
9/1/08	65%	217
9/1/09	100%	334

ESTIMATION OF EMISSIONS SAVINGS FROM WCDOT EMISSIONS REDUCTION PROGRAM

In order to evaluate the achievements of the proactive measures that WCDOT has taken to reduce the emissions from their transit bus fleet, the total fleet emissions output was estimated based on two scenarios. The baseline scenario considers minimum compliance with WCBOL Act 19 through 2009. The second scenario takes into account the proactive measures that WCDOT has implemented to date as well as one hypothetical pathway toward continuing a proactive retrofit program in the out years. The emissions data collected in Table 3 and Table 4 were utilized; data available in the WVU emissions database from prior emissions studies were also used. In cases where emissions data from either the Beeline or OCTA cycles were not available, those emissions were estimated from data available on other driving cycles.

In the analysis, emissions were estimated by multiplying the expected emissions levels (in g/mile) from each type of bus by the estimated annual miles traveled and summing the annual contributions for the five-year period. The following assumptions were used:

a. Vehicle Miles Traveled (VMT) was estimated from the national average VMT computed using data from the 2007 APTA Public Transportation Fact Book (APTA 2007). Based on these data, it was assumed that the average transit bus in the WCDOT fleet travels 43,500 miles/year. Since local in-route VMT data are not collected, national average values provide the best available approach.

b. Emissions levels were calculated from the emissions tests performed on the WCDOT buses and from tests of buses performed by WVU at other transit agencies. NO_x emissions levels for 2007 and newer buses were approximated by multiplying measured emissions of 2004 model year DPF equipped buses by the ratio of the 2007 to 2004 EPA NO_x certification limits (US DOT 2007). Emissions values used in the calculations are shown in Table 7.

c. Emissions calculations were based on the OCTA Cycle, which is a nationally recognized emissions test cycle for transit buses.

Table 7: Emissions Levels Used for Calculation of Emissions-Profile

Bus Type	Equip.	CO g/mile	NO_x g/mile	HC g/mile	PM g/mile	CO_2 g/mile	Fuel Eco. mile/gal
1986 MCI 40'Mechanical	DOC	3.90	40.50	2.12	0.55	2,734	3.51
1986 MCI 40' DDEC-1	DOC	7.50	36.10	0.51	1.28	2,600	3.70
1990 Flxible 40' DDEC-2	DOC	0.60	19.40	0.79	0.60	2,841	3.39
1995/1996 Orion 40' DDC-S50	DPF	0.40	42.20	0.08	0.01	2,635	3.66
1995/1996 Orion 40' DDC-S50	DOC	10.49	38.27	0.64	0.61	2,485	3.89
2002/2003 Neoplan 60' DDC-S60	DPF	0.10	30.70	0.02	0.01	3,558	2.71
2002/2003 Neoplan 60' DDC-S60	DOC	2.20	28.10	0.31	0.22	3,337	2.89
2002 Orion 30' DDC-S50	DOC	0.40	18.20	0.05	0.21	2,378	4.06
2002 Orion 30' DDC-S50	DPF	0.09	14.35	0.03	0.04	2,733	3.53
2005 Orion 30' DDC-S50	DOC	1.70	11.30	0.14	0.24	2,137	4.51
2005 Orion 30' DDC-S50	DPF	0.17	15.26	0.07	0.02	2,739	3.52
2006 Orion 40' Cummins ISM280	DOC	3.40	9.00	0.93	0.14	2,423	3.97
2006 Orion 40' Cummins ISM280	DPF	1.20	7.80	0.36	0.15	2,330	4.14
2006 Orion 40' Diesel-Hybrid	DPF	0.10	9.80	0.04	0.004	1,850	5.22
2007 Orion 40' Diesel-Hybrid	DPF	0.10	4.70	0.04	0.004	1,850	5.22
2007/2009 40' Diesel	DPF	0.29	7.31	0.002	0.02	2,854	3.38

Baseline Scenario

Considering the 334 WCDOT vehicles that will comprise the baseline bus fleet, a scenario was evaluated where the Act 19 implementation schedule discussed above is implemented just in time.

In computing the total emissions output that would occur if WCDOT met the minimum requirements of Act 19, it was assumed that retrofits would be performed as listed in Table 8. In this scenario, the 116 pre-1995 buses are retired and replaced by new 2007/2009 buses (except for the 11 1990 Flxibles retired in 2007), and that the remaining fleet is retrofitted starting with the oldest buses, thus, giving the better emissions impact. Year-by-year and total (five-year) estimated emissions are presented in Table 10.

Proactive Emissions Control Retrofit Program

As a result of the proactive actions taken by WCDOT, the transit agency was in compliance with the BAT requirements for 2007 one year in advance. Table 9 illustrates one possible proactive emissions reduction pathway that could be implemented over the next several years. The first two years (2005 and 2006) referenced in Table 9 reflect the proactive retrofits undertaken by WCDOT that preceded the requirements of Act 19. The remaining years (2007-2009) illustrate one possible scenario to meet and exceed the requirements of Act 19 through 2009. This scenario corresponds to the recommendations made below to continue retrofitting buses at about the same pace as was done in the 2005/2006 period. By following these recommendations, WCDOT would continue to comply with Act 19 one year in advance.

Table 8: Retrofit Schedule for Minimum Compliance with WCBOL Act 19

Year	Bus Characteristics	Quantity Retrofitted / Acquired
2005	No Retrofits Required	0
2006	No Retrofits Required	0
2007	1995/1996 Orion 40’ DDC-S50	84 Retr. – DPF
	2002/2003 Neoplan 60’ DDC-S60	29 Retr. – DPF
	2006 Orion 40’ Diesel-Hybrid	4 Acquired
2008	2002/2003 Neoplan 60’ DDC-S60	45 Retr. – DPF
	2002 Orion 30’ DDC-S50	15 Retr. – DPF
	2005 Orion 30’ DDC-S50	17 Retr. – DPF
	2006 Orion 40’ Cummins ISM280	23 Retr. – DPF
2009	1995/1996 Orion 40’ DDC-S50	84 - Replace with standard diesel buses (*)
	2006 Orion 40’ Cummins ISM280	78 Retr. – DPF
	1986 MCI 40’ Mechanical 1986 MCI 40’ DDEC-1	32 - Replace with standard diesel buses
	Total	334

(*) The 1995/1996 Orion 40’ buses previously retrofitted with DPF will no longer qualify as BAT under the grandfather clause and action will be required to maintain minimum compliance. Two options exist. The buses could be retrofitted with SCR systems or they could be replaced. Given that these buses have reached their 12 year service life, it is assumed that the buses are replaced with 2009 model year standard diesel buses.

Table 9: WCDOT Proactive Emissions Control Retrofit Scenario

Year	Bus Characteristics	Quantity Retrofitted / Acquired
2005	1995/1996 Orion 40’ DDC-S50	84 Ret. – DPF
2006	2002/2003 Neoplan 60’ DDC-S60	78 Ret. – DPF
	2006 Orion 40’ Diesel-Hybrid	4 Acquired
2007	2002 Orion 30’ DDC-S50	15 Ret. – DPF
	2005 Orion 30’ DDC-S50	17 Ret. – DPF
	2006 Orion 40’ Cummins ISM280	40 Ret. – DPF
2008	2006 Orion 40’ Cummins ISM280	64 Ret. – DPF
	1986 MCI 40’Mechanical 1986 MCI 40’ DDEC-1	32 - Replace with standard diesel buses
2009	1995/1996 Orion 40’ DDC-S50	84 - Replace with hybrid diesel buses
	Total	334

Results: Estimated Emissions Profiles

Estimated emissions from the above scenarios are shown in Table 10. The difference between the two scenarios corresponds to the emissions savings resulting from proactive steps taken by WCDOT in its emissions reduction program (ERP) during 2005/2006; for later years, the difference represents savings from the recommendations given in Table 9. Negative numbers indicate a reduction in emissions compared to the baseline scenario. A positive number indicates an increase in emissions over the baseline levels.

The first group (September 2005 to August 2007) shows the estimated savings from the proactive retrofit program that WCDOT has pursued to date. During this time, no action was required to comply with Act 19. Substantial reductions in CO, HC, and PM emissions are observed (between 20% and 60%) due to retrofits with diesel particulate filter.

The second part of Table 10 (September 2007 to August 2010) shows the year-by-year emissions savings that could be achieved through continued proactive emissions reduction measures. The final part of Table 10 summarizes the five-year emissions savings. The five-year emissions profile does not include implementation of retrofit NO_x reduction strategies above and beyond those strategies implemented by the OEM engine manufacturers to meet applicable EPA emissions standards.

Table 10: Estimated Emissions from the Baseline and Proactive Retrofit Scenarios

Scenario	**CO** (tons)	**NO_x** (tons)	**HC** (tons)	**PM** (tons)	**CO_2** (tons)	**Diesel Fuel Cons.** $\cdot 10^{-3}$ (gallons)
			Sept 2005 - Aug 2006			
Baseline – *Minimum Compliance*	75.1	386.5	11.3	5.6	42,173	3,970
ERP – *Proactive Approach*	36.3	401.7	9.1	3.3	42,752	4,024
Net Change	***-38.8***	***+15.1***	***-2.2***	***-2.3***	***+579***	***+54***
Percent Change	**-52%**	**+4%**	**-19%**	**-41%**	**+1%**	**+1%**
			Sept 2006 - Aug 2007			
Baseline – *Minimum Compliance*	75.1	386.5	11.3	5.6	42,173	3,970
ERP – *Proactive Approach*	26.9	405.8	8.0	2.4	43,426	4,086
Net Change	***-48.2***	***+19.2***	***-3.3***	***-3.2***	***+1,252***	***+116***
Percent Change	**-64%**	**+5%**	**-29%**	**-57%**	**+3%**	**+3%**
			Sept 2007 - Aug 2008			
Baseline – *Minimum Compliance*	31.3	390.1	8.2	2.6	41,498	3,906
ERP – *Proactive Approach*	21.1	394.2	6.5	1.8	42,537	4,001
Net Change	***-10.2***	***+4.1***	***-1.7***	***-0.8***	***+1,039***	***+95***
Percent Change	**-32%**	**+1%**	**-21%**	**-29%**	**+3%**	**+2%**
			Sept 2008 - Aug 2009			
Baseline – *Minimum Compliance*	22.9	395.2	6.9	1.8	42,609	4,008
ERP – *Proactive Approach*	8.2	343.5	2.2	0.8	42,483	3,993
Net Change	***-14.6***	***-51.7***	***-4.7***	***-1.0***	***-126***	***-15***
Percent Change	**-64%**	**-13%**	**-68%**	**-54%**	**0%**	**0%**
			Sept 2009 - Aug 2010			
Baseline – *Minimum Compliance*	7.8	209.2	1.9	0.9	43,326	4,073
ERP – *Proactive Approach*	7.1	199.2	2.1	0.8	39,463	3,709
Net Change	***-0.7***	***-10.0***	***+0.2***	***-0.1***	***-3,863***	***-364***
Percent Change	**-9%**	**-5%**	**+8%**	**-8%**	**-9%**	**-9%**
			5 year Emissions			
Baseline – *Minimum Compliance*	212.2	1,767.6	39.5	16.4	211,780	19,927
ERP – *Proactive Approach*	99.7	1,744.3	27.8	9.1	210,661	19,813
Net Change	***-112.5***	***-23.3***	***-11.7***	***-7.3***	***-1,119***	***-114***
Percent Change	**-53%**	**-1%**	**-30%**	**-44%**	**-1%**	**-1%**

Note: emissions are expressed in short tons

Results from Table 10 are also presented in graphical form. Figure 2 shows year by year CO emissions and Figure 3 shows NO_x emissions. HC emissions are presented in Figure 4, PM emissions in Figure 5, CO_2 emissions in Figure 6, and fuel consumption in Figure 7. Percentage changes are shown in Figures 8 and 9; Figure 8 includes CO, PM, and HC while Figure 9 shows percentage changes in NO_x, CO_2, and fuel consumption.

As the estimated emissions results shown in Table 10 and Figures 2 to 9 indicate, substantial reductions in CO, HC, NO_x, and PM emissions are achievable if WCDOT continues to pursue an aggressive strategy of retrofitting existing buses with DPF and to procure new technology diesel and hybrid buses. For example, retrofits in the first year resulted in significant reductions of PM (41%), CO (52%), and HC (19%), and a slight increase in NO_x, CO_2, and fuel consumption. Higher fuel consumption and CO_2 emissions are expected due to the additional flow restriction (pressure drop) imposed by the diesel particulate filters.

The slight increase in NO_x is thought to be due to the fact that the source data for a particular bus type are not from a single bus tested with and without DPF, but rather emissions testing from similar buses, some with DOC and some with DPF. Specifically, for the buses not tested in this study, most of the data come from averaging several similar buses. The chemical reactions naturally occurring in the particulate filter oxidize NO into NO_2, which in turn reacts with the carbon in the filter to produce CO_2 (Khair 2003). Temperatures in the after treatment system are not high enough to dissociate the exhaust N_2 and further produce NO_x; except for the reactions mentioned above, NO_x is produced in the engine. Also, previous studies on DPFs have shown a slight decrease in NO_x emissions (Alleman et al. 2006). It is thus concluded that the predicted effect on NO_x emissions is not relevant.

Procurement of substantial numbers of diesel-electric hybrid buses will decrease CO_2 emissions and fuel consumption. For instance, these preliminary calculations show that in 2009 the 88 hybrids (26% of the fleet) could decrease fuel consumption by 9% and NO_x emissions by 5%.

Figure 2: Annual CO Emissions

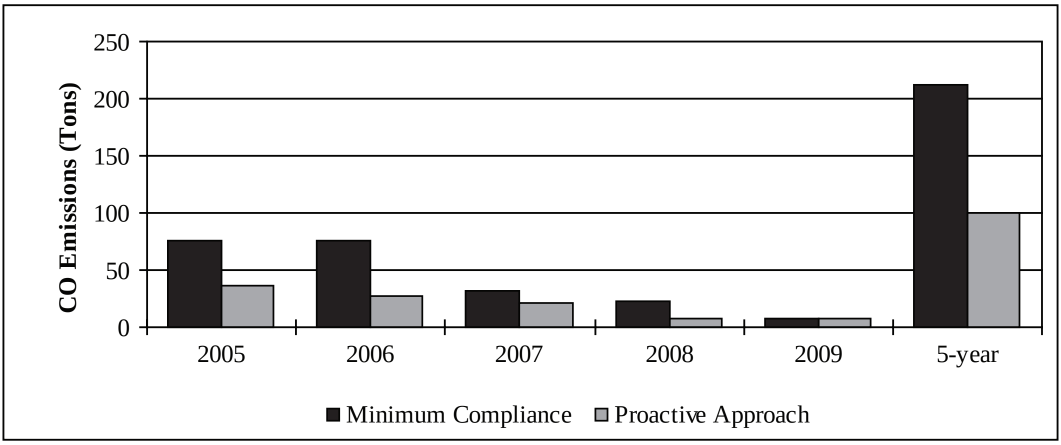


Figure 3: Annual NO_x Emissions

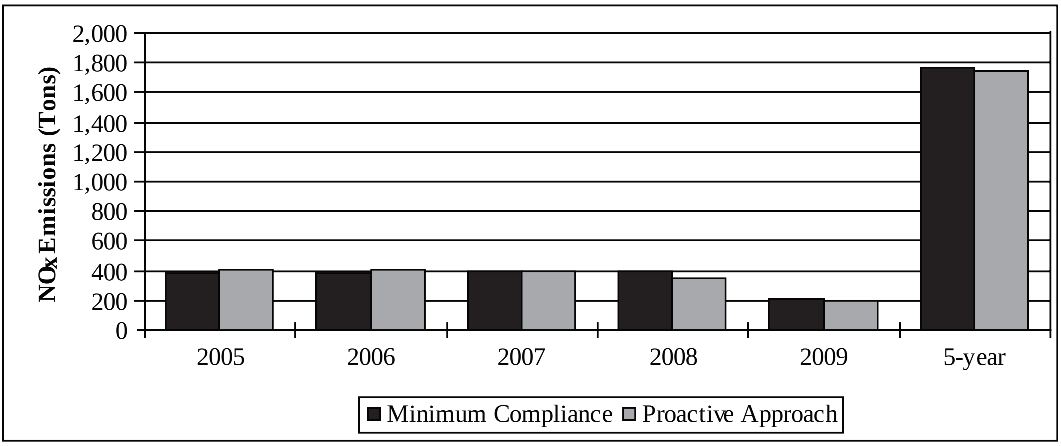


Figure 4: Annual HC Emissions

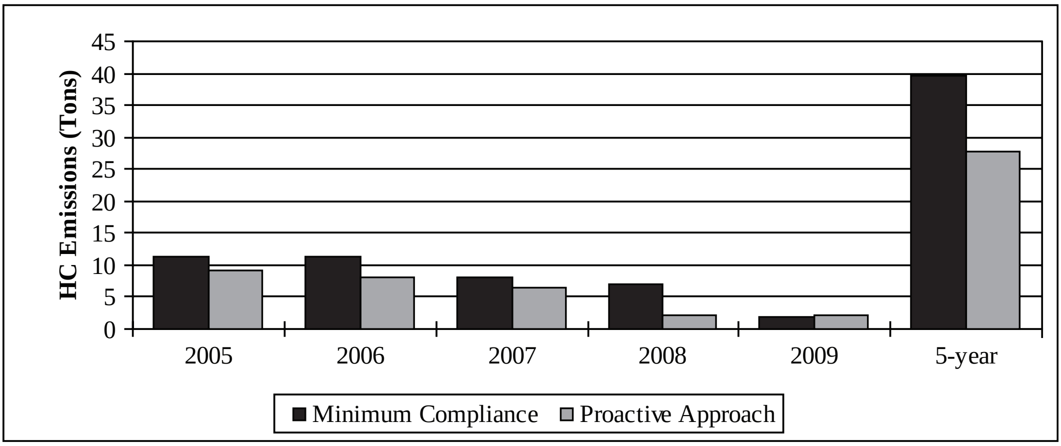


Figure 5: Annual PM Emissions

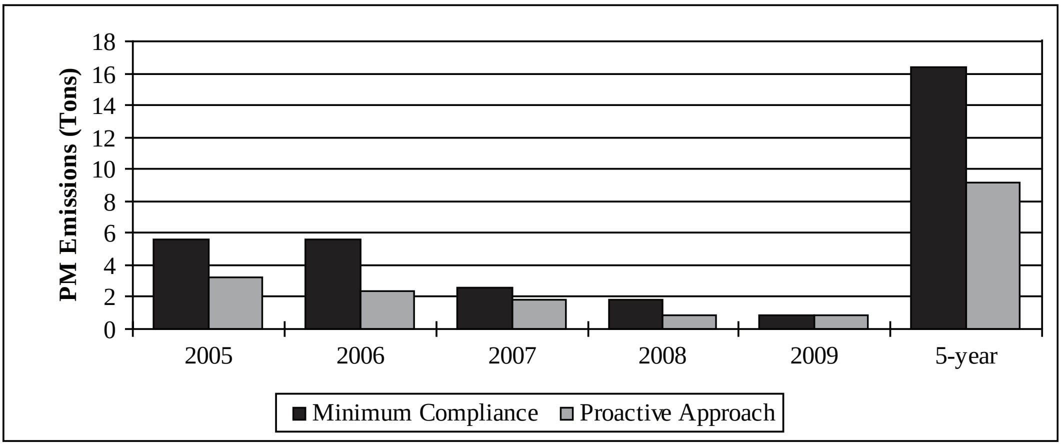


Figure 6: Annual CO_2 Emissions

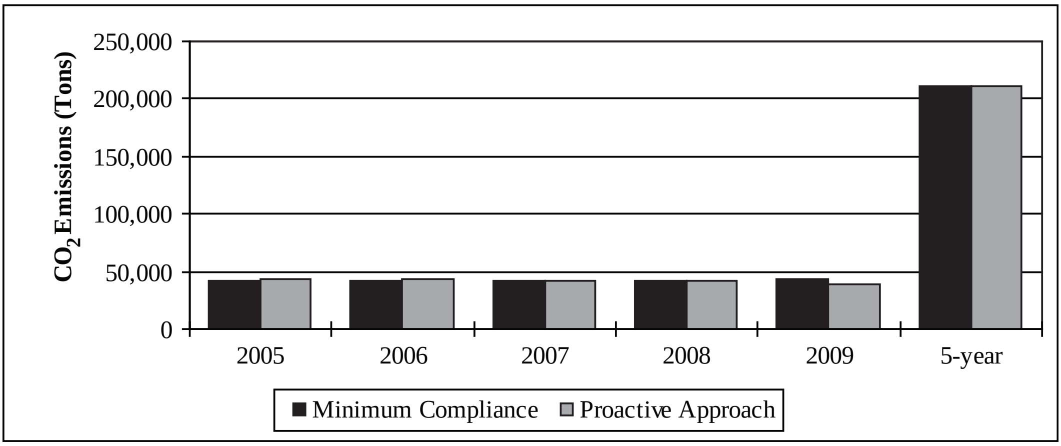


Figure 7: Annual Fuel Consumption

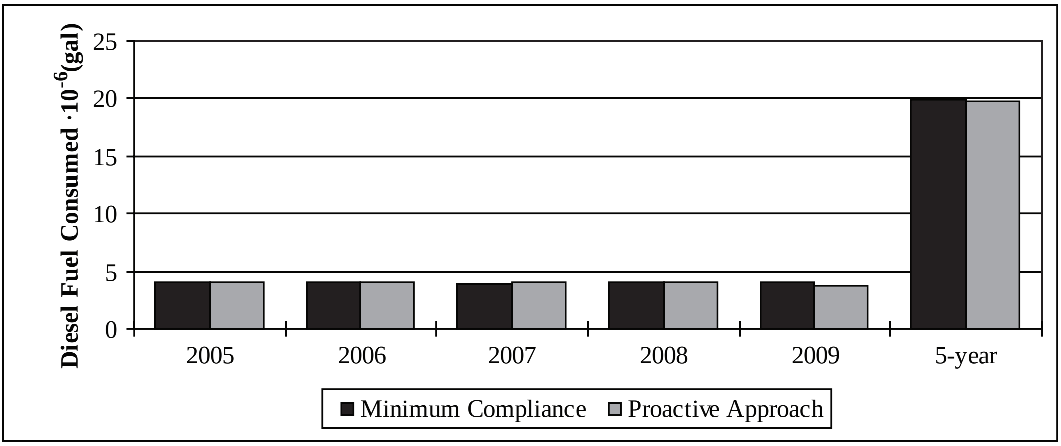


Figure 8: Percentage Changes in CO, PM and HC

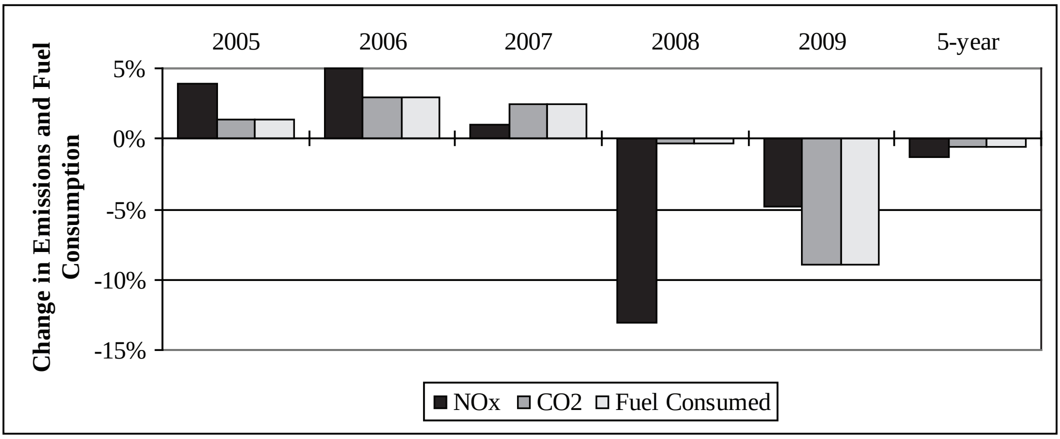
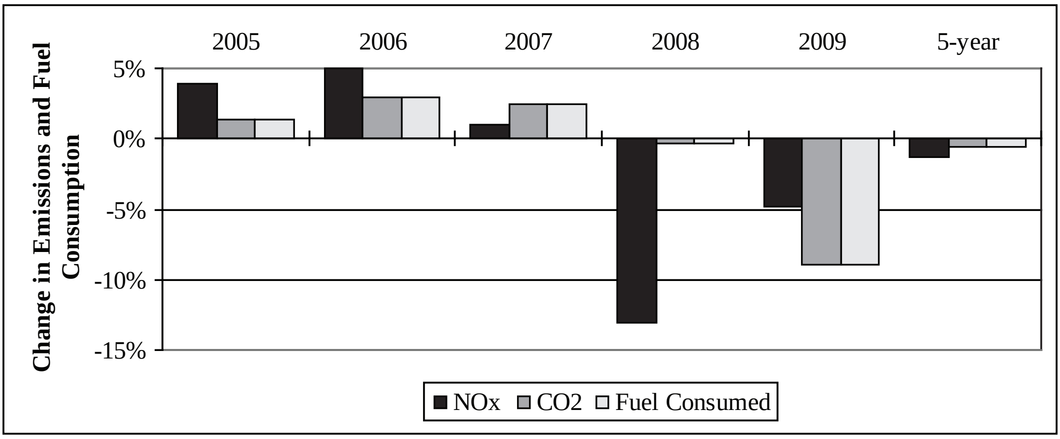


Figure 9: Percentage Changes in NO_x, CO_2 and Fuel Consumption



Note from Figure 8 and Figure 9 how CO_2 and NO_x vary in sympathy power, and therefore, with fuel consumption (or fuel economy, mpg); on the other hand, CO and PM are strongly dependent on the transient character of driving. The more transient the drive cycle the higher the PM and CO emissions.

Introduction into the fleet, to replace aging buses, of diesel-hybrid vehicles in 2009 and procurement of conventional diesels in 2008 will decrease the overall fuel consumption, so much as to offset the slight increase observed in the initial years of the analysis (2005 to 2007).

After 2009, the path taken by WCDOT in becoming compliant with the county's requirements will continue to have benefits over a minimum compliance approach. Particularly, the massive introduction of hybrids will yield significant reductions in emissions: 8% lower PM, 9% lower CO, 5% lower NO_x, and 9% lower CO_2 and fuel consumption. The predicted increase in HC emissions is most likely due to uncertainty in emissions values of MY 2009 buses.

Finally, the authors want to emphasize the effect of the proactive retrofitting program on PM, CO, and HC emissions, which showed an overall reduction of between 30% and 50%.

DISCUSSION AND RECOMMENDATIONS

A review of WCDOT's proactive efforts to reduce emissions from its heavy duty bus fleet found that the agency was in compliance with Act 19 based on the availability of BAT and other provisions cited in the Act. Concerning the use of ULSD, which was required by the Act no later than September 1, 2006, the entire WCDOT fleet has been operating on ULSD since 2001, which exceeds requirements by five years.

Concerning the requirement that diesel vehicles with a GVWR of more than 14,000 lb. utilize BAT or be equipped with an engine certified to the applicable 2007 EPA standard, the Act required that 117 buses (Table 6) meet this requirement by September 1, 2007. With 162 buses retrofitted with DPF and four hybrids equipped with DPF, a total of 166 were in compliance, exceeding the 2007 requirement by 49 buses.

Although WCDOT was in conformance with County Act 19 up to September 1, 2007, it was recommended that the agency continued its proactive stance in 2007 and beyond by continuing to exceed County Act 19 requirements. Just as WCDOT exceeded 2007 requirements in 2006, it was recommended that the county continue to meet Act 19 requirements one year in advance of the requirements. Knowing that Act 19 has a provision whereby retrofits are grandfathered for a three-year period, meeting requirements in the previous year allows WCDOT to be more selective in installing BAT as it is introduced.

For example, because WCDOT retrofitted 162 buses with DPF meeting BAT requirements at time of installation prior to 2007, any additional retrofits it made in 2007, although resulting in a significant emissions reduction, did not need to meet the BAT requirement. Without having met Act 19 requirements in advance, it is possible that WCDOT would be required to install a BAT technology just to meet the quota for a given year knowing that later in that same year a more effective (and possibly more attractive) technology would be verified as BAT.

Until recently, the only verified technologies available were DPFs that reduced PM, but did not reduce NO_x. However, there are two retrofit technologies currently available that reduce NO_x. One is the Johnson Matthey (JM) Exhaust Gas Recirculation Technology (EGRT), which uses EGR in combination with its CRT particulate filter. EGR works to reduce NO_x by taking cooled exhaust gas after it exits the DPF and re-circulating some of it back into the engine intake stream. JM's EGRT system reduces NO_x by 40% and is verified by CARB.

The other NO_x reduction system, also verified by CARB, is offered by Fleetguard Emission Solutions and its partner Cleaire Advanced Emission Controls, a division of Cummins West Inc. The Cleaire Longview emissions control system is an active single module that uses a DPF to reduce PM, and an NO_x-reduction catalyst that injects a small amount of diesel fuel into the catalyst to remove NO_x from the exhaust stream. Cleaire's Longview system is less effective than the JM system in that it is verified to reduce NO_x by 25%, compared to JM's EGRT system, which is verified to reduce NO_x by 40%.

It is assumed that the two NO_x-reduction technologies described above meet BAT requirements as defined by Act 19. As required by Act 19, Part 5, the Westchester County Commissioner of Health (or other commissioner) is obligated to publish and periodically revise a list of BAT.

In addition to the two currently verified NO_x-reduction technologies described above, there is a third approach, now applying for verification status that may prove more attractive as a retrofit to WCDOT. JM's SCRT device uses a urea-based, selective catalytic reduction (SCR) technology used in conjunction with the company's DPF (CRT particulate filter). To control emissions, engine exhaust first flows through JM's CRT to reduce CO, PM, and HC, as is currently done with the DPFs already retrofitted to 162 WCDOT buses. A controlled amount of urea is then injected into the exhaust stream before it enters the SCR catalyst, a separate catalyst placed after the DPF. Urea is an ammonia-like liquid that provides the necessary chemical conditions for the SCR catalyst to reduce NO_x. The SCR system consists of a commercially available urea injection system and a control system to deliver the urea. The system uses JM's proprietary SCR catalyst technology that is said to have advantages over other NO_x-reduction systems currently under development. It is assumed at this verification-pending stage that JM's SCR system could be added to the CRT system previously retrofitted to WCDOT buses. WCDOT will need to closely monitor the verification process to determine if this in fact becomes the case.

JM is currently working with both the EPA and CARB to verify the new system. The company expects to achieve a 50%-80% reduction in NO_x. In addition to JM's SCRT systems, there are other NO_x-reduction systems using similar technology that are in process with the EPA.

SCR technology is an interesting one in that several heavy duty diesel engine manufacturers are now targeting it as one of their primary technology solutions for NO_x control to meet the next round of EPA emission standards that become effective in 2010. One potential shortfall of the approach is that the liquid urea chemical must be stored onboard the vehicle and periodically replenished. If the urea fluid should run low, warning signals inform the driver. Running out of the fluid while on the road would cause the engine to shut down. The issue is mitigated by the fact that centrally-fueled fleets, such as those operated by WCDOT, have more control over their maintenance operations. Depending on the onboard storage capacity, urea refills may coincide with preventive maintenance inspections (PMIs) and oil change intervals, providing a scheduled (and more convenient) opportunity for urea replenishment. Working with the EPA, a broad range of companies, including the diesel engine OEMs, vehicle OEMs, oil companies, exhaust aftertreatment suppliers, component suppliers, urea suppliers, and the truck stop industry have formed a consortium committed to resolveing urea availability and ensuring its supply on a broad public scale.

The point of this discussion is that the proactive stance taken by WCDOT to retrofit to DPF before being required, and exceeding Act 19 requirements, allows the agency to “skip over” current verified NO_x technology, if desired, in favor of weighing a more effective approach. Without being ahead of the requirements in terms of compliance, WCDOT may have been placed in a position to retrofit to a technology for a limited number of buses to meet a quota knowing that those few buses would be the only ones with that particular technology. WCDOT’s proactive stance allows it more choices going forward, and to develop a more standardized approach to reducing emissions and complying with local county requirements.

Given that urea-based, SCR technology appears to be a viable and more effective approach to reducing NO_x for the purposes of meeting 2010 EPA diesel emission requirements, it was recommended that WCDOT pay particular attention to SCR developments. If verified by the EPA and CARB, the insight gained into SCR technology places WCDOT in a favorable position to understand and evaluate a technology that appears to be a current frontrunner to meet 2010 EPA diesel emission requirements. Assuming WCDOT goes ahead and becomes compliant with 2008 Act 19 requirements a year in advance in 2007, the agency would be in a position to voluntarily retrofit to SCR technology depending on the success and cost of the SCR-based system.

Table 11 outlines the recommendations for retrofitting buses in advance of county requirements. The recommendations were based on a current fleet size of 334 buses, where 116 of those buses would be replaced with buses that meet 2007 EPA emissions standards in 2008/2009. It should be noted that 2007 and newer buses are considered BAT for the purposes of Act 19 and do not require retrofits.

Although several retrofit scenarios could be followed, the recommendations offered here were based on doing 72 retrofits in 2007 and 64 in 2008, which represents a similar level of retrofits undertaken by WCDOT in 2005 and 2006, where 84 and 78 retrofits were done respectively. Proceeding with these retrofits is consistent with WCDOT’s proactive stance of reducing emissions in an aggressive manner.

Table 11: Recommended Retrofits

Year	Bus Year/ Make/Model	Retrofits	Type of Retrofit [A]	Cumulative Number of Buses Retrofitted
2007	‘02 Orion V – 30’	15	DPF	162 existing pre-‘07
	‘05 Orion V – 30’	17	DPF	+ 4 hybrids w/DPF
	‘06 Orion V – 40’	40	DPF	+ 72 retrofits in ‘07
	‘90 Flxible	11	Remove from fleet with no replacements (existing WCDOT strategy)	-11 retirements = 238 – 121 required for ‘07
2008	‘06 Orion V – 40’	64	DPF	238 existing pre-‘08 + 64 retrofits ‘08
	‘86/’87 MCI	32	Replace w/08 Bus	+32 new buses in ‘08 = 334 (entire fleet) – 224 required for ‘08
2009	95/96 Orion V – 40’	84	Replace with ‘08 hybrid (existing WCDOT strategy)	The entire fleet would have been converted to BAT in ’08, meeting ’09 requirements one year in advance. [B]

[A] It is difficult to determine which retrofit technologies may emerge in the future. SCR is used here because it currently appears to be the most viable. WCDOT will need to follow these developments closely.

[B] Note that any bus converted to BAT in a particular year must be retrofitted again three (3) years later if new BAT equipment becomes available.

The proactive approach of WCDOT towards emissions reduction is showed to save, over the five-year period, 112.5 tons (53%) of CO, 23.3 tons (1%) of NO_x, 11.3 tons (30%) of HC, 7.3 tons (44%) of PM, 1,119 tons (1%) of CO_2, and 114,000 gallons (1%) of diesel. In the first two years, when no retrofits were required, the proactive retrofits yielded a slight increase in fuel consumption, which was later offset by the inclusion of four hybrids to the fleet. Finally, if in 2009 WCDOT introduces, as planned, 84 hybrids to the fleet, the agency would annually save nearly 10% in fuel and CO_2 greenhouse gas emissions.

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