Emission Reduction Options for Ontario School Buses

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1 Background

Over the past few years, concern has grown throughout North America over the environmental and health risks from school bus exhaust. In February 2002, the Union of Concerned Scientists published an assessment of the issue[1] and the US EPA,[2] the US Department of Energy[3], and a number of state and local governments in the U.S. have been devoting resources to research, development and implementation of emission reduction technologies. In the fall of 2003, the Ontario Public Health Association completed an initial review of the literature on the subject[4] and decided to proceed with a more specific assessment of the emissions from school buses in Ontario and the technological options for emission reduction from the Ontario school bus fleet.

With the support of Environment Canada and the Laidlaw Foundation, the OPHA contracted with Torrie Smith Associates to conduct a study of the demography of the Ontario school bus fleet, to analyze the current level of emissions from school bus operations in Ontario, to identify technologies and techniques for reducing tailpipe emissions from Ontario school buses, and to review the costs of the various technological options. In carrying out the work, in addition to the research and analysis itself, we have met with the OPHA project steering committee and had individual exchanges with several of the committee members, and with Greg Rideout of the Environment Canada's Emissions Research and Measurement Division and Kim Perrotta of the Ontario Public Health Association. Key members of the Ontario School Bus Association were surveyed on the subject of bus emissions and emission reduction options, and the OSBA also provided information on the number of buses by fuel type for each of their members. We also acquired and analyzed Ontario school bus registration data from Polk Consulting, school bus industry data from Statistics Canada, NRCan data on school bus operations and energy consumption, and Ontario Drive Clean data on opacity tests of Ontario school buses.

In the 1970's and 1980's, most school buses were gasoline powered, but virtually all new school buses have been diesel powered since the late 1980's. In 2003, there were about 300 propane-powered and 700 gasoline-powered school buses in Ontario, but their numbers are declining. For practical reasons, our analysis focuses on the full-sized, diesel-powered school buses that make up over 90% of the approximately 15,000 vehicles in the Ontario school bus fleet.

Diesel engine technology and emission control techniques have been evolving at a rapid pace for the past 15 years. When diesel engines that meet the newest emission standards start entering the market in 2007, it will represent at least the third generation of technology to be introduced since the 1994 model year. The school bus fleet takes 15-20 years to turn over in Ontario, and emission control techniques are evolving three times that fast. This complicates the task of reviewing emission control opportunities; emissions vary enormously according the model year of the bus, and not all emission control technologies can be retrofit to buses of all ages. We set out to do a "snapshot" of the emission reduction opportunities for Ontario school buses, but

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[1] Monahan 2002.

[2] http://www.epa.gov/otaq/schoolbus/.

[3] http://www.rebuild.org/sectors/SectorPages/BusTransportation.asp

[4] OPHA 2003.

quickly realized that a "snapshot" would not be adequate, that we would need to identify and analyze opportunities in the context of the twin dynamics of school bus demography and diesel engine technology. To that end, this report is organized as follows:

- **Section 2** briefly reviews the basics of the air pollutant and greenhouse gas emissions from the diesel engines that power most Ontario school buses, as well as the evolution since 1990 of the regulated emission limits on these engines.
- This is followed in **Section 3** with a review of the demography of the Ontario school bus fleet and an analysis of how the combined effects of the fleet age profile and the changing emissions regulations determine the nature of the challenge of reducing emissions of air pollutants from Ontario school bus engines.
- **Section 4** analyzes the factors that affect tailpipe emissions (as opposed to the engine-based emission factors used in Section 3) and provides an estimate of the current and future tailpipe emissions of the Ontario school bus fleet, under "business as usual" conditions.
- **Section 5** reviews the emission reduction strategies, techniques and technologies that can be applied to reduce air pollutant and greenhouse gas emissions from school buses. Technologies are reviewed with respect to target pollutant, emission reduction effectiveness, retrofit applicability to buses of different ages, and costs.
- **Section 6** identifies and analyzes scenarios for reducing emissions from Ontario school buses by combining technologies targeted for specific pollutants and model year cohorts.
- Finally, in **Section 7** we summarize our conclusions, with an emphasis on their implications to the question of what policies and program approaches would be most appropriate for reducing emissions from Ontario school buses.

2 Diesel Engine Emissions and Emissions Regulations

Like most fossil fuel combustion engines, the essential process in diesel engines is a rapid-fire sequence of controlled explosions of complex hydrocarbon fuel. With diesel engines, the explosion is initiated by compression rather than by a spark, and the power output of the engine is controlled by varying the flow of fuel to the combustion chamber rather than by throttling the air supply. In diesel engines, the fuel-to-air ratio varies over a wide range with engine speed and load. Diesel engines tend to be more fuel efficient than spark ignition engines, but also more massive. They have long been the preferred power plant for hauling and heavy duty applications, including medium and large trucks, where durability and peak torque are critical.

The diesel engine produces a stream of hot, fast moving particles and gases at the outlet manifold of the combustion chamber. In addition to carbon dioxide (the primary greenhouse gas and a an unavoidable product of fossil fuel combustion), there are dozens of chemical compounds in diesel exhaust, with the composition depending on the distribution of the temperature, pressure and combustion chemistry throughout the combustion chamber and for the duration of the entire engine cycle. In addition to its fundamental dependence on the chemical composition of the engine fuel and lubricating oils, the exhaust stream varies with the load on the engine and is highly sensitive to engine design and geometry, turbocharging and air cooling techniques, as well as to fuel injection strategies and control technologies.

Diesel exhaust is relatively high in particulates and in nitrogen oxides. While there are some relatively "coarse" particles (diameters in the 5-10 micron range), most of the mass of diesel PM consists of fine particles with diameters in the range of 0.1 - 1.0 microns. In this size range, the particles have a relatively high ratio of surface area to mass, and they are excellent carriers for adsorbed organic and inorganic compounds. While the carbonaceous particles in this size range dominate the mass of diesel PM, they are surrounded by a fine mist of hot gases and ultrafine particles in the nuclei mode (diameters in range of 0.01 microns). In recent years there has been increasing concern about the relative public health and environmental significance of that portion of the emissions comprised of unregulated "toxic air contaminants (TAC's)", many of which are complex hydrocarbons. These include aldehydes (e.g. formaldehyde, methyl ethyl ketone), benzene, tolulene, phenol, furans, dioxins, chlorbenzene compounds, and various polycyclic hydrocarbons or PAH's (including naphthalene). These materials make up a small portion of the total *mass* of emissions but a relatively large portion of the total *number* of particulates in the emissions stream. Both their toxicity and their small size (enabling deep penetration into the human respiratory system) give rise to the concern over these emissions, although quantitative data on the composition and concentration of these substances in school bus exhaust is limited.[5] When and where combustion is incomplete, emissions of particulates, carbon monoxide and hydrocarbons will be relatively high; when and where combustion is complete and temperatures are higher, NO_x emissions will be relatively high. The tradeoff between particulate emissions and NO_x emissions is an ever-present challenge in reducing emissions from diesel vehicles.

Tailpipe emissions from heavy duty vehicles are not directly regulated. Instead it is the new diesel engines that power these vehicles that are required to meet emissions standards for particulate matter (PM), hydrocarbons (HC), nitrogen oxides (NO_x), and carbon monoxide (CO). The emissions limits are set in grams of pollutant per unit of energy at the engine shaft over a specified test cycle. The test cycle includes a range of loads and load durations intended to simulate the power demands on the engine during actual use, but the testing and compliance certification of the engine are based on performance during a test in which the engine is mounted on a test bench in a laboratory, outside of any vehicle. In recent years, the emission limits set by the U.S. Environmental Protection Agency have been adopted by reference in Canadian emissions regulations. The regulations are expressed in grams per brake horsepower-hour (g/bhph)[6] and Table 1 summarizes the limits over the 1990-2010 period.

Of the four regulated air pollutants (NO_x, HC, CO and PM), it is the requirements for PM, HC and NO_x emissions that are currently setting the agenda for emission reduction technology. With regard to carbon monoxide, the emission limits have not been adjusted since before 1990 and the actual emissions from diesel engines are well below (on the order of ten times lower) the 15.5 g/bhph limit. In addition, the same initiatives taken to reduce PM emissions have the effect of reducing CO emissions even further. Sulphur oxide emissions (SO_x) are directly related to the

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[5] We do know that the oxidation catalysts used in current PM and HC emission reduction technologies are effective at reducing emissions of toxic air contaminants, a fact that should be kept in mind when weighing the public health and environmental benefits of installing oxidation catalysts and catalyzed diesel particulate filters on school buses.

[6] Brake horsepower is a somewhat archaic unit of power defined as the power available at the shaft of an engine. One horsepower is equal to 746 Watts, and a horsepower-hour is therefore equal to 746 Watt-hours of energy, or 2.7 Megajoules (MJ).

sulphur content of diesel fuel. The maximum allowable level of sulphur in on-road diesel fuel will be reduced to "ultra low" levels starting in mid-2006, (i.e., from 500 ppm to 15 pm pursuant to the Canadian Sulphur in Diesel Fuel Regulations.) Accordingly, SOx emissions from diesel truck and bus engines will be virtually eliminated as a concern.

As the numbers in Table 1 illustrate, the reductions in allowable emissions from new diesel engines since 1990 have been frequent and significant. Compared to 1990, the new 2007 limits are 89% lower for hydrocarbons, 98% lower for PM and 97% lower for NO_x. Allowable emissions of particulate matter had already been lowered by about 90% by the mid-1990's, which is why it is now much less common to see thick, black smoke belching from the tailpipes of school buses and other heavy duty diesel vehicles.

Table 1

Evolution of Emission Standards for New Heavy Duty Diesel Engines Used for Urban Buses[7]

	(grams per brake horsepower-hour)			
Bus model year	**PM**	**CO**	**HC**	**NOx**
1989	0.60	15.5	1.3	6
1991	0.25	15.5	1.3	5
1994[8]	0.10	15.5	1.3	5
1998	0.10	15.5	1.3	4
2004[9]	0.10	15.5	2.4 NMHC + NOx	
2007[10]	0.01	15.5	0.14	0.2

To facilitate analysis of emissions from Ontario school buses of different ages, we have developed a number of "model year cohorts" with the cohorts defined by years in which significant changes were introduced in the allowable emissions of PM, HC or NO_x in new diesel engines. The cohorts, with the assumed emission levels (in grams per brake horsepower-hour) are defined in Table 2.

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[7] The standard in the table are for the U.S. regulated limits. The 1991 and 1994 standards were complied with on a voluntary basis in Canada. In subsequent years, the U.S. emission limits have been adopted by reference in Canadian regulations.

[8] Starting in 1993, a separate and lower standard was established for PM emissions from engines destined for "urban buses", as opposed to other heavy duty diesel vehicles, and by 1998 the "urban bus" PM standard was lowered to 0.05 g/bhph, half that of other heavy duty vehicle engines. The "urban bus" category is intended to cover transit buses and does not include school buses, however. Starting in 2007, the PM standard for ALL heavy duty diesel engines will be set at 0.01 grams per brake horsepower-hour.

[9] The interim standard introduced with the 2004 bus model year required that the sum of non-methane hydrocarbon (NMHC) emissions plus NO_x emissions should be no more than 2.4 grams per brake horsepower-hour. An optional standard allows a limit for the sum of non-methane hydrocarbon (NMHC) emissions plus NO_x emissions to be 2.5 grams per brake horsepower-hour, provided the NMHC emission level does not exceed 0.5 g/bhph.

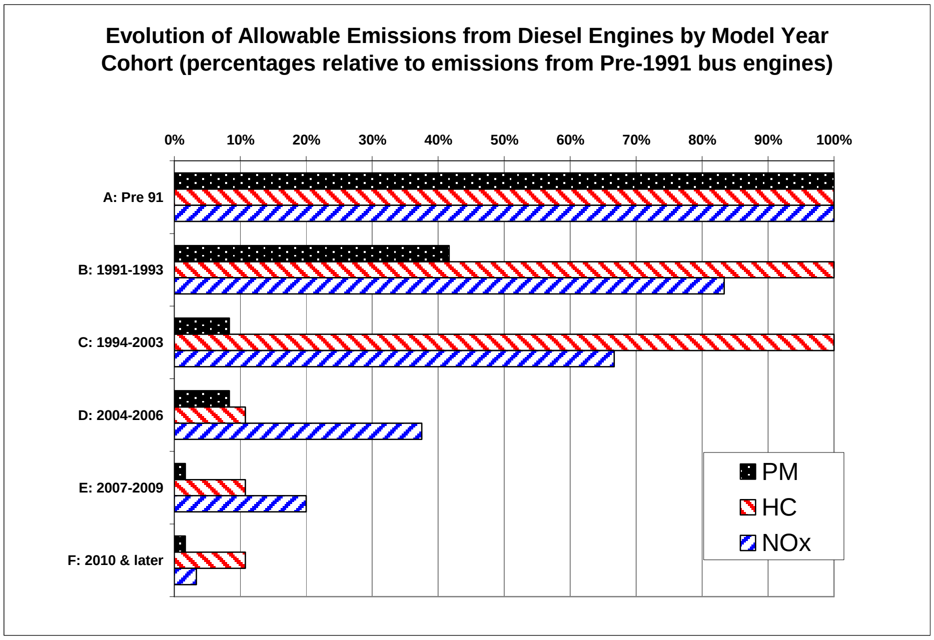
[10] With regard to the new emissions limits that come into effect in 2007, the PM standard must be fully implemented in all new vehicles starting with the 2007 model year but the NO_x and NMHC limits will be phased in. For the 2007-2009 model years, manufacturers are required to produce a sales weighted fleet average that is equivalent to a fleet in which 50% of the vehicles have engines that meet the new standard. It is now expected that most if not all manufacturers will comply by producing a vehicle fleet in which 100% of the vehicles achieve 50% of the required emission reduction., as compared with the 2004 limit,.

Table 2

Definition of Model Year Cohorts for School Bus Analysis				
Cohort	Model Years	Emissions (g/bhph)		
		PM	HC	NOx
A	Pre 1991	0.60	1.3	6
B	1991-1993	0.25	1.3	5
C	1994-2003	0.10	1.3	4
D	2004-2006[11]	0.10	0.14	2.25
E	2007-2009	0.01	0.14	1.2
F	2010 and later	0.01	0.14	0.2

Figure 1 illustrates the relative drops in emissions of PM, HC and NO_x from new diesel engines assumed for each of the model year cohorts. Changes and improvements to engine design and combustion chamber geometry, improved engine controls, electronically controlled fuel injection, turbocharging and other engine design and combustion control strategies have reduced emissions of PM and HC below the currently regulatory limits. The most recent 2004 limits on NO_x emissions are being met on new buses without after-treatment for NO_x removal, but the installation of catalyzed diesel particulate filters makes it possible to operate the engine so that the "engine out" NO_x emissions are below the 2004 emissions limit. While the 2007 standard for HC and PM can be and will be met through the application of catalyzed diesel particulate filters, the 0.2 grams/bhph standard for NO_x that must be met by all new buses starting in 2010 will probably require the application of NO_x after-treatment technology.

Figure 1



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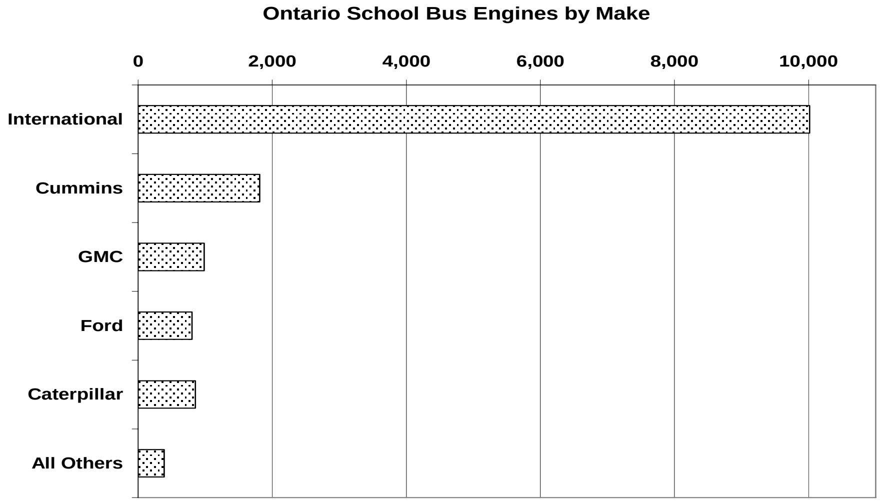
[11] The emission limits for NO_x and NMHC are not specified separately in the 2004 standard; the 0.14 and 2.25 g/bhph values uses here for NMHC and NO_x, respectively, are based on the pre-2004 limit for NMCH and our interpolation/estimate for the NO_x value.

3 The Ontario School Bus Fleet

Information on the demographics and operation of school buses in Ontario was obtained from the Ontario School Bus Association, Statistics Canada, the Ontario Drive Clean database, the database of the Office of Energy Efficiency of the NRCan and, through Polk Consulting, from the Ontario Ministry of Transportation vehicle registration database. According to the Ontario vehicle registration data obtained from Polk, in 2003 there 17,313 vehicles registered in Ontario as school buses. Of these, there were 2,457 records for which the vehicle registrant field was left empty, leaving 14,856 registrations with complete information. We have used a figure of 15,000 for purposes of modeling emissions from the Ontario school bus fleet. [12]

Figure 2



The engine technology in Ontario school buses is predominantly diesel, with over 93% of the buses being fueled by diesel (5% on gasoline and 2% on propane). International Diesel makes over two thirds of the diesel engines being used in Ontario school buses, and most of these are the T444E model. Most of the other engines are made by four firms – Cummins, GMC, Ford and Caterpillar.

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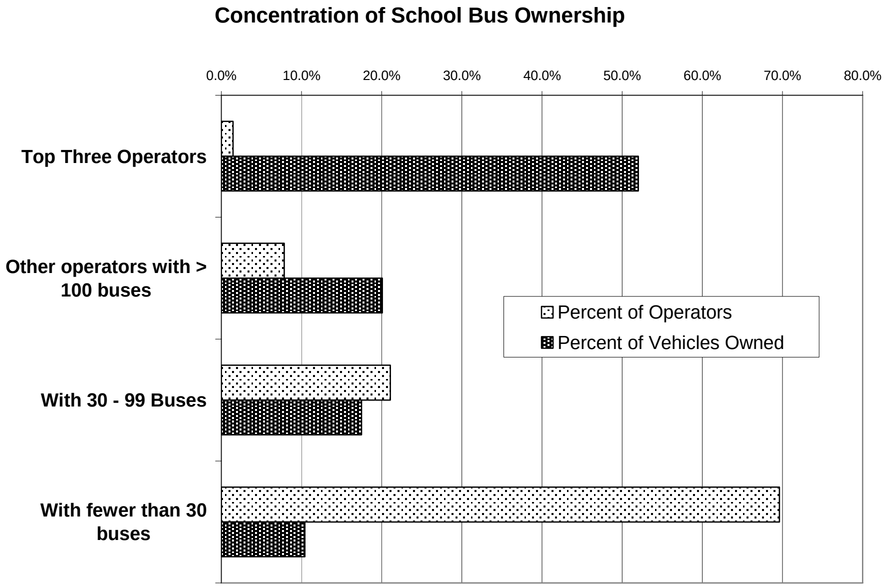
[12] We were unable to obtain a definitive explanation from Polk for the blank registrant fields, except that the field will be left empty if the bus is registered to an individual and is not being used for business purposes. A blank registrant field may also be an indication of a lapsed registration or a registration that is not valid for some other reason. A comparison of the 14,856 record set (complete set of fields) with the 17,313 record set (blank registrant field) does indicate that the larger set has a somewhat higher proportion of older buses (16 years old or more) and a slightly lower proportion of new buses (less than five years old), but the difference between the two sets is relatively small. The age profile of the smaller set is considered to be more representative of the population of school buses currently in use as school buses in Ontario, and that is the profile used as the basis for the analysis in this report.

School bus ownership is also concentrated. There are about 200 school bus operators in the Ontario School Bus Association, but the three largest fleets (Laidlaw, Stock and Northstar) account for 53% of the school buses in Ontario. Operators with fewer than 30 buses account for 75% of the OSBA membership but only 10% of the buses.

Figure 3



As described in the previous section, over the past fifteen years, allowable emissions from diesel engines have been reduced frequently, and often by relatively large amounts. To support the emissions analysis of Ontario’s school buses we have identified six model year cohorts with different allowable emission profiles:

Cohort A:	Pre-1991 Model Year
Cohort B:	MY 1991-1993
Cohort C:	MY 1994-2003
Cohort D:	MY 2004-2006
Cohort E:	MY 2007-2009
Cohort F:	MY 2010 and later

In developing projections of the school bus fleet, we have held the total number of buses at 15,000, for lack of a better assumption. With regard to bus turnover, we have assumed that buses are retired at the rate of 50% per year once they reach the age of 15, an approximation of current industry practice.[13] The resulting projection of the school bus fleet by MY cohort is shown in Figure 4.

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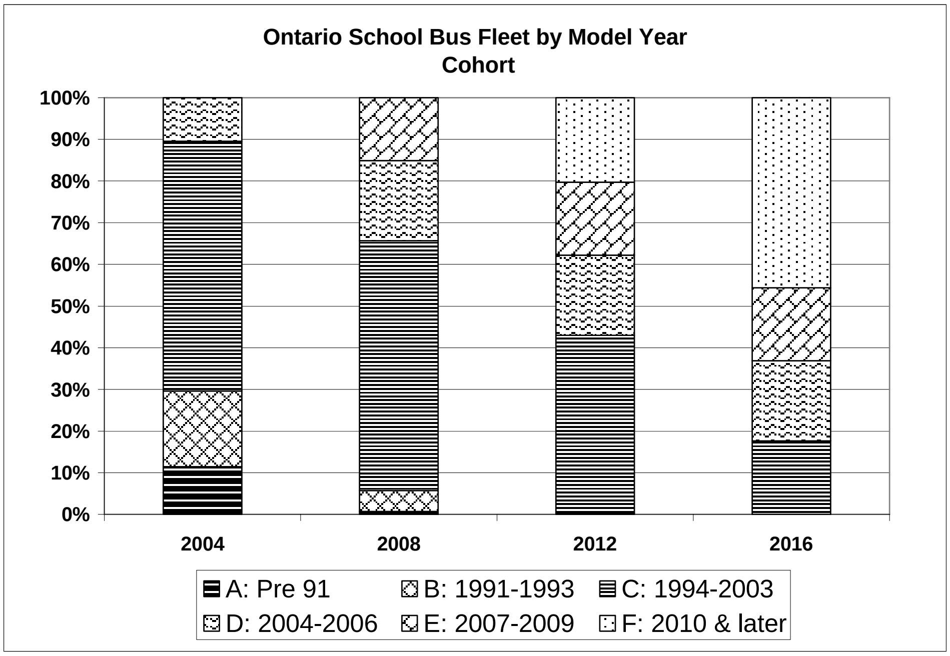
[13] The Ontario school bus fleet is “younger” than some other fleets. In Ontario, nearly 90% of the school bus fleet is less than 16 years old and 99% is less than 21 years old. In contrast, the turnover time for the California school bus fleet is about 25 years, which is one of the reasons their policies and programs for cleaning up school buses have emphasized incentives for the retirement of old buses.

Because the cohorts are defined by the years in which the most significant changes in allowable emissions take place, they cover varying number of years. The largest is the 1994-2003 cohort; as illustrated in Figure 4, this cohort represents the bulk of the bus population today and will remain the largest cohort for another ten years.

Figure 4



To the extent that actual tailpipe emissions are proportional to the g/bhph emission limits, the product of the emission limits for each cohort and the share of the bus population in that cohort will indicate the relative emissions of each of the key pollutants from each of the model year cohorts. This calculation was performed for HC, PM and NO_x emissions for the projected bus populations in 2004, 2008, 2012 and 2016, and the results are illustrated in Figure 5. Using the same assumptions, Figure 6 illustrates the relative contribution of each of the model year cohorts to *cumulative* emissions by 2008, 2012 and 2016 (starting in each case from 2005).

These figures illustrate a number of key features of the challenge of reducing air pollutant emissions from Ontario school buses:

- Buses in the 1994-2003 model year cohort dominate emissions well into the next decade, indicating that the emission reduction task is primarily a retrofit task. By 2016, buses in this cohort represent less than 20% of the bus population, but with status quo technology (i.e. in the absence of retrofit or early retirement) would still be the source of more than 40% of annual PM emissions, 50% of annual NOx emissions and over two thirds of annual HC emissions.

- The oldest buses in the pre-1994 model year cohorts are now at least ten years old and the contribution of these cohorts (A and B) to annual emissions is falling off rapidly as buses are retired. However, their emission factors are so much higher than subsequent model year cohorts that their contribution to cumulative emissions over the 2006-2016 time period remains significant, especially for particulates. This suggests early retirements and/or emission reduction retrofits in this group could still be an important component of an overall strategy.

- A significant portion of the 2004-2006 model year cohort consists of buses that have yet to be purchased. Buses that meet the 2007 standards for PM and HC emissions are already available, suggesting one possible strategy would be to accelerate the uptake of new buses that meet the 2007 PM standard

Figure 5

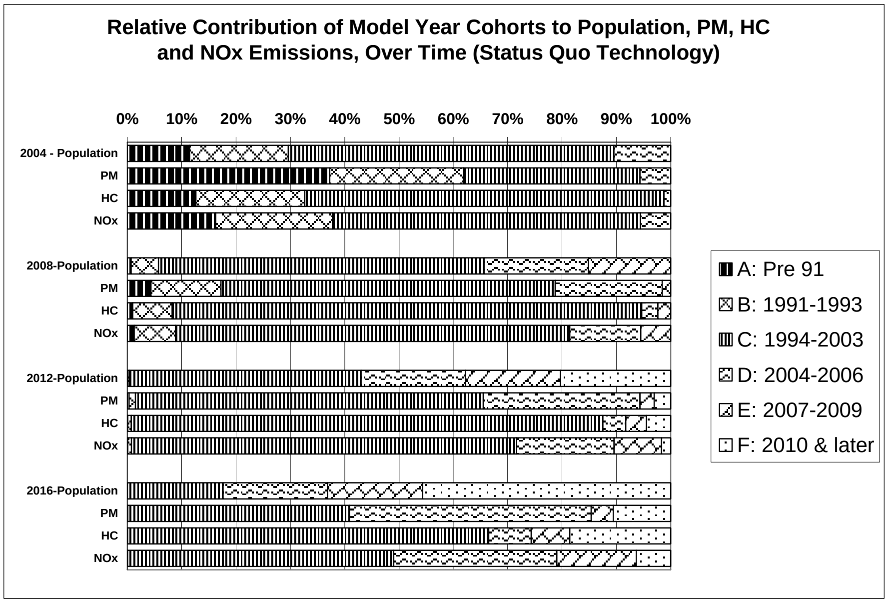
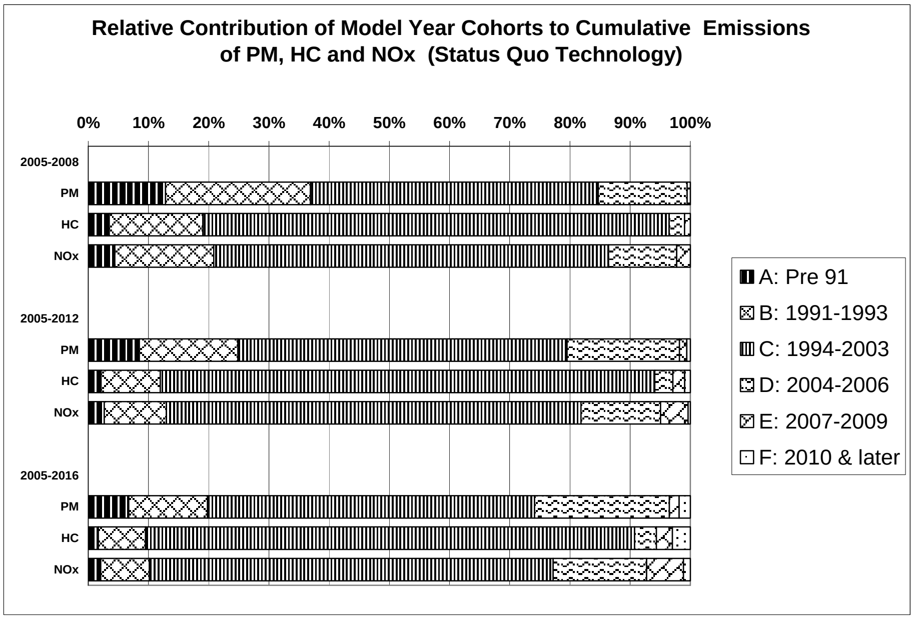


Figure 6



4 Tailpipe Emissions from Ontario School Buses

The emission rates in the previous section, expressed in grams per brake-horsepower-hour, are emissions per unit of energy delivered to the engine shaft during a specified test cycle that is carried out on a laboratory bench, with the engine removed from any vehicle.[14] The actual tailpipe emissions (expressed, for example, in grams per vehicle-km of travel) will depend not only on the emissions per brake horsepower-hour of engine output, but also on the efficiency with which the engine output is converted to forward motion over a range of loads, terrains, and driving conditions. This is turn depends not only on the overall efficiency of the vehicle, but on the weight of the vehicle and its load, the driving cycle (urban vs. highway, frequency of accelerations, etc.), vehicle maintenance, driver behaviour, and other factors.

One source of conversion factors for estimating tailpipe emissions (in grams per kilometre) from engine emission rates (in grams per brake horsepower-hour of engine output) is the background research and databases maintained to support the MOBILE model. The MOBILE model was developed in the U.S. to simulate tailpipe emissions from the on-road vehicle fleet in support of emission regulation research and standard setting, and it has been adapted by Environment Canada for application to the Canadian vehicle fleet. Essentially, it combines emission factors (in grams per kilometre for each pollutant) with estimates of distance traveled for vehicles of different makes, types, model years and ages to produce estimates of aggregate air pollutant emissions.

In the case of heavy duty vehicles, including school buses, the emission factors in grams per vehicle-kilometre traveled that are required by the MOBILE model are related to engine emissions (in grams per brake horsepower-hour) according to:[15]

$$Grams/vehicle-km = (grams/bhph) \times Conversion\,Factor\,(in\ bhph/km)$$

where

$$Conversion\,Factor\,(bhph/km) = \frac{Fuel\ Density\left(kg/Litre\right)}{BSFC\,(kg\ \ fuel/bhph) \times Fuel\ Economy\,(km/Litre)}$$

and where BSFC refers to the brake specific fuel consumption.

In developing the conversion factor for diesel school buses, the US EPA assumes a vehicle fuel efficiency of about 6.2 miles per US gallon and a corresponding BSFC of about 0.39 lbs/bhph which (after conversion to metric units) results in a conversion factor of about 1.85 bhph/km.

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[14] Specifically, the test cycle is the US EPA Federal Test Procedure (FTP) engine dynamometer certification test cycle used as the standard for emissions certification of heavy duty vehicle engines. More details on this and other test cycles available at http://www.dieselnet.com/standards/cycles/ftp_trans.html.

15 USEPA 2002a, USEPA 2002b. The factors in Table 3 represent estimates of the emissions per vehicle-km from diesel school buses that have engines with emissions per brake horsepower-hour that conform to the regulated limits described in Table 2.

Applying this conversion factor to the regulatory emission levels (in grams/bhph) in Table 2 yields the vehicle emission factors indicated in Table 3.

Table 3

School Bus Emission Factors Derived from Regulatory Engine Emission Limits and MOBILE Conversion Factors				
Cohort	Model Years	Emissions (grams per vehicle-km)		
		PM	**HC**	**NOx**
A	Pre 91	1.12	2.42	11.18
B	1991-1993	0.47	2.42	9.32
C	1994-2003	0.19	2.42	7.46
D	2004-2006	0.19	0.26	4.19
E	2007-2009	0.02	0.26	2.24
F	2010 & later	0.02	0.26	0.37

The factors in Table 3 are only indicative of actual on-road emissions as they are the result of a simple across-the-board application of the US EPA MOBILE6 diesel school bus conversion factor to the regulated emission limits for the diesel engines used in school buses. Also, they are based on the regulated diesel engine emission limits, which in turn are associated with a specific engine test cycle that is designed to represent typical engine loads and power cycles but does not represent actual on-road driving conditions. Nevertheless, the numbers in Table 3 should provide a rough indication of tailpipe emissions for diesel school buses.

There are very few empirical studies of actual tailpipe emissions from school buses, although the recent surge in interest in school bus emissions, particularly in the U.S., is beginning to yield more analysis. We used three studies that measured tailpipe emissions from school buses under chassis dynamometer or on-road conditions. Two of the studies used a single diesel school bus and one tested two buses, and the emission results for all four buses are shown in Table 4 for the tests where no after burner pollution control technologies were applied. The studies all used different driving cycles, none of which correspond to the test cycle used for the engine testing described above, but all of which are similar insofar as they simulate the stop-and-go pattern of school bus operation.

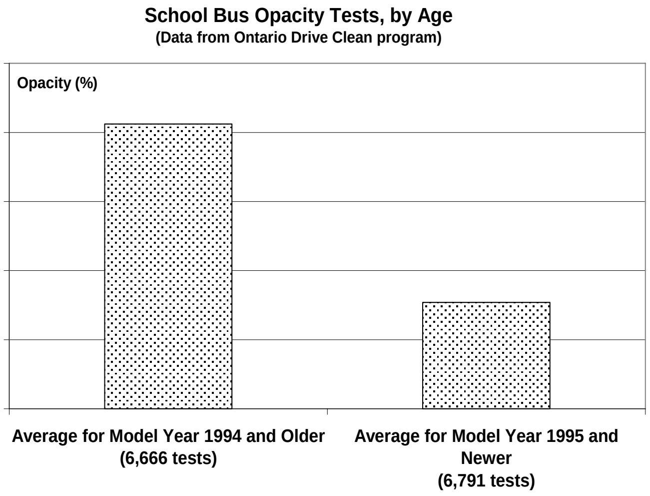
While this is not much to go on, some insight can be gained by comparing the results in Table 3 and Table 4. Considering the different methods, the different driving cycles and all the other variables and uncertainties, the empirical data are in reasonable agreement with the predicted emission factors (using the MOBILE method), although the data suggests that actual emissions tend to be lower than the absolute values computed by the method used for Table 2, particularly for the newer (post 1994) buses. The measured emissions are particularly low relative to the computed results for THC for all cohorts, but there is too little data to be conclusive (THC emission measurements are particularly sensitive to testing and sampling methods). The relative differences between the cohorts area comparable for the computed and measured values.

Table 4

Measured Tailpipe Emissions from Four Diesel School Buses, No After Treatment Technology							
				Emissions in grams per km			
Cohort	**Model Year**	**Fuel**	**Driving Cycle**	**PM**	**NOx**	**THC**	**Source Document**
A	1988	Reg diesel (383 ppm)	Norwich School Bus Route	0.784	6.735	N/A	Rideout 2004
B	1992	Diesel (hi sulphur, presumably in 350-400 ppm range or higher)	New York Composite	0.500	8.973	1.190	Rideout and Brown
B	1992	Diesel (hi sulphur, presumably in 350-400 ppm range or higher)	CBD	0.400	8.046	1.220	Rideout and Brown
C	1998	350 ppm diesel	CSHVC	0.115	8.829	0.243	Ullman 2003
C	2000	Regular diesel (383 ppm)	Norwich School Bus Route	0.112	6.090	N/A	Rideout 2004
C	2000	ULSD (17 ppm)	Norwich School Bus Route	0.107	5.553	0.137	Rideout 2004

We also reviewed data from the Ontario Drive Clean program, which contains more than 13,000 records for school bus tests.[16] In addition to the opacity test results themselves, the Drive Clean database contains a great deal of information about the vehicles being tested (e.g. vehicle and engine makes and models and model years, number of cylinders, engine size, transmission type, odometer reading at the time of the test, model year). We searched for correlations between various vehicle attributes and the opacity test results and the only clearly significant correlation we found was with the model year (engine and vehicle model years were recorded as identical for virtually all the vehicles tested). As model year increases opacity declines, but not smoothly. There is a distinct drop in opacity starting with Model Year 1995, as illustrated in Figure 6, clearly reflecting the drop in the allowable PM emissions that was implemented starting in the 1994 Model Year.

Figure 7



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[16] The Ontario Drive Clean program provided a database of all their school bus test results.

We conclude that for purposes of policy analysis and the assessment of emission reduction technologies, the vehicle emission factors in Table 3 provide the best available basis for estimating emissions of NO_x, PM and THC from Ontario school buses. These factors are based on the regulated emission limits for diesel engines combined with a sound and well documented method used by the US EPA for conversion to tailpipe emission factors for application in the MOBILE6 model. They are in reasonable agreement with the empirical data that is available, and more importantly they provide a consistent framework for estimating emissions from existing and future vehicles.

To complete a baseline or "status quo" scenario of air emissions from the school bus fleet requires an estimate of the distance traveled by the buses, and we have assumed the average annual distance traveled by school buses in Ontario to be 22,000 km, consistent with Statistics Canada data[17] and an estimate of 20-24,000 km per year received from the Ontario School Bus Association. For purposes of projecting future emissions, we have assumed that school buses of all ages are operated for the average 22,000 km per year, and that the total number of school buses remains constant at 15,000. With regard to fleet turnover, we have assumed that buses are retired at the rate of 50% per year once they reach the age of 15, an approximation of current industry practice, resulting in projected fleet profile illustrated above in Figure 4.

Finally, with respect to greenhouse gas emissions, we have assumed diesel bus fuel economy of 32.5 Litres/100 km and that this remains unchanged in the status quo projection. There has been very little improvement in school bus fuel efficiency in the past ten years, and the pollutant emission reduction technologies that are implicit in the status quo projection developed here are not expected to result in significant fuel economy improvements.

The resulting status quo projection of greenhouse gas and air pollutant emissions from Ontario's diesel school bus fleet is summarized in Table 5 (annual figures for 2004, 2008, 2012 and 2016) and Table 6 (cumulative figures for the 2006-2016 period). The status quo projection includes no assumption of improved fuel efficiency or alternative (lower carbon) fuels, and so the carbon dioxide emissions are constant (in line with the assumption of constant total bus-kilometres). Each model year cohort contributes to the total CO_2 emissions in proportion to its share of total vehicles and total vehicle-kilometres, as indicated by the identical percentages on the rows for VKT and CO2 in Table 5 and Table 6. Total annual VKT and total annual CO_2 emissions exhibit the same disaggregation by model year cohort (Figure 8 and Figure 9). In the status quo projection, over the 2006-2016 period, the percent contribution of each MY cohort to total VKT and to total CO_2 emissions are identical, as shown in Figure 10.

For the other air pollutants – PM, HC and NOx – the combination of the aging fleet and changing emission regulations results in declining emissions over the status quo projection period, with the rate of decline and the disaggregation between model year cohorts varying according the specifics of the emission regulation schedule for each pollutant, as illustrated for PM in Figure 11 and Figure 12, for HC in Figure 13and Figure 14, and for NOx in Figure 15 and Figure 16.

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[17] Statistics Canada, "Passenger Bus and Urban Transit Statistics, 1999 and 2000" (Catalogue 53-215-XIB)

Table 5. Status Quo Projection of VKT and Emissions from Model Year Cohorts

	A Pre91	B 1991-1993	C 1994-2003	D 2004-2006	E 2007-2009	F Post 2009	Total
2004							
VKT (thousands)	37,840	59,931	197,809	34,419	-	-	330,000
PM (kg)	42,323	27,930	36,874	6,416	-	-	113,543
HC (kg)	91,700	137,973	479,360	8,983	-	-	718,015
NO_x (kg)	423,231	558,594	1,474,954	144,364	-	-	2,601,143
CO2 (tonnes)	35,148	55,667	165,361	28,773	-	-	284,950
2008							
VKT (thousands)	2,336	16,560	197,809	63,387	49,908	-	330,000
PM (kg)	2,613	7,717	36,874	11,816	930	-	59,950
HC (kg)	5,661	38,124	479,360	16,542	13,025	-	552,712
NO_x (kg)	26,126	154,348	1,474,954	265,861	111,642	-	2,032,930
CO2 (tonnes)	2,170	15,382	165,361	52,989	41,722	-	277,624
2012							
VKT (thousands)	121	1,035	140,771	63,387	57,785	66,901	330,000
PM (kg)	136	482	26,241	11,816	1,077	1,247	41,000
HC (kg)	294	2,383	341,137	16,542	15,080	17,460	392,896
NO_x (kg)	1,356	9,647	1,049,652	265,861	129,261	24,942	1,480,718
CO2 (tonnes)	113	961	117,680	52,989	48,306	62,141	282,190
2016							
VKT (thousands)	-	54	58,132	63,387	57,785	150,642	330,000
PM (kg)	-	25	10,837	11,816	1,077	2,808	26,563
HC (kg)	-	125	140,875	16,542	15,080	39,314	211,937
NO_x (kg)	-	506	433,462	265,861	129,261	56,163	885,253
CO2 (tonnes)	-	50	48,597	52,989	48,306	139,923	89,866

Percentage by Model Year Cohort

	A Pre91	B 1991-1993	C 1994-2003	D 2004-2006	E 2007-2009	F Post 2009	Total
2004							
VKT (thousands)	11%	18%	60%	10%	0%	0%	100%
PM (kg)	37%	25%	32%	6%	0%	0%	100%
HC (kg)	13%	19%	67%	1%	0%	0%	100%
NO_x (kg)	16%	21%	57%	6%	0%	0%	100%
CO2 (tonnes)	12%	20%	58%	10%	0%	0%	100%
2008							
VKT (thousands)	1%	5%	60%	19%	15%	0%	100%
PM (kg)	4%	13%	62%	20%	2%	0%	100%
HC (kg)	1%	7%	87%	3%	2%	0%	100%
NO_x (kg)	1%	8%	73%	13%	5%	0%	100%
CO2 (tonnes)	1%	6%	60%	19%	15%	0%	100%
2012							
VKT (thousands)	0%	0%	43%	19%	18%	20%	100%
PM (kg)	0%	1%	64%	29%	3%	3%	100%
HC (kg)	0%	1%	87%	4%	4%	4%	100%
NO_x (kg)	0%	1%	71%	18%	9%	2%	100%
CO2 (tonnes)	0%	0%	42%	19%	17%	22%	100%
2016							
VKT (thousands)	0%	0%	18%	19%	18%	46%	100%
PM (kg)	0%	0%	41%	44%	4%	11%	100%
HC (kg)	0%	0%	66%	8%	7%	19%	100%
NO_x (kg)	0%	0%	49%	30%	15%	6%	100%
CO2 (tonnes)	0%	0%	17%	18%	17%	48%	100%

Table 6

Status Quo Projection of VKT and Emissions, 2006-2016 Cumulative Totals

	A Pre 91	B 1991-1993	C 1994-2003	D 2004-2006	E 2007-2009	F Post 2009	Total
VKT (thousands)	18,664	115,500	1,624,254	697,256	553,217	621,141	3,630,033
PM (kg)	20,875	53,827	302,779	129,976	10,313	11,579	529,349
HC (kg)	45,229	265,903	3,936,133	181,967	144,376	162,103	4,735,712
NOx (kg)	208,750	1,076,530	12,111,179	2,924,469	1,237,512	231,576	17,790,016
CO2 (tonnes)	17,336	107,283	1,357,820	582,881	462,470	576,947	3,104,737
Percentage by Model Year Cohort							
VKT	1%	3%	45%	19%	15%	17%	100%
PM	4%	10%	57%	25%	2%	2%	100%
HC	1%	6%	83%	4%	3%	3%	100%
NOx	1%	6%	68%	16%	7%	1%	100%
CO2	1%	3%	44%	19%	15%	19%	100%

Figure 8

Annual VKT by MY Cohort, Status Quo Projection

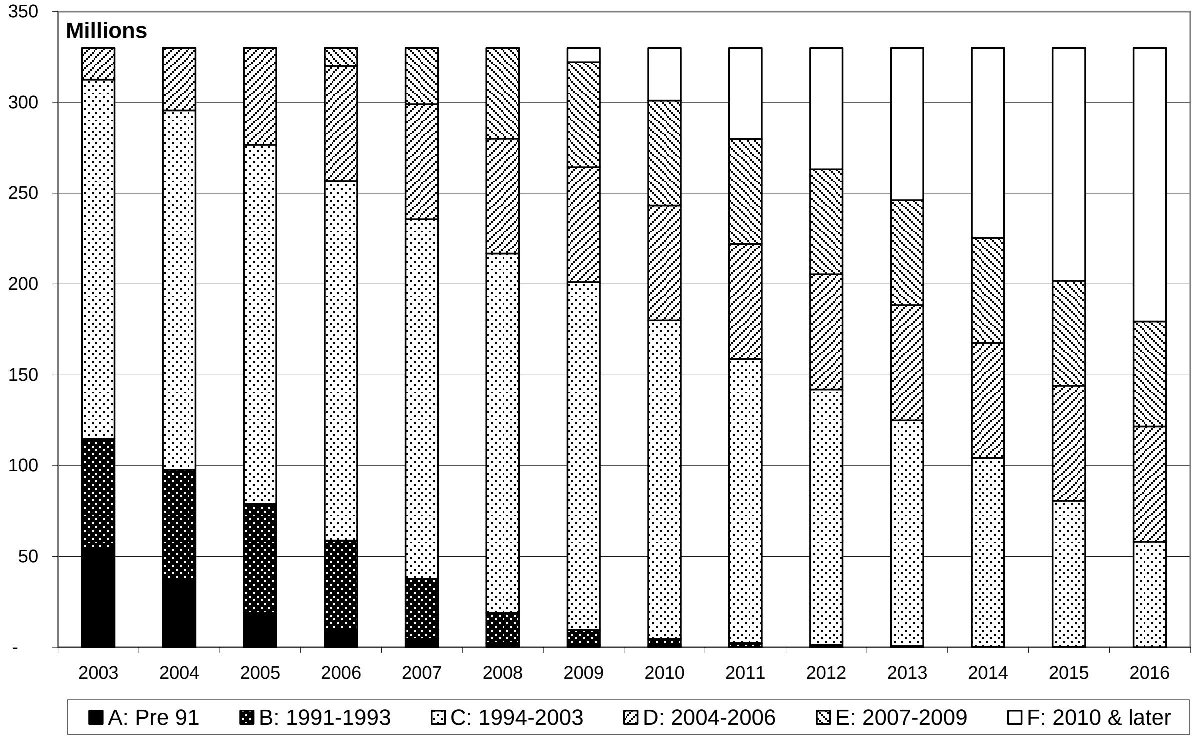


Figure 9

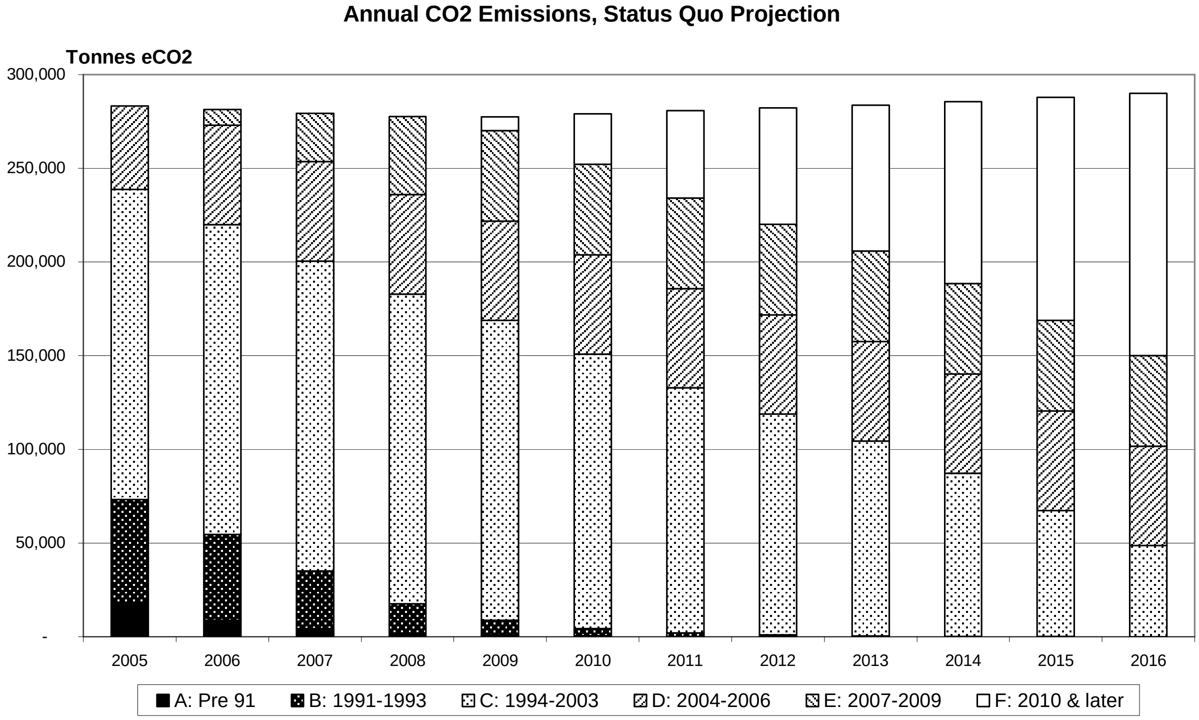


Figure 10

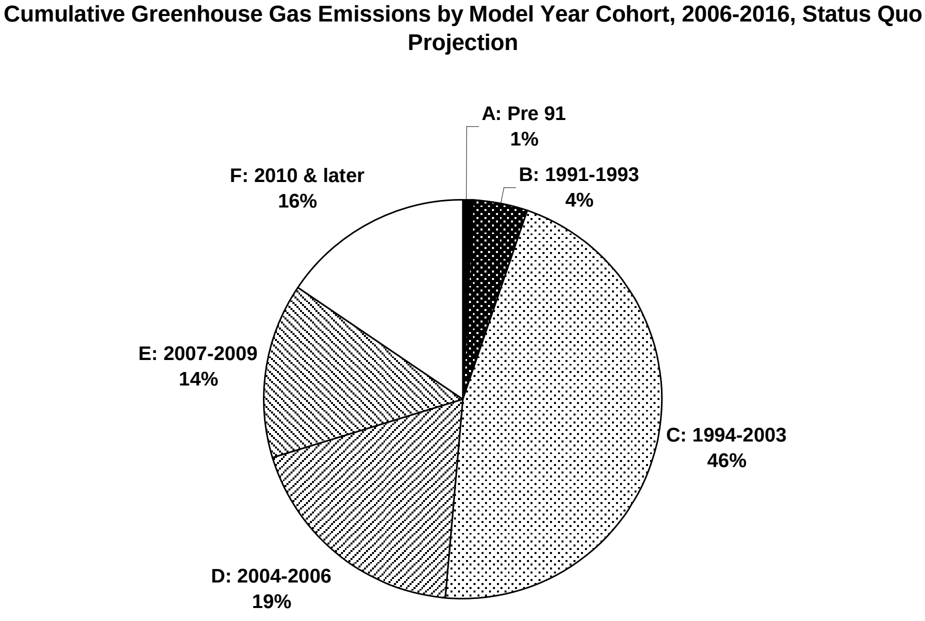


Figure 11

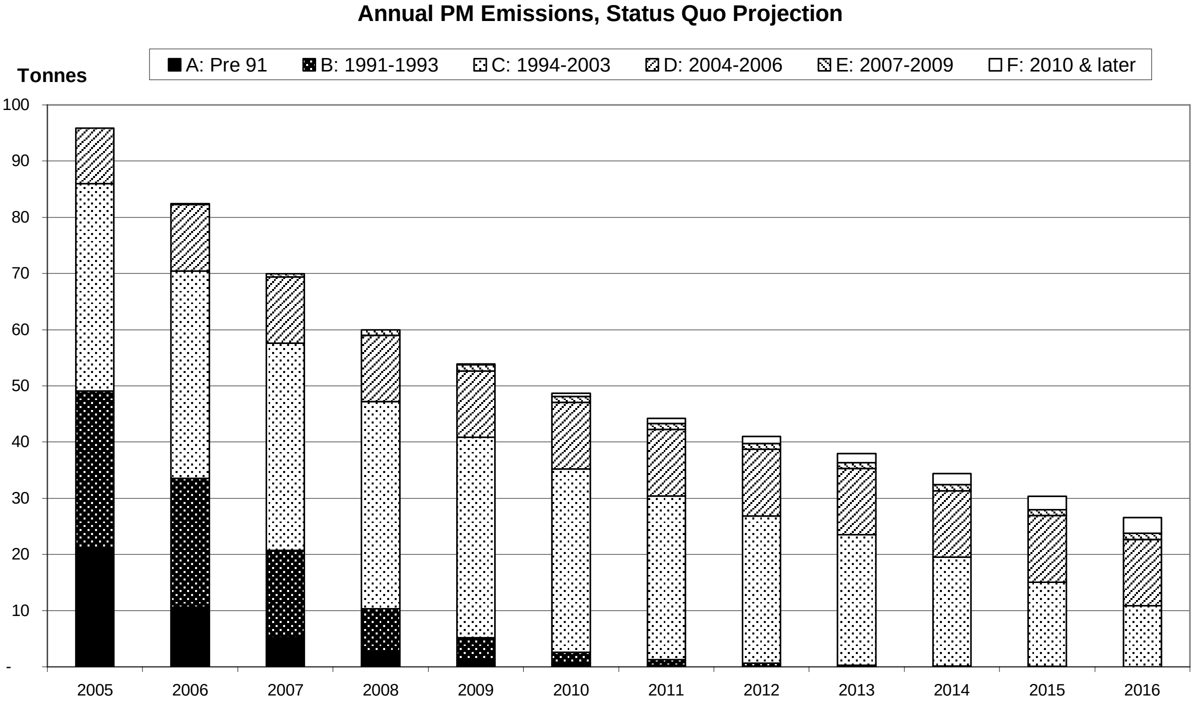


Figure 12

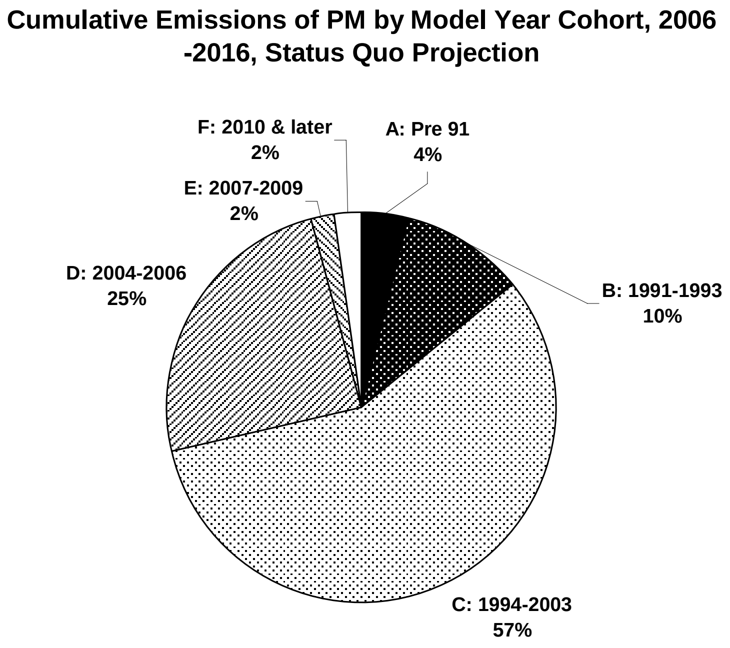


Figure 13

Annual HC Emissions, Status Quo Projection

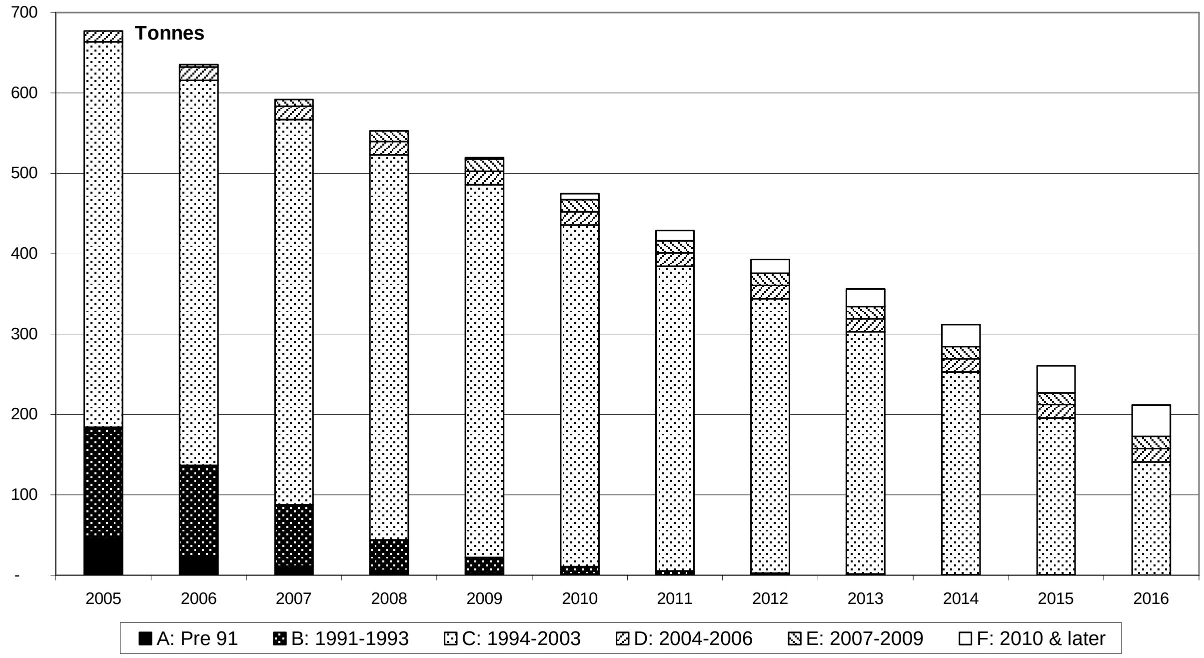


Figure 14

Cumulative Emissions of HC by Model Year Cohort, 2006-2016, Status Quo Projection

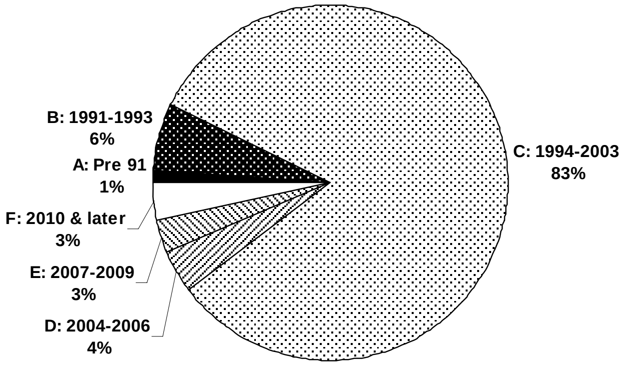


Figure 15

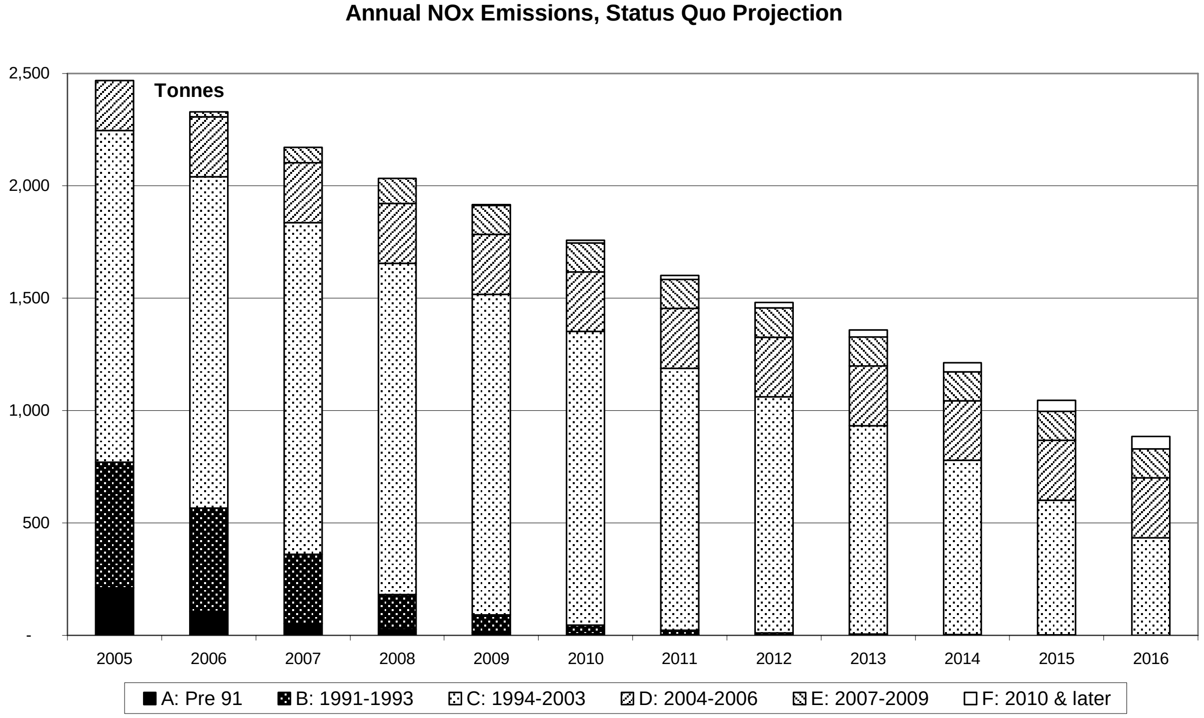
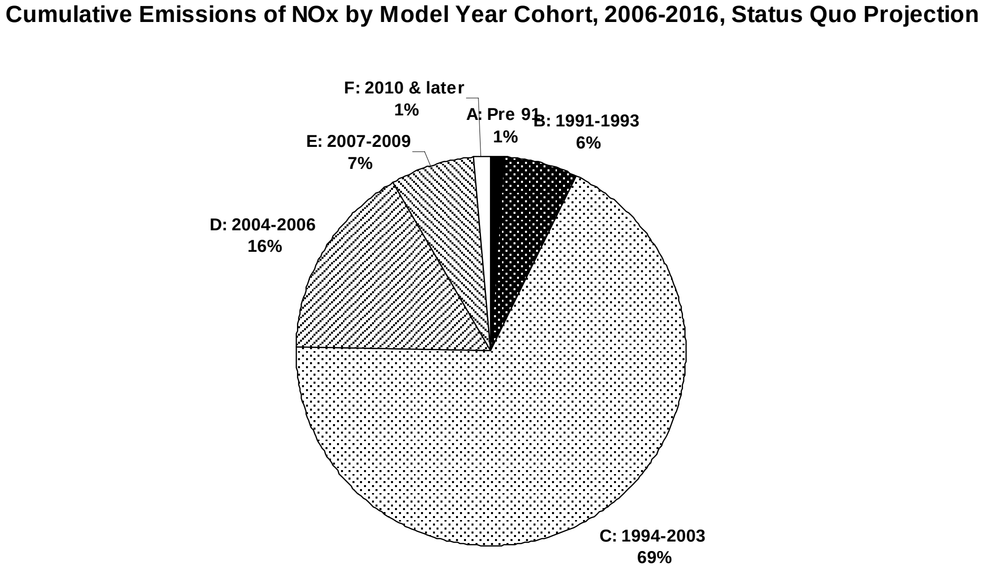


Figure 16



For particulate matter, emissions from the Cohort C and D buses (MY 1994 – 2006) dominate emissions in the status quo projection, on both an annual and cumulative basis through the year 2016. The pre-1994 buses have much higher PM emissions per bus, but they are rapidly diminishing in numbers, and the post 2006 buses have very low PM emissions per bus. In our status quo projection, the Cohort C and D buses account for fully 82% of PM emissions over the entire 2006-2016 period. With 96% of the PM emissions between 2006 and 2016 coming from buses that will already be on the road before the 2007 standard takes effect, reducing PM emissions from Ontario school buses is essentially a retrofit challenge, and more specifically is mainly about PM reduction retrofits for the critical Cohort C (1994-2003) buses.

As with particulate matter, the annual and cumulative emissions of hydrocarbons over the 2006-2016 status quo projection are heavily dominated by the 1994-2003 MY cohort; HC emissions drop off significantly starting with the model year 2004 buses. Pre-1994 buses are also a significant source of HC emissions now but drop off quickly over the next few years due to attrition. Even by 2016, two thirds of annual HC emissions in the status quo projection are from MY Cohort C (1994-2003), and on a cumulative basis the Cohort C buses account for fully 83% of HC emissions in the status quo projection over the 2006-2016 period.

With regard to NO_x, emissions in the status quo projection come down more gradually than emissions of PM and HC, reflecting the emission limit schedule for this pollutant and the expected time it will take to implement the pending standard (phased in over the 2007-2010 period). Emissions of pre-2007 buses dominate annual and cumulative emissions of NO_x over the 2006-2016 period. Interestingly, the catalyzed diesel particulate filters that are so effective at reducing PM emissions are also being used as an enabling technology for reducing NO_x emissions. A diesel engine operating on ultra low sulphur fuel and equipped with a catalyzed diesel particulate filter can be operated with lower NO_x (but therefore higher PM) emissions in the engine-out exhaust because the DPF can still bring the tailpipe emissions of PM and HC down below emission limits. This has allowed the diesel engine makers to utilize engine control and exhaust gas recirculation strategies to reduce engine-out NO_x emissions to the 2004 limit and current thinking is that the interim 2007 limit will also be met without the need for NO_x after-treatment technology. The 2010 limit presents a more difficult challenge and current thinking is that after-treatment technology (NO_x adsorbers or selective catalytic reduction) will be required. However, there is currently an intensive research effort focused on how diesel engine-out NO_x emissions might be brought down to much lower levels, perhaps even low enough to meet the 2010 standard without after-treatment technology. The air-fuel charge inside current diesel engines is heterogeneous, leading inevitably to regions and/or time periods of “excessive” NO_x production; design concepts based on producing a more homogenous and tightly controlled air-mix in the combustion chamber could lead to significantly lower engine-out NO_x emissions.

Finally, with regard to greenhouse gas emissions (essentially CO_2 emissions), these continue unabated in the status quo projection; we have assumed the Cohort C, D and E buses are 10% more efficient than the older (pre 1994) buses, but that this gain is lost in the Cohort F buses (2010 and onward) due to the fuel economy penalty anticipated with the NO_x control strategies.

In summary, air pollutant emissions from new diesel engines are much lower now than they were 10-15 years ago, and will decline again over the 2007-2010 period as the next round of emission limits comes into force. While alternative fuels (e.g. compressed natural gas, propane) have been seriously considered and partially adopted in some jurisdictions as a means for reducing emissions in new diesel vehicles, it is now clear that the preferred strategy for achieving cleaner diesel vehicles will consist primarily of improvements to conventional diesel engines operating on ultra low sulphur fuel (less than 15 ppm), combined with the application of after-treatment technologies such as catalyzed diesel particulate filters and NO_x reduction devices. While there is a cost premium associated with these new engines and control technologies, it is much smaller than the vehicle, fueling infrastructure and other costs associated with a switch to natural gas. The dominant trend in diesel vehicle engineering is toward an integrated approach to engine design, combustion control and after-treatment technology that will exploit the synergies between the engine-out exhaust stream and the capabilities of emission reduction technologies to meet the pending emission limits for PM, HC and NO_x. These same technologies will also reduce the emissions of unregulated toxic air contaminants to very low levels, but they will not be effective at reducing greenhouse gas emissions.

The low emission buses that will become standard over the 2007-2010 period, combined with demographics of the Ontario school bus fleet, result in a outlook in which emissions over the 2006-2016 time period are heavily dominated by buses that are already on the road, and especially the Cohort C buses (1994-2003 model years). Reducing emissions from Ontario school buses is therefore primarily a question of reducing emissions from these buses, either through early replacement or through the retrofit of emission reduction technologies.

5 Emission Reduction Strategies, Techniques and Technologies

Reducing emissions from the existing fleet of Ontario school buses can be achieved by switching to cleaner and/or lower carbon fuels, through the retrofit of various after-treatment technologies (although not for greenhouse gases), and by operating and maintenance practices that reduce emissions and/or fuel consumption. Fuel switching options are relatively expensive, although they can deliver greenhouse gas reductions that the pollution reduction retrofits do not. Operating and maintenance practices for clean and efficient vehicle performance are relatively inexpensive, but generally yield emission reductions that are small compared to either fuel switching or emission reduction retrofits. Emission reduction retrofit technologies offer the largest and most cost effective opportunities for PM, HC and NO_x reduction, but are generally not effective at reducing greenhouse gas emissions.

A number of fuel switching and emission reduction retrofit options are discussed in more detail below, after a discussion of the role of the pending new limits on sulphur in on-road diesel fuel and the role of maintenance and operating practices on reducing emissions.

5.1 Ultra low sulphur Fuel

Starting in mid-2006, the maximum allowable sulphur content in on-road diesel fuel in Canada will be reduced from its current limit of 500 ppm to 15 ppm. This is necessary to both reduce sulphurous emissions from diesel vehicles and to enable the use of the catalyzed filters that will become standard equipment starting with the 2007 model year diesel engines. While ultra low sulphur fuel will not be universally available at Ontario diesel pumps until mid-2006, it can be and is being bulk purchased by fleet operators for a cost premium of $0.03-$0.05 per litre as compared with standard and premium grade diesel fuels. At the average fuel economy (32.5 L/100 km) and distance traveled (22,000 km per year) assumed for Ontario school buses in this analysis, annual per bus fuel consumption is 7,150 Litres, and per bus fuel costs are therefore in the range of $4000-$5000 per year. In comparison, the current cost premium for ultra low sulphur diesel translates into an incremental annual cost of about $350 per bus. Presumably any permanent increase in the price of diesel fuel when the ultra low sulphur regulation takes effect in 2006 will be no more than this current premium.

As noted above, the move to these ultra-ultra low sulphur concentrations in on-road diesel fuel essentially eliminates concern about SO_x pollution from school buses and other diesel vehicles. Insofar as sulphates make up some of the particulate matter in diesel exhaust, switching to ultra low sulphur fuel will also translate into a reduction in the mass of particulate matter being emitted, although the percent reduction will depend on the properties of the fuel and the catalyst, and will typically be less than 10%.

The primary advantage of the ultra low sulphur fuel is the enabling role it plays in application of catalyst based technologies for reducing PM, HC and NO_x. Diesel oxidation catalysts will work with conventional diesel fuel (and some are designed for conventional fuel, with catalyst selection to inhibit SO_2 oxidation) but they are more effective with ultra low sulphur fuel. A DOC which promotes the oxidation of SO_2 to SO_3 can lead to an increase in emissions of sulphates and sulphuric acid, and an overall increase in PM emissions.

For catalyzed diesel particulate filters (DPF’s), ultra low sulphur fuel is required to prevent clogging or “poisoning” of the catalytic filter, and this is the major reason for making ultra low sulphur diesel fuel mandatory before the 2007 model year diesel engines (on which DPF’s will be standard equipment).

Some of the NO_x after-treatment technologies under development (e.g. NO_x adsorbers) are particularly prone to sulphur “poisoning” and will eventually become “clogged” with sulphur, even with diesel fuel with 15 ppm sulphur. Solutions to this problem are currently the focus of an intensive research and development effort, but it is possible that meeting the 2010 NO_x emission limit will require that sulphur concentrations in diesel fuel be lowered even further than the pending 15 ppm limit.

5.2 Maintenance

Emissions of air pollutants and greenhouse gases will be lower in buses that are properly maintained and serviced for clean and efficient operation. Prompt attention to leaky gaskets and seals will reduce evaporative emissions and regular maintenance of the engine and auxiliary systems will reduce tailpipe emissions associated with incomplete combustion or sub-optimal combustion conditions.

5.3 Operation and Fuel Management

The manner in which the bus is operated will affect both the fuel consumption (greenhouse gas emissions) and common air contaminant emissions. Engine idling and rapid acceleration increase emissions as well as vehicle maintenance costs. Future diesel engine and vehicle designs may reduce the extent to which emissions and fuel consumption "spike" during periods of rapid acceleration, but for existing buses the bus driver is the key player in reducing fuel consumption and emissions from unnecessary rapid acceleration.

Emissions from bus idling will not generally represent a large percentage of bus emissions; on average, Ontario school buses consume about 40 Litres of fuel per day of operation, and bus idling consumes fuel at a rate of about two Litres per hour. Emissions that occur during idling are nevertheless of particular concern because the emissions often occur in situations where there is direct exposure to passengers, drivers and other members of the school community. The bus operators we interviewed all had anti-idling policies, but consideration should be given to including an environmental/public health component to the school bus driver training curriculum so that drivers are educated on the effects of their driving techniques on tailpipe emissions. The US EPA web site (http://www.epa.gov/otaq/schoolbus/antiidling.htm) contains examples of anti-idling policies developed by school boards in Canada and the USA, as well as other useful information, model practices and links. There is also information on the use of driver training to reduce emissions on NRCan's Fleet Smart web site.[18]

There are also technological options that can facilitate the reduction of idling time in school buses. The operation of lights and safety equipment and the need to heat the bus are the most common reasons for bus idling. With regard to the operation of the safety lights and equipment, they should be wired so that they will operate even with the ignition off and the door open. This wiring configuration should be specified in all new school buses, and existing buses can be rewired if necessary to allow the safety equipment to operate when the ignition is off. As experience in New Brunswick has confirmed, the safety lights can be operated this way without draining the battery (http://www.nb.lung.ca/schools/3000e/ehi_sbi_e.htm).

Simple plug-in engine block heaters are a cost effective way to reduce bus "warm up" time, and cost about $100. Diesel powered engine block heaters are also available, but are more expensive (in the range of $2,000 per bus); these heaters use only a fraction of the diesel fuel required to idle the engine. Finally, at a cost in the range of $3,000-$3,500 per bus (installed), there are auxiliary heaters that use diesel fuel to heat both the engine block and the passenger compartment; they use only 10-15% of the fuel required to keep the engine idling and provide both maintenance and safety advantages over the practice of engine idling. However, while installing such a device yields financial and economic benefits beyond the fuel savings, the fuel savings themselves would not justify its installation, even on a bus that is being idled excessively (more than an hour a day).

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[18] http://oee.nrcan.gc.ca/transportation/fleetsmart.cfm?text=N&printview=N.

Even when bus idling is being minimized, fuel consumption and emissions will be higher for some buses than for others depending on the nature of the route, driving practices, and bus maintenance. Fuel consumption and emissions can be higher by 25% or more for driving cycles that include frequent accelerations, hilly terrain, or severe traffic congestion [Brown 1997]. Fleet operators would be well advised to track the fuel consumption and odometer readings of their buses and investigate situations where a particular bus, route or driver is exhibiting above average consumption compared to their fleet or to the provincial average, which is about 32.5 L/100 km.

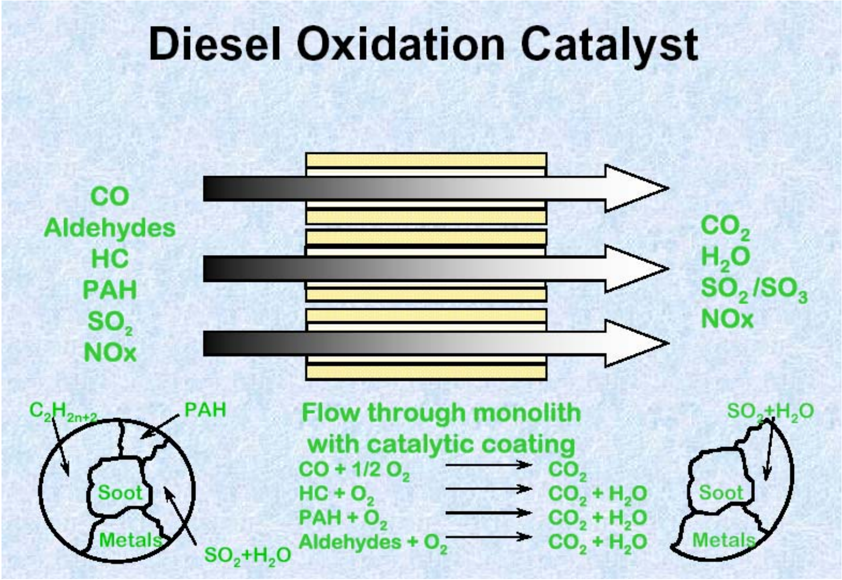
5.4 Fuel Switching Options and Emission Reduction Technologies

5.4.1 Diesel Oxidation Catalyst

5.4.1.1 How It Works

An oxidation catalyst facilitates the oxidation of hydrocarbons at lower temperatures than would otherwise be needed to initiate the combustion reaction. The diesel oxidation catalyst (DOC) is perhaps the simplest "after-treatment" technology, consisting of a catalyst-coated honeycomb through which the exhaust gas passes; it can be installed upstream of the muffler or can be integrated with the vehicle muffler. Diesel oxidation catalysts can be installed on school buses of any age and can be operated with regular diesel fuel (i.e. sulphur concentrations in the 300-500 ppm range), although they are more effective when used in conjunction with ultra low sulphur fuel.

Figure 17



The basic chemistry of the oxidation catalyst is illustrated in Figure 17; carbon monoxide, hydrocarbons, and toxic contaminants such as the ketones and polycyclic aromatic hydrocarbons (PAH's) are oxidized to CO_2 and water vapour.

A significant percentage of the mass (25-30% typically) of PM emissions from diesel engines is in the form of soluble organic hydrocarbons that have been adsorbed or condensed onto soot particles (inorganic carbon particulates). The diesel oxidation catalyst facilitates the "burning off" of this "soluble organic fraction" (SOF), resulting in a reduction in the mass of particulate emissions in addition the reduction in total hydrocarbon emissions.

Diesel oxidation catalysts are not effective for reducing NO_x emissions. It is possible that the DOC could slightly increase the mass of NO_x emissions in the exhaust stream (through further oxidation of the NO that comprises most of the engine-out NO_x emissions). Some chassis dynamometer tests have indicated such an increase, but the measured effect is small and statistically inconclusive.[19]

With regard to sulphur, diesel oxidation catalysts can facilitate the oxidation of SO_2 to SO_3 and SO_4, leading to an undesirable increase in tailpipe sulphate emissions. This is not an issue when sulphur concentrations are below 15 ppm, which will be the standard for on-road diesel fuel after mid-2006.

The amount of CO_2 generated in the conversion of the CO and HC in diesel exhaust is minuscule compared to the CO_2 content in the exhaust from the primary fuel combustion process itself.

5.4.1.2 Air Pollutant and Greenhouse Gas Impacts

Diesel oxidation catalysts are very effective at removing hydrocarbons from the exhaust stream. Brown and Rideout[20] conducted chassis dynamometer testing of two MY1992 school buses with and without DOC's, and utilizing diesel fuel with sulphur in the 500+ ppm range. Over a two year period they found PM, HC and CO were reduced an average of 30%, 88/% and 93%, respectively. As noted above, DOC's are effective at reducing the particulates in the nuclei mode that make up a small percentage of the mass of diesel exhaust but constitute the majority of the particulate numbers. These "ultra fine" particulates are the source of increasing public health concern and discussions about a regulatory limit on the number of particles in diesel exhaust, and it is an important advantage of the catalyst technologies that they remove a large portion of these particles from the tailpipe emissions.[21]

More recent on-road testing of DOC performance on a MY2000 school bus with both regular (383 ppm) and ultra low (17 ppm) sulphur indicates an 80-90% reduction in CO and a 13-15% reduction in PM. The DOC reduced total hydrocarbon emissions by 95% when the bus was running on ultra low sulphur fuel; no data are available for the regular diesel fuel case in this test, but given the high reduction of CO in both the regular and ultra low sulphur fuel tests, it is likely that a DOC will reduce THC in a late model school bus by about 90% even when running on regular diesel fuel.[22]

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[19] Brown and Rideout 1996, 1997

[20] Brown and Rideout 1997

[21] Kittelson 2004, Ayala 2004, Gautam 2004

[22] Rideout 2004

These results are consistent with the expected performance of this technology and with results published for other diesel vehicle types.[23] For purposes of modeling the effect of diesel oxidation catalysts on Ontario school bus emissions, we have assumed DOCS achieve an 85% reduction in hydrocarbons and a 25% reduction in particulate matter, relative to the uncontrolled emissions baseline described in the previous section. The DOC will also reduce carbon monoxide emissions by 80-90% or more, but as explained in the previous section of this report, carbon monoxide emissions are already well below regulated maximums and are not a limiting consideration in this analysis. With regard to greenhouse gas emissions, we have assumed that the DOC does not significantly change the bus fuel consumption and therefore has no effect of carbon dioxide emissions.

5.4.1.3 Cost

The diesel oxidation catalyst is a proven, mass-produced technology. As a stand alone device, installed upstream of the vehicle muffler, costs are consistently reported in the range of USD 1,000-3,000 USD per vehicle for single installations and USD 1,000-2,000 when purchased in quantity.[24] The cost of an integrated muffler/DOC will be up to twice as much as a stand alone DOC.

5.4.1.4 Market Readiness and Infrastructure Issues

The diesel oxidation catalyst is a proven technology that has been used for years and is installed on tens of thousands of urban transit buses in Europe, Asia and North America.[25] DOC's will be an important component of emission reduction strategies for new heavy duty diesel vehicles in which DOC's will be integrated with particulate filters and NO_x reduction devices to achieve multiple pollutant reduction targets. Oxidation catalysts are essentially a passive, maintenance-free technology, and the large body of experience with their operation provides a high degree of confidence in their reliability and performance. They can be retrofit to heavy duty diesel vehicles of any vintage. They work on vehicles using fuel with sulphur levels in the 500 ppm range, but they are more effective when used with ultra low sulphur fuel.

5.4.2 Catalyzed Diesel Particulate Filter

5.4.2.1 How It Works

Sometimes called the "continuously regenerating diesel particulate filter", the catalyzed diesel particulate filter" (DPF) is a two stage device that achieves deep reductions in total hydrocarbons and carbon monoxide as well as in total particulate mass. The first, catalytic stage of the DPF is designed to oxidize NO to NO2, which then serves as an oxidant in the second stage of the DPF in which the particulate matter is burned off. The DPF technology requires ultra low sulphur fuel to be effective. The essential processes in a DPF are illustrated in Figure 18 and a cutaway diagram of one of several such devices currently available is shown in Figure 19 .

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[23] For example see MECA 2000, EPA 2004, Chatterjee 2004
[24] MECA 1999, MECA 2000a
[25] Bertelsen 2004

Figure 18

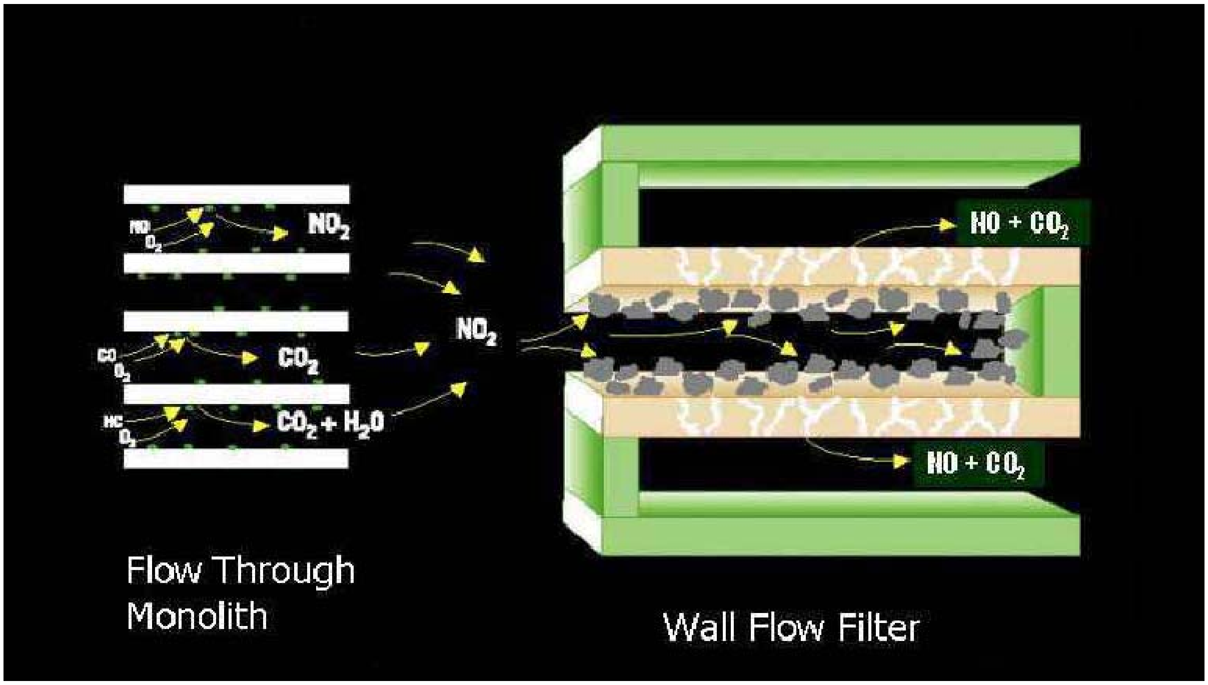
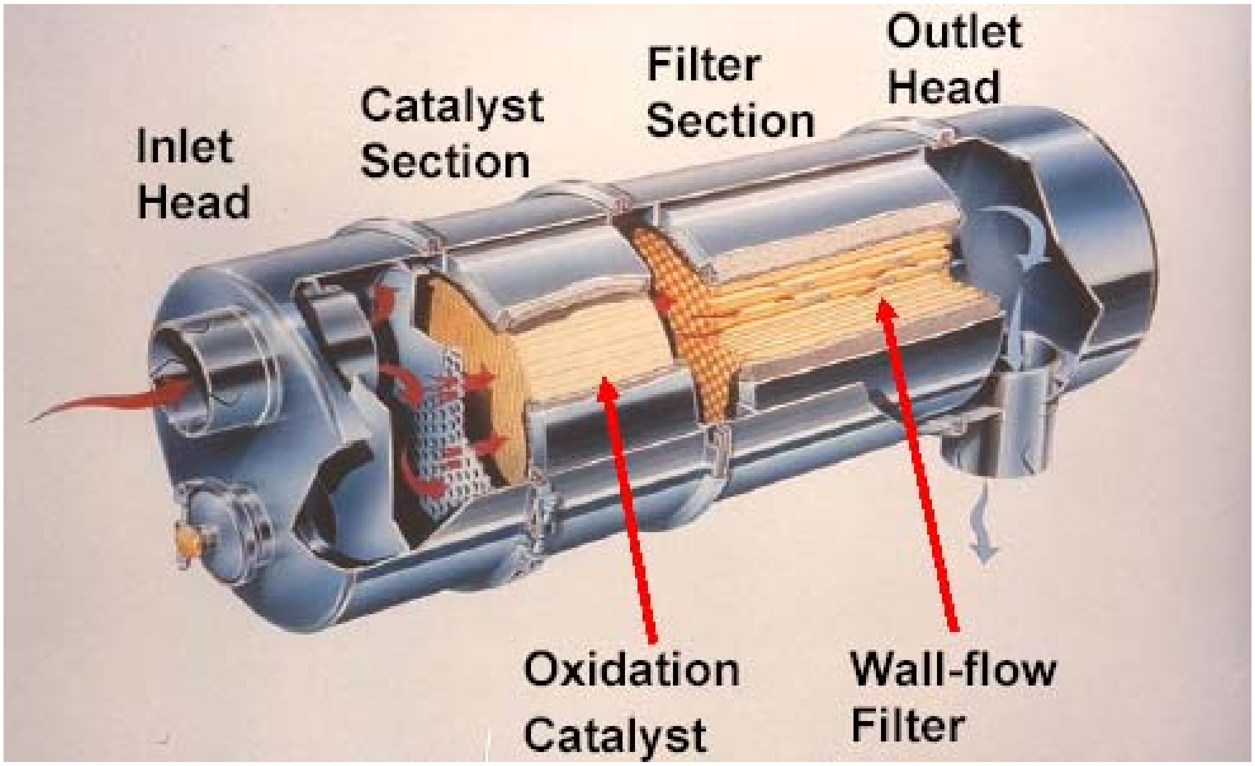


Figure 19

Johnson-Matthey Continuously Regenerating Technology (CRT)® Catalyzed Diesel Particulate Trap



Non-catalytic diesel particulate traps are after-treatment devices that physically capture the particulates in diesel exhaust, utilizing a wire mesh or ceramic foam or some other physical trap for the particles. As the carbon soot builds up in the trap its efficiency diminishes and the filter must be "regenerated", usually either by physically cleaning it out or by burning off the captured material at high temperatures. The need to periodically regenerate the particulate trap create maintenance and/or operational expenses that make these types of traps undesirable for school bus operations, but the development of the continuously self-regenerating catalyzed diesel particulate filter represents a significant breakthrough in particle trap technology as it can be operated in a passive mode, with low and infrequent maintenance requirements.

As with diesel oxidation catalysts, DPF's can be stand-alone devices or they can be integrated into the vehicle muffler. The effectiveness of the DPF is closely tied to the temperature and chemical composition of the engine-out exhaust. They are most effective when mounted close to the engine so as to maximize the temperature of the exhaust entering the device, and they work best when installed on buses with electronic engine control modules so that the combined effect of the ECM settings and the DPF can be optimized to achieve target emission levels for PM, HC and NO_x. While the DPF does not by itself have a significant effect on NO_x emissions, it is so effective at reducing PM emissions that DPF equipped vehicles can be tuned for low engine-out NO_x as the DPF will then bring the associated higher PM emissions back down below regulated maximums. The use of DPF is therefore integral to engine-maker strategies for meeting the 2007 NO_x interim limit as well as for meeting the PM and HC limits.

The DPF is well suited to retrofit applications, but is not recommended for buses that predate the 1994 model year (Cohorts A and B in our analysis) or which do not have the electronically controlled fuel injection that was introduced in the mid-1990's to satisfy the lowering of allowable PM emissions from new diesel engines.

Finally, as already noted, the DPF requires ultra low sulphur fuel (less than 15 ppm). As the sulphur concentration increases above this level, the catalyst becomes increasingly "poisoned", as sulphur oxidation essentially blocks the catalytic oxidation of the targeted particulates and hydrocarbons for which the filter is intended.

5.4.2.2 Air Pollutant and Greenhouse Gas Impacts

Chassis dynamometer and on-road testing of school buses with and without catalyzed diesel particulate filters confirm the DPF as a highly effective technology for the removal of particulate matter and hydrocarbon constituents of diesel exhaust, including the unregulated toxic hydrocarbons and "ultra fine" particulates discussed in the previous section on diesel oxidation catalysts. In addition, the DPF facilitates a reduction of engine-out NOx emissions.

In chassis dynamometer tests reported by Ullman [2003], a school bus with a MY2001 International DT530 engine (Model C275) configured to meet 1998 emission standards was retrofit with an Engelhard DPX catalyzed DPF and a low NO_x engine control module and tested over the City Suburban Heavy Vehicle Cycle (CSHVC). With the retrofit configuration, hydrocarbons and carbon monoxide in the tailpipe exhaust were reduced to extremely low levels, and TPM was reduced by 95%. The low NO_x configuration resulted in a 29% reduction in NO_x, but with a significant increase in the NO_2/NO ratio. A fuel economy penalty of 5% was observed, a result of the low NO_x ECM calibration. Ullman also measures for several dozen toxic air contaminants with and without the DPF and found that DPF to be very effective at reducing tailpipe emissions of these contaminants. In most cases, the DPF reduced emissions of aldehydes, ketones, PAH's and other hydrocarbons to trace levels. Ullman also tested a compressed natural gas bus (without a catalyzed diesel particulate filter) and found that emissions of toxic contaminants were generally lower and often much lower for the DPF-equipped diesel bus than for the CNG bus.

Using on-road testing of a late model school bus, Rideout [2004] found the DPF technology reduced TPM by 83%, carbon monoxide by 97% and THC by 78%. There is no indication that in this test the DPF equipped bus was tuned for low NO_x emissions; NO_x emissions were down 9% in the DPF-equipped bus but there was no apparent change in fuel economy.

Ullman and Rideout's results corroborate industry claims and other research on the effect of ultra low sulphur fuel and DPF technology on transit buses. New York City Transit operates over 1,500 diesel transit buses with DPF's, most of which are retrofits. The New York City transit buses have been tested before and after 9-12 months of in-service operation of the buses, and no adverse maintenance or operational issues have been encountered. The New York buses are reported to have CO and PM emissions that are done by more than 90% and hydrocarbons by more than 70%, as well as achieving 99% removal of carbonyls and an 80% reduction in PAH emissions [Lanni 2001, Chatterjee 2002]. However, the NY transit buses already had oxidation catalysts as part of their baseline configuration, so the 70% HC reduction with addition of DPF translates into a 90%+ reduction relative to the non-DOC technology assumed in our baseline analysis.

For purposes of modeling the impact of DPF technology on Ontario school buses, we have assumed that when retrofit on Cohort C buses (MY1994-2003), they reduce PM and HC emissions by 90% compared to baseline conditions. If installed with a low NO_x engine control calibration, we assume NO_x emissions are reduced (for Cohort C buses only) by 25%, but with a 5% increase in CO_2 emissions resulting from the associated fuel economy penalty. For the Cohort D buses (MY 2004-2006), DPF retrofits reduce PM by 90% relative to our baseline but we have not assumed THC or NO_x impacts in modeling DPF on this cohort, as THC and NO_x emissions from these buses are already significantly lower than the Cohort C buses and we do not have research on the impact of DPF retrofit on post-2003 MY buses.

5.4.2.3 Cost

MECA [2000a] reports costs of USD 3,000-4,000 for in-line DPF and USD 3,750-5,000 for muffler replacements equipped with DPF, with the lower costs reflecting bulk purchase rates. When the low NO_x ECM configuration is included, MECA suggests a price of USD 7,500. These prices are in line with industry claims and other reported DPF prices. New York City Transit, for example, has performed approximately 1,600 retrofit installations of diesel particulate filters with the total for purchase and installation averaged USD 5,900 per bus, with a range of USD 5,000 to USD 7,500. This includes USD 4,200 – USD 6,100 to purchase the DPF kit and between USD 200 and USD 1,200 for the installation (4-21 hours) [Lowell 2003]. New York City Transit removes and cleans the filters on an annual basis (2-4 hours per bus) but this would not be necessary for the much lighter duty cycle of Ontario school buses. For policy planning purposes, we recommend a figure of CAD 10,000 per retrofit be assumed for installing a CPDF on Cohort C or D buses, with a low NO_x engine calibration.

5.4.2.4 Market Readiness and Infrastructure Issues

While improvements are ongoing, the DPF is a mature technology; there are several competitive products on the market, and on a worldwide basis there are now over 50,000 vehicles retrofit with DPF technology [Clean Air Task Force], some with over 500,000 vehicle-kilometres. There are no significant maintenance or infrastructure issues with the application of this technology to buses of MY1994 or later. The DPF does require ultra low sulphur fuel, and until this fuel is universally available starting in mid-2006, bus operators using DPF technology will need to acquire this fuel and pay the associated premium. In addition to the relatively small price premium, until the ultra low sulphur fuel regulation takes effect in 2006 availability may be an obstacle to DPF deployment for operators in remote areas or for small fleet operators that refuel at retail pumps.

5.4.3 Exhaust Gas Recirculation

5.4.3.1 How It Works

Exhaust gas recirculation (EGR) entails the recycling of cleaned and cooled exhaust gas to the inlet manifold of the engine or turborcharger. The exhaust gas is passed through a catalyzed diesel particulate filter before being returned to the engine where it is mixed with inlet air. Inert gases in the returned exhaust displace some of the oxygen that would otherwise be available for NO_x formation. The cooled exhaust gas also facilitates lower NO_x formation by lowering the combustion temperature in the engine. There is a corresponding increase in engine-out particulate emissions, but these are removed by the DPF.

5.4.3.2 Air Pollutant and Greenhouse Gas Impacts

EGR is a NO_x reduction technology but it operates in the context of an integrated approach to combustion and emissions reduction that includes electronically controlled combustion and catalyzed diesel particulate filters. Cooled EGR has been widely adopted to meet the 2004 NO_x limit for new diesel engines (about 50% below the previous limit of 4 grams per brake horsepower-hour) and further refinements to cooled EGR technology will be employed by most if not all the engine makers as a central part of their integrated approach to meeting the *de facto* 2007 NO_x standard of 1.2 grams per brake horsepower-hour. A fuel economy penalty of 2-5% can be expected, with a corresponding increase in CO_2 emissions. The 2010 NO_x limit of 0.2 grams per brake horsepower-hour represents a much deeper cut in NO_x than can be achieved with EGR, but EGR will likely be a standard feature of new diesel engines from this point forward.

There are no published reports of retrofit of EGR to school buses (Cohort C, MY1994-2003) but EGR technology could be retrofit to these vehicles and presumably could bring their NO_x emissions down to the 2004 limit for new engines of about 2.2 grams per brake horsepower-hour, or by about 45% over the baseline for Cohort C buses.

5.4.3.3 Cost

Cooled EGR would not be installed on a bus except as part of an integrated technology package that included a catalyzed diesel particulate filter. There are no explicit published figures for the cost of such retrofits, but a range of CAD 10,000-20,000 per bus would be reasonable for Cohort C bus retrofits that included EGR and DPF technology and associated ECM modifications for low NO_x operation.

5.4.3.4 Market Readiness and Infrastructure Issues

EGR has been employed for years on all light duty diesel vehicles in Europe and is a well understood and mature technology. Its application in heavy duty diesel vehicles in North America is more recent but it is an integral component of the strategy engine makers are employing to meet the 2004 and 2007 limits on NO_x emissions and it is now generally a standard feature in new diesel engines.

5.4.4 Selective Catalytic Reduction

5.4.4.1 How It Works

Selective catalytic reduction is an after-treatment technology for lowering NO_x emissions through the reduction of exhaust stream NO and NO_2 by urea or ammonia in the presence of a catalyst. Urea is generally favoured as the reductant due to the hazards of handling ammonia. The process results in gaseous nitrogen (N_2) and water vapour according to:

$$4\,NO + 4\,NH_3 + O_2 \longrightarrow 4\,N_2 + 6\,H_2O$$

$$6\,NO_2 + 8\,NH_3 \longrightarrow 7\,N_2 + 12\,H_2O$$

The reductant is stored on-board and is injected into the exhaust stream; the volume of urea consumed is on the order of 13% of diesel fuel consumption for a bus, requiring relatively frequent refilling. SCR will also contribute to the control of hydrocarbon and particulate emissions but is normally employed in concert with a DPF or oxidation catalyst to ensure HC and PM emissions are below allowable levels and also to minimize the risk of ammonia emissions to the atmosphere. As described by MECA [2000]:

> Like an oxidation catalyst, SCR causes chemical reactions without being changed or consumed. However, unlike oxidation catalysts, a reductant is added to the exhaust stream in order to convert NOx to nitrogen and oxygen in an oxidizing environment. The reductant can be ammonia but in mobile source applications, urea is normally preferred. The reductant is added at a rate calculated from an algorithm which estimates the amount of NOx present in the exhaust stream as a function of the engine operating conditions, e.g., vehicle speed and load. As the exhaust gases along with the reductant pass over a catalyst applied to a ceramic or metallic substrate, 75 to 90% of NOx emissions, 50 to 90% of HC emissions, and 30 to 50% of PM emissions are reduced. SCR also reduces the characteristic odor produced by a diesel engine and the diesel smoke.

A schematic of how SCR could be integrated into a multi-pollutant reduction strategy is shown in Figure 20 [Greszler 2004] and a typical diesel SCR unit is shown in Figure 21.

Figure 20

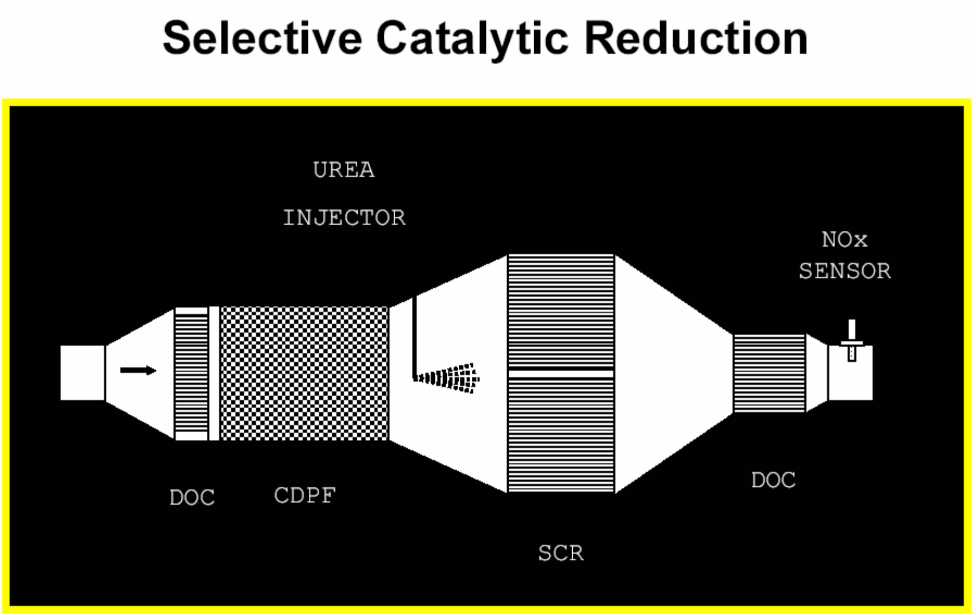


Figure 21

Diesel SCR unit (MECA)

The catalytic reduction process must be precisely controlled to avoid either too much or too little urea injection, and the process is sensitive to the flow and temperature of the exhaust gas (cold start operation is problematic), as well as to the level of NO_x in the engine-out stream. With too little urea injection NO_x emissions are not effectively reduced and with too much it will pass through the catalyst and be emitted as ammonia. These devices require that the vehicle be operated with ultra low sulphur diesel fuel.

5.4.4.2 Air Pollutant and Greenhouse Gas Impacts

Selective catalytic reduction (SCR) using urea as a reducing agent has been shown to be effective in reducing NO_x emissions by up to 90 percent while simultaneously reducing HC emissions by 50-90% and PM emissions by 30-50% [MECA 2000]. When fully developed it may be possible to avoid any fuel economy penalty, but currently a 2-3% increase in vehicle fuel consumption is expected with the use of SCR, with corresponding increases in CO_2 emissions.

5.4.4.3 Cost

It is too soon to specify what the cost of retrofitting SCR technology to Ontario school buses would be, but MECA [2000a] indicates a range of USD 18,000-45,000 for SCR technology for vehicles in the 200-300 HP range for low sales volumes, and a range of USD 10,000-18,500 for high volume sales (over 10,000 units).

5.4.4.4 Market Readiness and Infrastructure Issues

Although SCR itself has been widely applied to stationary diesel combustion, its application to diesel vehicles is still under development. It is one of the serious contenders for meeting future ultra-low NO_x emission limits, but is more likely to be deployed in Europe than in North America (where NO_x adsorber technology is currently the preferred strategy for any necessary after-treatment needed to meet the 2010 NO_x standard). SCR has very significant infrastructure requirements, including the need for a urea distribution and refilling network at diesel refueling locations. Such an infrastructure is partially developed in Europe but not in North America and this is one reason why SCR is currently more favoured in Europe than in North America as a possible way to meet the ultra-low NO_x emission standards in the future. Even with the network in place, it would be necessary to ensure that the reductant tanks were being refilled when necessary [EPA 2004].

SCR is not currently a viable candidate for retrofit on Ontario school buses.

5.4.5 Lean Nitrogen Catalysts

5.4.5.1 How It Works

The NO_x in diesel exhaust gas can be reduced to nitrogen gas (N_2), water vapour and CO_2 by the addition of reducing agents (usually by injecting fuel into the exhaust stream). This can be done in a “flow through” device not unlike an oxidation catalyst, and like DOC technology can be installed on stand alone basis or integrated with the muffler. The resulting NO_x emission reductions are probably not sufficient to meet the 2010 standard and flow-through lean nitrogen catalyst devices are not currently a favoured option by most engine makers. The process operates over a fairly narrow temperature range, the fuel economy penalty can be up to 10%.

5.4.5.2 Air Pollutant and Greenhouse Gas Impacts

NO_x reductions in the range of 10-40% [Bertlesen 2004] are achievable with flow-through lean nitrogen catalysts. Fuel economy penalties are in the 5-10% range.

5.4.5.3 Cost

No information available.

5.4.5.4 Market Readiness and Infrastructure Issues

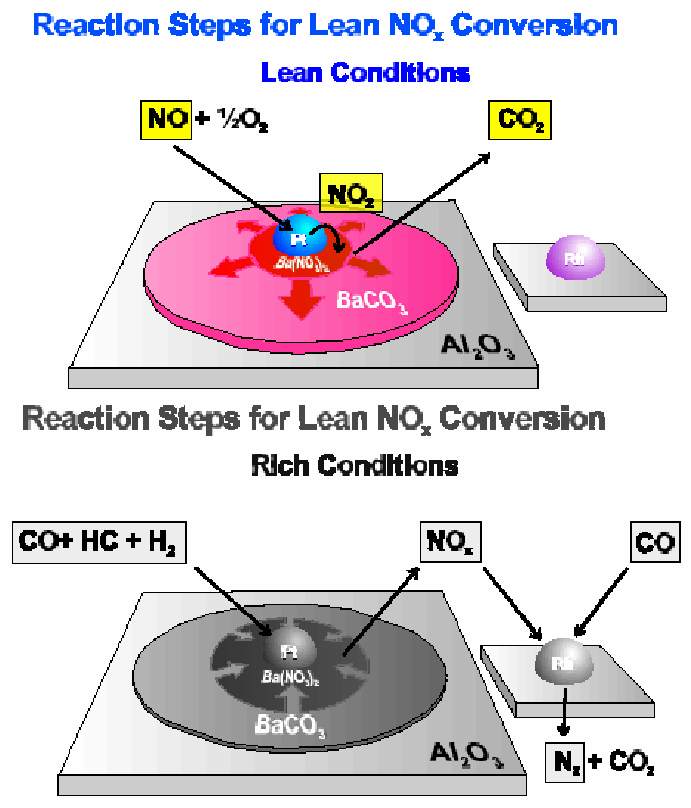
In general, interest in lean NO_x catalytic processes is focused on the adsorber technology which promises much higher emission reductions (capable of meeting the 2010 standard) over a wider range of engine operating conditions. Flow through lean nitrogen catalysts could be retrofit to existing buses and there is at least one product on the U.S. market

5.4.6 NO_x Reduction Adsorbers

5.4.6.1 How It Works

Diesel exhaust is “lean” (i.e. it contains an abundance of oxygen) and this presents a challenge to the objective of reducing NO_x to N_2 with after-treatment devices. NO_x adsorbers utilize a two stage approach in which the NO is catalytically oxidized to NO_2 and stored as a nitrate in a chemical “trap” (alkaline earth oxide). When the storage medium nears capacity, the engine is run “rich” for a few seconds (by throttling the intake air, or by exhaust gas recirculation, or by injecting fuel directly into the adsorber) and this results in the NO_x being released. The released NO_x is then reduced to N_2 by reaction with CO on a precious metal catalyst site, as illustrated in Figure 22 [from MECA 2000b].

Figure 22



In the event that advancements in diesel engine design cannot by themselves meet the 2010 NO_x emission standard of 0.2 grams/bhph in the engine-out exhaust, the NO_x adsorber is one of the leading after-treatment candidates for doing so, especially in North America where there the urea distribution network (needed for SCR) is not in place and where there are concerns about compliance in the refueling and operation of the devices [EPA 2004]. Research and technology development is therefore fairly intense at this time to resolve issues related to sulphur tolerance and thermal durability of NO_x adsorbers so that they might be ready for the 2010 model year engines. To the extent that there is sulphur in the fuel, it will catalytically react with oxygen and then with the NO_x storage medium (e.g. barium sulphate), thus reducing the storage sites available for NO_x. The temperatures in the exhaust stream passing through the adsorber are insufficient for the thermal decomposition of the barium sulphate or for its complete reduction during the periodic rich excursions used to purge the substrate of stored NO_x. Even at very low concentrations of sulphur in the fuel (i.e. 15 ppm, the pending standard) sulphur contamination of the adsorber will still occur. It takes temperatures above 600 deg C in a rich exhaust atmosphere, maintained for several minutes, for "desulphurization" of the adsorber substrate, and even then gradual sulphur contamination of the adsorber occurs. There is a significant fuel economy penalty associated with the desulphurization step and the high temperatures required are a source of thermal stress on the engine components. Adsorber research is therefore focused of reducing sulphur tolerance, improving the desulphurization process, and reducing the thermal stress caused by the temperature excursions associated with the rich burning episodes and the desulphurization process [MECA 2000b].

5.4.6.2 Air Pollutant and Greenhouse Gas Impacts

NO_x adsorbers have the potential to reduce NO_x emissions by 80-95%. The regeneration step does introduce a fuel economy penalty of 2-6%. The fuel economy penalty is higher in single path than in dual path systems where one path is in sorption mode while the other one is being regenerated, but the dual path systems will have higher capital costs.

5.4.6.3 Cost

It is too early in the development of the NO_x adsorber technology to specify how much it would cost as a retrofit option, or even which Model Year Cohorts would be compatible with the technology. The complex valve and piping configurations needed for exhaust flow management and adsorber regeneration make this an inherently expensive technology, as compared for example with catalyzed diesel particulate filters. Should adsorber retrofits prove feasible, costs will likely be more than CAD 20,000 per bus. However, costs could come down if NO_x adsorbers become mass produced standard equipment in diesel engines after 2010.

5.4.6.4 Market Readiness and Infrastructure Issues

NO_x adsorbers have been successfully employed on lean burning gasoline engines but are not yet market ready for heavy duty diesel engines. The US EPA believes that NO_x adsorbers could be ready for application on new diesel engines in 2007 [EPA 2004] but that they will probably not be needed to meet emission standards until the 2010 model year. The NO_x adsorber is not expected to have significant infrastructure issues, and this is one of its advantages over SCR technology.

5.4.7 Biodiesel Fuel

5.4.7.1 How It Works

Biodiesel is a fuel that is very similar in its combustion profile to petroleum-based diesel but it is derived from vegetable oils or animal fats (from rendering plants). It can be blended with petroleum diesel fuel (for example B20 refers to diesel fuel that is 20% biodiesel and 80% petroleum diesel) or it can be burned neat as 100% biodiesel (B100). There are unresolved issues related to the viscosity of B100 in cold temperatures, and the effect it has as a solvent on engine components (especially in pre-1994 buses). The City of Berkeley, California has been successfully operating its diesel vehicle fleet (including fire trucks) on B100 since 2003, but further technical progress will be needed to replicate this experience in the Canadian climate. Even B20 is not yet widely accepted as a reliable substitute for regular diesel in cold weather conditions, and some engine manufacturers will not warranty their engines' performance if B20 is used. Reliable performance is of paramount importance to school bus operators and their clients, especially on cold winter days; uptake of biodiesel in concentrations above 10% will require demonstrated resolution of cold weather issues.

5.4.7.2 Air Pollutant and Greenhouse Gas Impacts

Biodiesel is inherently ultra low sulphur, relatively clean-burning fuel, and compared to mineral diesel fuel, emission reductions are proportional to the amount of biodiesel in the blended fuel. B100 combustion emits about 50% lower particulates than conventional diesel, and at least 50% less CO and hydrocarbons. Toxic air contaminants such as formaldehyde, ketones, etc are 60-90% lower with biodiesel than with mineral diesel oil. Engine-out NO_x emissions will be up to 10% higher with biodiesel, more so for plant-derived biodiesel than for tallow-derived biodiesel. Because the tailpipe emissions of CO_2 from biodiesel combustion are biogenic and offset by the atmospheric carbon that was fixed in the growing of the plant or animal from which the fuel is derived, tailpipe CO_2 emissions from biodiesel are not included in quantification of anthropocentric greenhouse gas emissions.[26] We have assumed a 16% reduction in GHG emissions for B20 blend.

5.4.7.3 Cost

The market for biodiesel is still new in Ontario, and price fluctuations can be expected until a fully developed and competitive market is developed. The City of Brampton, for example, paid a $0.04 per Litre (7%) premium for B20 in 2002 and expected the premium in 2003 to be $0.12 per Litre (20%). In general, biodiesel can cost up to twice as much as mineral diesel, so that the price premium is roughly the same as the percent of biodiesel in the blend (e.g. a B20 blend would carry a 20% cost premium over regular diesel).

Perhaps the most important aspect of the potential for biodiesel application in Ontario is the extent to which it is competitive with the DPF and NO_x reduction technologies being developed for diesel engines. These "green diesel" technologies achieve emission reductions that are equal to or greater than the emission reductions delivered by biodiesel, and may be superior on the

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[26] It is often pointed out that while biodiesel may represent a "zero ghg emission" fuel when only the tailpipe emissions are considered, there is considerable fossil fuel combustion and other greenhouse gas emissions associated with the upstream production and processing of the raw plant or animal tallow feedstock, and so a "full lifecycle" emissions analysis of biodiesel would show that it is not a zero GHG emission fuel, at least not as presently produced. Assuming the biodiesel is produced from soybeans that are grown with relatively fertilizer-intensive and fuel-intensive agricultural technology, the upstream greenhouse gas emissions from biodiesel are in the range of 25 kg eCO_2 per GJ of fuel. However, if full lifecycle emission factors are to be applied to biodiesel in evaluating options, then they must also be applied to petroleum-based fuels, which also have upstream greenhouse gas emissions associated with their production. In Canada, we estimate the upstream emissions for petroleum-derived diesel fuel to be 17.8 kg per GJ. Given that mineral diesel also emits about 70 kg eCO_2 per GJ from the tailpipe, total lifecycle emissions of petroleum diesel are about 88 kg eCO_2 per GJ of fuel, as compared with about 18 kg eCO_2 per GJ for biodiesel.

issue of NO_x emissions. Of course biodiesel can be used in these new “green” engines, and they generally run even cleaner than they will with ultra low sulphur mineral diesel, but given that the new standards will be met with the new “green diesel” technologies, there will be little incentive to pay a premium for biodiesel fuel, and little if any incremental improvement in environmental performance.

The one unique advantage that biodiesel does have over “green diesel” technology with ultra low sulphur mineral diesel is the much lower greenhouse gas emissions with biodiesel fuel. However, if biodiesel is not needed to achieve the particulate and hydrocarbon emission reductions mandated by the new standards, then opting for its application will depend on how cost effectively it can reduce greenhouse gas emissions relative to other GHG reduction options.

Biodiesel may be economically attractive compared to retrofitting existing school buses with PM and hydrocarbon reduction technologies, but it is not clear that it would be. Typical annual fuel costs for Ontario school buses are in the range of $4,500-$5,500 per year per bus, so at current premiums B20 would increase fuel costs in the range of $1,000 per bus per year for B20 and by about $5,000 per bus per year for B100. In contrast DPF retrofits can achieve reductions of PM and HC that are much deeper and longer lasting for an initial capital cost of $10,000 per bus or less.

Biodiesel may be most valuable in the short term as a way of bringing down particulate emissions in the Cohort A and B (pre MY1994) buses that are not eligible for DPF retrofits and in any event will be retired before the capital cost of such retrofits could be amortized. A combination of biodiesel and DOC technology may also be a cost effective strategy for some bus cohorts.

5.4.7.4 Market Readiness and Infrastructure Issues

Additional experience with the cold weather application of biodiesel is still needed to identify barriers and solutions for the more widespread adoption in Canadian conditions. Until these issues are demonstrated to be resolved, Canadian fleet operators can be expected to take a “go slow and go low” approach to biodiesel, either avoiding biodiesel altogether or sticking to blends with 10% or less biodiesel. In non-winter seasons, biodiesel can be burned in existing diesel engines, but there are some outstanding issues with regard to engine warranties. Biodiesel is not yet widely available at retail pumps and this represents a serious obstacle to most school bus operators. Finally, there is the question of the compatibility of biodiesel with the ultra low sulphur mineral diesel that will become the standard for diesel fuel in Canada in mid-2006; while no serious new issues are expected, operators can be expected to take a “wait and see” attitude before committing to biodiesel blends in the post 2006 diesel engine environment.

5.4.8 Compressed Natural Gas (CNG)

5.4.8.1 How It Works

Natural gas is comprised mainly of methane (CH_4) and is generally a cleaner burning fuel than diesel. It requires a vehicle that is designed or modified to burn natural gas. Converting a standard diesel vehicle to burn natural gas requires significant changes to the vehicle and the engine, including a completely new fuel system (remove diesel injectors for gas injection or carburetion), a complete new control system, a new ignition system, combustion chamber modifications, unique turbocharger configurations and controls, and specialized (and heavy) fuel tanks for holding the pressurized gas.

5.4.8.2 Air Pollutant and Greenhouse Gas Impacts

Compared with conventional diesel school buses, CNG powered buses have much lower particulate emissions, but even after subtracting methane emissions from the total, their total hydrocarbon emissions are comparable to or higher than conventional diesel, and their NO_x and carbon monoxide emissions also tend to be higher. Ullman [2003] compared air pollutant and toxic contaminant emissions for conventional diesel, low emitting diesel (i.e. ultra low sulphur, low NO_x ECM settings and DPF) and a natural gas school bus and the results are summarized in Table 7. For each row in the table, the entry is in bold italics for the bus configuration with the lowest emissions. Except for greenhouse gas emissions, the low emitting diesel bus outperforms the natural gas bus in every category; in fact for many of the categories, the conventional diesel configuration has lower emissions the CNG bus. Emissions from the CNG school bus could be reduced further by installing oxidation catalyst technology, but we were unable to find any research on this. Even if such after-burner technologies (which may be necessary in the future to keep existing CNG vehicles in compliance with emission regulations) did bring emissions of the CNG buses down to or below the LED levels, there remains the issue of cost effectiveness (see next section).

Table 7

Comparison of Conventional Diesel, Low Emitting Diesel, and CNG School Buses
(all figures in grams/mile unless otherwise noted)

	Conventional Diesel	Low Emitting Diesel (low S, low NO_x ECM, DPF)	CNG
NO_x	14.13	***10.08***	16.19
PM	0.18	***0.01***	0.05
THC	0.39	***trace***	9.34
NMHC	0.39	***trace***	0.65
Methane	Trace	***trace***	8.69
CO	1.76	***trace***	4.78
CO_2	1526	1623	***1200***
Fuel (miles per US gallon) diesel or equivalent	6.6	6.3	***4.3***
Polycyclic organic matter (including PAH’s) (mg/mi)	2.8	***0.076***	0.16
Formaldehyde, (mg/mi)	27	***5.2***	500
Acetaldehyde (mg/mi)	9.5	***2.7***	24
Benzene (mg/mi)	4.7	***not detected***	4.3

5.4.8.3 Cost

CNG buses have a significant cost premium as compared with conventional diesel buses, a premium which is much higher than the cost of ultra low sulphur fuel and low emitting technologies necessary to achieve the LED profile summarized in Table 7. As a retrofit option CNG is even less cost competitive with LED technologies. Fuel costs may be somewhat lower for CNG buses, but this may not hold over the fifteen year life of the bus. Most transit operators that have invested in CNG buses for part of their fleet have experienced significant incremental maintenance costs as well. In short, CNG is not a cost competitive strategy for achieving air pollutant reductions in Ontario school buses. Like biodiesel, CNG does deliver a greenhouse gas benefit that the LED technologies do not, but even here the cost premium is high compared to other ways to achieve green gas emission reductions in general, and even when compared with biodiesel for lowering emissions from school buses.

By way of illustration, New York City Transit has extensive, practical experience with both DPF equipped diesel and CNG-powered buses and finds the low emitting diesel bus is by far the most economical way to achieve emission reductions from their transit bus fleet. According to Lowell [2003]:

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

5.4.8.4 Market Readiness and Infrastructure Issues

CNG vehicle technology is mature, including for application to heavy duty diesel vehicles. Natural gas is readily available as a vehicle fuel in most parts of Ontario. However, there are significant maintenance and fuel handling infrastructure requirements that are borne by fleet operators that commit to running all or part of their fleet on natural gas, and these costs are a significant barrier to the widespread deployment of CNG school buses, especially as a retrofit option.

5.4.9 Diesel Electric Hybrid Buses

Diesel electric hybrid vehicles have a diesel combustion engine and one or more electric motors. In series configurations, the electric motors provide the traction and the diesel engine is used to provide the power to the electric motors. In parallel configurations (the popular Toyoto Prius is an example), the combustion engine can power the drive train directly as well as provide the electricity generation for the electric motors. Electric hybrid motor vehicles usually incorporate some on-board battery storage and regenerative braking. The advantages of the electric hybrid drive system include the efficiency with which it can deliver high torque (this is why it is used in train locomotives), the overall improvement in fuel efficiency (the electric motors deliver traction so much more efficiently than the combustion engine that the energy losses from the on-board power generation can be offset). The parallel hybrid concept allows the combustion engine to be off in low power output conditions (such as those characteristic of the stop and go pattern of urban driving), thus reducing emissions in congested urban cores. The series hybrid configuration allows the diesel motor to be downsized as it no longer needs to be large enough to meet peak power requirements (the electric motors do that) and the diesel engine can also be run at a more constant power output, both advantageous for lowering emissions.

New York City Transit has over 150 hybrid buses, and has found the infrastructure and facility preparations for accommodating hybrid buses minor, especially compared to the major infrastructure modifications required to fuel and maintain CNG buses. Emissions are lower than for CNG or green diesel and the buses have faster acceleration, better traction and smoother braking than conventional diesel technology. At this time it is not technically or economically feasible to retrofit existing school buses to diesel electric hybrid technology. There may be a role for diesel electric hybrid technology for new school buses, but it seems more likely that this technology will first be deployed on public transit buses where the incremental capital cost is a smaller percentage of the bus cost and where the high vehicle utilization leads to a stronger justification for the initial capital investment.

5.5 Summary of School Bus Emission Reduction Options

Table 8

School Bus Emission Reduction Measures					
	PM	**HC**	**NOx**	**eCO2**	**Estimated Implementation Cost**
	grams per year			**kg per year**	
Cohort A -- Pre 1991					
Baseline Emissions per Bus	***24,600***	***53,300***	***246,100***	***20,400***	
Per Bus Emission Reductions per Year					
Maintenance and Driver Behaviour	2,500	5,300	24,600	2,000	Low cost
Replace with New (Cohort D) Bus	20,500	47,600	153,800	2,000	Buses this old would be fully depreciated. Best technology would cost an estimated USD 7,500 more than conventional new bus. For CNG buses there is a capital cost premium in the range of $50,000 per bus, maintenance costs will be higher, and fuelling infrastructure must be readily available. The CNG bus options have much larger premiums, in the range of $50,000 per bus for CNG, plus higher maintenance costs (in the range of $5,000 per year). There is insufficient information to specify the cost premium for electric hybrid school buses; currently, it would be in the tens of thousands of dollars per bus.
Replace with Best Technology (Cohort E)	24,200	47,600	196,900	2,000	
Replace with a CNG Bus[27]	23,370	(26,650)	82,100	1,484	
Diesel Oxidation Catalyst (DOC)	6,200	45,300	-	-	USD 1,000-3,000
Run on B20	2,500	5,300	(4,900)	3,300	Fuel cost premium of 20%, around $1,000 per year

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[27] CNG buses emit less CO2 per kilometer traveled, but this is partly offset by their higher emissions of CH4. The value shown in the eCO2 column represents the net emission reduction of equivalent CO2 (eCO2), after allowing for the methane offset.

School Bus Emission Reduction Measures

	PM	HC	NOx	eCO2	Estimated Implementation Cost
	grams per year			kg per year	
Cohort B -- 1991-1993					
Baseline Emissions per Bus	***10,300***	***50,600***	***205,100***	***20,400***	
Per Bus Emission Reductions per Year					
Maintenance and Driver Behaviour	1,000	5,100	20,500	2,000	Low cost
Replace with New (Cohort D) Bus	6,200	44,900	112,800	2,000	Buses this old would be fully depreciated. Best technology would cost about USD 7,500 more than a conventional new bus; the CNG and hybrid electric options have large premiums (tens of thousands of dollars) relative to a new diesel bus.
Replace with Best Technology (Cohort E)	9,900	44,900	155,900	2,000	
Replace with a CNG Bus[28]	9,070	(29,350)	41,100	1,484	
Diesel Oxidation Catalyst	2,600	43,000	-	-	USD 1,000-3,000
Run on B20	1,000	5,100	(4,100)	3,300	Fuel cost premium of 20%, around $1,000 per year
Cohort C -- 1994-2003					
Baseline Emissions per Bus	***4,100***	***53,300***	***164,000***	***18,400***	
Per Bus Emission Reductions per Year					
Maintenance and Driver Behaviour	400	5,300	16,400	1,800	Low cost
Replace with New (Cohort D) Bus	-	47,600	71,700	-	Dependent on the undepreciated value of the bus being replaced.
Replace with Best Technology (Cohort E)	3,700	47,600	114,800	-	
Replace with CNG Bus[28]	2,870	(26,650)	-	1,064	
Diesel Oxidation Catalyst	1,000	45,300	-	-	USD 1,000-3,000
Diesel Particulate Filter (Catalyzed)	3,690	47,970	-	-	USD 5,000-8,000
Diesel Particulate Filter (Catalyzed), Low NOx configuration	3,690	47,970	41,000	(920)	USD 6,000-9,000
Run on B20	400	5,300	(3,300)	2,900	Fuel cost premium of 20%, around $1,000 per year

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[28] CNG buses emit less CO2 per kilometer traveled, but this is partly offset by their higher emissions of CH4. The value shown in the eCO2 column represents the net emission reduction of equivalent CO2 (eCO2), after allowing for the methane offset.

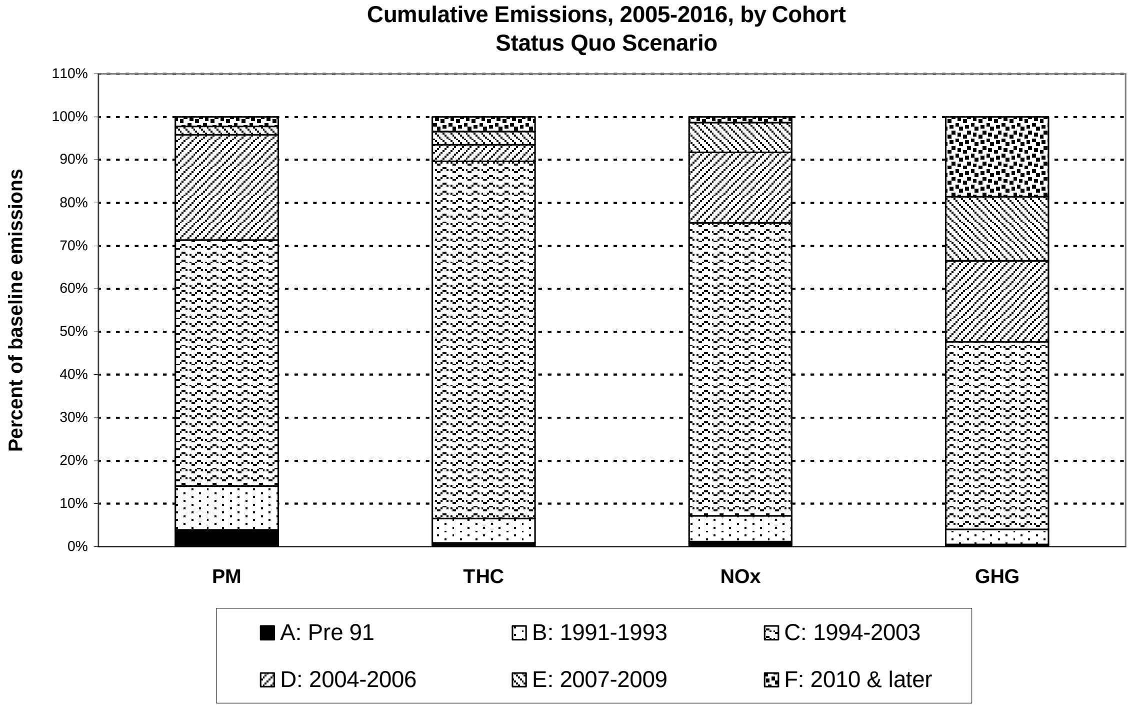
School Bus Emission Reduction Measures

	PM	HC	NOx	eCO2	Estimated Implementation Cost
	grams per year			kg per year	
Cohort D – 2004-2006					
Baseline Emissions per Bus	***4,100***	***5,700***	***92,300***	***18,400***	
Per Bus Emission Reductions per Year					
Maintenance and Driver Behaviour	400	600	9,200	1,800	Low cost
Replace with Best Technology (Cohort E)	3,700	-	43,100	-	USD 2,500 est.
Run on B20	400	600	(1,800)	2,900	Fuel cost premium of 20%, around $1,000 per year

6 Emission Reduction Scenarios for Ontario's School Bus Fleet

In Section 4, we developed a "business as usual" scenario of Ontario school bus emissions by subdividing the fleet into six age cohorts, each with different emission profiles corresponding to the emission limits extant at the time the buses were built, aging the fleet to the year 2016, and tracking both annual and cumulative emissions over the 2006-2016 period. Figure 23 summarizes the percent contribution of each cohort to total cumulative emissions over the 2006-2016 period. In absolute terms, the baseline scenario has cumulative emissions over this period of 530 tonnes of PM, 4,740 tonnes of THC, 17,800 tonnes of NO_x and 3.1 million tonnes of carbon dioxide. Carbon dioxide emissions are generall proportional to VKT by cohort, although there is a slight increase in the post-2007 cohorts that reflects the fuel economy pental that is anticipated with the NO_x control technologies. For the other pollutants, some cohorts contribute disproportionately to the 2006-2016 cumulative total. For example, Cohorts A and B account for a disproportionate share of cumulative PM emissions due to the high PM emissions of these old buses, whereas Cohort C buses dominate THC and NO_x emissions by virtue of the large number of buses in this cohort and the steep drop in the emission factors for THC and NO_x in the post-2003 buses.

Figure 23



The technology profiles in Section 5 provide an indication of the emission reductions that can be achieved with particular technologies applied to individual buses with specified baseline emission profiles, but to fully assess the emission reduction benefits of any particular option it is also necessary to consider the impact over time, given the changing demographics of the bus fleet. Table 8 summarizes the emission reduction options and costs of greatest relevance for each bus cohort, but the cost effectiveness of policy strategies for reducing emissions from the fleet depends on both the per bus costs and the demographics of the fleet. For example, the Cohort A and Cohort B buses are in their final years of service now, and the economic value of and the cumulative impact of emission reduction technologies applied to those buses must be assessed in the context of their attrition.

To do this, we developed and applied a simple, dynamic model that takes into account both the changing age profile of the fleet and the impact of specified retrofit technologies on the emission factors for the individual cohorts. In consultation with the OPHA we then identified a short list of alternative emission reduction scenarios and computed the costs and impacts of these scenarios over time. All scenarios are based on the same assumptions with respect to the demography of the school bus fleet illustrated in Figure 4: the total number of buses is held constant at 15,000, every bus travels 22,000 km per year regardless of age, and all buses of any particular model year remain in-service for 15 years, after which they are retired at the rate of 50% per year. The introduction of ULSD in 2006 is included in all scenarios and so there is no incremental cost for ULSD in one scenario as compared to any other. Of course there are any number of retrofit scenario elements that could be identified and analyzed but for practical purposes, we have not included options that cost more than about $10,000 per bus to implement for Cohorts C and D or more than about $3,000 per bus for the older Cohorts A and B.

The final list of scenarios includes the following:

1) Retire all pre-1994 Buses with Best Current Technology (the 2007 Cohort E level technology) by 2007.
2) Run the entire fleet on B20, beginning in 2006. The results and the costs of this scenario can be linearly scaled down for lower percent blends.
3) Retrofit 1994-2003 model year buses with DOC's by the end of 2006. The results are show for the entire cohort and separately for the 1994-1998 and 1999-2003 segments.
4) Retrofit 1994-2003 model year buses with DPF's by the end of 2006. The results are show for the entire cohort and separately for the 1994-1998 and 1999-2003 segments.

The cumulative emission reductions over the 2006-2016 period are shown in Table 9, but care must be taken in comparing the different scenarios. For example, only the total *mass* of PM and other emission reductions is show here, but the relative impact on toxics and ultrafine particulates must also be taken into account in comparing DOC and CDF technology. There is a significant cost premium for the CDF technology, but it delivers lower NO_x emissions and in general a much cleaner and less toxic exhaust stream than the DOC technology without the catalyzed filter.

- The 1994-2003 MY buses dominate emissions and the largest reductions can be obtained by retrofitting diesel oxidation catalysts (DOC) or catalyzed diesel particulate filters (DPF) technology to these buses. The CDF technology is more expensive, but yields greater reductions of fine particulates and toxics, as well as facilitating a reduction in NO_x that the DOC does not.

Table 9

Cumulative Emission Reductions from Ontario School Bus Fleet

		PM	HC	NOx	GHG	
		kg	kg	kg	tonnes	
Baseline Emissions, 2006-2016		529,349	4,735,712	17,790,016	2,814,872	
Emission Reduction Scenarios:	**No. of buses affected:**	**Cumulative Emission Reductions 2006-2016**				**Notes on Cost**
Early Retirement of Old Buses	1,700	72,200	276,118	985,163	12,457	The old buses in question are fully depreciated. A theoretical cost could be computed based on the value to the owners of deferring their replacement, but this was beyond the scope of this study.
B20 Starting in 2006	15,000	41,990	458,250	(306,552)	378,992	Approx. $115 million. The cost of fueling the Ontario school bus fleet is about $80 million per year. Assuming a 20% premium for B20, the premium would be about $16 million per year. Discounted at 8%, over the 2006-2016 period, the biodiesel premium would have a net present value of about $115 million.
DOC's on 1994-2003 MY Buses	9,000	75,695	3,345,713			$22.5 million to fit 9,000 buses with DOC's
DOC's on 1994-1998 MY Buses	5,000	25,229	1,115,126			$10.1 million to fit approx 4,000 buses
DOC's on 1999-2003 MY Buses	4,000	50,466	2,230,587	457149		$12.4 million to fit approx 5,000 buses
CDF's on 1994-2003 MY Buses	9,000	272,502	3,542,520	2,653,334		$90 million to fit 9,000 buses with CDF's at $10k each
CDF's on 1994-1998 MY Buses	5,000	90,825	1,180,722	884,356		$40 million to fit 4,000 buses with CDF's
CDF's on 1999-2003 MY Buses	4,000	181,677	2,361,798	1,768,978		$50 million to fit 5,000 buses with CDF's

- The cost data are approximate and should be viewed in context. About $100 million dollars is spent every year in Ontario on new school buses, and the replacement value of the Ontario school bus fleet is approximately 1.5 billion dollars. Annual fuel costs are more than $75 million, and the total operating budget of the fleet is well in excess of $500 million.

- Most of the emission reductions from the retirement of the older buses occurs in the first few years of the scenario period; conversely, to achieve these reductions relative to the baseline would require the measure be fully implemented by 2007.

- Regarding the biodiesel option, we have already noted that school bus operators are unlikely to opt for a B20 blend until cold weather performance and fuel availability improves. For lower blends (e.g. B10), the emission reductions and the costs in Table 9 can be scaled down linearly (i.e. B10 would cost half as much and have half the impact of a B20 blend). Unless and until the cost premium comes down, the biodiesel alternative would appear to be a relatively expensive way to reduce emissions compared to either DOC's or CDF's. It is the only option considered here that yields a greenhouse gas reduction, but at a cost in the range of $250/tonne eCO2, it would appear relatively expensive as a GHG reduction option at this time. It has the additional disadvantage of increasing NO_x emissions.

- An illustration of the need to consider the dynamics of the school bus demographics is illustrated by the emission reductions from retrofitting the Cohort C buses (MY 1994-2003). The total emission reductions from retrofitting the MY 1993-2004 cohort with DOC or CDF technology are shown, but Table 9 also shows separate costs and results for MY 1994-1998 buses and MY 1999-2004 buses. While about half the total buses in the cohort are in each of these segments at the beginning of the scenario period (45% for MY 1994-1998, 55% for 1999-2004), the cumulative emission reductions are about twice as much for the newer buses as they will be in-service longer than the older buses and will therefore accumulate more reductions. On the basis of emission reductions per dollar invested, therefore, it is more cost effective to retrofit the newer buses in this cohort.

7 Summary and Policy Implications

In a "business as usual" scenario, air pollutant emissions from Ontario school buses will decline slowly, especially after 2007, as buses that conform to the new emission limits gradually displace the current fleet. We have developed a status quo projection of emissions until the year 2016 that is summarized in Table 5 and Table 6, and illustrated in Figure 11 through Figure 16. Starting in mid-2006, ultra low sulphur fuel will become standard throughout Canada and starting with MY 2007 diesel engines, catalyzed diesel particulate filters will result in substantial reductions in PM and HC emissions from new buses. Greenhouse gas emissions will continue more-or-less unabated in this scenario, as the new pollution control technologies do not have a significant impact on fuel economy (and in some cases there can be a slight fuel economy penalty).

In this “status quo” outlook, for the next ten years the air pollutant emissions from Ontario school buses will be dominated by the emissions from the existing fleet, most of which are MY 1994 or later. The diesel oxidation catalysts, catalyzed diesel particulate filters and low NO_x engine-out technologies and strategies that have been developed to meet the impending standards can be retrofit to the existing fleet to achieve reductions in PM, HC and NO_x emissions, but there are significant costs involved, ranging from $3,000 to $10,000 per bus.

The older buses (pre MY1994 buses) are not compatible with the DPF technology, and while they could be fit with diesel oxidation catalysts, that would not address the particulate problem these vehicles represent. There is also little in-service life remaining for these buses and the investment in DOC technology might be better directed toward accelerating their retirement of these older buses. If they can be retired by the end of 2006, significant reductions in particulate emissions can be achieved.

For MY1994 and later buses, there are two contending strategies for emission reductions, one based on diesel oxidation catalysts and the other, more expensive strategy based on catalyzed particular filters and low NO_x engine control configurations. In both cases, hydrocarbon and toxic air contaminants can be reduced by 80-90%, but the DPF-based strategy also delivers substantial PM and NO_x reductions.

However, there are neither regulations nor incentives for these emission reduction initiatives and in the absence of policy initiatives, it is very unlikely that any of the emission reduction strategies described here will be implemented. The scenarios we have outlined in the previous section indicate that to fully retrofit the Ontario school bus fleet for low emissions of air pollutants would cost $30-$100 million, most of which is the capital cost of DOC and DPF retrofits.

Whether such an investment is “worth it” from a policy perspective would require a comparison of the health impacts and the value to society of achieving these reductions with other strategies for air pollutant and greenhouse gas emission reductions. While such an analysis was beyond the scope of this study (the OPHA is preparing a companion document on the policy options for reducing emissions from school buses), the following observations may be of some use in considering policy approaches.

- By comparison with the costs identified here, the Ontario school bus fleet has a replacement value of about $1.5 billion, and annual capital investment in new buses is in the range of $100 million per year. In this context, the costs of the emission reduction retrofit seem reasonable, but at a time when school boards have been cutting school bus services and negotiating very tight margins with transportation suppliers, the cost of the emission reduction investment looms large. As a rule of thumb, the air pollutant emission reduction investment is about equal to one year’s capital investment in new buses.

- It is important to consider the structure of the Ontario school bus industry when shaping policy recommendations for accelerating the rate of emission reduction in the Ontario school bus fleet. School bus budgets have been cut deeply and frequently by Boards throughout the province. The school bus fleet is now largely consolidated in a small number of companies that are operating very large fleets of school buses across Canada and North America. Most school bus operators, however are small or medium sized firms, often locally based, that run relatively small fleets (less than 30 buses). The same policies and approaches that will be most effective with the large firms are not likely to be effective with these small and medium sized firms. The smaller companies are generally undercapitalized and often contract out for everything from maintenance to drivers, and are struggling to cover their operating costs. Assistance to cover the capital cost of the recommended technologies will likely be necessary to deploy the retrofit options in large or small firms.

- Bulk purchase arrangements could significantly reduce the costs of the technologies identified in the scenarios presented here, and government may wish to consider playing a leadership or coordinating role in negotiating preferred prices with suppliers.

- In addition to direct government assistance for technology upgrade (which is now being widely employed in the U.S. to retrofit school buses), other approaches might be effective with the large operators. For example, consideration should be given to a program focusing on the top five or ten operators that would develop a joint government/industry schedule for emission reductions by those firms. This would kick-start the transition, cover over half the bus fleet in the province, and would also have the effect of deploying the technologies and the retrofits on a sufficient scale that the smaller and medium companies would then benefit from the expertise and parts and service infrastructure that would grow up around the new technologies.

- While we have assumed that the Ontario school bus fleet will maintain its current age profile (with 90% of the fleet renewed after fifteen years and 99% after 20 years), it is possible that financial pressures and uncertainty over the future societal commitment to school busing will cause school bus operators to hold off on investments in new vehicles and run the older buses longer than they have in the past. Incentives to retire pre-1994 MY school buses could make a difference in such a scenario.

- It is also possible that there will be a real and permanent increase in the cost of new school buses (on the order of $5-10,000) in 2007 when the low emission technology becomes standard equipment. Operators seeking to avoid this increase might accelerate their replacement investment between now and then, suggesting a possible role for policies that promote or incent the accelerated adoption of the 2007 standard in new bus purchases.

- There is some statistical evidence that the older school buses are more likely to belong to the smaller school bus operators than the large firms. This would be consistent with the tendency for the smaller firms to be undercapitalized relative to the larger transnational conglomerates that operate fleets that number in the thousands of buses. As with the previous point, this suggests that assistance or incentives to invest in new vehicles could be effective at getting the oldest and dirtiest school buses off the road.

- When considering policies for the accelerated retirement of school buses from the Ontario fleet, the final destination of the buses should be considered. We could find only anecdotal evidence on this point, but it is clear that at least some of Ontario's retired school buses remain in-service, either in Ontario or elsewhere, for example in public and private transit fleets in developing countries. Emission reduction technologies that are retrofit to Ontario school buses, even old Ontario school buses, will continue delivering environmental benefits even after the bus has been retired from the Ontario school bus fleet, and this is worth consideration in the context of the Ontario's commitment to sustainable development. A deliberate strategy to encourage the retirement of older, higher-emitting buses from the active Ontario school bus fleet may be transferring the emissions source to another location and another operator, perhaps one less able than Ontario to invest in emission reduction technology.

- Consideration should be given to including in the provincial curriculum for school bus operator training a module on fuel management and low emission driving techniques. While the school bus operators we interviewed have anti-idling policies, there does not appear to be any uniform training on this or the more general topic of lowering bus emissions through driving technique.

8 Glossary of Terms

Carbonaceous matter: Carbon-containing compounds that are associated with particulate matter in diesel exhaust. In this document, the term carbonaceous matter includes all organic and elemental carbon-containing compounds that are found in the particle phase. In other documents, this term is sometimes used interchangeably to refer to the insoluble fraction of diesel particulate matter or the soot fraction. [EPA 2002].

Diesel engine exhaust (DE): Gaseous and particle-phase emissions resulting from the combustion of diesel fuel in an internal-combustion, compression-ignition engine. DE includes emissions from a diesel engine or diesel vehicle (inclusive of after treatment devices), but does not include emissions from brake and tire wear. [EPA 2002]

Diesel particulate matter (DPM): The particle-phase compounds emitted in DE. DPM can refer to both primary emissions and secondary particles that are formed by atmospheric processes. In this document, DPM refers to primary particles. Primary diesel particles are considered fresh after being emitted and aged after undergoing oxidation, nitration, or other chemical and physical changes in the atmosphere. [EPA 2002]

Elemental carbon (EC): Carbon that has undergone pyrolysis (i.e., has been stripped of hydrogen). In pure form, EC contains only carbon atoms, although EC as it exists in combustion particulate matter is likely to contain some hydrogen atoms. [EPA 2002]

Organic carbon (OC): Carbon- and hydrogen-containing molecules emitted in DE largely as the result of unburned diesel fuel and, to a lesser extent, from engine lubrication oil. OC compounds also can contain oxygen, nitrogen, and sulfur, as well as other elements in small quantities. [EPA 2002]

Soluble organic fraction (SOF): The organic portion of DPM that can be extracted from the particle matrix into solution. [EPA 2002]

Soot: Agglomerations of EC and OC particles. Soot also is often characterized as the insoluble portion of DPM, and is therefore considered to be mainly EC by some investigators. [EPA 2002].

9 References

[Ayala 2004]
Alberto Ayala, Research Division, California Air Resources Board (CARB), “On-Road Diesel Emissions and Options for Control”, presentation to The California Air Pollution Control Officer’s Association (CAPCOA) Conference on Diesel, Diamond Bar, California, January 2004.

[Bascue 2003]
Andrew Bascue, “Reducing Emissions from Your School Bus Fleet” presentation slides for Andrew Bascue, EPA Region 2, July 2003.

[Bertelsen 2004]
Bruce Bertelsen, EETPI, “Reducing Emissions from Existing Diesel Engines: The Critical Role of Diesel Retrofit Technologies” bbertelsen@eetpi.org, January 2004.

[Brown and Rideout 1996]
Brown, K. F., et al. “Urban Driving Cycle Results of Retrofitted Diesel Oxidation Catalysts on Heavy Duty Vehicles”, Diesel Exhaust After-treatment 1996 (SP-1140), SAE 960134. February, 1996.

[Brown and Rideout 1997]
Brown, K. F., et al. “Urban Driving Cycle Results of Retrofitted Diesel Oxidation Catalysts on Heavy Duty Vehicles: One Year Later”, Diesel Exhaust After-treatment (SP-1227), SAE 970186. February, 1997.

[Bush]
Bush, Christopher, et al., “Performance and Durability Evaluation of Continuously Regenerating Particulate Filters on Diesel Powered Urban Buses at NY City Transit – Part II” Society of Automotive Engineers.

[Chatterjee 2001]
Chatterjee, S., et al. “Emissions Reductions and Operational Experiences with Heavy Duty Diesel Fleet Vehicles Retrofitted with Catalytically Regenerated Particulate Filters in Southern California”, SAE 2001-01-0512, 2001.

[Chatterjee 2002]
Chatterjee, S., et al. “Performance and Durability Evaluation of Continuously Regenerating Particulate Filters on Diesel Powered Urban Buses at NY City Transit - Part II”, SAE 2002-01-0430, 2002.

[Chatterjee 2004]
Sougato Chatterjee, “Catalytic Emission Control for Heavy Duty Diesel Engines”, presentation by S. Chatterjee of Johnson Manley Environmental Catalysts and Technologies to The California Air Pollution Control Officer’s Association (CAPCOA) Conference on Diesel, Diamond Bar, California, January 2004.

[EPA 2002a]
ARCADIS Geraghty & Miller, Inc., Update Heavy-Duty Engine Emission Conversion Factors for MOBILE6: Analysis of Fuel Economy, Non-Engine Fuel Economy Improvements and Fuel Densities”, Final Report M6.HDE.002 (prepared in May 1998), for Assessment and Modeling Division, Office of Transportation and Air Quality, U.S. Environmental Protection Agency, EPA420-R-02-005, January 2002.

[EPA 2002b]
Louis Browning (ARCADIS Geraghty & Miller, Inc.), “Update Heavy-Duty Engine Emission Conversion Factors for MOBILE6: Analysis of BSFCs and Calculation of Heavy-Duty Engine Emission Conversion Factors” Final Report M6.HDE.004 (prepared in May 1998), for Assessment and Modeling Division, Office of Transportation and Air Quality, U.S. Environmental Protection Agency, EPA420-R-02-006, January 2002.

[EPA 2004]
U.S. Environmental Protection Agency, Highway Diesel Progress Review – Report 2, Assessment and Standards Division, Office of Transportation and Air Quality, USEPA, Report

[Gautam 2004]
Mridul Gautam, Scott Wayne, Greg Thompson, Nigel Clark, Donald Lyons, Dan Carder, Sandeep Mehta, Wesley Riddle, Department of Mechanical and Aerospace Engineering, West Virginia University, “Concentrations and Size Distributions of Particulate Matter Emissions from Catalyzed Trap-Equipped Heavy-duty Diesel Vehicles Operating on Ultra-low Sulfur EC-D Fuel”, presentation to The California Air Pollution Control Officer’s Association (CAPCOA) Conference on Diesel, Diamond Bar, California, January 2004.

[Jackson 2004]
Michael D. Jackson, “Diesel — What the Future Holds”, presentation to The California Air Pollution Control Officer’s Association (CAPCOA) Conference on Diesel, Diamond Bar, California, January 2004.

[Kittleson 2004]
David B. Kittelson, Center for Diesel Research, University of Minnesota, “Ultrafine and Nanoparticle Emissions: An Ongoing Challenge”, presentation to The California Air Pollution Control Officer’s Association (CAPCOA) Conference on Diesel, Diamond Bar, California, January 2004.

[Lanni 2001]
Lanni, T., et al. “Performance and Durability Evaluation of Continuously Regenerating Particulate Filters on Diesel Powered Urban Buses at NY City Transit”, SAE 2001-01-0511, 2001.

[Lowell 2003]
Lowell, Dana M. et. al., “Comparison of Clean Diesel Buses to CNG Buses”, New York City Transit, Dept. of Buses, Research and Development.

[Lowell 2003]
Dana Lowell, MTA New York City Transit, “NYCT Experience with Clean Diesel Technologies”, Philadelphia Diesel Difference Conference, May 2003. Dana Lowell, NYCT, (718) 927-8620, dalowel@nyct.com.

[MECA 1999]
Manufacturers of Emission Controls Association, “Demonstration of Advanced Emission Control Technologies Enabling Diesel Powered Heavy-Duty Engines to Achieve Low Emission Levels”, Final Report, Manufacturers of Emission Controls Association, 1660 L Street, NW Suite 1100, Washington, DC 20036. www.meca.org. June 1999.

[MECA 2000]
Manufacturers of Emission Controls Association, “Emission Control Retrofit of Diesel-Fueled Vehicles”, Manufacturers of Emission Controls Association, 1660 L Street NW, Suite 1100, Washington, DC 20036. www.meca.org. March 2000.

[MECA 2000a]
Manufacturers of Emission Controls Association, “Report of Agreed-Upon Procedures” prepared by Mark L. Gollub, CPA, November 2000.

[MECA 2000b]
Manufacturers of Emission Controls Association, “Catalyst-Based Diesel Particulate Filters and NOx Adsorbers: A Summary of the Technologies and the Effects of Fuel Sulfur”, Manufacturers of Emission Controls Association, 1660 L Street NW, Suite 1100, Washington, DC 20036. www.meca.org. August 2000.

[Monahan 2002]
Monahan, Patrick, “Pollution Report Card: Grading America’s School Bus Fleets”, Union of Concerned Scientists, Washington, February 2002. Available from www.ucsusa.org or from UCS Publications, Two Brattle Square, Cambridge, MA 02238-9105, or email pubs@ucsusa.org.

[Monahan and Friedman 2004]
Patricia Monahan and David Friedman, “The Diesel Dilemma: Diesel’s Role in the Race for Clean Cars“, Union of Concerned Scientists, January 2004.

[OPHA 2003]
Ontario Public Health Association, "Literature Review: Air Pollution and Children's Exposures Related to School Buses", OPHA, Toronto, October 2003.

[Rideout 2004]
Greg Rideout, Environmental Technology Centre, Emissions Research and Measurement Division, Environment Canada, personal communications based on research-in-progress including on-road emissions monitoring of school buses with and without DOC and CRDPF technology and with variable sulphur concentrations in the fuel.

[Ullman 2003]
Ullman, T. L., et al. "Comparison of Exhaust Emissions, Including Toxic Air Contaminants, From School Buses in Compressed Natural Gas, Low Emitting Diesel, and Conventional Diesel Engine Configurations", SAE 2003-01-1381, 2003.
EPA420-R-04-004, March 2004.