Final Report

Effects of MMT in Gasoline on Emissions from On-Road Motor Vehicles in Canada

November 11, 2002

For:
Canadian Vehicle Manufacturers' Association, and
Association of International Automobile Manufacturers of Canada

Air Improvement Resource, Inc.

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1.0 Executive Summary

The gasoline additive methylcyclopentadienyl manganese tricarbonyl, or MMT, is in widespread use in Canada as an octane enhancer. The manganese (Mn) in MMT forms manganese oxides during combustion, some of which deposits on the spark plugs, combustion chamber, and the exhaust system. The remainder of manganese oxides not deposited in the engine and exhaust system are emitted into the atmosphere. Automakers have long been concerned that manganese oxides can also have negative impacts on engines and emission control systems.

The Alliance of Automobile Manufacturers (The Alliance), the Association of International Automobile Manufacturers (AIAM), and the Canadian Vehicle Manufacturers Association (CVMA) conducted a multi-year test program to determine the impacts of MMT on exhaust hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NOx) from advanced technology vehicles, notably "Tier 1" vehicles, and Low Emission Vehicles, or LEVs. This testing program was conducted in two parts. The first part tested forty Tier 1, transitional low emission vehicles (TLEVs), and low emission vehicles (LEVs) on both MMT-containing and no-MMT gasoline. The second part tested sixteen LEVs. The Mn concentration in the test fuel for both testing programs was 8.3 milligrams per liter manganese, or 0.031grams Mn per U.S. gallon.

The purpose of this modeling study was threefold:

(1) examine the impact of MMT on exhaust HC, CO, and NOx emissions of different vehicles in the automakers' test program,
(2) to develop MMT correction factors by vehicle class and technology type that could be used with standard emission models, and
(3) project HC, CO, and NOx emissions into the future for Canada.

Examination of various sources indicates that MMT use in Canada is around 90%, so virtually every gasoline vehicle would be expected to contain some MMT. Data from Environment Canada[1] indicate that the average Mn concentration is about 0.022 grams per U.S. gallon, or a little less than the concentration used in the test program above. However, maximum Mn levels encountered in Canada are well above the test program concentration.

Analysis of the data indicates that for Tier 1 vehicles, prolonged fueling with MMT (through 80,000 km or 50,000 mi) increases hydrocarbon emissions, has little effect on CO emissions, and reduces NOx emissions. For LEVs, prolonged use of MMT increases all three emissions – HC, CO, and NOx. The increases in emissions become more dramatic as vehicles age. The analysis also examined two Low Emission Vehicles that were very close to EPA's Tier 2 emission standards. These two vehicles saw very

[1] Environment Canada "Additives in Canadian Fuels" March, 2000

dramatic increases in HC, CO, and NOx emissions with prolonged use of MMT. The effects of MMT on both LEVs, and vehicles which are close to the Tier 2 standards raises serious questions about the continued use of MMT in Canada, since LEVs were introduced in model year 2000 and Tier 2 vehicles are slated for widespread introduction into Canada starting with the 2004 model year (October, 2003).

Extensive modeling of fleet emissions for gasoline vehicles in Canada was conducted for calendar years 1995-2020. The modeling estimated emission differences between a no-MMT case and two MMT cases. The first case, called the "Base MMT Case", assumed that MMT penetration was 100% at 0.031 g Mn/gal, and that the test data can be used to directly estimate the impacts of MMT in Canada without adjusting for average manganese concentration differences. The second case, called "MMT Concentration," assumed 100% MMT penetration, but MMT effects are adjusted for the lower average Canadian concentration.

VOC, CO, and NOx emissions inventories were estimated for all gasoline vehicles except motorcycles for all of Canada, from 1995-2020. Emission inventory differences between the Base MMT, MMT Concentration, and the no-MMT case were estimated for calendar years 2010 and 2020, and then the percent differences from the no-MMT case were estimated (in the no MMT case, MMT was assumed to have been removed in 1995). The results are shown in Table ES-1 below. The table shows percent changes for each of the pollutants, and also for VOC + NOx, which are the two primary pollutants that contribute to ozone formation.

Table ES-1. Percent Changes in Inventories Due to MMT
(positive indicates MMT has higher inventory, negative indicates MMT lower)

Year	Case	VOC + NOx	VOC	CO	NOx
2010	Base MMT	2%	8%	11%	-4%
	MMT Concentration	1%	6%	8%	-3%
2020	Base MMT	46%	36%	75%	65%
	MMT Concentration	32%	26%	35%	45%

The table shows that for both the Base MMT and MMT Concentration cases, in 2010 and 2020, VOC + NOx are higher with MMT that without.

For the individual pollutants, VOC and CO are higher with MMT than without, but NOx is lower in 2010. The NOx effect is primarily due to MMT's effects on Tier 1 vehicles. This analysis did not examine the effects for pre-Tier 1 vehicles. As low emission vehicles and Tier 2 vehicles are introduced, however, MMT increases emission of all three pollutants, regardless of which case is examined.

This analysis indicates that if MMT use is not discontinued before widespread introduction of NLEVs and Tier 2 vehicles (NLEV introduction started in 2001), VOC, CO, and NOx emissions from gasoline motor vehicles in Canada in the future may be significantly higher than those contained in Environment Canada's (EC) air quality planning inventories.

2.0 Introduction

The gasoline additive methylclopentadienyl manganese tricarbonyl, or MMT, is in widespread use in Canada as an octane enhancer. The manganese in MMT forms manganese oxides, sulfides, and phosphates during combustion, some of which deposit on the spark plugs, combustion chamber, and the exhaust system. The remainder of manganese compounds not deposited in engine and exhaust system are emitted into the atmosphere. Automakers have long been concerned that manganese compounds can also have negative impacts on engines and emission control systems.

The Alliance of Automobile Manufacturers (The Alliance), the Association of International Automobile Manufacturers (AIAM), and the Canadian Vehicle Manufacturers (CVMA) conducted a multi-year test program to determine the impacts of MMT on exhaust hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NOx) from advanced technology vehicles, notably "Tier 1" vehicles, and Low Emission Vehicles, or LEVs. This testing program was conducted in two parts. The first part tested forty Tier 1, transitional low emission vehicles (TLEVs), and low emission vehicles (LEVs). The second part tested sixteen LEVs. The test programs are described in two reports. [1,2] This multi-year testing effort found that MMT increases HC, has little effect on CO, and slightly reduces NOx emissions from Tier 1 vehicles (through 50,000 miles). For LEVs, MMT increases HC, CO, and NOx emissions and caused vehicles to exceed the HC certification standard. The effects of MMT become more dramatic as vehicles age.

In December of 2001, AIR, Inc. completed the most recent assessment of emission inventories from on-road vehicles in Canada. [3] This inventory modeling did not account for the effects of MMT in gasoline because its effects on emissions of advanced technology vehicles were not fully understood at that time.

The purpose of this study is to:

(1) examine the impact of MMT on exhaust HC, CO, and NOx emissions of different vehicles in the automakers' test program
(2) develop MMT correction factors by vehicle class and technology type that could be used with standard emission models, and
(3) project HC, CO, and NOx emissions into the future for Canada, with and without MMT.

The scope of this study is to estimate the impacts of MMT on exhaust HC, CO, and NOx emissions from Tier 1 and later gasoline-fueled vehicles. MMT may have effects on pre-Tier 1 vehicles, and may have many other effects, for example, it is likely that there will be increased exhaust PM emissions from the combustion of manganese. Vehicle fuel economy may also be negatively affected, however, the magnitude of the impact on total Canadian fuel consumption has not been estimated in the study. Finally, MMT could significantly increase costs for vehicle owners and manufacturers due to its impacts on emission control systems (increase frequency of OBD MIL illumination, service, etc.). The total cost impact of MMT has not been estimated in this study.

The remainder of this report is divided into 3 sections. Section 3 (Background) discusses background information on MMT and recent Canadian emission inventory modeling used as the baseline in this analysis. Section 4 (Analysis of MMT Data) discusses our analysis of the automakers' MMT data for the purpose of developing emission impacts by vehicle class, technology and vehicle age. This analysis parallels the analysis done by Professor Richard Gunst for both the Part 1 and Part 2 studies, except that in this case we have chosen different vehicle groupings to match the various emission standards as they are phased-in for passenger cars, light duty trucks, and heavy-duty gasoline vehicles. Finally, Section 5 (Canadian Emission Modeling) estimates MMT's impact on HC, CO, and NOx inventories from 1995 through 2020.

3.0 Background

The gasoline additive methylclopentadienyl manganese tricarbonyl, or MMT, is in widespread use in Canada to increase gasoline octane and reduce engine knock from gasoline vehicles. Engine knock, or pre-ignition, is closely related to the octane number of gasoline. Although there is no national requirement for the concentration of MMT in Canada the industry practice limit is set by the Canadian General Standards Board for manganese in gasoline at 18 mg Mn/liter, or 0.068 g Mn/U.S. gal. Almost 90% of gasoline sold in Canada contains MMT (more detail on MMT penetration and concentration in Canada is presented in Section 5).

In the U.S., MMT is banned in California and in areas with federal reformulated gasoline (RFG). In other parts of the U.S., the legal limit for MMT is 1/32 g Mn/U.S. gallon, or 0.031 g Mn/gal. This is less than one-half of the limit in Canada. Extensive fuel surveys conducted by the automobile manufacturers indicate MMT is rarely used in the U.S. Reasons for this may be that various oxygenates and other blending components are used in the U.S. to improve octane, as alternatives to MMT.

In 2002, the Canadian Vehicle Manufactures Association (CVMA) and the Association of International Automobile Manufacturers of Canada (AIAMC) sponsored a comprehensive review of reports related to MMT. [4] The study, entitled "Impacts Associated With the Use of MMT as an Octane Enhancing Additive in Unleaded Gasolines – A Critical Review" was conducted by Sierra Research. Sierra reviewed dozens of studies related to MMT that have been published in the last 20 years. Among Sierra's findings are the following:

- Manganese oxides resulting from the combustion of manganese deposit in the engine combustion chamber, on spark plugs, and in the exhaust system, including catalytic converters and oxygen sensors
- Deposits on spark plugs and in combustion chambers lead to engine-out HC increases, and spark plug deposits can lead to spark plug misfire
- Manganese oxide deposits can, under some conditions, result in plugging of catalytic converters, and in general, higher PM emissions
- Small improvements in catalytic converter efficiency have been reported, which may be attributable to preferential adsorption of catalyst poisons by the oxides, and moderate reductions in NOx emissions in two test programs involving late 1980s and early 1990s vehicles. However, recent findings demonstrate that the slight improvement in catalytic converter efficiency is overwhelmed by the increases in engine-out emissions.

The automobile manufacturers have been concerned that while MMT may improve octane, it causes manganese oxide deposits on spark plugs, intake and exhaust valves, combustion chambers, exhaust system, oxygen sensors, and catalytic converters. A buildup of these deposits has been shown to increase hydrocarbon emissions. However, most of the testing programs conducted to date have been on vehicles designed for the 1980s and early 1990s (i.e., so called Tier 0 vehicles and earlier).

Emission standards of new vehicles are changing very rapidly in this time period and even over the next decade. Tier 1 vehicles were introduced starting in 1994, and these vehicles were equipped with onboard diagnostics systems which continually test the emission control system, illuminating a malfunction indicator light, or MIL, when part of the emission control system could be compromised. Once the MIL is on, the vehicle owner is expected to seek a repair. Low emission vehicles were broadly introduced in 2001 for passenger cars and light duty trucks up to 6,000 lbs gross vehicle weight. The LEV HC standards are 70% lower than the Tier 1 standards, and the NOx standards are 50% below the Tier 1 NOx standards. Tier 2 standards were implemented by the EPA and proposed by Environment Canada for the 2004 and later time period. These standards further reduce NOx emissions by another (on average) 65%, and extend the applicability of the standards to all passenger cars, light duty trucks, and medium duty passenger vehicles up to and in some cases exceeding 8,500 lbs gross vehicle weight. The Tier 2 standards also increase emission control system durability periods (the mileage over which vehicles must meet their emission standards) from 100,000 miles to 120,000 miles. Of course, LEVs and Tier 2 vehicles also are equipped with onboard diagnostics, and these systems become proportionally more stringent with each reduction in the emission standards.

Due to the rapid introduction of much lower emitting vehicles, and the lack of robust test data on how these vehicles respond to MMT, the automobile manufacturers designed and conducted an extensive research program to determine MMT's long-term effects on the emissions and emission control systems from Tier 1 vehicles and LEVs. This testing program was conducted in two parts. In the first part, Tier 1 and transitional low emission vehicles (TLEVs), and one model of LEV, were tested on Clear (i.e., gasoline containing no MMT) and MMT-containing gasoline for at least 50,000 miles. In the second part, twenty low emission vehicles, or LEVs were tested on Clear and MMT-containing fuels for 100,000 miles. These testing programs are described in the two reports referenced earlier [1,2].

Overall, the results from the automakers' testing program indicate that MMT increases HC emissions for Tier 1 and LEV vehicles, it lowers NOx for Tier 1 vehicles (through 50,000 miles), but increases NOx and CO emission for LEVs. Also, MMT's effects on emissions become more dramatic with increasing mileage accumulation. Of course, LEVs are now the current technology and Tier 2 vehicles are the vehicles of the near future, so any increase in emissions from these vehicles is particularly troubling. Because of the mixed effects between technologies and the fact that MMT's effects increase with vehicle age, it is necessary to perform emission inventory modeling of the fleet of on-road vehicles over a number of years to determine the overall MMT effects on the fleet as new vehicles are added and older ones are retired from the fleet.

The most recent work on inventory modeling in Canada was conducted by AIR and SENES for Environment Canada (EC) in 2001. [3] In this study, AIR used an updated version of the MOBILE5 model to estimate on-road inventories in Canada from 1995 through 2020.[2] Four different scenarios were evaluated, as follows:

1. Baseline: included Tier 1 and NLEV standards for light duty, and 1998 NOx standards for heavy-duty vehicles, and I/M programs in Ontario and Lower Fraser Valley
2. Scenario 1: Baseline + light duty Tier 2 standards starting in 2004
3. Scenario 2: Scenario 1 + 2004 heavy-duty NOx standards
4. Scenario 3: Scenario 2 + 2007 heavy-duty NOx/PM standards and low sulphur diesel fuel

This modeling included EC's estimate of growth in travel and also its low sulphur gasoline requirements. For heavy-duty vehicles, all scenarios also included the effects of off-cycle emissions and the heavy-duty consent decrees, minus the engine rebuild programs. All scenarios showed significant reductions in HC, CO, NOx and PM out into the future. The modeling did not include any MMT effects for gasoline vehicles.

This MMT study uses the HC, CO, and NOx emissions from gasoline-fueled vehicles from Scenario 3 above, which is closest to Canada's proposed path forward, as a baseline for making MMT adjustments.

[2] MOBILE6 became available in January of 2002.

4.0 Analysis of Part 1 and Part 2 MMT Data

Extensive statistical analysis was performed on the Part 1 and Part 2 data as a part of the original study, so that work does not need to be repeated in this study. [1,2] However, for modeling purposes, estimates of MMT's impact must be developed for different vehicle classes and technologies. For example, MMT effects must be developed for passenger cars, light duty trucks, medium duty passenger vehicles, and heavy-duty gasoline vehicles. This study will assume that MMT has no effect on emissions from motorcycles. Also, MMT effects must be evaluated for Tier 1 vehicles, low emission vehicles or, LEVs, and Tier 2 vehicles, because the effects are likely to be quite different for the different technologies.

This section is divided into the following subsections:

- Summary of MMT Test Procedures
- Data Analysis
- Results
- MMT Correction Factors
- Mapping of Groups Into Vehicle Class and Standard Level

4.1 Summary of MMT Test Procedures

A brief summary of testing procedures used in the MMT testing is contained in this section. Readers are referred to the Part 1 and Part 2 reports for more complete details of the testing.

Vehicles used in the Part 1 and Part 2 testing are shown in Table 1. All vehicles were new at the start of the test program. Also shown are their model year and numerical emission standards. Four identical vehicles of each make and model year were used in the testing. Two of each vehicle accumulated mileage on Clear gasoline, and the other two accumulated mileage on gasoline containing MMT. The concentration of MMT used in both phases of testing was 1/32 gram Mn per US gallon, or 0.031 g Mn/gallon.

Prior to being used in the test program, each vehicle was tested on MMT-free certification fuel to ensure that each vehicle met its respective emission standards. After this initial testing, Clear vehicles accumulated mileage on conventional commercial fuel (with seasonal volatility and without oxygenates) with minimum 87 octane, and MMT vehicles accumulated mileage on the same gasoline with MMT. Mileage accumulation on the fuels was conducted using a modification of EPA's proposed Standard Mileage Accumulation (SMA) testing cycle.

Part 1 vehicles were tested at the following mileage intervals:

- New
- 4,000 miles

- 15,000 miles
- 25, 000 miles
- 35,000 miles
- 50,000 miles
- 75,000 miles (LEV model only)

Part 2 vehicles were tested at the same mileages, and two other mileages were added:

- 75,000 miles
- 100,000 miles

All emission tests at these mileages for all vehicles were conducted with gasoline meeting California's Phase 2 specifications. Emission test procedures consisted of the 1975 Federal Test Procedure, including cold start, hot stabilized, and hot start operation, and, for Part 1 vehicles, the Highway Fuel Economy Test (HFET). A minimum of two replicate tests were conducted on each vehicle at each mileage interval, and in some cases, a third test was performed. For both phases of testing, emissions were collected on an engine-out and tailpipe basis to allow for evaluation of catalyst efficiencies.

Table 1. Vehicles Used in Testing Program

						50,000 Mile Emission Standard (100,000 mile standards in parentheses)		
Part	Vehicle Class	Technology	Make	Model	Model Year	HC	CO	NOx
1	PC	Tier 1	Toyota	Corolla	1996	0.25 (0.31)	3.4 (4.2)	0.4 (0.6)
		TLEV	Chevrolet	Cavalier	1997	0.125 (0.156)	3.4 (4.2)	0.4 (0.6)
		TLEV	GM	Saturn	1997	0.125 (0.156)	3.4 (4.2)	0.4 (0.6)
		TLEV	DCX	Intrepid	1996	0.125 (0.156)	3.4 (4.2)	0.4 (0.6)
		TLEV	DCX	Neon	1996	0.125 (0.156)	3.4 (4.2)	0.4 (0.6)
		TLEV	Ford	Escort	1996	0.125 (0.156)	3.4 (4.2)	0.4 (0.6)
		TLEV	Ford	Crown Vic	1996	0.125 (0.156)	3.4 (4.2)	0.4 (0.6)
		LEV	Honda	Civic	1996	0.075 (0.090)	3.4 (4.2)	0.2 (0.3)
	LDT2	Tier 1	Chevrolet	S10 Blazer	1996	0.32 (0.400)	4.4 (5.5)	0.7 (0.9)
		TLEV	DCX	Caravan	1996	0.16 (0.200)	4.4 (5.5)	0.7 (0.9)
2	PC	LEV	VW	Beetle	1999	0.075 (0.090)	3.4 (4.2)	0.2 (0.3)
		LEV	DCX	Breeze	1998	0.075 (0.090)	3.4 (4.2)	0.2 (0.3)
		LEV	Ford	Escort	1998	0.075 (0.090)	3.4 (4.2)	0.2 (0.3)
	MDV2	LEV	Chevrolet	Tahoe	1999	0.195 (0.280)	5 (7.3)	0.6 (0.9)

PC = passenger car

4.2 Data Analysis

AIR obtained the raw emission data for all vehicles from the automobile manufacturers. Prior to analyzing the data, the data were grouped by approximately similar numerical HC and NOx emission standards, so that the groupings could be used to represent the various vehicle classes and emission standard levels. AIR developed four groups, as follows:

- Group 1 – The Part 1 Tier 1 S10 Blazer, and the Part 2 LEV Tahoe (2 models)

- Group 2 – The Part 1 TLEVs, the Part 1 Tier 1 Corolla and S10 Blazer, and the Part 2 LEV Tahoe (10 models)

- Group 3 – The Part 1 Honda LEV Civic, and the Part 2 Beetle, Breeze, and Escort (4 models)

- Group 4 – The Part 1 Honda Civic and the Part 2 Escort (2 models)

The first group was developed to represent Tier 1 and LEV light duty trucks and heavy-duty vehicles. The Chevrolet S10 has a hydrocarbon standard of 0.32 g/mi, and the LEV Tahoe is at 0.195 g/mi. The NOx standards are at 0.7 g/mi, and 0.6 g/mi, respectively. The DCX TLEV Caravan was included in Group 2 because of its lower HC standard.

The second group was developed to approximately represent Tier 1 passenger cars. This group contains two Tier 1 vehicles (the Toyota Corolla and the S10), the TLEVs, and the Part 2 LEV Tahoe. The passenger car TLEV NMOG standard at 0.125 g/mi is lower than the Tier 1 NMHC standard of 0.25, but the NOx standard of 0.4 g/mi is identical to the Tier 1 passenger car and LDT1 NOx standard. The reader will note that we have included both the LEV Tahoe and the Chevrolet S10 in both Group 1 and Group 2.

Group 3 was developed to represent LEV passenger cars and LDT1s. All vehicles are LEV passenger cars in this group.

For Group 4, there were no Tier 2 vehicles tested, because they were not available during the program. However, two of the passenger car LEVs -- the Part 1 Honda Civic and the Part 2 Escort -- have 50,000-mile emissions that are very close to the 50,000-mile Tier 2 Bin 5 NOx standard of 0.05 g/mi.[3] This is shown in Figure 1 below. These vehicles were selected to represent vehicles certified to Tier 2 standards. While it would be preferable to have one or two larger vehicles, including LDTs included with this group, since all passenger cars and LDTs from 0-8,500 lbs GVW must meet a Tier 2 average NOx level of 0.07 g/mi at 120,000 miles, there were no larger vehicles in this test data with NOx emissions in this range.

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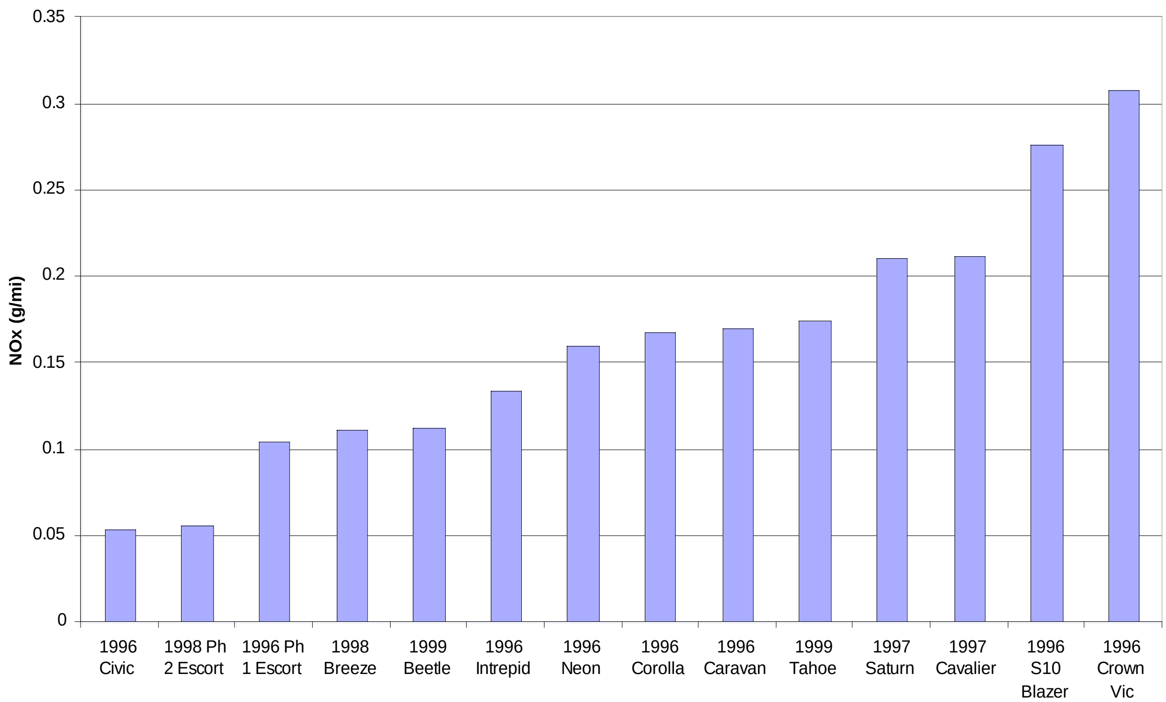
[3] Tier 2 emission standards are divided into different levels called Bins. Manufacturers can produce vehicles in any Bin structure as long as an overall NOx average is met. The final Tier 2 NOx average is 0.07 g/mi at 120,000 miles, which is the same standard as Bin 5.

Figure 1. 50K NOx Emissions of Phase 1 and Phase 2 Test Vehicles on California Phase 2 Gasoline



After grouping the data, the following process was used to determine emission rates vs mileage for the Clear and MMT fleets. This process follows a similar process used by the investigators analyzing the data in the Part 1 and Part 2 reports:

1. All emission tests on California Phase 2 fuel were utilized.
2. The log transformation of emissions was determined for each vehicle and test point.
3. For each Group, the average of the log of emissions was computed at each mileage point.
4. The log averages were transformed back to real g/mi space.
5. Linear regressions, and in some cases, power curves were fit through the averages to determine emissions vs mileage.
6. MMT correction factors vs mileage were determined by taking the ratio of MMT emissions vs Clear emissions.

4.3 Results

Emissions vs mileage for Clear and MMT vehicles for each group are shown in Attachment 1. Observations on these plots are found below.

Group 1 – For NMHC, MMT appears to increase emissions at all mileages (every MMT average is above every Clear average). For CO, MMT appears to have little or no effect. For NOx, MMT appears to reduce emissions at higher mileages (above 20,000 miles, the

MMT averages are always below the Clear averages). For all Group 1 vehicles, linear regressions seem to provide a reasonable fit of the data.

Group 2 – In Group 2, only the LEV Tahoe was tested through 100,000 miles; the remainder of the vehicles were tested at 50,000 miles and less. For NMHC, MMT appears to increase emissions at all mileages. CO again shows little or no effects of MMT (the LEV Tahoe has a CO standard of 5.0 g/mi, which may explain why the points at higher mileages appear to be much higher than the others below 50,000 miles), but NOx is lower at all mileages for MMT.

Group 3 – For NMHC, MMT increases emissions at all mileages, and the increase grows with mileage. CO emissions also increase with MMT. In the case of CO, we have fitted a power curve (y = exp[ax+b]) to the data because the MMT and Clear emissions at 4,000 miles, 15,000 miles, and 25,000 miles are equal, but at higher mileages the Clear emissions are much lower than the MMT emissions.[4] Finally, NOx is lower at low mileages (except for the 4,000-mile point) for MMT, but much higher at higher mileages. We have fitted a power curve through these points because the emissions of MMT and Clear are equivalent at 4,000 miles.

Group 4 – For HC, MMT increases emissions at all mileage points. MMT also has the same effect on CO. MMT increases NOx emissions at the higher mileages, with the crossover point being about 20,000 miles. Again, we have fitted a power curve to the Clear NOx because at low mileages the emissions are very similar, while at higher mileages, the emissions from MMT vehicles are much higher than the Clear vehicles.

Overall, these analyses show that MMT increases HC emissions for all vehicles (Groups 1-4), with the greatest increases coming on the advanced technology vehicles (Groups 3 and 4). MMT appears to have little effect on CO emissions from higher mileage vehicles, but starts to have an effect at increasing emissions for the more advanced technology vehicles. Finally, MMT appears to reduce NOx emissions for earlier vehicles, but increases NOx significantly for advanced technology vehicles such as LEVs and Tier 2 vehicles. This effect becomes much more pronounced as these vehicles increase in age.

4.4 MMT Correction Factors

The modeling work conducted by AIR for Environment Canada in 2001 utilized the MOBILE5b model and EPA's emission rates for 1988 and later light duty vehicles and light duty trucks from EPA's Tier 2 Final Rule. This modeling did not take into account the impacts of MMT on emissions, in spite of the fact that MMT is in widespread use in Canada, because there was not enough information at the time to indicate that emissions should be adjusted for MMT use. The goal of this study is to estimate MMT's impact on these emission rates and emission inventories. Therefore, what is needed is a

[4] A linear regression through the Clear data produced a higher 4K level than MMT, when the averages at low mileages are essentially equivalent.

set of MMT correction factors that can be used in conjunction with the 2001 modeling system to adjust the EPA emission rates for gasoline for MMT use.

MMT correction factors vs age were estimated for Tier 1 and later vehicles from the above plots to use in modeling emissions in Canada. The MMT correction factors were estimated with the following equation:

$$CF_{MMT} = Emissions_{MMT}/Emissions_{Clear}$$

Where:

CF_{MMT} = MMT correction factor
$Emissions_{MMT}$ = emissions with MMT fuel
$Emissions_{Clear}$ = emissions with Clear fuel

The correction factors are used in the MOBILE5 model to correct the emissions within the model to operation on MMT fuel.

$$EF_{MMT} = EF_{EPA} * CF_{MMT}$$

Where:

EF_{MMT} = emission factor in g/mi for a particular model year, adjusted for MMT
EF_{EPA} = EPA emission factor for a particular model year, not adjusted for MMT
CF_{MMT} = MMT correction factor

Since the EPA emission factors include both on-cycle and off-cycle operation, this analysis will adjust both on-cycle and off-cycle exhaust emissions for the MMT effect. Also, these MMT correction factors have been developed on so-called “normal-emitting” vehicles, however the MOBILE model includes both normal emitters and high emitters. No data is available on MMT’s effects on high emitting vehicles, but if most high emitting vehicles have some catalytic activity, then we would expect MMT to have some effect even on high emitters. Therefore, for this analysis, we have assumed that MMT has the same percentage effect on both normal and high emitting vehicles. The MMT correction factors for the various groups are shown in Figures 2-4.

Figure 2
NMHC MMT Correction Factors

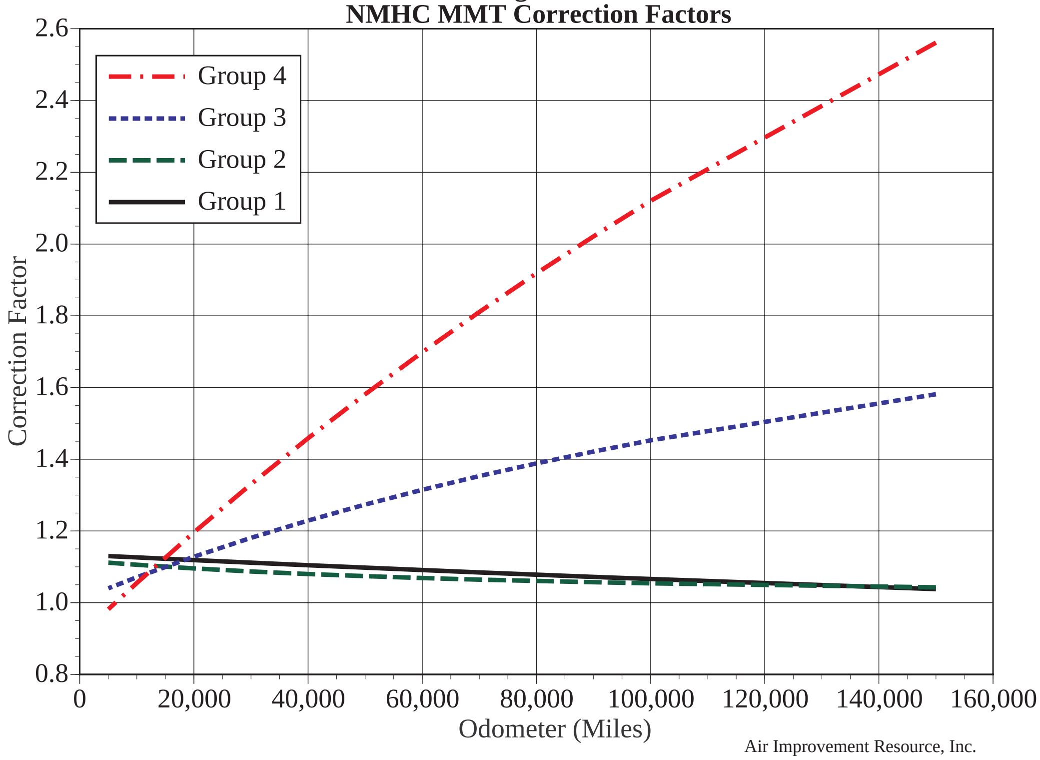


Figure 3
CO MMT Correction Factors

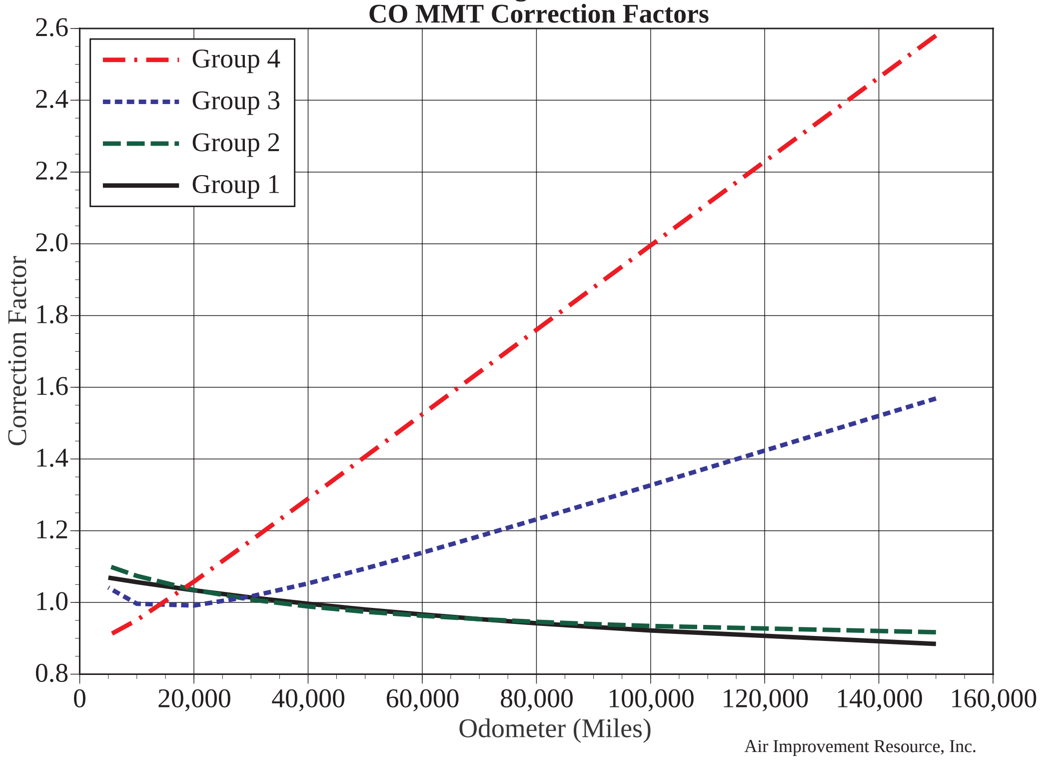
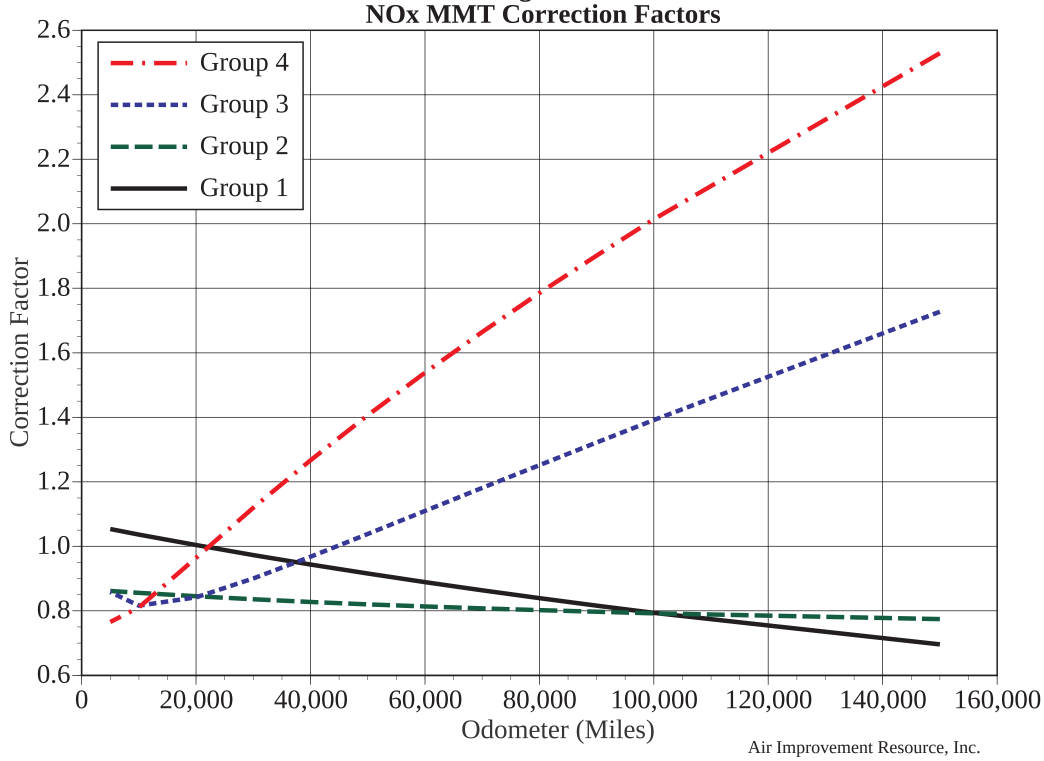


Figure 4
NOx MMT Correction Factors



The correction factors in Figures 2, 3, and 4 were used in conjunction with the MOBILE5 model to estimate emissions with MMT in Canada. No adjustments were made to pre-Tier 1 vehicles. The figures above assume 100% MMT use and also assume that the concentration of MMT used in gasoline in Canada is nearly the same as the Part 1 and Part 2 testing of 0.031 g Mn/U.S. gal. The correction factors were extrapolated beyond 150,000 miles, in the same way that EPA's emission factors are often extrapolated beyond the available data.[5] These issues are discussed further in the next section.

[5] As vehicles attain higher mileages, their proportion of activity diminishes significantly, lessening the impact of the extrapolation.

5.0 Canadian Emission Modeling

The previous section showed that the use of MMT affects exhaust HC, CO, and NOx emissions, and these effects vary dramatically for different technology vehicles, and as vehicles age. In particular, LEVs, particularly the cleanest LEVs that appear to be forerunners of Tier 2 vehicles appear to be very sensitive to the use of MMT. Because the effects vary by vehicle type and age, it is necessary to perform inventory modeling over a number of years in order to evaluate the overall effects of MMT on the vehicle fleet.

This section discusses how the emission inventory modeling was conducted. The first section discusses MMT penetration in Canada, and also discusses surveys of MMT concentration and how this concentration compares to the test data described in Section 4.0.

5.1 MMT Use in Canada

There are several sources of MMT use in Canada, as follows:

- Environment Canada's "Additives in Canadian Fuel Report, 1999"
- Ethyl Corporation Press Releases
- The auto industry biannual service station fuel survey

Environment Canada

Under the Fuels Information Regulations, No. 1 of the Canadian Environmental Protection Act, companies producing or importing more than 400 m^3 annual of liquid fuel containing an additive must submit information on the fuel additives used to Environment Canada. The information must be provided within 60 days of the first use or any change in the use of an additive.

The most recent information is available in the 1999 Report. [5] Fifteen refiners, representing 87 percent of Canadian gasoline production and distribution, reported some use of a metal antiknock and octane improver additive (MMT). The range of concentration was from 0.0 to 18 mg Mn/L, with a volume-weighted average of 6.04 mg Mn/L. In terms of g/U.S. gallons, this is 0.0 to 0.067 g Mn/gal, with an average of 0.022 g Mn/U.S. gal.

Ethyl Corporation

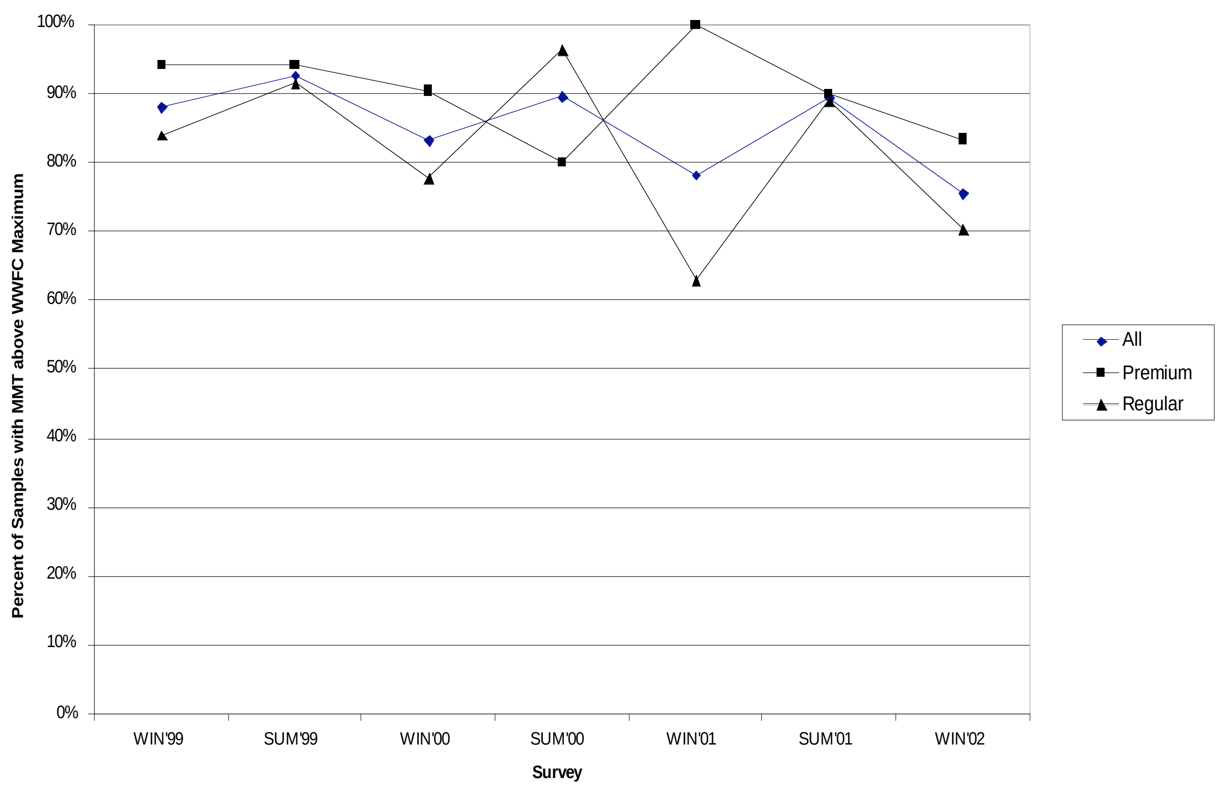
Ethyl Corporation, the manufacturer of MMT, indicated in June of 2002 that "MMT has been used continuously in Canada in over 90% of unleaded petrol for more than 23 years." [6]

Automakers' Fuel Surveys

Another source of information on MMT is a service station survey conducted by The Alliance of Automobile Manufacturers. [7] In Canada, gasoline samples are collected at service stations in six cities, twice a year (winter and summer), and sent to an independent laboratory for analysis. The cities in the survey are Vancouver, Edmonton, Toronto, Montreal, Halifax, and St John. Samples are collected for premium, regular, and mid-grade, although not all three types of gasoline are surveyed at every service station. Only major service stations are sampled – the Alliance sample does not include independent distributors. If MMT use among independent distributors is different than the major distributors, then MMT use in Canada could be significantly different than indicated by the Alliance survey.

Data on manganese penetration from the Alliance surveys since the 1998 summer survey is shown in Figure 5 and in Table 2.[6] The figure shows that for the surveys over the past few years, MMT penetration is in the 80-95% range for both regular gasoline and premium gasoline. The average over this period is 85% for all fuels, 90% for premium, and 82% for regular. This is consistent with Ethyl's claim that MMT use is around 90%.

Figure 5. Percent of Samples With MMT Alliance Surveys



[6] WWFC stands for World Wide Fuel Charter

Figure 6. Average Mn Concentrations in Gasoline Containing MMT

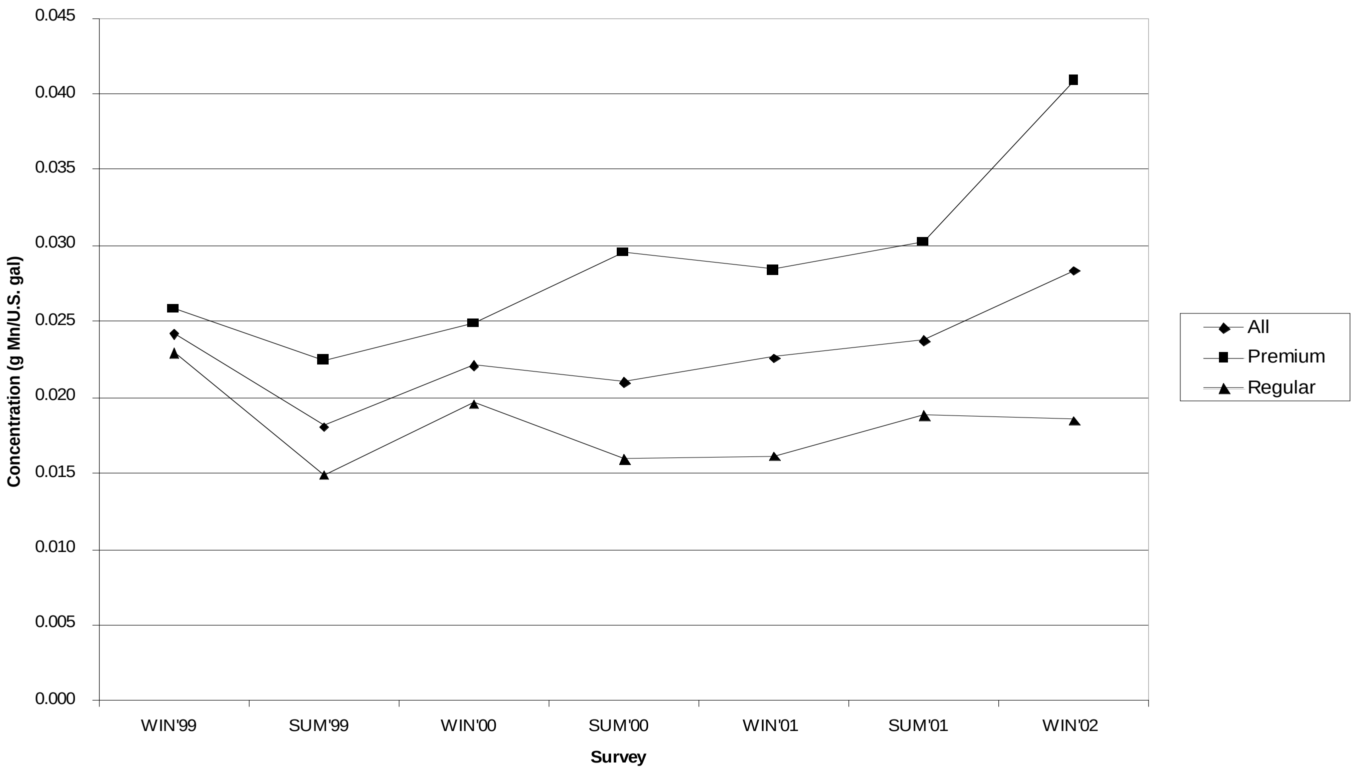


Table 2. MMT Penetration from Alliance Surveys (%)								
Fuel	Win99	Sum99	Win00	Sum00	Win01	Sum01	Win02	Average
All	88	93	83	90	78	89	76	85
Premium	94	94	90	80	100	90	83	90
Regular	84	92	78	96	63	89	70	82

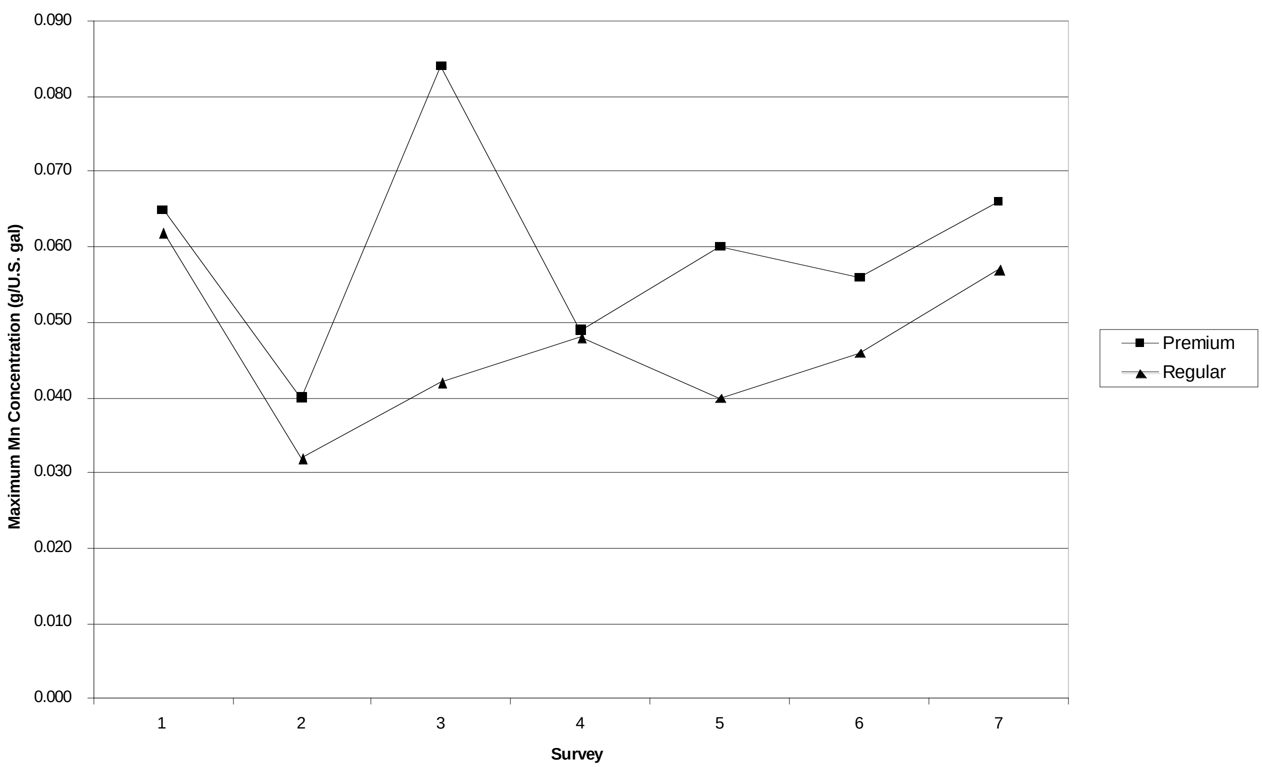
5.2 MMT Concentrations

Trends in MMT concentration for both premium and regular from the Alliance surveys are shown in Figure 6 and Table 3. There is a slight upward trend in MMT concentration for all fuels, which appears to be driven by a trend to higher MMT concentrations in premium. MMT concentrations in regular appear to have been relatively constant in the last few years. The average premium concentration for the last few years is 0.026 g Mn/U.S. gal, for regular is somewhat lower at 0.019 g Mn/U.S. gal, and for all fuels in the survey is 0.023 g Mn/U.S. gal.

Table 3. MMT Average Concentrations from Alliance Surveys (g Mn/U.S. gal)								
Fuel	Win99	Sum99	Win00	Sum00	Win01	Sum01	Win02	Average
All	0.024	0.018	0.022	0.021	0.023	0.024	0.028	0.023
Premium	0.026	0.023	0.025	0.030	0.028	0.030	0.041	0.029
Regular	0.023	0.015	0.020	0.016	0.016	0.019	0.019	0.018

Maximum concentrations from the Alliance survey are shown in Figure 7. Maximum concentrations vary between 0.030 and 0.085 g Mn/U.S. gal.

Figure 7. Maximum Mn Concentrations



5.3 Implications of Canadian MMT Penetration and MMT Concentrations on Modeling Results

It is clear that MMT use in Canada is very high – perhaps 90% or greater, depending on the extent of use among the smaller independent gasoline distributors. Therefore, it is likely that virtually all, Canadian vehicles have some MMT in the fuel tanks – thus, this analysis will assume 100% penetration of MMT in Canada.

With regard to concentrations, as discussed earlier, the Part 1 and Part 2 testing was conducted with MMT at a concentration of 0.031 g Mn/gal, which is the legal limit in the U.S. for conventional gasoline. It is also much lower than the maximum concentrations observed in Canada. According to the auto industry's survey data, regular gasoline has average about 0.019 g Mn/gal for the last few years, and premium has averaged about 0.026 g Mn/gal. The data from Environment Canada indicate an overall volume-weighted average of 0.22 g Mn/gal.

The auto manufacturers MMT testing was very comprehensive, and covered advanced technology vehicles to very high mileages. This data showed significant effects of MMT on tailpipe emissions, especially for LEVs. However, given the resources required to conduct this type of testing, there is not any data at either higher or lower MMT concentrations (than the level of 0.031 g Mn/gal). We would expect there to be some effect of MMT on emissions of advanced technologies at all concentrations of MMT. It is not known, however, if the emission effects over time are proportional to concentration. The effects could be non-linear, that is, the emission effect could increase more rapidly at higher concentrations.

Given the difference in the concentration in the test data and the Canadian average MMT level as determined by the fuel survey data, it was decided to model two cases: (1) a primary case in which the Canadian emission effects are assumed to be the same as the test data, and (2) a second case in which MMT effects are assumed to be proportional to concentration, and the effects are corrected from the 0.031 g Mn/gal level to 0.022 g Mn/gal, the level estimated by Environment Canada. The equation used to correct the MMT effects for concentration is shown below:

$$CF_{mmt,\ adj} = [1+(mmt_c/0.031)*(CF_{mmt}-1)] * mmt_f + (1-mmt_f)$$

Where:

$CF_{mmt,\ adj}$ = adjusted mmt correction factor
mmt_c = mmt concentration, in g Mn/gal (input variable)
mmt_f = mmt penetration (fraction)
0.031 = concentration in g Mn/gal of the Part 1 and Part 2 testing programs

The above equation essentially mitigates both the positive and negative effects of MMT in proportion to concentration and penetration. For this analysis, the penetration is assumed to be 1.0. Table 4 below illustrates how the equation adjusts a hypothetical unadjusted set of MMT correction factors from 0.8 to 2.0.

Table 4. MMT Correction Factors Adjusted for 0.022 g Mn/gal MMT Concentration	
Unadjusted MMT Correction Factor	Adjusted MMT Correction Factor
0.8	0.858
1.2	1.142
1.4	1.284
1.6	1.426
1.8	1.568
2.0	1.710

5.4 Mapping of Groups into Vehicle Technologies

In Section 4, MMT effects were developed for four groups of vehicles. These group effects need to be applied across different vehicle types and emission standard levels. The vehicle class and model year mapping for the groups is shown in Table 5. Vehicle class definitions used in Table 5 are as follows:

PC: passenger cars
LDT1: Light duty truck up through 3,750 lbs loaded vehicle weight (LVW)/6,000 lbs GVW
LDT2: Light duty truck greater than 3,750 lbs LVW/6,000 lbs GVW
LDT3: Heavy light duty truck up through 5,750 lbs LVW/8,500 lbs GVW
LDT4: heavy light duty truck greater than 5,750 lbs LVW/8,500 lbs GVW
MDPV: medium duty passenger vehicles above 8,500 lbs gross vehicle weight (GVW)
HDGV: heavy-duty gasoline vehicle over 8,500 lbs GVW

Table 5. MMT Correction Factor Group Mapping						
	Vehicles					
Years	PC and LDT1	LDT2	LDT3	LDT4	MDPVs	HDGV
Tier 1 Period (1995-2000)	Group 2	Group 1	Group 1	Group 1	Group 1	Group 1
NLEV Period (2001-2003)	Group 3	Group 3	Group 1	Group 1	Group 1	Group 1
Interim Tier 2 (2004-2006)	Group 4	Group 4	Group 3	Group 3	Group 1	Group 1
Final Tier 2 (2007+)	Group 4	Group 4	Group 4	Group 4	Group 4	Group 3
Group 1: Part 1 Tier 1 S10 Blazer and Part 2 Tahoe LEV Group 2: Part 1 TLEVs, Part 1 Tier 1 Corolla, Part 2 LEV Tahoe Group 3: Part 1 and Part 2 LEVs (minus the Tahoe) Group 4: Part 1 Civic and Part 2 Escort						

Tier 1 Period – PCs and LDT1s will use the Group 2 MMT correction factors, whereas all heavier trucks will use the Group 1 MMT correction factors through 2004.

NLEV Period – The NLEV standards applied to PCs, LDT1s, and LDT2s, thus, these two groups will use the Group 3 correction factors. All others will use Group 1 correction factors.

Interim Tier 2 – Interim Tier 2 standards apply in the 2004-2006 time period. PCs, LDT1s, and LDT2s will use the Group 4 correction factors, LDT3s and LDT4s will use the Group 3 correction factors, and MDPVs and HDGVs will continue to use the Group 1 correction factors.

Final Tier 2 – All vehicles except HDGVs will use the Group 4 correction factors except HDGVs, which will use the Group 3 correction factors.

The MOBILE5 model contains 3 gasoline truck classes instead of the six truck classifications shown in Table 5. The 3 gasoline trucks classes in MOBILE5 are LDT1s (0-6,000 lbs GVW), LDT2s (6,500-8,500 lbs GVW), and HDGVs (8,500+ lbs GVW). The MOBILE5 nomenclature (LDT1, LDT2, etc.) bears little resemblance to the newer nomenclature used in Table 5 and used by the EPA in its Tier 2 rule. Thus, the correction factors above must be weighted together with travel fractions into the MOBILE5 categories. The weighting factors used in this analysis are shown in Table 6. These were obtained for the year 2020 from the EPA Tier 2 analysis. [8]

Table 6. LDT Truck VKT Fractions Used to Combine LDTs MOBILE5 Model

MOBILE Truck Class	Regulatory Vehicle Class	Regulatory Class Fraction
LDT1	LDT1	0.24
	LDT2	0.76
LDT2	LDT3	0.68
	LDT4	0.32
HDGV	MDPV	0.18
	Remainder	0.82

5.5 Results

Inventory analyses were conducted for two cases, as follows:

Base MMT Case: Uses Group 1 through Group 4 correction factors, 100% penetration of MMT at 0.031 g Mn/gal.

MMT Concentration Case: Uses Group 1 through Group 4 correction factors, 100% penetration of MMT, and adjusts MMT effects for Canadian average concentration of 0.022 g Mn/gal, as determined in Environment Canada 1999 Additives report.

These cases are shown further in Table 7.

Table 7. Emission Inventory Case		
Case	MMT Penetration	Correction Factors Adjusted for Concentration?
Base MMT	100%	No
MMT Concentration	100%	Yes

In each comparison, VOC (exhaust and evaporative), CO, and NOx results are shown from 1995 through 2020 for all gasoline vehicles except motorcycles in Canada. Each plot shows a “with MMT” line and a “without MMT” line. The without MMT line reflects the same inventories as in the December 21, 2001 AIR report to Environment Canada. Actual inventories for all cases are shown in Attachment 2.

5.5.1 Base MMT Case Compared to No MMT

Inventory results for the Base Case and for No MMT are shown in Table 8 and Figures 8, 9, and 10. Table 8 shows that VOC and CO inventories are 8%, 11%, higher in 2010 with MMT than without. NOx inventories are 4% lower due to MMT. In 2020, however, VOC, CO, and NOx are 36%, 75%, and 65% higher due to the use of MMT. The figures are shaded in the 1995-2005 time period to indicate that the effects in this timeframe are somewhat dependent on the MMT response of pre-Tier 1 vehicles, and these vehicles were not modeled in this study. Pre-1995 Tier 1 vehicles contribute only 14% of the vehicle kilometers traveled in 2005, and this value continues to decline after 2005. The figures show that VOC emissions with MMT are higher than without MMT starting in 2003-2004, and are much higher in 2020 due to the increased sensitivity of Tier 2 vehicles. CO inventories are somewhat lower with MMT until about 2007, and then become much higher. NOx inventories are lower with MMT until about 2010, when they become much higher.

Table 8. Base Case Emission Inventories (Gasoline Vehicles – annual tonnes)				
Year	Case	VOC	CO	NOx
2010	Base MMT	162,732	1,682,027	147,849
	No MMT	150,430	1,519,655	154,719
	Difference	12,302	162,372	6,870
	% Difference	8%	11%	-4%
2020	Base MMT	183,475	2,485,855	119,400
	No MMT	134,932	1,423,428	72,322
	Difference	48,543	1,062,427	47,078
	% Difference	36%	75%	65%

Figure 8
LDGV+LDVT1/2+HDGV Total VOC Emissions-Canada

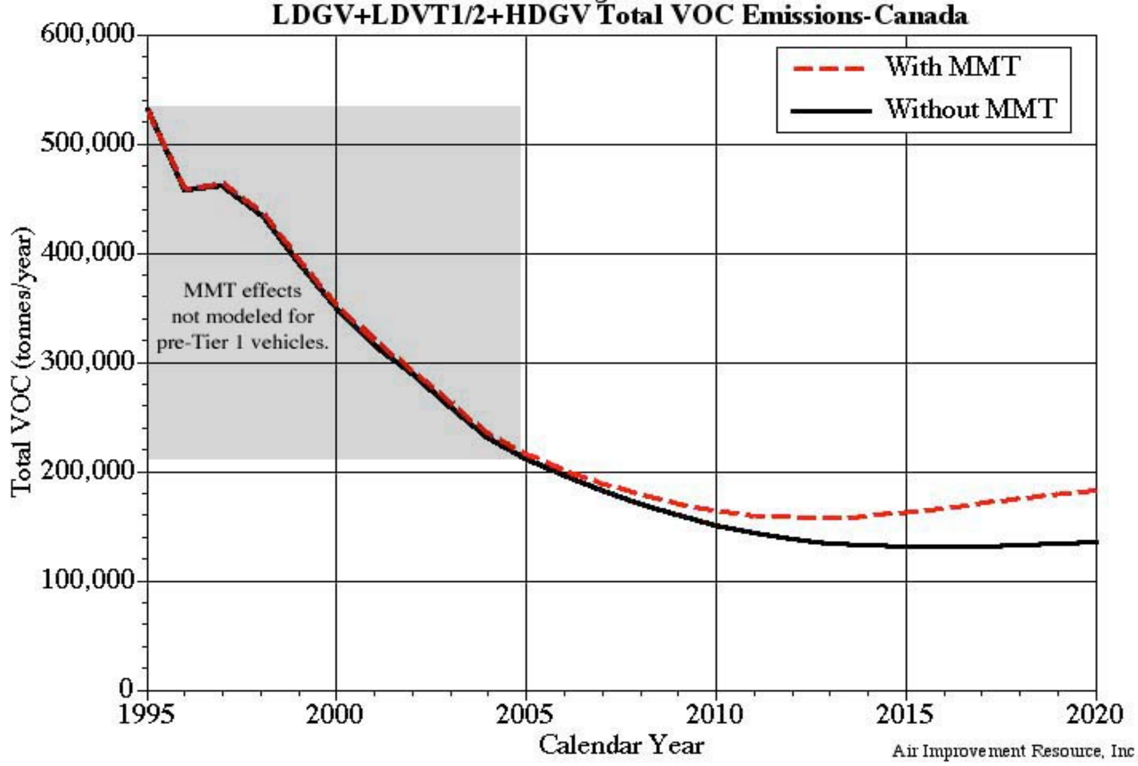
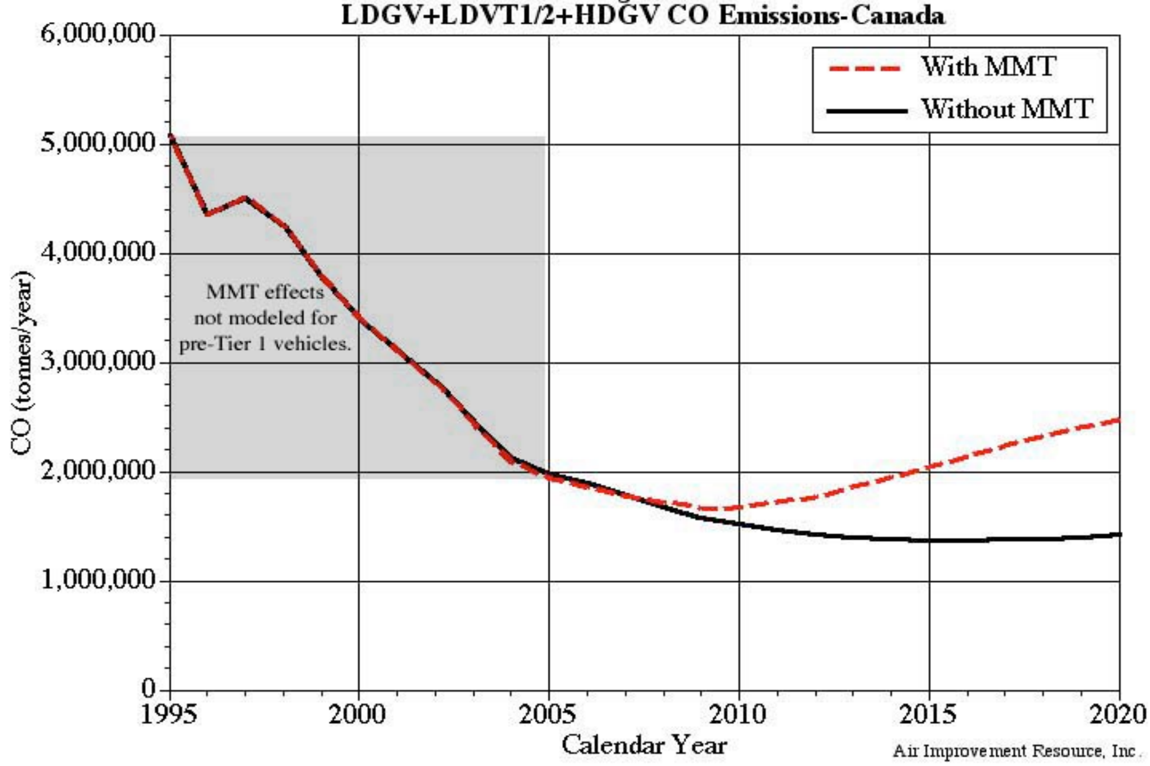
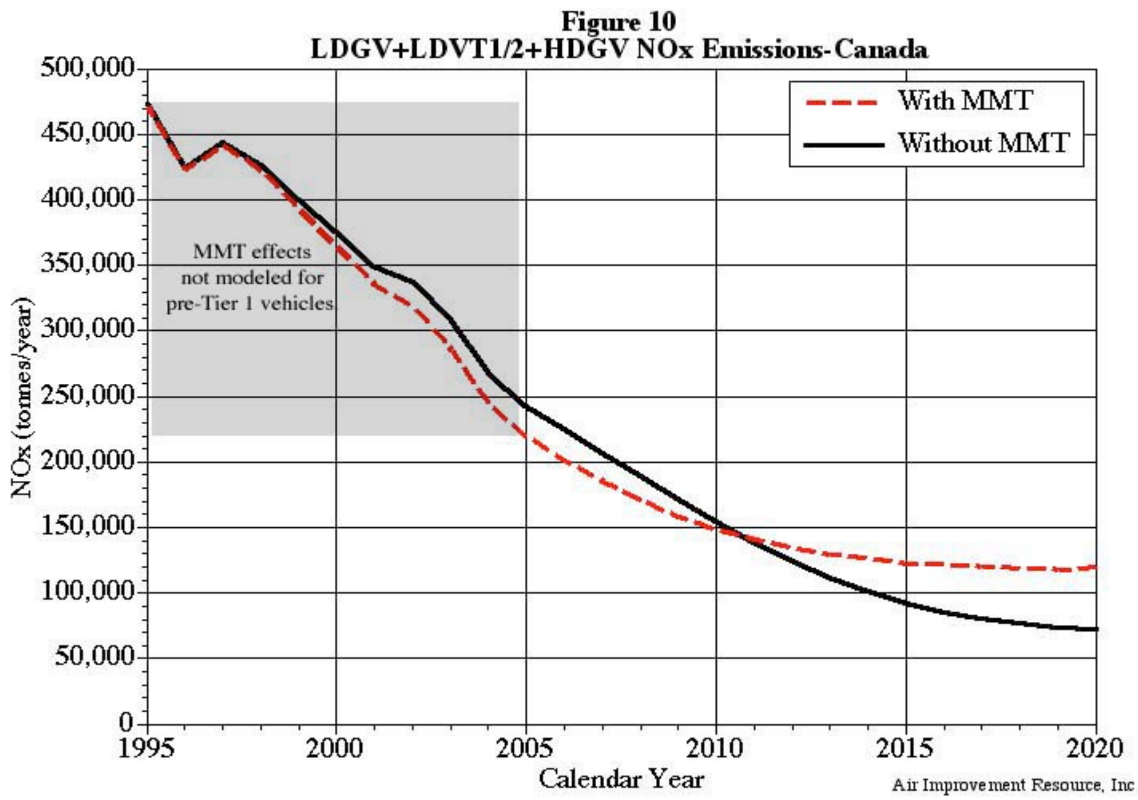


Figure 9
LDGV+LDVT1/2+HDGV CO Emissions-Canada





5.5.2 MMT Concentration Case Compared to No MMT

In this case, MMT effects for Tier 2 vehicles are based on the Group 4 effects, and MMT penetration is 100% but the MMT effects have been adjusted for concentration effects from 0.031 g Mn/gal to 0.022 g Mn/gal. Results are shown in Table 9 and Figures 11, 12 and 13. Table 9 shows that VOC and CO inventories are 6% and 8% higher in 2010 with MMT. NOx inventories are 4% lower with MMT. In 2020, however, VOC, CO, and NOx inventories are 26%, 35%, and 45% higher with MMT.

Table 9. MMT Concentration Case (Gasoline Vehicles – annual tonnes)

Year	Case	HC	CO	NOx
2010	MMT	159,161	1,634,885	149,259
	No MMT	150,430	1,519,655	154,719
	Difference	8,731	115,230	-5,460
	% Difference	6%	8%	-4%
2020	MMT	169,382	2,177,412	105,197
	No MMT	134,932	1,423,428	72,322
	Difference	34,450	753,984	32,875
	% Difference	26%	35%	45%

Figure 11
LDGV+LDVT1/2+HDGV Total VOC Emissions-Canada
Group 4 Effects = Group 3

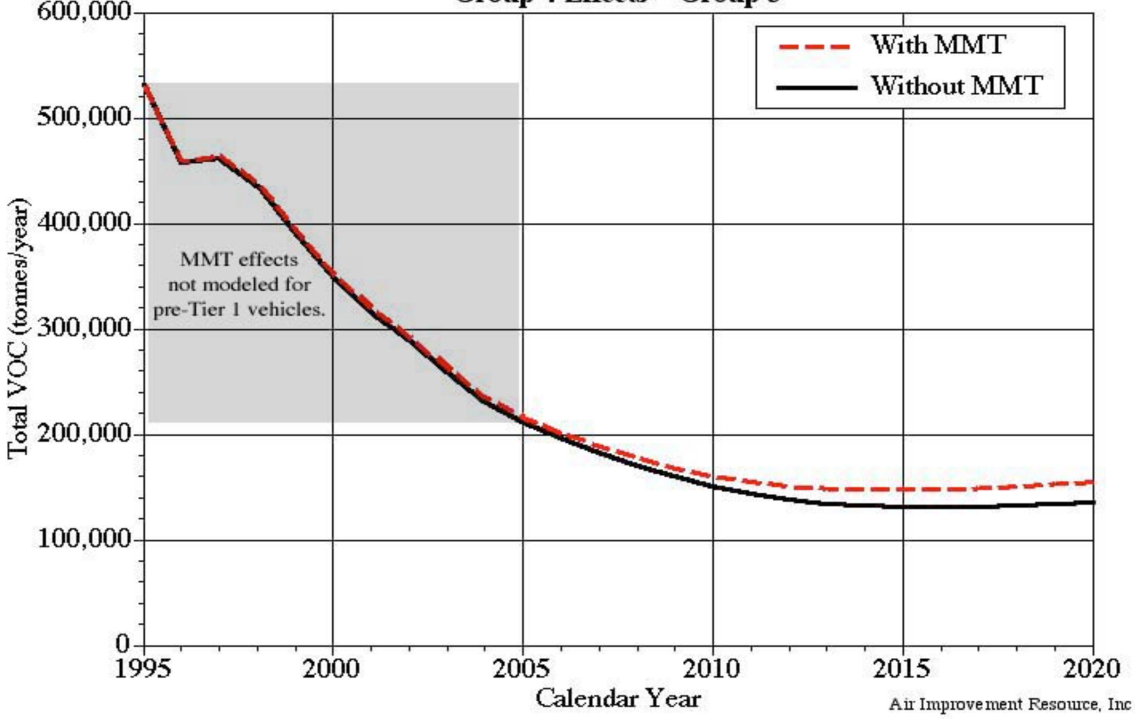
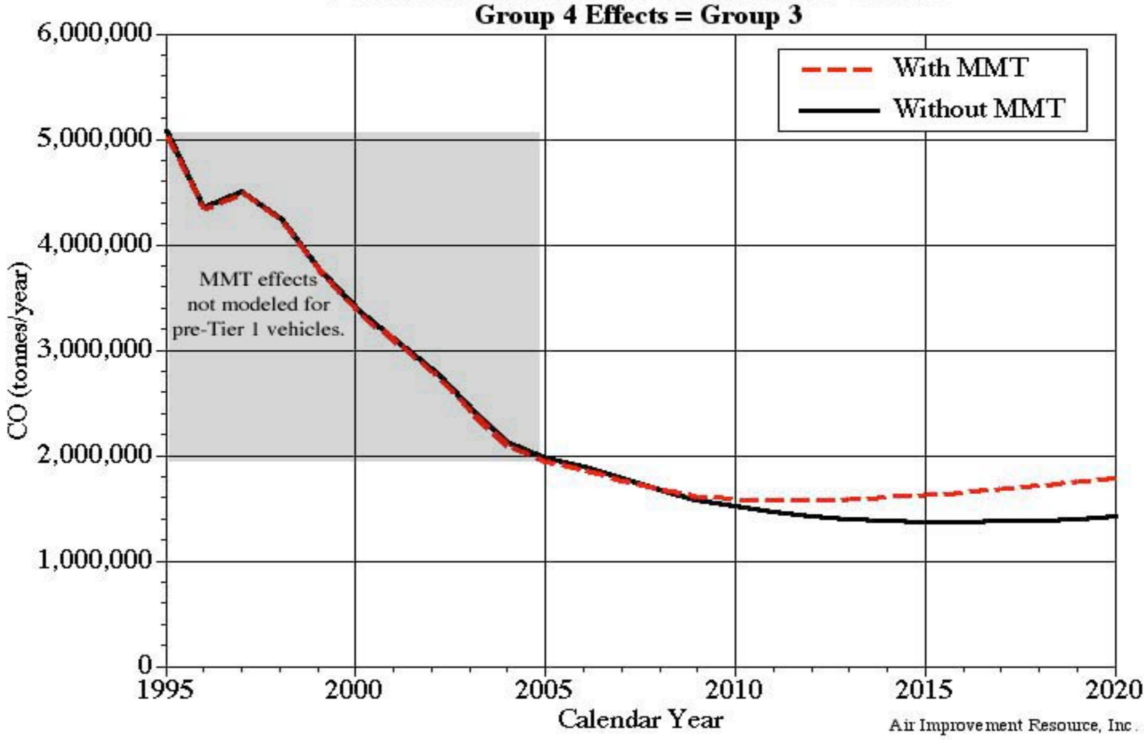
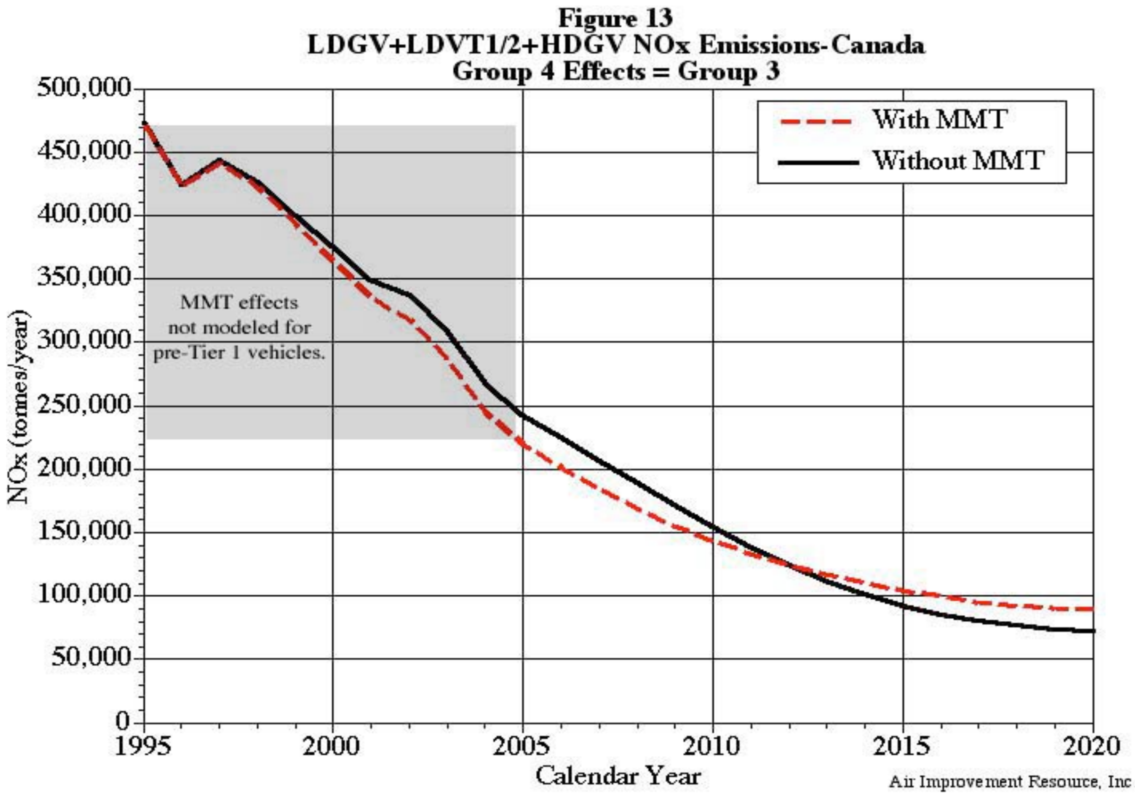


Figure 12
LDGV+LDVT1/2+HDGV CO Emissions-Canada
Group 4 Effects = Group 3





5.6 Discussion of Results

A summary of the percent differences in 2010 and 2020 for the Base MMT Case and the MMT Concentration Case is shown in Table 10 below.

Table 10. Percent Changes in Inventories Due to MMT
(positive indicates MMT has higher inventory, negative indicates MMT lower)

Year	Case	VOC + NOx	VOC	CO	NOx
2010	Base MMT	2%	8%	11%	-4%
	MMT Concentration	1%	6%	8%	-4%
2020	Base MMT	46%	36%	75%	65%
	MMT Concentration	32%	26%	35%	45%

The table shows that for both the Base MMT and MMT Concentration cases, in 2010 and 2020, VOC + NOx are higher with MMT that without.

For the individual pollutants, VOC and CO are higher with MMT than without, but NOx is lower in 2010. The NOx effect is primarily due to MMT's effects on Tier 1 vehicles. This analysis did not examine the effects for pre-Tier 1 vehicles. As low emission vehicles and Tier 2 vehicles are introduced, however, MMT increases emission of all three pollutants, regardless of which case is examined.

This analysis indicates that if MMT use is not discontinued before widespread introduction of NLEVs and Tier 2 vehicles (NLEV introduction started in 2001), VOC, CO, and NOx emissions from gasoline motor vehicles in Canada in the future may be significantly higher than those estimated for Environment Canada for air quality planning purposes.

References

1. "The Impact of MMT on Vehicle Emissions and Durability – Part 1", A Joint Study by the Alliance of Automobile Manufacturers, The Association of International Automobile Manufacturers and the Canadian Vehicle Manufacturers Association, July 29, 2002.

2. "The Impact of MMT on Vehicle Emissions and Durability – Part 2", A Joint Study by the Alliance of Automobile Manufacturers, The Association of International Automobile Manufacturers and the Canadian Vehicle Manufacturers Association, July 29,2002

3. "Updated Estimate Of Canadian On-Road Vehicle Emissions for the Years 1995-2020", Revised 18 December 2001, AIR and SENES for Environment Canada.

4. "Impacts Associated With the Use of MMT as an Octane Enhancing Additive in Unleaded Gasolines – A Critical Review", Sierra Research, July 2002.

5. "Additives in Canadian Fuels 1999", Environment Canada, March 2000.

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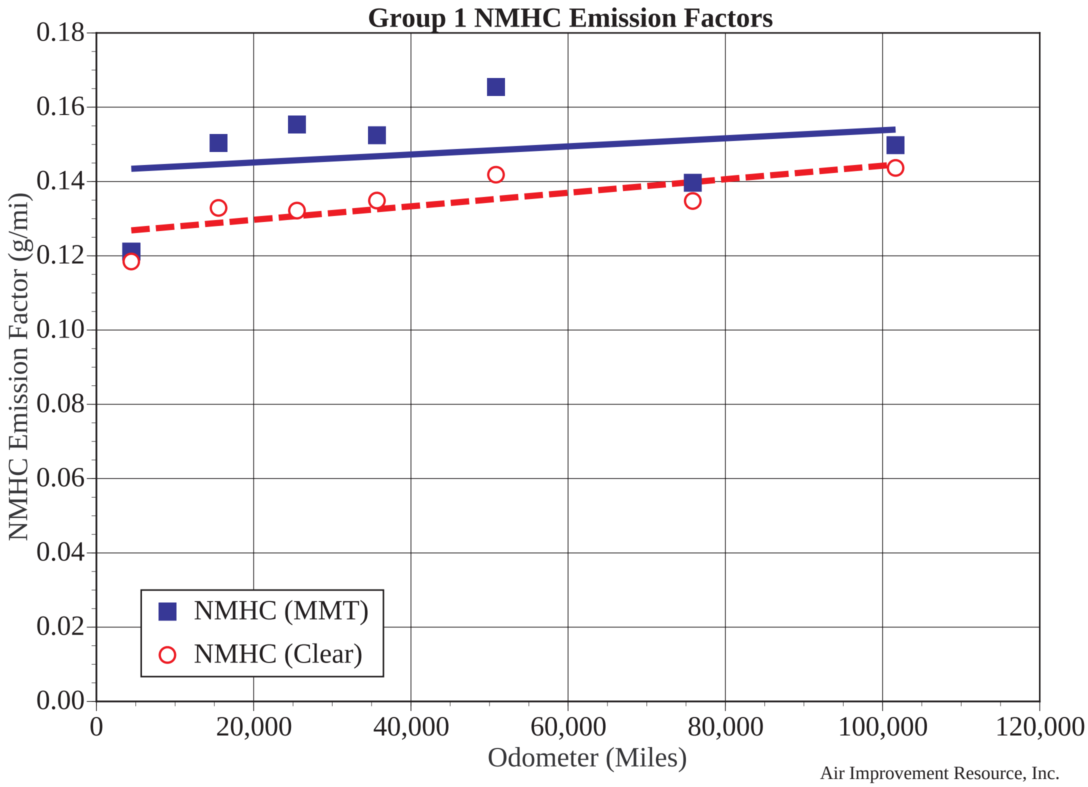
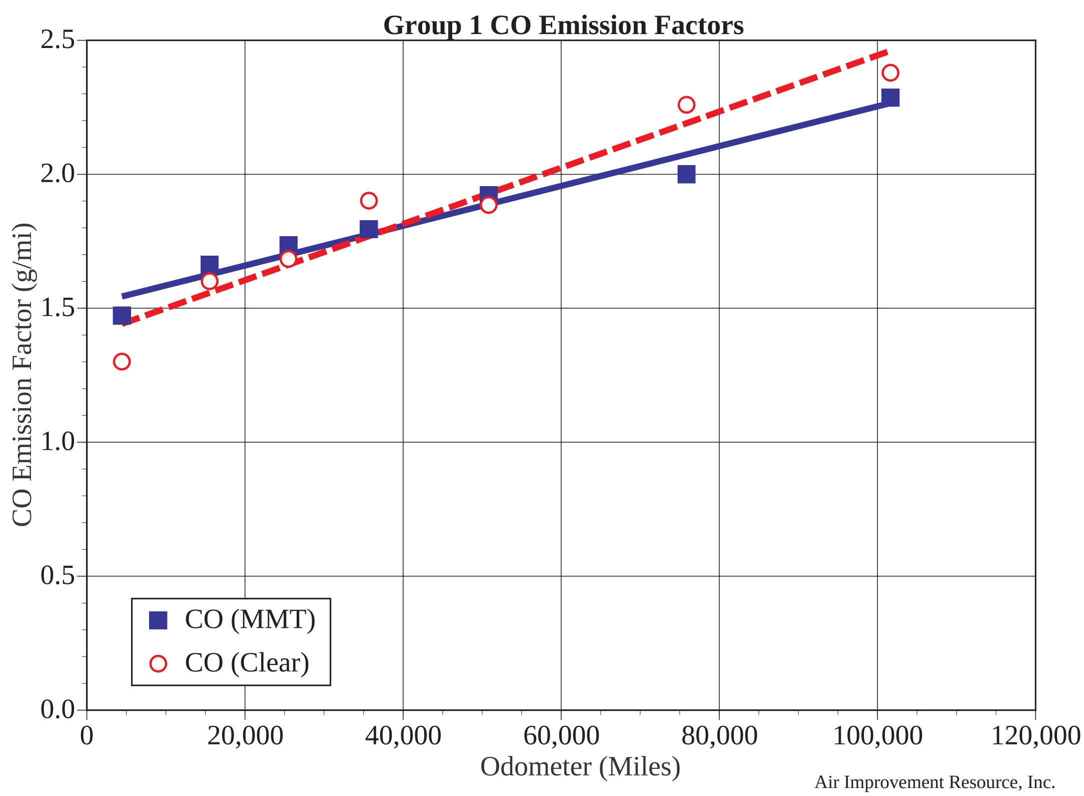
7. North American Fuel Surveys, 1999-2002, Alliance of Automobile Manufacturers.

8. "Development of Light-Duty Emission Inventory Estimates in the Notice of Proposed Rulemaking for Tier 2 and Sulfur Standards", EPA420-R-99-005, March 1999.

Attachment 1

Group 1-4 Analysis With All Vehicles


Group 1 NMHC Emission Factors
NMHC Emission Factor (g/mi)
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0
20,000
40,000
60,000
80,000
100,000
120,000
Odometer (Miles)
NMHC (MMT)
NMHC (Clear)
Air Improvement Resource, Inc.


Group 1 CO Emission Factors
CO Emission Factor (g/mi)
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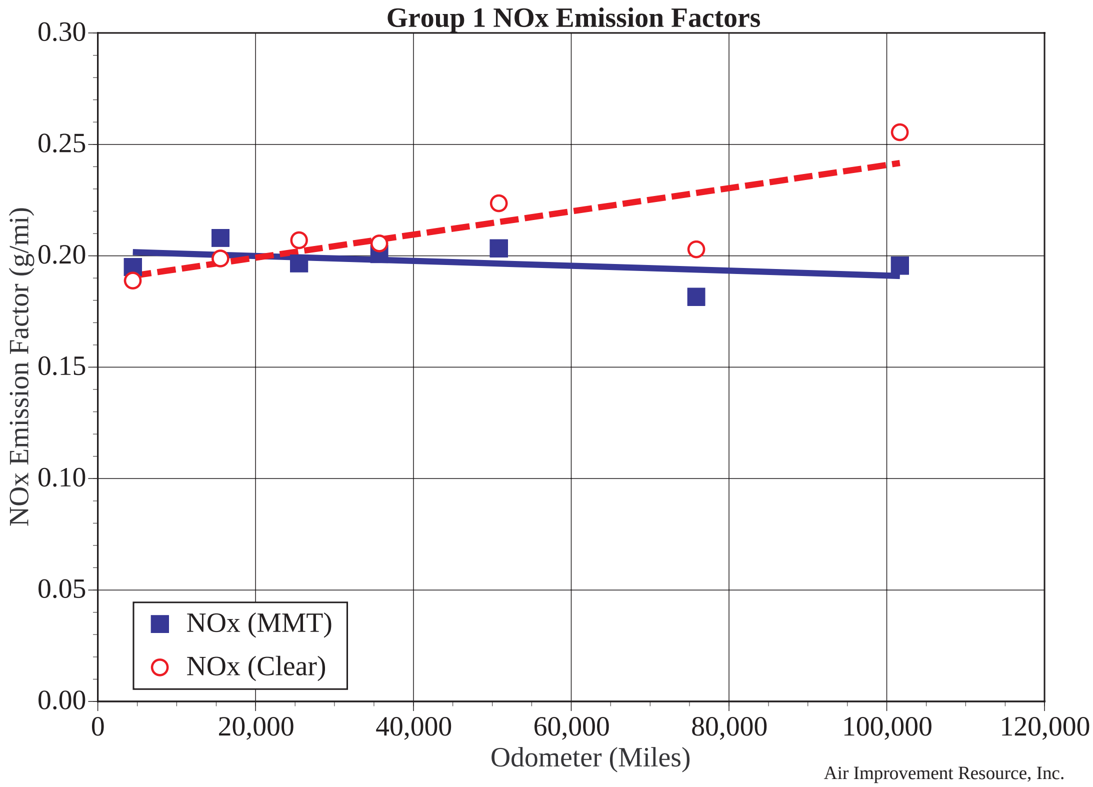
2.0
1.5
1.0
0.5
0.0
0
20,000
40,000
60,000
80,000
100,000
120,000
Odometer (Miles)
CO (MMT)
CO (Clear)
Air Improvement Resource, Inc.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NOx Emission Factor (g/mi)
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0.20
0.15
0.10
0.05
0.00
0
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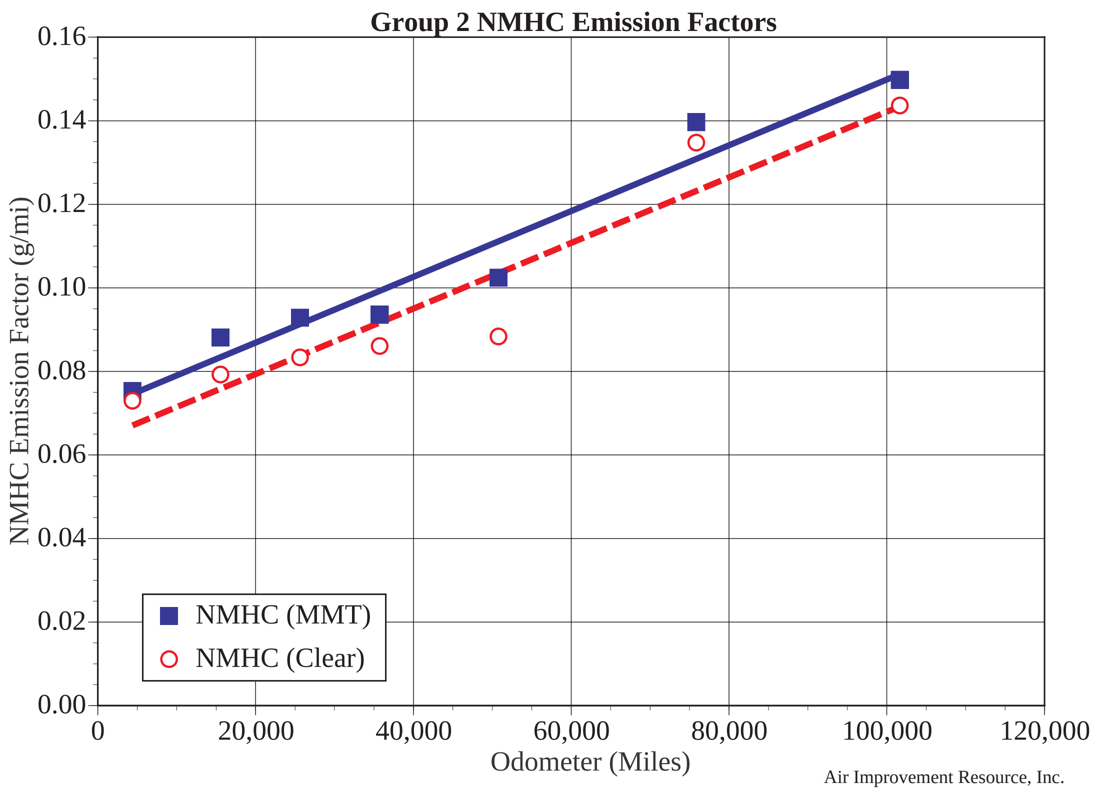
40,000
60,000
80,000
100,000
120,000
Odometer (Miles)
NOx (MMT)
NOx (Clear)
Air Improvement Resource, Inc.


Group 2 NMHC Emission Factors
NMHC Emission Factor (g/mi)
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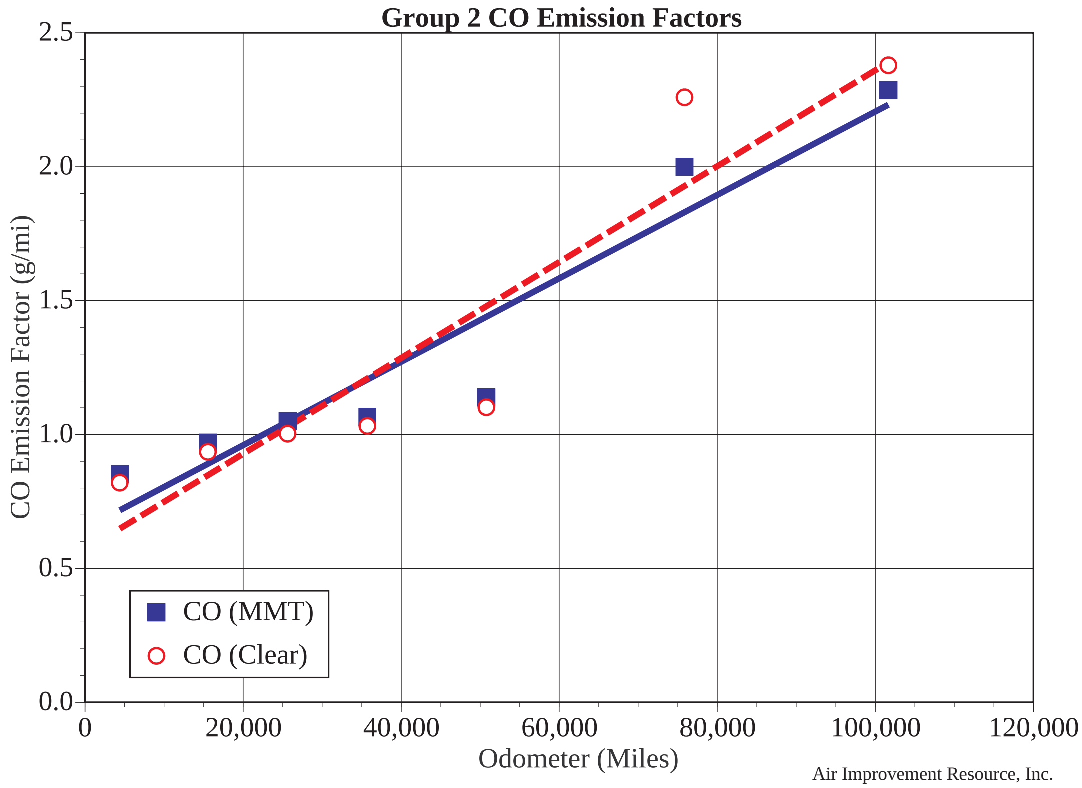
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0
20,000
40,000
60,000
80,000
100,000
120,000
Odometer (Miles)
NMHC (MMT)
NMHC (Clear)
Air Improvement Resource, Inc.


Group 2 CO Emission Factors
CO Emission Factor (g/mi)
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2.0
1.5
1.0
0.5
0.0
0
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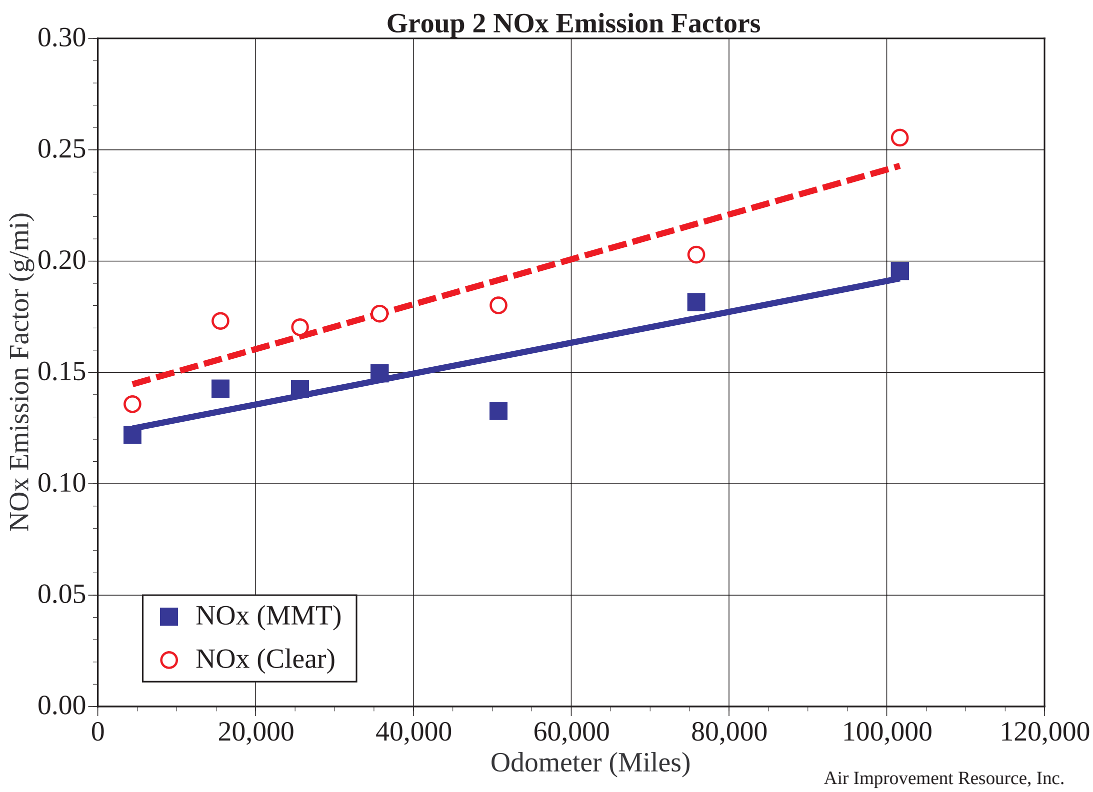
60,000
80,000
100,000
120,000
Odometer (Miles)
CO (MMT)
CO (Clear)
Air Improvement Resource, Inc.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NOx Emission Factor (g/mi)
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0.20
0.15
0.10
0.05
0.00
0
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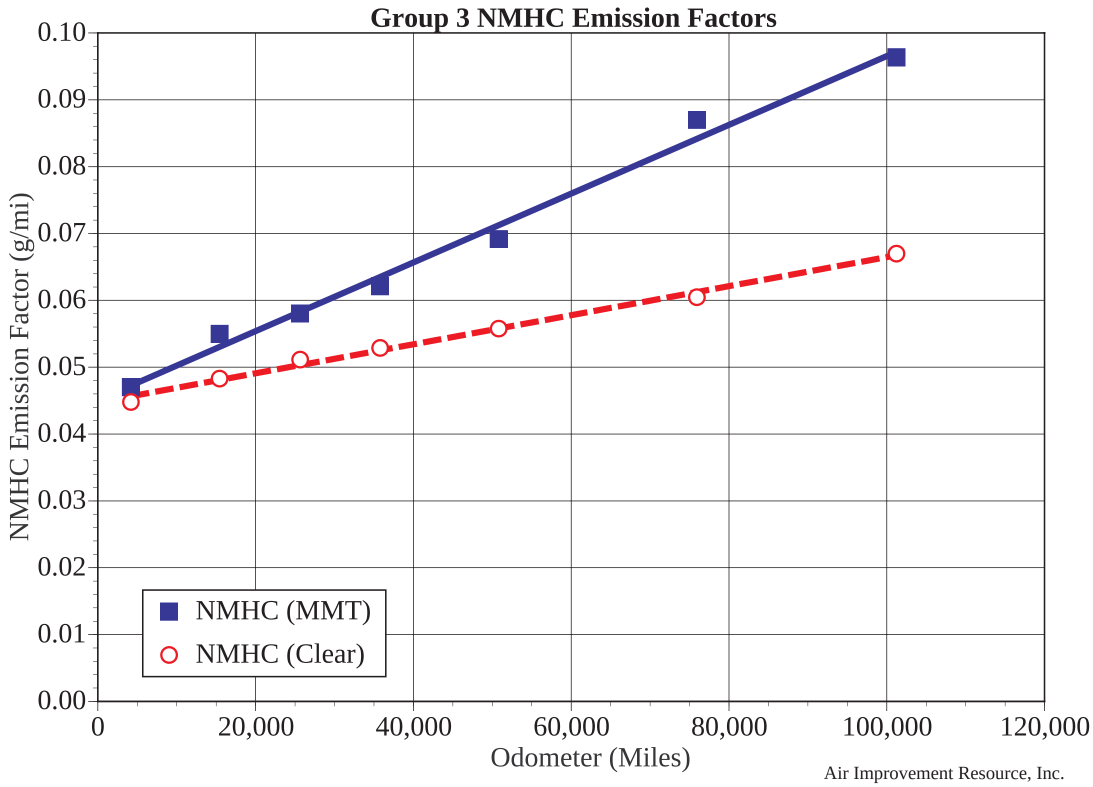
40,000
60,000
80,000
100,000
120,000
Odometer (Miles)
NOx (MMT)
NOx (Clear)
Air Improvement Resource, Inc.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NMHC Emission Factor (g/mi)
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0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
NMHC (MMT)
NMHC (Clear)
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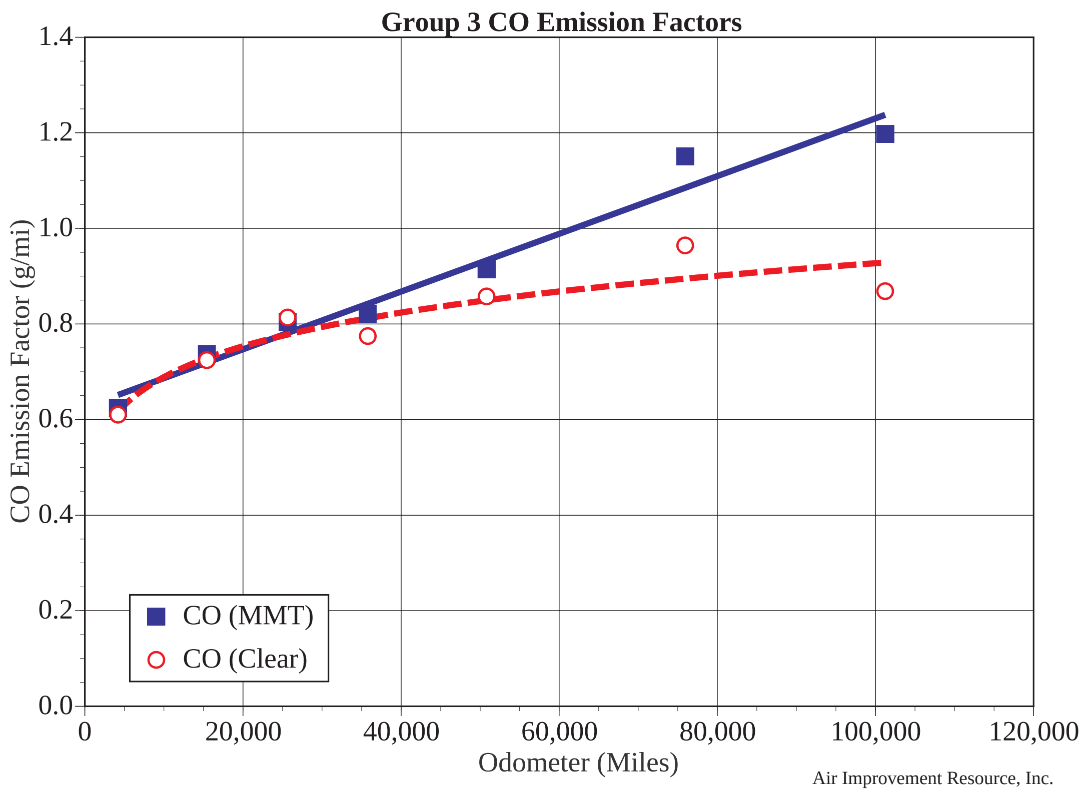
20,000
40,000
60,000
80,000
100,000
120,000
Odometer (Miles)
Air Improvement Resource, Inc.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CO Emission Factor (g/mi)
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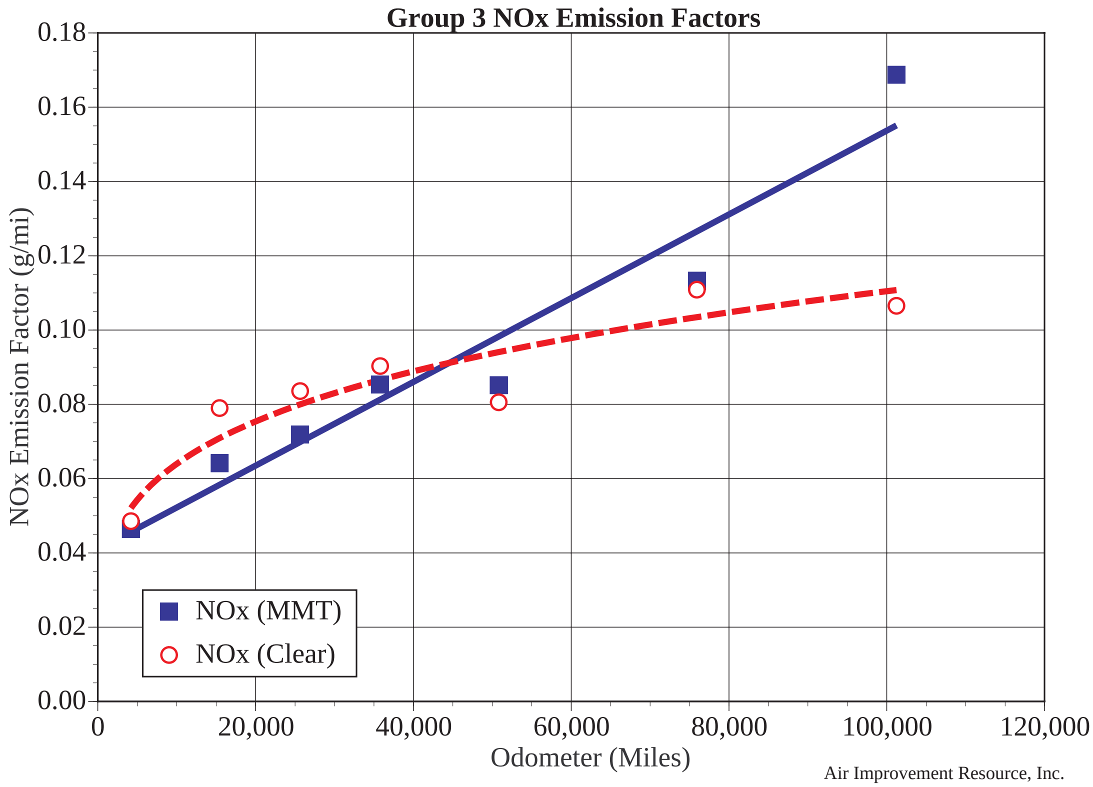
1.2
1.0
0.8
0.6
0.4
0.2
0.0
CO (MMT)
CO (Clear)
0
20,000
40,000
60,000
80,000
100,000
120,000
Odometer (Miles)
Air Improvement Resource, Inc.


Group 3 NOx Emission Factors
NOx Emission Factor (g/mi)
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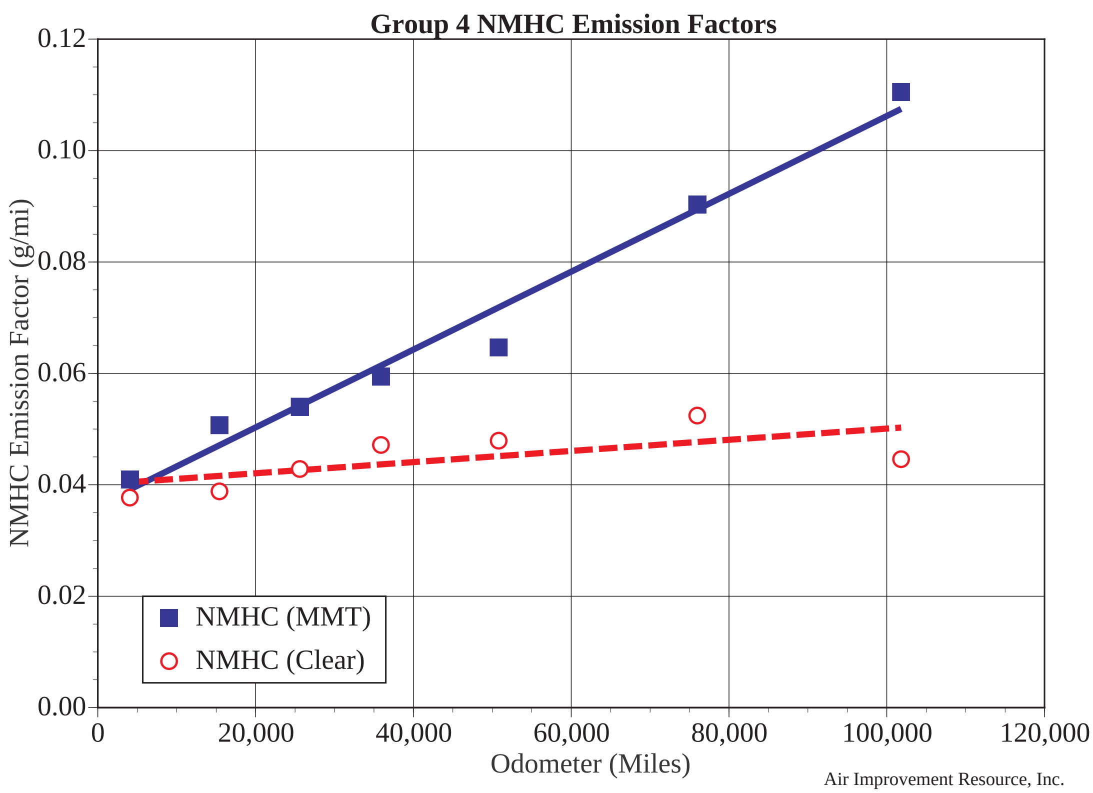
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0
20,000
40,000
60,000
80,000
100,000
120,000
Odometer (Miles)
NOx (MMT)
NOx (Clear)
Air Improvement Resource, Inc.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NMHC Emission Factor (g/mi)
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0.06
0.04
0.02
0.00
0
20,000
40,000
60,000
80,000
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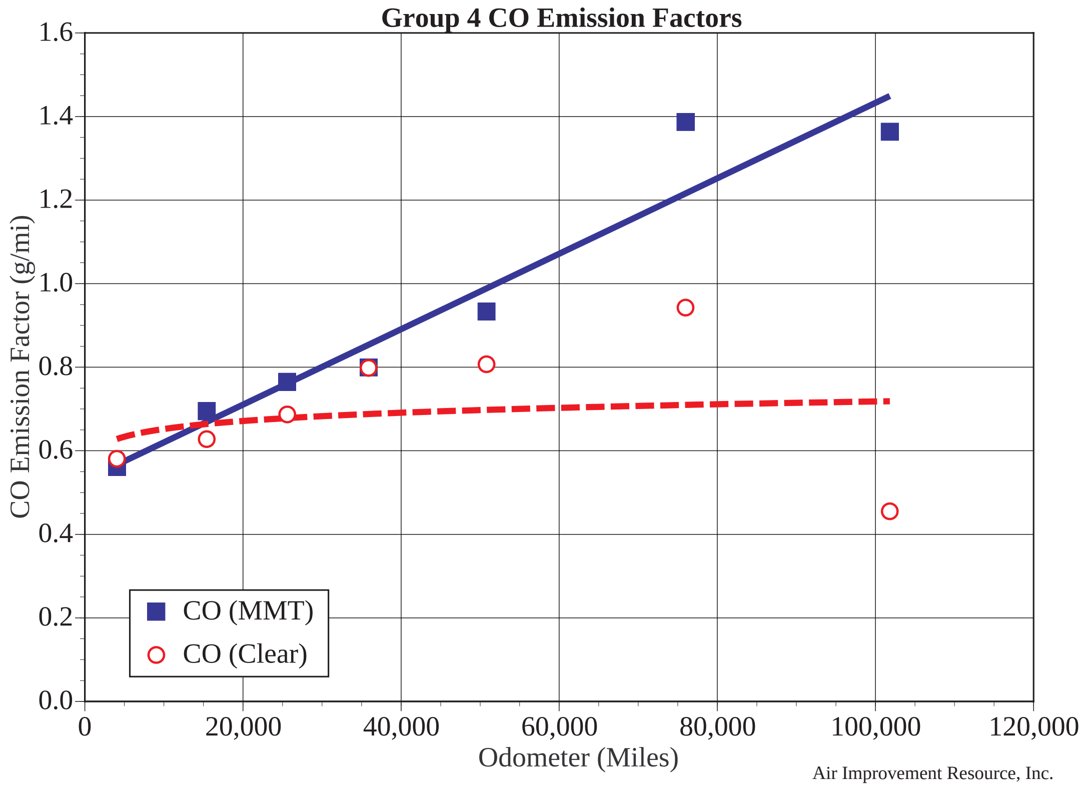
120,000
Odometer (Miles)
NMHC (MMT)
NMHC (Clear)
Air Improvement Resource, Inc.


Group 4 CO Emission Factors
CO Emission Factor (g/mi)
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1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
20,000
40,000
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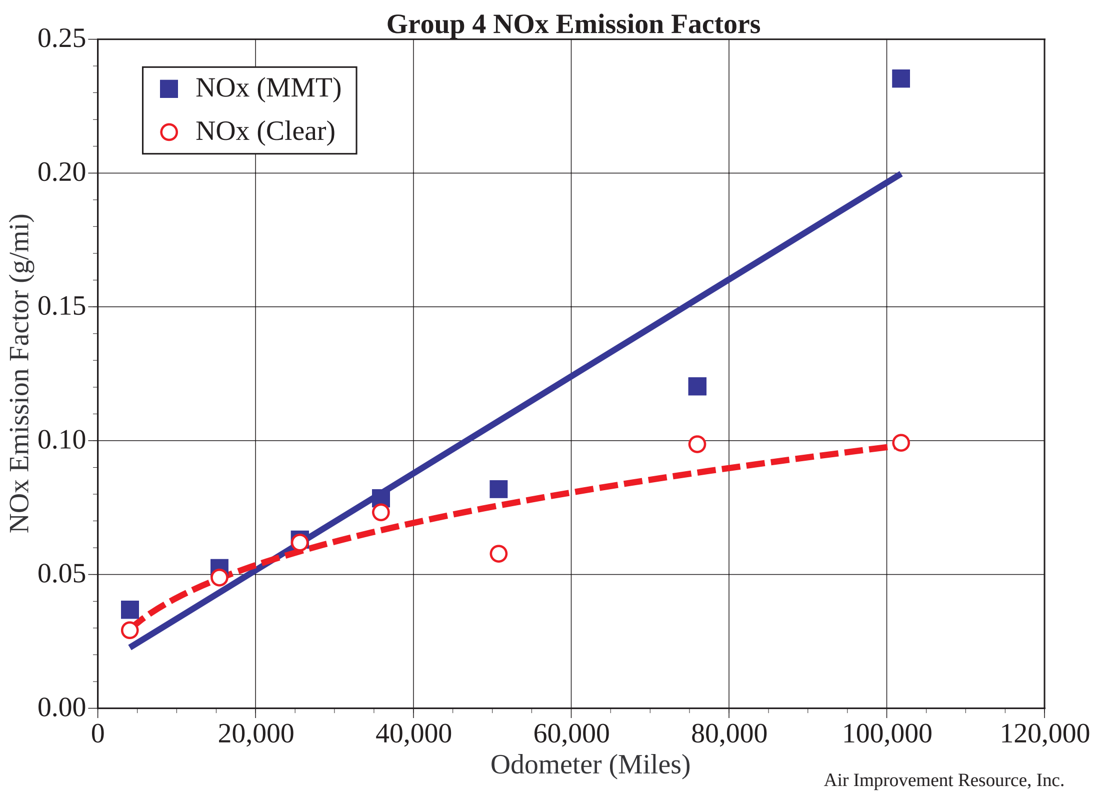
100,000
120,000
Odometer (Miles)
CO (MMT)
CO (Clear)
Air Improvement Resource, Inc.


Group 4 NOx Emission Factors
NOx Emission Factor (g/mi)
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0.15
0.10
0.05
0.00
0
20,000
40,000
60,000
80,000
100,000
120,000
Odometer (Miles)
NOx (MMT)
NOx (Clear)
Air Improvement Resource, Inc.

Attachment 2

Gasoline Vehicle Emission Inventories For All Cases

1 – No MMT
2 – MMT (100% Penetration, 0.031 g Mn/gal Concentration)
3 – MMT (100% Penetration, Concentration Adjusted to 0.022 g Mn/gal)

Canadian Emission Inventories – No MMT										
		Annual Tonnes/Year								
Pollutant	CY	LDGV	LDGT1	LDGT2	HDGV	LDDV	LDDT	HDDV	MC	Total
Total VOC	1995	350,680	97,439	71,357	11,870	655	3,381	45,110	1,585	582,079
	1996	287,650	86,902	71,270	11,689	632	3,301	44,645	1,553	507,643
	1997	293,991	90,613	65,316	12,701	644	3,567	46,001	1,493	514,325
	1998	278,709	83,565	62,164	11,737	639	2,992	41,811	1,485	483,102
	1999	242,983	76,893	59,039	11,100	600	2,810	37,580	1,477	432,482
	2000	212,055	70,836	55,838	10,583	564	2,687	34,633	1,477	388,674
	2001	187,481	65,789	53,200	9,849	533	2,593	31,597	1,477	352,519
	2002	168,392	60,745	51,373	9,013	507	2,590	29,234	1,477	323,332
	2003	149,370	54,440	46,838	8,328	504	2,601	27,207	1,477	290,766
	2004	131,915	48,250	43,483	7,887	489	2,640	25,102	1,477	261,245
	2005	120,236	44,009	40,388	7,634	495	2,664	22,893	1,477	239,796
	2006	110,448	41,014	37,621	7,431	494	2,720	20,613	1,477	221,819
	2007	101,783	38,371	35,319	7,155	495	2,763	18,647	1,477	206,011
	2008	94,662	36,099	33,172	6,861	505	2,814	16,299	1,477	191,889
	2009	88,653	34,152	31,179	6,361	516	2,853	14,257	1,477	179,448
	2010	83,003	32,420	28,794	6,213	527	2,896	12,479	1,477	167,810
	2011	79,497	31,086	27,111	6,080	543	2,934	11,511	1,477	160,240
	2012	76,282	30,161	25,515	5,914	557	2,979	10,599	1,477	153,483
	2013	74,852	29,640	24,376	5,866	571	3,014	9,743	1,477	149,539
	2014	74,112	29,373	23,285	5,789	585	3,051	9,052	1,477	146,725
	2015	73,939	29,340	22,478	5,723	599	3,078	8,288	1,477	144,922
	2016	74,190	29,474	21,808	5,696	612	3,122	7,706	1,477	144,086
	2017	74,755	29,804	21,385	5,665	625	3,173	7,163	1,477	144,047
	2018	75,437	30,272	21,038	5,635	638	3,228	6,748	1,477	144,474
	2019	76,371	30,868	20,786	5,621	652	3,285	6,378	1,477	145,439
	2020	77,480	31,537	20,287	5,628	665	3,345	6,051	1,477	146,469
CO	1995	3,352,131	1,001,402	562,017	159,744	1,470	6,035	209,690	10,361	5,302,851
	1996	2,775,296	869,788	550,432	154,717	1,433	6,104	211,856	10,361	4,579,988
	1997	2,891,642	922,633	529,673	169,928	1,448	6,612	236,347	10,361	4,768,644
	1998	2,747,923	838,013	513,510	156,877	1,462	5,730	236,652	10,300	4,510,466
	1999	2,395,283	746,474	488,077	144,403	1,412	5,653	241,623	10,300	4,033,224
	2000	2,135,908	676,500	458,648	134,697	1,362	5,619	246,683	10,300	3,669,718
	2001	1,924,843	623,738	443,646	122,295	1,317	5,614	247,153	10,300	3,378,906
	2002	1,735,579	573,667	414,297	106,979	1,288	5,686	247,851	10,300	3,095,649
	2003	1,488,264	499,383	367,306	93,896	1,289	5,764	249,195	10,300	2,715,398
	2004	1,288,580	431,964	325,766	86,600	1,282	5,859	250,978	10,300	2,401,329
	2005	1,199,639	393,794	309,233	83,163	1,302	5,924	236,595	10,300	2,239,951
	2006	1,139,032	370,268	302,584	80,440	1,310	6,019	219,511	10,300	2,129,464
	2007	1,075,037	349,618	284,171	77,301	1,319	6,096	196,140	10,300	1,999,984
	2008	1,007,909	332,367	267,772	74,148	1,343	6,174	174,917	10,300	1,874,930
	2009	966,034	316,368	234,873	63,832	1,366	6,235	155,373	10,300	1,754,382
	2010	926,178	305,958	225,032	62,487	1,392	6,297	137,629	10,300	1,675,274
	2011	896,115	298,217	214,637	60,924	1,425	6,361	123,370	10,300	1,611,349
	2012	869,042	293,228	202,135	61,906	1,458	6,431	107,334	10,300	1,551,835
	2013	850,818	290,448	195,207	62,937	1,491	6,495	92,758	10,300	1,510,453
	2014	836,541	288,916	189,705	64,059	1,523	6,562	77,647	10,300	1,475,254
	2015	830,779	289,330	186,044	65,227	1,557	6,622	64,013	10,300	1,453,872
	2016	829,785	291,066	182,517	66,466	1,589	6,700	50,739	10,300	1,439,161
	2017	833,696	294,512	180,942	67,759	1,622	6,783	39,517	10,300	1,435,131
	2018	839,233	299,039	178,771	69,145	1,655	6,872	31,632	10,300	1,436,647
	2019	848,897	304,993	178,969	70,572	1,689	6,966	27,361	10,300	1,449,749
	2020	860,746	311,735	178,886	72,061	1,723	7,064	23,402	10,300	1,465,916
NOx	1995	313,000	83,883	56,921	18,594	1,714	7,169	493,770	567	975,617
	1996	270,303	78,491	56,909	19,041	1,611	7,100	498,420	567	932,442
	1997	285,129	83,635	54,265	21,228	1,617	7,637	563,419	567	1,017,497
	1998	275,758	78,712	51,888	20,740	1,594	6,439	574,436	561	1,010,127
	1999	252,346	75,901	50,568	20,695	1,502	6,101	573,173	561	980,846
	2000	232,661	73,126	48,997	20,610	1,416	5,877	520,608	561	903,855
	2001	211,778	69,948	47,299	20,343	1,344	5,739	455,455	561	812,466
	2002	201,824	68,438	46,944	20,054	1,290	5,743	408,829	561	753,682
	2003	181,333	62,962	43,750	19,948	1,274	5,774	370,508	561	686,109

	2004	154,198	54,386	39,334	19,838	1,276	5,842	346,917	561	622,352
	2005	137,865	49,064	36,117	19,798	1,273	5,889	323,790	561	574,357
	2006	125,490	45,558	34,517	19,219	1,265	5,968	300,279	561	532,857
	2007	113,165	41,963	32,787	18,398	1,259	6,023	272,786	561	486,942
	2008	101,954	38,257	31,302	17,545	1,276	6,090	247,841	561	444,826
	2009	91,225	34,684	29,455	16,608	1,292	6,145	224,117	561	404,087
	2010	80,811	30,912	27,031	15,965	1,316	6,204	202,900	561	365,699
	2011	71,417	27,196	24,961	15,355	1,347	6,266	180,962	561	328,065
	2012	62,893	24,193	23,153	14,742	1,378	6,335	159,220	561	292,474
	2013	55,286	21,578	21,408	13,750	1,409	6,397	137,713	561	258,101
	2014	49,126	19,486	19,970	12,354	1,440	6,463	118,931	561	228,332
	2015	44,278	17,894	18,867	11,007	1,471	6,522	102,549	561	203,148
	2016	40,771	16,698	17,598	10,224	1,502	6,597	88,253	561	182,205
	2017	38,365	16,015	16,730	9,340	1,533	6,680	75,649	561	164,872
	2018	36,613	15,670	15,811	8,436	1,564	6,767	64,839	561	150,261
	2019	35,598	15,529	15,061	7,664	1,597	6,859	56,783	561	139,652
	2020	35,133	15,533	14,522	7,144	1,629	6,954	48,982	561	130,458

Canadian Emission Inventories – Base Case With MMT										
		Tonnes/Year								
Pollutant	CY	LDGV	LDGT1	LDGT2	HDGV	LDDV	LDDT	HDDV	MC	Total
Total	1995	350,774	97,482	71,413	11,870	655	3,381	45,110	1,585	582,271
VOC	1996	288,171	87,222	71,557	11,694	632	3,301	44,645	1,553	508,776
	1997	294,652	91,040	65,735	12,712	644	3,567	46,001	1,493	515,842
	1998	279,686	84,158	62,640	11,755	639	2,992	41,811	1,485	485,167
	1999	244,203	77,636	59,589	11,124	600	2,810	37,580	1,477	435,020
	2000	213,542	71,744	56,387	10,614	564	2,687	34,633	1,477	391,649
	2001	189,194	66,796	53,802	9,885	533	2,593	31,597	1,477	355,876
	2002	170,214	61,772	52,014	9,054	507	2,590	29,234	1,477	326,863
	2003	151,342	55,493	47,526	8,376	504	2,601	27,207	1,477	294,528
	2004	133,945	49,299	44,155	7,944	489	2,640	25,102	1,477	265,052
	2005	122,515	45,161	41,034	7,700	495	2,664	22,893	1,477	243,939
	2006	113,218	42,416	38,248	7,499	494	2,720	20,613	1,477	226,684
	2007	105,338	40,132	35,978	7,223	495	2,763	18,647	1,477	212,055
	2008	99,197	38,358	33,878	6,927	505	2,814	16,299	1,477	199,456
	2009	94,486	37,065	31,956	6,427	516	2,853	14,257	1,477	189,037
	2010	90,530	36,182	29,740	6,280	527	2,896	12,479	1,477	180,113
	2011	89,063	35,906	28,261	6,149	543	2,934	11,511	1,477	175,844
	2012	88,105	36,061	26,977	5,988	557	2,979	10,599	1,477	172,742
	2013	89,229	36,797	26,283	5,943	571	3,014	9,743	1,477	173,057
	2014	91,097	37,885	25,707	5,871	585	3,051	9,052	1,477	174,726
	2015	93,305	39,061	25,506	5,818	599	3,078	8,288	1,477	177,132
	2016	95,889	40,337	25,636	5,815	612	3,122	7,706	1,477	180,594
	2017	98,356	41,607	26,034	5,814	625	3,173	7,163	1,477	184,251
	2018	100,654	42,880	26,346	5,803	638	3,228	6,748	1,477	187,775
	2019	102,873	44,185	26,983	5,811	652	3,285	6,378	1,477	191,645
	2020	105,027	45,401	27,203	5,844	665	3,345	6,051	1,477	195,013
CO	1995	3,353,237	1,001,728	562,197	159,744	1,470	6,035	209,690	10,361	5,304,462
	1996	2,780,458	871,944	551,212	154,792	1,433	6,104	211,856	10,361	4,588,162
	1997	2,896,083	924,700	530,620	170,033	1,448	6,612	236,347	10,361	4,776,204
	1998	2,752,499	840,189	514,371	156,970	1,462	5,730	236,652	10,300	4,518,174
	1999	2,397,989	748,000	488,594	144,449	1,412	5,653	241,623	10,300	4,038,020
	2000	2,135,419	676,768	458,762	134,663	1,362	5,619	246,683	10,300	3,669,576
	2001	1,919,852	622,515	443,102	122,152	1,317	5,614	247,153	10,300	3,372,006
	2002	1,722,207	568,913	413,052	106,690	1,288	5,686	247,851	10,300	3,075,989
	2003	1,468,946	492,552	364,823	93,342	1,289	5,764	249,195	10,300	2,686,211
	2004	1,265,357	423,382	322,001	85,653	1,282	5,859	250,978	10,300	2,364,811
	2005	1,175,308	385,055	303,544	81,713	1,302	5,924	236,595	10,300	2,199,742
	2006	1,121,790	365,190	295,639	78,637	1,310	6,019	219,511	10,300	2,098,396
	2007	1,076,390	351,703	275,670	75,098	1,319	6,096	196,140	10,300	1,992,717
	2008	1,037,270	345,549	258,904	71,440	1,343	6,174	174,917	10,300	1,905,896
	2009	1,035,616	344,381	227,011	60,696	1,366	6,235	155,373	10,300	1,840,979
	2010	1,049,967	353,009	219,840	59,211	1,392	6,297	137,629	10,300	1,837,645
	2011	1,084,300	368,675	213,955	57,619	1,425	6,361	123,370	10,300	1,866,005
	2012	1,126,929	386,686	207,262	58,496	1,458	6,431	107,334	10,300	1,904,896
	2013	1,186,198	409,767	208,839	59,884	1,491	6,495	92,758	10,300	1,975,731
	2014	1,247,864	435,007	213,136	61,550	1,523	6,562	77,647	10,300	2,053,590
	2015	1,309,993	458,528	221,206	64,153	1,557	6,622	64,013	10,300	2,136,371
	2016	1,372,598	481,348	232,852	67,689	1,589	6,700	50,739	10,300	2,223,815
	2017	1,427,365	501,751	246,829	72,038	1,622	6,783	39,517	10,300	2,306,205
	2018	1,475,493	520,621	257,940	75,524	1,655	6,872	31,632	10,300	2,380,037
	2019	1,517,832	539,040	274,162	79,281	1,689	6,966	27,361	10,300	2,456,632
	2020	1,557,582	555,704	288,658	83,911	1,723	7,064	23,402	10,300	2,528,343
NOx	1995	312,717	83,896	56,972	18,594	1,714	7,169	493,770	567	975,398
	1996	268,427	78,478	57,062	19,067	1,611	7,100	498,420	567	930,731
	1997	282,256	83,367	54,340	21,244	1,617	7,637	563,419	567	1,014,446
	1998	271,087	78,103	51,794	20,700	1,594	6,439	574,436	561	1,004,714
	1999	245,978	74,768	50,210	20,574	1,502	6,101	573,173	561	972,866
	2000	224,365	71,288	48,410	20,392	1,416	5,877	520,608	561	892,917
	2001	201,727	67,347	46,381	20,019	1,344	5,739	455,454	561	798,573
	2002	188,666	64,033	45,664	19,595	1,290	5,743	408,829	561	734,381
	2003	166,871	57,823	41,884	19,248	1,274	5,774	370,508	561	663,942
	2004	140,264	49,118	36,865	18,796	1,276	5,842	346,917	561	599,640

	2005	124,069	43,595	32,898	18,330	1,273	5,889	323,790	561	550,405
	2006	112,531	40,309	30,779	17,456	1,265	5,968	300,279	561	509,148
	2007	102,136	37,324	28,507	16,347	1,259	6,023	272,786	561	464,943
	2008	93,635	34,716	26,762	15,223	1,276	6,090	247,841	561	426,105
	2009	86,641	32,568	24,994	14,058	1,292	6,145	224,117	561	390,376
	2010	80,960	30,742	22,836	13,311	1,316	6,204	202,900	561	358,830
	2011	76,831	29,493	21,338	12,596	1,347	6,266	180,962	561	329,394
	2012	73,169	28,619	20,115	11,725	1,378	6,335	159,220	561	301,123
	2013	70,632	28,190	19,399	10,796	1,409	6,397	137,713	561	275,097
	2014	68,488	28,072	19,122	9,510	1,440	6,463	118,931	561	252,587
	2015	66,590	27,945	19,215	8,494	1,471	6,522	102,549	561	233,346
	2016	65,305	27,882	19,566	7,955	1,502	6,597	88,253	561	217,622
	2017	64,288	27,835	20,052	7,348	1,533	6,680	75,649	561	203,945
	2018	63,659	27,945	20,298	6,588	1,564	6,767	64,839	561	192,221
	2019	63,368	28,197	20,723	5,799	1,597	6,859	56,783	561	183,886
	2020	63,840	28,554	21,398	5,608	1,629	6,954	48,982	561	177,526

MMT Concentration Case

Canadian Emission Annual Inventories from Passenger Cars, LDT1s, LDT2s and HDGVs With 0.022 g/gal MMT

		Tonnes/Year								
Pollutant	CY	LDGV	LDGT1	LDGT2	HDGV	LDDV	LDDT	HDDV	MC	Total
Total VOC	1995	350,747	97,470	71,397	11,870	655	3,381	45,110	1,585	582,215
	1996	288,020	87,129	71,474	11,693	632	3,301	44,645	1,553	508,447
	1997	294,460	90,916	65,613	12,709	644	3,567	46,001	1,493	515,402
	1998	279,403	83,986	62,502	11,750	639	2,992	41,811	1,485	484,568
	1999	243,849	77,420	59,430	11,117	600	2,810	37,580	1,477	434,283
	2000	213,110	71,480	56,228	10,605	564	2,687	34,633	1,477	390,785
	2001	188,697	66,504	53,627	9,875	533	2,593	31,597	1,477	354,902
	2002	169,685	61,474	51,828	9,042	507	2,590	29,234	1,477	325,838
	2003	150,770	55,187	47,326	8,362	504	2,601	27,207	1,477	293,435
	2004	133,356	48,995	43,960	7,928	489	2,640	25,102	1,477	263,947
	2005	121,853	44,827	40,847	7,681	495	2,664	22,893	1,477	242,736
	2006	112,413	42,009	38,066	7,479	494	2,720	20,613	1,477	225,272
	2007	104,306	39,621	35,787	7,203	495	2,763	18,647	1,477	210,300
	2008	97,880	37,702	33,673	6,908	505	2,814	16,299	1,477	197,259
	2009	92,792	36,219	31,731	6,408	516	2,853	14,257	1,477	186,253
	2010	88,345	35,090	29,466	6,260	527	2,896	12,479	1,477	176,541
	2011	86,286	34,507	27,927	6,129	543	2,934	11,511	1,477	171,314
	2012	84,672	34,348	26,552	5,966	557	2,979	10,599	1,477	167,151
	2013	85,055	34,719	25,730	5,920	571	3,014	9,743	1,477	166,229
	2014	86,166	35,414	25,004	5,847	585	3,051	9,052	1,477	166,596
	2015	87,682	36,239	24,627	5,790	599	3,078	8,288	1,477	167,780
	2016	89,589	37,183	24,525	5,780	612	3,122	7,706	1,477	169,995
	2017	91,504	38,180	24,684	5,771	625	3,173	7,163	1,477	172,579
	2018	93,333	39,220	24,805	5,754	638	3,228	6,748	1,477	175,204
	2019	95,179	40,319	25,184	5,756	652	3,285	6,378	1,477	178,231
	2020	97,030	41,376	25,195	5,781	665	3,345	6,051	1,477	180,920
CO	1995	3,352,924	1,001,635	562,145	159,744	1,470	6,035	209,690	10,361	5,304,004
	1996	2,778,958	871,321	550,987	154,771	1,433	6,104	211,856	10,361	4,585,791
	1997	2,894,781	924,100	530,345	170,003	1,448	6,612	236,347	10,361	4,773,997
	1998	2,751,170	839,561	514,120	156,944	1,462	5,730	236,652	10,300	4,515,939
	1999	2,397,194	747,558	488,444	144,435	1,412	5,653	241,623	10,300	4,036,620
	2000	2,135,553	676,693	458,730	134,673	1,362	5,619	246,683	10,300	3,669,614
	2001	1,921,296	622,867	443,260	122,194	1,317	5,614	247,153	10,300	3,374,001
	2002	1,726,095	570,297	413,413	106,774	1,288	5,686	247,851	10,300	3,081,705
	2003	1,474,562	494,536	365,542	93,503	1,289	5,764	249,195	10,300	2,694,692
	2004	1,272,102	425,877	323,094	85,928	1,282	5,859	250,978	10,300	2,375,419
	2005	1,182,378	387,594	305,196	82,134	1,302	5,924	236,595	10,300	2,211,424
	2006	1,126,809	366,667	297,654	79,161	1,310	6,019	219,511	10,300	2,107,430
	2007	1,076,003	351,100	278,138	75,738	1,319	6,096	196,140	10,300	1,994,834
	2008	1,028,752	341,725	261,478	72,226	1,343	6,174	174,917	10,300	1,896,915
	2009	1,015,406	336,249	229,293	61,607	1,366	6,235	155,373	10,300	1,815,830
	2010	1,014,021	339,356	221,346	60,162	1,392	6,297	137,629	10,300	1,790,504
	2011	1,029,677	348,216	214,154	58,579	1,425	6,361	123,370	10,300	1,792,082
	2012	1,052,069	359,550	205,774	59,486	1,458	6,431	107,334	10,300	1,802,403
	2013	1,088,832	375,125	204,880	60,770	1,491	6,495	92,758	10,300	1,840,651
	2014	1,128,442	392,587	206,334	62,279	1,523	6,562	77,647	10,300	1,885,674
	2015	1,170,873	409,399	210,997	64,465	1,557	6,622	64,013	10,300	1,938,226
	2016	1,215,025	426,110	218,239	67,334	1,589	6,700	50,739	10,300	1,996,036
	2017	1,255,008	441,580	227,703	70,796	1,622	6,783	39,517	10,300	2,053,309
	2018	1,290,781	456,294	234,954	73,672	1,655	6,872	31,632	10,300	2,106,160
	2019	1,323,628	471,086	246,527	76,753	1,689	6,966	27,361	10,300	2,164,311
	2020	1,355,284	484,870	256,788	80,470	1,723	7,064	23,402	10,300	2,219,901
NOx	1995	311,824	83,765	56,845	18,583	1,711	7,171	494,766	567	975,231
	1996	268,110	78,372	56,924	19,050	1,607	7,099	499,793	567	931,524
	1997	282,019	83,335	54,205	21,227	1,612	7,635	564,402	567	1,015,002
	1998	271,420	78,188	51,716	20,707	1,588	6,438	575,401	561	1,006,019
	1999	246,914	74,985	50,208	20,605	1,496	6,097	574,025	561	974,891
	2000	225,964	71,712	48,469	20,446	1,411	5,872	521,305	561	895,739
	2001	203,951	67,982	46,539	20,102	1,341	5,733	456,022	561	802,231

	2002	191,901	65,195	45,930	19,715	1,289	5,737	409,294	561	739,621
	2003	170,540	59,194	42,328	19,434	1,273	5,768	370,897	561	669,995
	2004	143,809	50,527	37,486	19,077	1,275	5,838	347,182	561	605,754
	2005	127,572	45,059	33,728	18,728	1,272	5,886	324,133	561	556,940
	2006	115,811	41,715	31,754	17,935	1,265	5,966	300,845	561	515,851
	2007	104,898	38,564	29,636	16,912	1,259	6,023	273,645	561	471,498
	2008	95,657	35,636	27,970	15,865	1,276	6,091	248,913	561	431,968
	2009	87,617	33,083	26,179	14,771	1,291	6,147	225,327	561	394,976
	2010	80,572	30,686	23,950	14,051	1,315	6,205	204,045	561	361,387
	2011	74,921	28,712	22,287	13,366	1,347	6,268	182,017	561	329,479
	2012	69,860	27,218	20,899	12,571	1,377	6,336	160,400	561	299,223
	2013	65,866	26,153	19,882	11,621	1,409	6,399	138,886	561	270,777
	2014	62,566	25,461	19,271	10,302	1,439	6,464	120,004	561	246,069
	2015	59,819	24,903	19,020	9,173	1,471	6,523	103,554	561	225,023
	2016	57,897	24,502	18,903	8,557	1,501	6,599	89,036	561	207,556
	2017	56,487	24,264	18,993	7,872	1,532	6,681	76,189	561	192,580
	2018	55,541	24,235	18,897	7,074	1,564	6,768	65,295	561	179,936
	2019	55,056	24,380	18,980	6,292	1,596	6,860	57,138	561	170,864
	2020	55,265	24,637	19,296	5,999	1,628	6,955	49,233	561	163,574