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Update of Methane and Nitrous Oxide Emission Factors for On-Highway Vehicles

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Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

1.1 Purpose

The U.S. Environmental Protection Agency Office of Transportation and Air Quality (OTAQ) are currently developing a new mobile source emissions factor model called MOVES. This new model will estimate greenhouse gas (GHG) emissions for highway vehicles and will be incorporated into transportation GHG inventory development. Besides other improvements in the methodology, the model will use updated emission factors for nitrous oxide (N_2O) and methane (CH_4). While MOVES is somewhat behind schedule, data to update N_2O and CH_4 emission factors are available for this year's inventory. These revised emission factors will be incorporated into the model itself.

1.2 Previous Emission Factors

Emission factors used in the US EPA *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2001*[1] are listed in Table 1 and are taken from Annex E of that document. It states "The EPA does not systematically track emissions of CH_4 and N_2O; therefore, estimates of these gases were developed using a methodology similar to that outlined in the Revised1996 IPCC Guidelines[2]" Many of these values will be updated with new information detailed in this report. In addition, MOVES specifies separate running and start emissions, which are combined in the emission factors shown in Table 1.

1.3 Definitions of Emission Control Technologies and Standards

The N_2O and CH_4 emission factors used depend on the emission standards in place and the corresponding level of control technology for each vehicle type. The definitions of these control technologies are listed in Annex E of the EPA *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2001*[1] and reproduced here:

Uncontrolled (Unc) -- Vehicles manufactured prior to the implementation of pollution control technologies are designated as uncontrolled. Gasoline light-duty cars and trucks (pre-1973), gasoline heavy-duty vehicles (pre-1984), diesel vehicles (pre-1983), and motorcycles (pre-1996) are assumed to not have significant control technologies in place.

Non-catalyst (Ncat) -- These emission controls were common in gasoline passenger cars and light-duty gasoline trucks during model years (1973-1974) but phased out thereafter, in heavy-duty gasoline vehicles beginning in the mid-1980s, and in motorcycles beginning in 1996. This technology reduces hydrocarbon (HC) and carbon monoxide (CO) emissions through adjustments to ignition timing and air-fuel ratio, air injection into the exhaust manifold, and exhaust gas recirculation (EGR) valves, which also helps meet vehicle NOx standards.

Oxidation catalyst (Ocat) -- This control technology designation represents the introduction of the catalytic converter, and was the most common technology in gasoline passenger cars and light-duty gasoline trucks made from 1975 to 1980 (cars) and 1975 to 1985 (trucks). This technology was also used

[1] EPA. "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2001," Report EPA 430-R-03-004, April 2003.

[2] *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories,* Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

Table 1. Previous Emission Factors for N_2O and CH_4 for Highway Vehicles

Vehicle Type/Control Technology	**N_2O (g/mi)**	**CH_4 (g/mi)**
Gasoline Passenger Cars (LDGV)		
Low Emission Vehicles	0.0283	0.0402
EPA Tier 1 [a]	0.0463	0.0483
EPA Tier 0 [a]	0.0816	0.0644
Oxidation Catalysts	0.0518	0.1126
Non-Catalyst	0.0166	0.1931
Uncontrolled	0.0166	0.2173
Gasoline Light-Duty Trucks (LDGT)		
Low Emission Vehicles	0.0354	0.0483
EPA Tier 1 [a]	0.0581	0.0563
EPA Tier 0 [a]	0.1022	0.1126
Oxidation Catalysts	0.0649	0.1448
Non-Catalyst	0.0208	0.2253
Uncontrolled	0.0208	0.2173
Gasoline Heavy-Duty Vehicles (HDGV)		
Low Emission Vehicles	0.1133	0.0708
EPA Tier 1 [a]	0.1394	0.0966
EPA Tier 0 [a]	0.1746	0.1207
Oxidation Catalysts [b]	0.1109	0.1448
Non-Catalyst	0.0354	0.2012
Uncontrolled	0.0354	0.4345
Diesel Passenger Cars (LDDV)		
Advanced	0.0161	0.0161
Moderate	0.0161	0.0161
Uncontrolled	0.0161	0.0161
Diesel Light Duty Trucks (LDDT)		
Advanced	0.0322	0.0161
Moderate	0.0322	0.0161
Uncontrolled	0.0322	0.0161
Diesel Heavy Duty Vehicles (HDDV)		
Advanced	0.0483	0.0644
Moderate	0.0483	0.0805
Uncontrolled	0.0483	0.0966
Motorcycles (Mot)		
Non-catalysts Control	0.0071	0.2092
Uncontrolled	0.0071	0.4184

Sources: IPCC/UNEP/OECD/IEA (1997), EPA (1998)
[a] The categories “EPA Tier 0” and “EPA Tier 1” were substituted for the early three-way catalyst and advanced three-way catalyst categories, respectively, as defined in the Revised 1996 IPCC Guidelines. Detailed descriptions of emissions control technologies are provided at the end of this annex.
[b] The methane emission factor was assumed based on the oxidation catalyst value for gasoline light-duty trucks.

in some heavy-duty gasoline vehicles between 1982 and 1997. The two-way catalytic converter oxidizes HC and CO, significantly reducing emissions over 80 percent beyond non-catalyst-system capacity. One reason unleaded gasoline was introduced in 1975 was due to the fact that oxidation catalysts cannot function properly with leaded gasoline.

EPA Tier 0 (T0) --This emission standard from the Clean Air Act was met through the implementation of early "three-way" catalysts, therefore this technology was used in gasoline passenger cars and light-duty gasoline trucks sold beginning in the early 1980s, and remained common until 1994. This more sophisticated emission control system improves the efficiency of the catalyst by converting CO and HC to CO_2 and H_2O, reducing NOx to nitrogen and oxygen, and using an on-board diagnostic computer and oxygen sensor. In addition, this type of catalyst includes a fuel metering system (carburetor or fuel injection) with electronic "trim" (also known as a "closed-loop system"). New cars with three-way catalysts met the Clean Air Act's amended standards (enacted in 1977) of reducing HC to 0.41 g/mile by 1980, CO to 3.4 g/mile by 1981 and NOx to 1.0 g/mile by 1981.

EPA Tier 1 (T1) -- This emission standard created through the 1990 amendments to the Clean Air Act limited passenger car NOx emissions to 0.4 g/mile, and HC emissions to 0.25 g/mile. These bounds represent a 60 and 40 percent reduction, respectively, from the EPA Tier 0 standard set in 1981. For light-duty trucks, this standard set emissions at 0.4 to 1.1 g/mile for NOx and 0.25 to 0.39 g/mile for HCs, depending upon the weight of the truck. Emission reductions were met through the use of more advanced emission control systems, and applied to light-duty gasoline vehicles beginning in 1994. This advanced emission control systems included advanced three-way catalysts, electronically controlled fuel injection and ignition timing, EGR, and air injection.

Low Emission Vehicles (LEV) -- This emission standard requires a much higher emission control level than the Tier 1 standard. Applied to light-duty gasoline passenger cars and trucks beginning in small numbers in the mid-1990's, LEV includes multi-port fuel injection with adaptive learning, an advanced computer diagnostics systems and advanced and close coupled catalysts with secondary air injection. LEVs as defined here include transitional low-emission vehicles (TLEVs), low emission vehicles, ultra-low emission vehicles (ULEVs) and super ultra-low emission vehicles (SULEVs). In this analysis, all categories of LEVs are treated the same due to the fact that there are very limited CH_4 or N_2O emission factor data for LEVs to distinguish among the different types of vehicles. Zero emission vehicles (ZEVs) are incorporated into the alternative fuel and advanced technology vehicle assessments.

Moderate control (Mod) -- Improved injection timing technology and combustion system design for light- and heavy-duty diesel vehicles (generally in place in model years 1983 to 1995) are considered moderate control technologies. These controls were implemented to meet emission standards for diesel trucks and buses adopted by the EPA in 1985 to be met in 1991 and 1994.

Advanced control (Adv) -- EGR and modern electronic control of the fuel injection system are designated as advanced control technologies. These technologies provide diesel vehicles with the level of emission control necessary to comply with standards in place from 1996 through 2003.

2 METHODOLOGY

Data obtained from EPA[3] included testing on many of the vehicle type/control technology categories listed in Table 1. This data has been used to develop new overall emission factors as well as running and start emission profiles for MOVES.

Overall emissions which compare directly to those listed in Table 1 were determined using the U.S. Federal Test Procedure (FTP). The FTP incorporates three driving segments in which the vehicle's exhaust is captured in separate "bags," one for each driving segment. Each bag is analyzed separately and then combined to calculate composite emissions. The formula to calculate composite emissions for the FTP emissions test is given below:[4]

$$\text{Composite} = \frac{\text{Bag1} * 0.43 + \text{Bag2} + \text{Bag3} * 0.57}{\text{FTP distance}} \qquad \text{Equation 1}$$

Where FTP distance is approximately 7.44 miles

The federal test procedure includes both starts and running emissions. The bag 1 segment starts from a 12 hour soak at approximately 75ºF and is driven over a transient driving cycle for 505 seconds with an average speed of 25.55 mph. It contains cold start emissions and running emissions. The bag 2 segment has no start and represents running emissions. Its length is 867 seconds with an average speed of 16.02 mph. The third bag segment is a repeat of the bag 1 segment, but after only a 10 minute soak. This contains both hot start emissions and running emissions. In addition, some of the data included a hot running 505 second (HR505) driving cycle. This cycle contains only running emissions (no starts) during the same cycle used for Bag 1 and Bag 3. It can be used to calculate cold and hot start emissions from the Bag 1 and Bag 3 segments of the FTP. Since the HR505 cycle has an average speed of 25.55 mph and the Bag 2 driving cycle has an average speed of 16.02 mph, the two cycles could be used to determine speed factors at low speed. In this report, however, they are used to determine whether grams per mile or grams per hour are more constant over the low speed range. Details of the cycles are given in Table 2.

Table 2. Driving Cycles

Cycle	Length		Average Speed (mph)	Start
	Time (seconds)	Distance (miles)		
FTP [a]	1372	7.44	19.53	Cold/Hot
Bag 1	505	3.58	25.55	Cold
Bag 2	867	3.86	16.02	No
Bag 3	505	3.58	25.55	Hot
HR505	505	3.58	25.55	No

[a] While the FTP actually lasts 1877 seconds, the bag 1 and bag 3 results are multiplied by 43% and 57% respectively to represent cold start activity 43% of the time and hot start activity 57% of the time.

[3] The datasets received from EPA represented 13,277 FTP tests on 6,950 vehicles for methane emissions and 95 FTP tests on 64 vehicles for nitrous oxide emissions. It also included 14,636 non-FTP tests on 2,963 vehicles for methane emissions and 232 non-FTP tests on 74 vehicles for nitrous oxide. The non-FTP tests included a hot running 505 as well as several other driving cycles not utilized in this report. Methane tests were performed in various U.S. locations during the period between April 1982 and June 2000. Nitrous oxide tests were performed in various U.S. locations during the period between January 2000 and June 1998.

[4] Code of Federal Regulations Title 40: Protection of the Environment, Chapter 1, Part 600, Section 1134-78.

Since there are many more FTP tests than HR505 tests, FTP bag 2 emissions in grams per mile are being used in this report to calculate running emissions. To calculate start emissions, the running emissions were subtracted from the FTP emissions in grams per mile and multiplied by the length in miles of the FTP (approximately 7.44 miles). This provided average start emissions which combined both cold and hot start emissions. These are shown in Equations 2 and 3 below. Running emissions were then compared against the HR505 emission rate for vehicles in which both an FTP and HR505 were run.

Running Emissions (g/mi) = Bag2 Emissions (g/mi) Equation 2

Start Emissions (g/start) = (FTP Emissions – Bag 2 Emissions) x Actual FTP Distance Equation 3

Another approach to calculate running emissions is to calculate them in grams per hour using the average speed of each cycle. Start emissions can then be calculated from the FTP emissions in grams per hour and the running emissions in grams per hour as shown in Equations 4 through 6.

FTP Emissions (g/hr) = FTP Emissions (g/mi)
x Actual FTP distance x 3600 second/hr / 1372 seconds Equation 4

Running Emissions (g/hr) = Bag2 Emissions (g/mi)
x Bag 2 distance x 3600 sec/hr / 867 seconds Equation 5

Start Emissions (g/start) = (FTP Emissions (g/hr) – Running Emissions (g/hr))
x (1372/3600) hrs Equation 6

Because the distribution of each set of tests varied, an arithmetic mean was used to determine the average of all tests. In addition to the arithmetic mean (Average), a standard deviation (SD) and a 95% confidence interval (95% CI) were also calculated for each set of data. Only data taken at the FTP temperature range (68ºF to 86ºF) were used in this analysis. Temperature correction factors using additional data at higher temperatures might be part of a later report.

3 RESULTS

Emission factor results for nitrous oxide and methane for on-highway vehicles are discussed in this section. Only some of the vehicle type/emission tier categories produced statistically significant results within the 95% confidence interval. Those data are discussed here. Those categories that did not have enough data to produce statistically significant results within the 95% confidence interval are discussed in Section 4. Recommended emission factors for all categories are given in Section 5.

3.1 Nitrous Oxide Emission Factors

Emission factors for nitrous oxide are presented in this subsection. Emission results for the federal test procedure are discussed in Section 3.1.1, running and start emissions are discussed in Section 3.1.2, and comparisons of running emissions from Bag 2 with HR505 emissions are discussed in Section 3.1.3.

3.1.1 N_2O Federal Test Procedure Results

Emission factors for N_2O for on-highway vehicles are given in Table 3 for the federal test procedure. FTP emissions include both start and running emissions. Emission factors are displayed in both grams per mile and grams per hour.

Table 3. N_2O Emission Factors for the Federal Test Procedure

Vehicle Type	Emission Tier	No of Test Pts	FTP Emissions (g/mi)			FTP Emissions (g/hr)			FTP Dist (mi)
			Average	SD	95% CI	Average	SD	95% CI	
LDGV	LEV	7	0.012	0.009	0.007	0.245	0.179	0.133	7.491
	T1	12	0.030	0.012	0.007	0.582	0.243	0.138	7.472
	T0	12	0.054	0.050	0.028	1.057	0.987	0.559	7.494
LDGT	LEV	5	0.009	0.007	0.006	0.178	0.135	0.118	7.489
	T1	16	0.067	0.061	0.030	1.321	1.193	0.584	7.466
HDDV	Adv	6	0.005	0.001	0.001	0.096	0.016	0.012	7.470

The gram per mile emission factors are compared against Table 1 IPCC emission factors in Table 4. As can be seen from this table, the newly calculated emission factors are in most cases lower than previous values. This is most likely because newer technologies are represented in the dataset versus those used to derive the IPCC factors. The newer values better represent the current vehicle fleet.

Table 4. N_2O Emission Factors Comparisons against previous IPCC values

Vehicle Type	Emission Tier	Emission Factors (g/mi)	
		IPCC	This Study
LDGV	LEV	0.028	0.012
	T1	0.046	0.030
	T0	0.082	0.054
LDGT	LEV	0.035	0.009
	T1	0.058	0.067
HDDV	Adv	0.048	0.005

3.1.2 N_2O Running and Start Emissions

Running emissions in grams per mile and start emissions in grams per start, calculated using Equations 2 and 3, are provided in Table 5 along with standard deviations (SD) and 95% confidence intervals (95% CI). Running emissions in grams per hour and start emissions in grams per start, calculated using Equations 5 and 6, are provided in Table 6.

Table 5. N_2O Running and Start Emission Factors using Equations 2 and 3

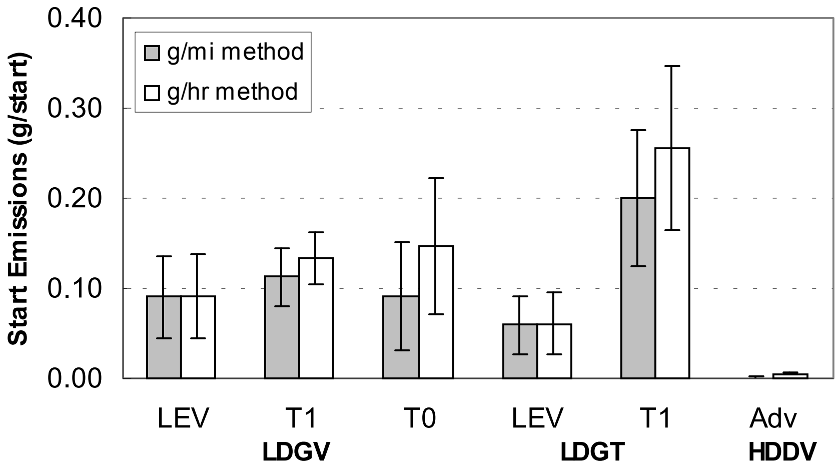
Vehicle Type	Emission Tier	Running Emissions (g/mi)			Start Emissions (g/start)		
		Average	SD	95% CI	Average	SD	95% CI
LDGV	LEV	0.000	0.001	0.001	0.090	0.063	0.046
	T1	0.015	0.014	0.008	0.113	0.056	0.032
	T0	0.042	0.044	0.025	0.092	0.107	0.060
LDGT	LEV	0.001	0.002	0.002	0.059	0.036	0.032
	T1	0.041	0.052	0.025	0.200	0.154	0.076
HDDV	Adv	0.005	0.001	0.001	-0.002	0.003	0.003

Table 6. N_2O Running and Start Emission Factors using Equations 5 and 6

Vehicle Type	Emission Tier	Running Emissions (g/hr)			Start Emissions (g/start)		
		Average	SD	95% CI	Average	SD	95% CI
LDGV	LEV	0.007	0.018	0.013	0.091	0.064	0.047
	T1	0.235	0.218	0.123	0.132	0.051	0.029
	T0	0.671	0.716	0.405	0.147	0.134	0.076
LDGT	LEV	0.019	0.035	0.031	0.061	0.039	0.034
	T1	0.652	0.835	0.409	0.255	0.186	0.091
HDDV	Adv	0.083	0.019	0.015	0.005	0.002	0.001

Comparisons of start emissions using the two methods (g/mi and g/hr) are shown in Figure 1. As can be seen from this figure, the start emissions calculated using the two methods are statistically similar within the 95% confidence interval, except for the heavy-duty diesel vehicle. In that case assuming no start emissions is a good assumption.

Figure 1. Comparison of Start Emissions using two methods



3.1.3 N_2O HR505 Comparisons

Several of the vehicles tested in the dataset provided by EPA also included hot running 505 test emissions along with the FTP emissions tests. Since not all vehicles in the dataset also included HR505 tests, comparisons were made for those vehicles that did have both tests. Since the HR505 test contains no starts, it is equivalent to a running emission. The HR505 emissions are compared in terms of grams per mile in Table 7 and grams per hour in Table 8 to the FTP Bag 2 running emissions presented in Section 3.1.2.

Table 7. HR505 Comparison with Bag 2 Running emissions in grams per mile

Vehicle Type	Emission Tier	No of Test Pts	FTP Bag 2 Emissions (g/mi)			HR505 Emissions (g/mi)		
			Average	SD	95% CI	Average	SD	95% CI
LDGV	T1	9	0.018	0.014	0.009	0.022	0.016	0.010
LDGT	T1	12	0.052	0.056	0.032	0.059	0.054	0.031

Table 8. HR505 Comparison with Bag 2 Running emissions in grams per hour

Vehicle Type	Emission Tier	No of Test Pts	FTP Bag 2 Emissions (g/hr)			HR505 Emissions (g/hr)		
			Average	SD	95% CI	Average	SD	95% CI
LDGV	T1	9	0.295	0.219	0.143	0.574	0.400	0.261
LDGT	T1	12	0.827	0.898	0.508	1.508	1.397	0.791

Running emissions are compared on a grams per mile basis in Figure 2 and a grams per hour basis in Figure 3. As can be seen in those figures the Bag 2 running emissions in either grams per mile or grams per hour are statistically similar to the HR505 running emissions. In absolute value, however, the bag 2 emission levels in grams per mile are closer to the HR505 emission levels in grams per mile than the comparison in grams per hour. Thus, it is suggested that emission rates in grams per mile be used for the low speed case. Conversion to grams per hour should be done at FTP speed, which is somewhere between the Bag 2 and HR505 speeds.

Figure 2. Comparison of Running Emissions in grams per mile

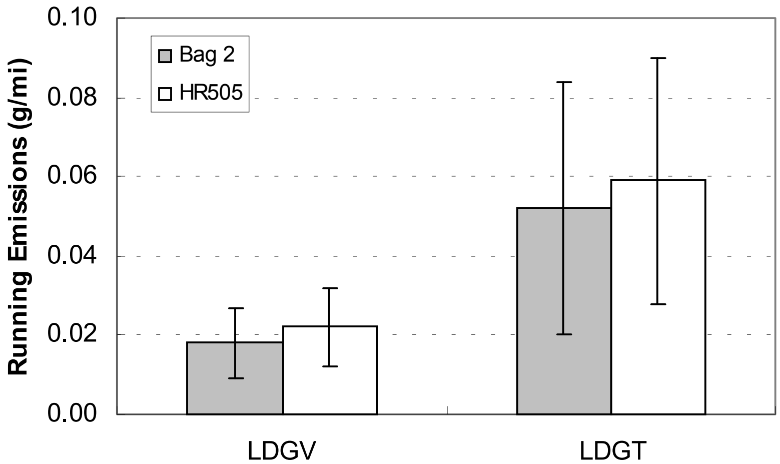
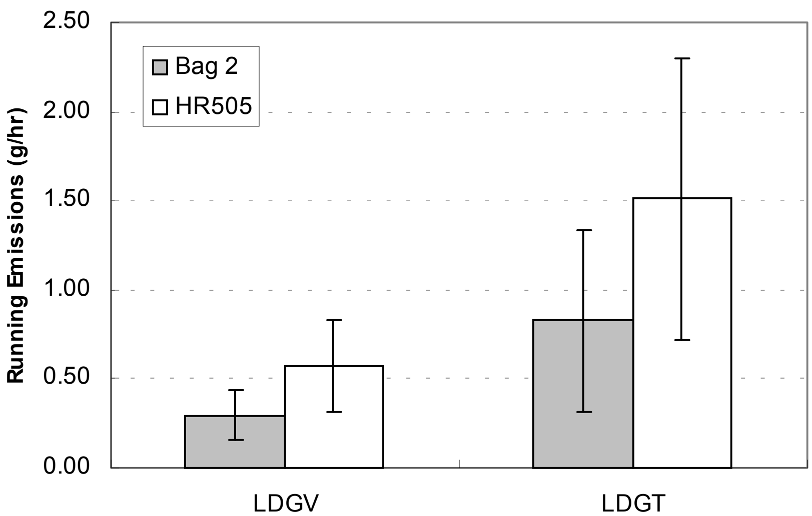


Figure 3. Comparison of Running Emissions in grams per hour



3.2 Methane Emission Factors

Emission factors for methane are presented in this section. Emission results for the federal test procedure are discussed in Section 3.2.1, running and start emissions are discussed in Section 3.2.2, and comparisons of running emissions from Bag 2 against HR505 emissions are discussed in Section 3.2.3.

3.2.1 CH_4 Federal Test Procedure Results

Emission factors for CH_4 for on-highway vehicles are given in Table 9 for the federal test procedure. The federal test procedure combines both start and running emissions. Emission factors are displayed in both grams per mile and grams per hour.

Table 9. CH_4 Emission Factors for the Federal Test Procedure

Vehicle Type	Emission Tier	No of Test Pts	FTP Emissions (g/mi)			FTP Emissions (g/hr)			FTP Dist (mi)
			Average	SD	95% CI	Average	SD	95% CI	
LDGV	LEV	7	0.013	0.006	0.005	0.254	0.121	0.089	7.434
	T1	131	0.020	0.010	0.002	0.383	0.193	0.033	7.453
	T0	9504	0.066	0.087	0.002	1.294	1.711	0.034	7.457
	Ocat	690	0.133	0.129	0.010	2.609	2.536	0.189	7.475
	Ncat	20	0.162	0.130	0.057	3.199	2.552	1.118	7.509
LDGT	LEV	10	0.017	0.016	0.010	0.327	0.306	0.190	7.443
	T1	80	0.034	0.018	0.004	0.672	0.358	0.078	7.441
	T0	1666	0.071	0.067	0.003	1.396	1.308	0.063	7.449
	Ocat	455	0.143	0.112	0.010	2.804	2.185	0.201	7.455
HDGV	T1	36	0.047	0.018	0.006	0.904	0.361	0.118	7.401
	T0	101	0.218	0.115	0.022	4.230	2.213	0.432	7.393
	Ocat	90	0.209	0.076	0.016	4.018	1.453	0.300	7.354
HDDV	Adv	8	0.004	0.003	0.002	0.081	0.049	0.034	7.471

The gram per mile emission factors are compared against the Table 1 IPCC emission factors in Table 10. As can be seen from this table, the newly calculated emission factors are in most cases lower than previous values. This is most likely because newer technologies are represented in the dataset versus those used to derive the IPCC factors. The newer values better represent the current vehicle fleet. In the HDGV case, however, the results from the data analysis were higher than those developed by IPCC, except for the EPA Tier 1 case. Since the IPCC HDGV values were estimated from the light-duty gasoline vehicle values based upon fuel economy, it is suggested that the newer values be used as these represent real test data.

Table 10. CH_4 Emission Factors Comparisons against previous IPCC values

Vehicle Type	Emission Tier	Emission Factors (g/mi)	
		IPCC	This Study
LDGV	LEV	0.040	0.013
	T1	0.048	0.020
	T0	0.064	0.066
	Ocat	0.113	0.133
	Ncat	0.193	0.162
LDGT	LEV	0.048	0.017
	T1	0.056	0.034
	T0	0.113	0.071
	Ocat	0.145	0.143
HDGV	T1	0.097	0.047
	T0	0.121	0.218
	Ocat	0.145	0.209
HDDV	Adv	0.064	0.004

3.2.2 CH_4 Running and Start Emissions

Running emissions in grams per mile and start emissions in grams per start, calculated using Equations 2 and 3, are provided in Table 11 along with standard deviations (SD) and 95% confidence intervals (95% CI). Running emissions in grams per hour and start emissions in grams per start, calculated using Equations 5 and 6, are provided in Table 12.

Table 11. CH_4 Running and Start Emission Factors using Equations 2 and 3

Vehicle Type	Emission Tier	Running Emissions (g/mi)			Start Emissions (g/start)		
		Average	SD	95% CI	Average	SD	95% CI
LDGV	LEV	0.009	0.006	0.004	0.032	0.024	0.018
	T1	0.012	0.011	0.002	0.055	0.034	0.006
	T0	0.062	0.102	0.002	0.034	0.192	0.004
	Ocat	0.132	0.155	0.012	0.009	0.300	0.022
	Ncat	0.155	0.151	0.066	0.059	0.298	0.131
LDGT	LEV	0.011	0.017	0.011	0.046	0.015	0.009
	T1	0.023	0.019	0.004	0.082	0.040	0.009
	T0	0.062	0.073	0.003	0.072	0.148	0.007
	Ocat	0.130	0.125	0.012	0.099	0.250	0.023
HDGV	T1	0.024	0.020	0.007	0.163	0.060	0.020
	T0	0.194	0.105	0.020	0.183	0.263	0.051
	Ocat	0.179	0.066	0.014	0.215	0.178	0.037
HDDV	Adv	0.006	0.004	0.003	-0.011	0.011	0.008

Table 12. CH_4 Running and Start Emission Factors using Equations 5 and 6

Vehicle Type	Emission Tier	Running Emissions (g/hr)			Start Emissions (g/start)		
		Average	SD	95% CI	Average	SD	95% CI
LDGV	LEV	0.139	0.096	0.018	0.044	0.024	0.008
	T1	0.196	0.173	0.030	0.071	0.029	0.005
	T0	0.989	1.648	0.033	0.116	0.143	0.003
	Ocat	2.125	2.500	0.187	0.184	0.207	0.015
	Ncat	2.500	2.443	1.071	0.266	0.231	0.101
LDGT	LEV	0.169	0.271	0.168	0.060	0.017	0.011
	T1	0.374	0.303	0.066	0.114	0.042	0.009
	T0	0.989	1.164	0.056	0.155	0.140	0.007
	Ocat	2.090	2.015	0.185	0.272	0.216	0.020
HDGV	T1	0.390	0.320	0.105	0.196	0.056	0.018
	T0	3.074	1.652	0.322	0.441	0.313	0.061
	Ocat	2.831	1.026	0.212	0.452	0.218	0.045
HDDV	Adv	0.090	0.062	0.043	-0.003	0.006	0.004

Comparisons of start emissions using the two methods (g/mi and g/hr) are shown in Figure 4 for light-duty vehicles and Figure 5 for heavy-duty vehicles. As can be seen from these figures, the start emissions calculated using the two methods do not result in statistically the same value within the 95% confidence interval, except for a few cases. As described in Section 3.2.3 below, the grams per mile method produced running emission values that are closer to the HR505 values, so it is recommended to use start emissions based upon the grams per mile method.

Figure 4. Comparison of Start Emissions for light-duty vehicles using two methods

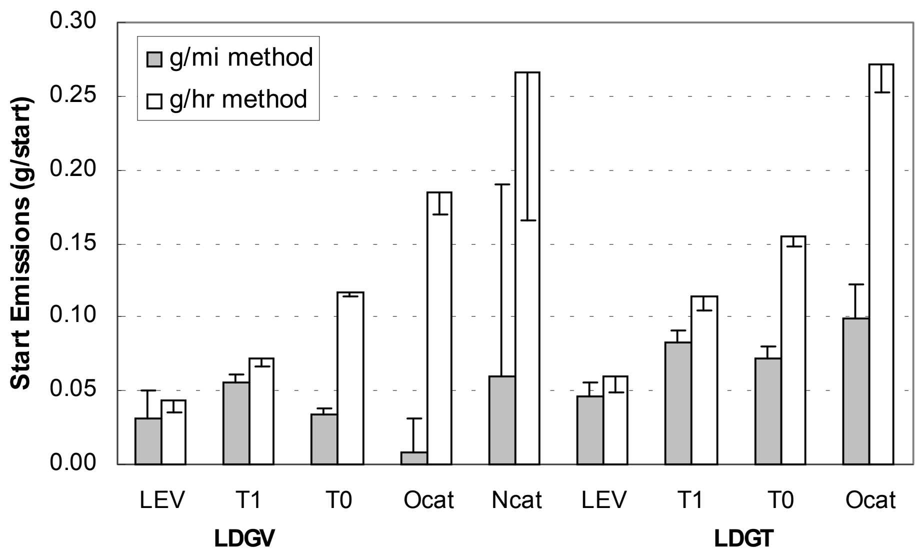
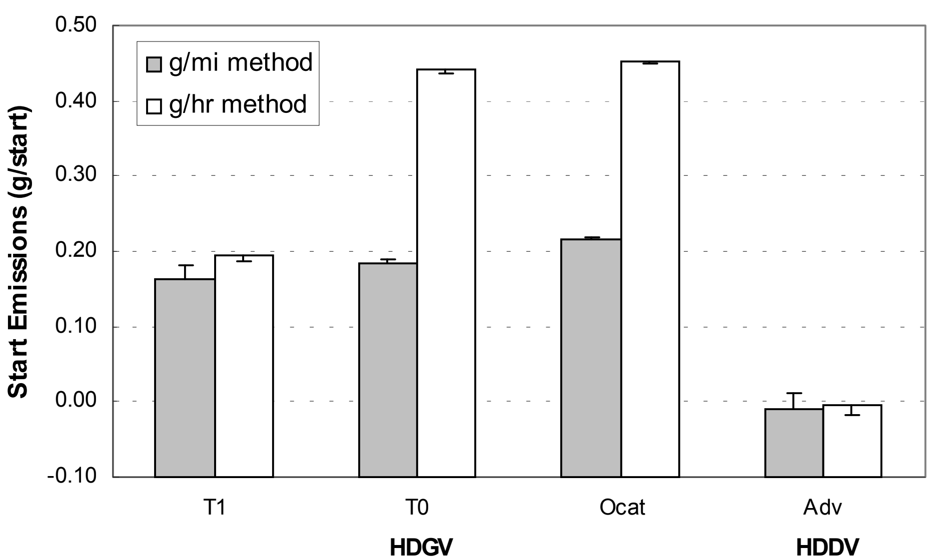


Figure 5. Comparison of Start Emissions for heavy-duty vehicles using two methods



3.2.3 CH_4 HR505 Comparisons

Several of the vehicles tested in the dataset provided by EPA also included hot running 505 test emissions along with the FTP emissions tests. Since not all vehicles in the dataset also included HR505 tests, comparisons were made for those vehicles that did have both tests. Since the HR505 test contains no starts, it is equivalent to a running emission. The HR505 emissions are compared in terms of grams per mile in Table 13 and grams per hour in Table 14 to the FTP Bag 2 running emissions presented in Section 3.2.2.

Table 13. HR505 Comparison with Bag 2 Running emissions in grams per mile

Vehicle Type	Emission Tier	No of Test Pts	FTP Bag 2 Emissions (g/mi)			HR505 Emissions (g/mi)		
			Average	SD	95% CI	Average	SD	95% CI
LDGV	T1	31	0.015	0.013	0.005	0.014	0.009	0.003
	T0	51	0.085	0.119	0.033	0.062	0.074	0.020
	Ocat	7	0.097	0.105	0.077	0.069	0.050	0.037
LDGT	LEV	2	0.040	0.019	0.026	0.033	0.022	0.030
	T1	43	0.023	0.018	0.005	0.022	0.015	0.005
	T0	33	0.130	0.109	0.037	0.096	0.076	0.026
	Ocat	6	0.430	0.426	0.341	0.302	0.267	0.214
HDGV	T1	22	0.042	0.046	0.019	0.050	0.049	0.021
	T0	76	0.196	0.100	0.022	0.156	0.078	0.017
	Ocat	74	0.189	0.067	0.015	0.175	0.085	0.019

Table 14. HR505 Comparison with Bag 2 Running emissions in grams per hour

Vehicle Type	Emission Tier	No of Test Pts	FTP Bag 2 Emissions (g/hr)			HR505 Emissions (g/hr)		
			Average	SD	95% CI	Average	SD	95% CI
LDGV	T1	31	0.248	0.212	0.075	0.354	0.221	0.078
	T0	51	1.366	1.918	0.526	1.598	1.891	0.519
	Ocat	7	1.556	1.671	1.238	1.758	1.278	0.947
LDGT	LEV	2	0.630	0.304	0.421	0.829	0.558	0.773
	T1	43	0.376	0.295	0.088	0.572	0.393	0.117
	T0	33	2.070	1.738	0.593	2.450	1.934	0.660
	Ocat	6	6.886	6.855	5.485	7.708	6.862	5.490
HDGV	T1	22	0.643	0.758	0.324	1.266	1.247	0.521
	T0	76	3.108	1.565	0.352	3.965	1.959	0.440
	Ocat	74	2.984	1.044	0.238	4.407	2.115	0.482

Running emissions are compared on a grams per mile basis in Figure 6 and a grams per hour basis in Figure 7. As can be seen in those figures the Bag 2 running emissions in either grams per mile or grams per hour are statistically similar to the HR505 running emissions within the 95% confidence interval. In absolute value, however, the bag 2 emission levels in grams per mile are closer to the HR505 emission levels in grams per mile than the comparison in grams per hour. Thus, it is suggested that emission rates in grams per mile be used for the low speed case. Conversion to grams per hour should be done at FTP speed, which is somewhere between the Bag 2 and HR505 speeds.

Figure 6. Comparison of Running Emissions in grams per mile

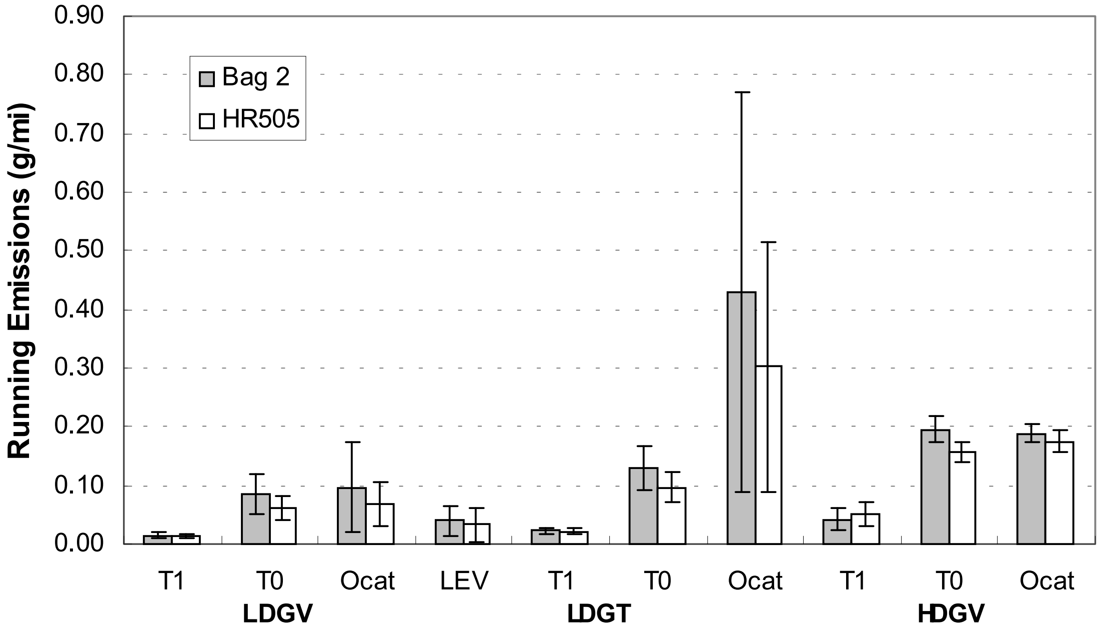
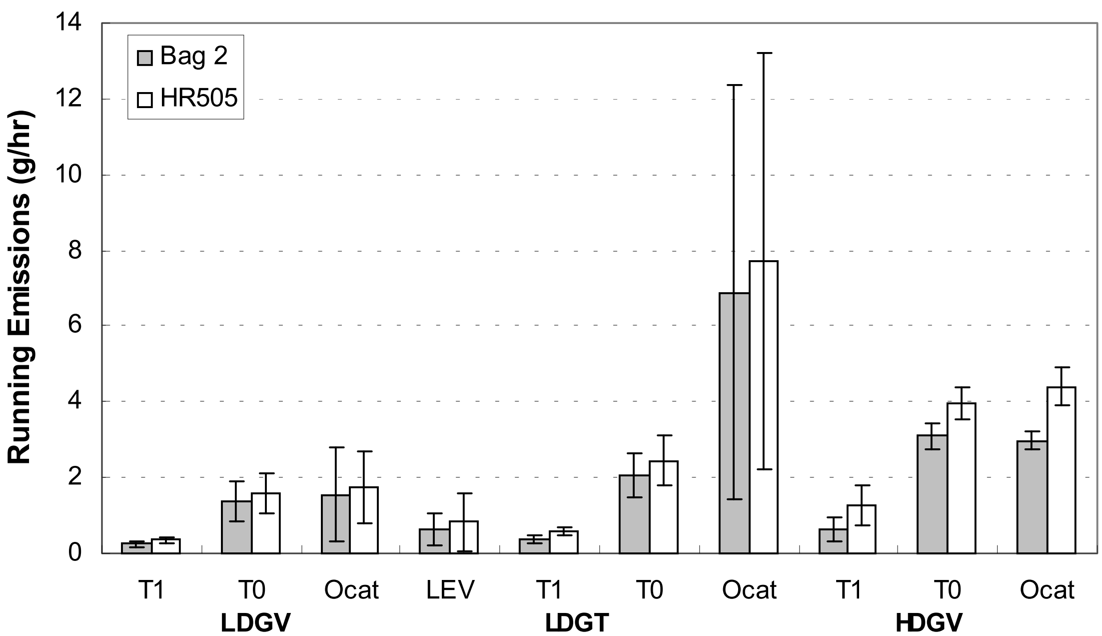


Figure 7. Comparison of Running Emissions in grams per hour



4 EMISSION ESTIMATES FOR OTHER CATERGORIES

Several of the vehicle types/control technology categories either contained no data or statistically insignificant data within the 95 percent confidence interval. For these data, estimation of emission factors is needed. This section discusses how the IPCC data was derived and makes recommendations for newer estimates.

4.1 Nitrous Oxide Emission Factor Estimates

Nitrous oxide emissions data was either non-existent or produced statistically insignificant results in the case of most of the older control technologies for gasoline light-duty vehicles. In addition, there were either no or statistically insignificant data for heavy-duty gasoline vehicles and light duty diesel vehicles and trucks. For heavy-duty diesel vehicles, only the most advanced control technology had any data and that was only for sanitation trucks. There were no motorcycle data.

The data shown in Table 4 indicates that the new data produces statistically significant values that are lower than the previous IPCC values. Most of the values used currently in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2001* come from an EPA report by Harvey Michaels.[5] In this report, Michaels examined limited data for gasoline passenger cars and developed new N_2O emission factors based upon that data. For other vehicle types, he used the ratio of fuel economies to produce new values. For diesel vehicles, he suggested using the European values listed in the IPCC guidelines.

A similar method is suggested here. To estimate the emission factors of N_2O for other vehicle types, but the same emission tier, it is suggested that the ratio of CO_2 emissions be used. CO_2 emissions per mile were extracted from the Harvey Michaels report and converted to grams per mile. These values are shown on Table 15. Estimates of CO_2 emissions for LEV and Tier 1 heavy-duty gasoline vehicles were estimated from the CO_2 emissions for Tier 0 heavy-duty gasoline vehicles and the ratio of CO_2 emissions between a Tier 1 and LEV light-duty truck and a Tier 0 light-duty truck.

4.1.1 N_2O Estimates for Light-Duty Gasoline Vehicles

The datasets provided by EPA produced statistically significant emission factors for LEV, Tier 1 and Tier 0 vehicles. There was no data for any of the earlier technologies such as oxidation catalyst, non-catalyst, and uncontrolled. To estimate emissions for the oxidation catalyst category, the Tier 0 emission levels were multiplied by the ratio of CO_2 emissions for the Tier 0 light-duty gasoline vehicle divided by the oxidation catalyst CO_2 emissions for the same vehicle type. This ratio was applied to the FTP, running and start emissions. For the non-catalyst and uncontrolled, previous IPCC values were used for the FTP values, and the ratio of FTP to running and start emissions for the oxidation catalyst category was used to determine the running and start emissions for the non-catalyst and uncontrolled levels. Estimated values for these three control technologies are shown in Table 16.

4.1.2 N_2O Estimates for Light-Duty Gasoline Trucks

The datasets provided by EPA produced statistically significant emission factors for LEV and Tier 1 vehicles only. Estimated emission factors for the other control technologies for light-duty trucks were estimated from the emission factors for light-duty gasoline cars based upon the ratio of the light-duty truck CO_2 emission rate versus the light-duty gasoline car CO_2 emission rate. Estimated values for the

[5] EPA, "Emissions of Nitrous Oxide from Highway Mobile Sources: Comments on the Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-1996 (March 1998)," Report No. EPA420-R-98-009, August 1998.

Table 15. CO_2 Emissions in grams per mile for Vehicle Types and Emission Control Technologies

Vehicle/Control Technology	CO_2 (g/mi)
Gasoline Passenger Cars	
Low Emission Vehicles	451
Tier 1	459
Tier 0	480
Oxidation Catalyst	616
Non-Catalyst	855
Uncontrolled	814
Gasoline Light-Duty Trucks	
Low Emission Vehicles	637
Tier 1	637
Tier 0	801
Oxidation Catalyst	801
Non-Catalyst	967
Uncontrolled	932
Gasoline Heavy-Duty Vehicles	
Low Emission Vehicles	1,301
Tier 1	1,301
Tier 0	1,637
Oxidation Catalyst	1,667
Non-Catalyst Control	2,124
Uncontrolled	2,124
Diesel Passenger Cars	
Advanced	381
Moderate	399
Uncontrolled	513
Diesel Light Trucks	
Advanced	531
Moderate	533
Uncontrolled	668
Diesel Heavy-Duty Vehicles	
Advanced	1,588
Moderate	1,627
Uncontrolled	1,765
Motorcycles	
Non-Catalyst Control	352
Uncontrolled	428

various emission control categories where there were not statistically significant data are shown in Table 17.

Table 16. Estimated N_2O Emission Factors for Light-Duty Gasoline Vehicles

Emission Control Technology	FTP (g/mi)	Running (g/mi)	Start (g/start)
Oxidation Catalyst	0.042	0.032	0.072
Non-Catalyst	0.017	0.013	0.028
Uncontrolled	0.017	0.013	0.028

Table 17. Estimated N_2O Emission Factors for Light-Duty Gasoline Trucks

Emission Control Technology	FTP (g/mi)	Running (g/mi)	Start (g/start)
Tier 0	0.090	0.069	0.153
Oxidation Catalyst	0.054	0.042	0.093
Non-Catalyst	0.019	0.015	0.032
Uncontrolled	0.019	0.015	0.032

4.1.3 N_2O Estimates for Heavy-Duty Gasoline Trucks

The datasets provided by EPA did not produce any statistically significant emission factors for heavy-duty trucks [because N_2O emissions were measured for only a single heavy-duty gasoline truck]. Emission factors for heavy-duty gasoline trucks were estimated from light-duty gasoline trucks based upon the ratio of CO_2 emissions for each control technology. Estimated values for the various emission control categories where there were not statistically significant data are shown in Table 18.

Table 18. Estimated N_2O Emission Factors for Heavy-Duty Gasoline Trucks

Emission Control Technology	FTP (g/mi)	Running (g/mi)	Start (g/start)
LEV	0.019	0.002	0.120
Tier 1	0.138	0.083	0.409
Tier 0	0.183	0.142	0.313
Oxidation Catalyst	0.113	0.088	0.194
Non-Catalyst	0.041	0.032	0.070
Uncontrolled	0.043	0.033	0.074

4.1.4 N_2O Estimates for Motorcycles

The datasets provided by EPA did not contain any test data for motorcycles. Emission factors for motorcycles were estimated from light-duty gasoline cars based upon the ratio of CO_2 emissions for the two control technologies. Estimated values for motorcycles are shown in Table 19.

Table 19. Estimated N_2O Emission Factors for Motorcycles

Emission Control Technology	FTP (g/mi)	Running (g/mi)	Start (g/start)
Non-Catalyst	0.007	0.005	0.012
Uncontrolled	0.009	0.007	0.015

4.1.5 N_2O Estimates for Heavy-Duty Diesel Vehicles

The datasets provided by EPA only produced statistically significant emission factors for the advanced control technology. While the data only represented the light heavy-duty trucks (i.e., with GVWR between 8,500 and 10,000 pounds), the same engine technology would apply to other heavy-duty truck types. Also since the advanced technology does not include any aftertreatment devices, it is assumed that the N_2O emissions from the other categories are the same as those for the advanced technology. Estimated values for the various emission control categories where there were not statistically significant data are shown in Table 20.

Table 20. Estimated N_2O Emission Factors for Heavy-Duty Diesel Vehicles

Emission Control Technology	FTP (g/mi)	Running (g/mi)	Start (g/start)
Moderate	0.005	0.005	-0.002
Uncontrolled	0.005	0.005	-0.002

4.1.6 N_2O Estimates for Light-Duty Diesel Cars and Trucks

The datasets provided by EPA did not produce any statistically significant emission factors for either light-duty diesel cars or trucks. Emission factors for light-duty cars and trucks were estimated from heavy-duty diesel vehicles based upon the ratio of CO_2 emissions for the various control technologies. Estimated values for the light-duty diesel cars and trucks are shown in Table 21.

Table 21. Estimated N_2O Emission Factors for Light-Duty Diesel Vehicles and Trucks

Vehicle Type	Emission Control Technology	FTP (g/mi)	Running (g/mi)	Start (g/start)
Light-Duty Diesel Vehicles	Advanced	0.001	0.001	0.000
	Moderate	0.001	0.001	0.000
	Uncontrolled	0.001	0.002	-0.001
Light-Duty Diesel Trucks	Advanced	0.002	0.002	-0.001
	Moderate	0.002	0.002	-0.001
	Uncontrolled	0.002	0.002	-0.001

4.2 Methane Emission Factor Estimates

While significantly more data were available for the methane emission factor analysis, there were still several categories of vehicle/control technology combinations for which there was either no or not enough data to produce statistically significant results within the 95% confidence interval. This included most diesel vehicles, motorcycles and earlier technologies of gasoline vehicles (non-catalyst and uncontrolled).

The data in Table 10 indicate that the IPCC LEV and T1 emission factors for light duty gasoline vehicles and trucks were higher than the new data suggests. This is most likely because the newer data represents advancements in emission control above that used to determine the IPCC values. The IPCC values were determined from EPA's earlier mobile source emission factor model MOBILE5.

In order to estimate methane emissions for other vehicles, the ratio of CO_2 emissions were used to extrapolate values similar to that for N_2O emission factors.

4.2.1 CH_4 Estimates for Light-Duty Gasoline Vehicles

Statistically significant data were available for all but the uncontrolled light-duty gasoline vehicle category. This was estimated from the non-catalyst emission factors based upon the ratio of CO_2 emission rates. Estimated methane emission factors for uncontrolled light-duty gasoline cars are given in Table 22.

Table 22. Estimated CH_4 Emission Factors for Light-Duty Gasoline Vehicles

Emission Control Technology	FTP (g/mi)	Running (g/mi)	Start (g/start)
Uncontrolled	0.171	0.162	0.062

4.2.2 CH_4 Estimates for Light-Duty Gasoline Trucks

The datasets provided by EPA produced statistically significant emission factors for all but the non-catalyst and uncontrolled categories. Estimated emission factors for these control technologies were estimated from the emission factors for light-duty gasoline cars based upon the ratio of the light-duty truck CO_2 emission rate versus the light-duty gasoline car CO_2 emission rate for the given control technology. Estimated values for the various emission control categories where there were not statistically significant data are shown in Table 23.

Table 23. Estimated CH_4 Emission Factors for Light-Duty Gasoline Trucks

Emission Control Technology	FTP (g/mi)	Running (g/mi)	Start (g/start)
Non-Catalyst	0.184	0.175	0.067
Uncontrolled	0.195	0.186	0.071

4.2.3 CH_4 Estimates for Heavy-Duty Gasoline Trucks

The datasets provided by EPA produced statistically significant emission factors for Tier 1, Tier 0, and oxidation catalyst heavy-duty gasoline trucks. Emission factors for the other categories were estimated from light-duty gasoline trucks based upon the ratio of CO_2 emissions for each control technology. Estimated values for the various emission control categories where there were not statistically significant data are shown in Table 24.

Table 24. Estimated CH_4 Emission Factors for Heavy-Duty Gasoline Trucks

Emission Control Technology	FTP (g/mi)	Running (g/mi)	Start (g/start)
LEV	0.034	0.022	0.094
Non-Catalyst	0.403	0.384	0.147
Uncontrolled	0.445	0.423	0.162

4.2.4 CH_4 Estimates for Motorcycles

The datasets provided by EPA did not contain any test data for motorcycles. Emission factors for motorcycles were estimated from light-duty gasoline cars based upon the ratio of CO_2 emissions for the two control technologies. Estimated values for motorcycles are shown in Table 25.

Table 25. Estimated CH_4 Emission Factors for Motorcycles

Emission Control Technology	FTP (g/mi)	Running (g/mi)	Start (g/start)
Non-Catalyst	0.067	0.064	0.024
Uncontrolled	0.090	0.085	0.033

4.2.5 CH_4 Estimates for Heavy-Duty Diesel Vehicles

The datasets provided by EPA only produced statistically significant emission factors for the advanced control technology. Since the advanced technology does not include any aftertreatment devices, it is assumed that the CH_4 emissions from the other categories are the same as those for the advanced technology. Estimated values for the various emission control categories where there were not statistically significant data are shown in Table 26.

Table 26. Estimated CH_4 Emission Factors for Heavy-Duty Diesel Vehicles

Emission Control Technology	FTP (g/mi)	Running (g/mi)	Start (g/start)
Moderate	0.004	0.006	-0.011
Uncontrolled	0.004	0.006	-0.011

4.2.6 CH_4 Estimates for Light-Duty Diesel Cars and Trucks

The datasets provided by EPA did not produce any statistically significant emission factors for either light-duty diesel cars or trucks. Emission factors for light-duty cars and trucks were estimated from heavy-duty diesel vehicles based upon the ratio of CO_2 emissions for the various control technologies. Estimated values for the various emission control categories for light-duty diesel cars and trucks are shown in Table 27.

Table 27. Estimated CH_4 Emission Factors for Light-Duty Diesel Vehicles and Trucks

Vehicle Type	Emission Control Technology	FTP (g/mi)	Running (g/mi)	Start (g/start)
Light-Duty Diesel Vehicles	Advanced	0.001	0.001	-0.003
	Moderate	0.001	0.001	-0.003
	Uncontrolled	0.001	0.002	-0.003
Light-Duty Diesel Trucks	Advanced	0.001	0.002	-0.004
	Moderate	0.001	0.002	-0.004
	Uncontrolled	0.002	0.002	-0.004

5 RECOMMENDED EMISSION FACTORS FOR ON-HIGHWAY VEHICLES

Table 28 presents previous IPCC values used in the 2001 US Inventory and newly recommended emission factors for methane and nitrous oxide emissions for all categories. Values in bold represent those derived using statistically significant data within the 95% confidence interval.

Table 28. Recommended Values for N_2O and CH_4 Emission Factors

	Nitrous Oxide				Methane			
Vehicle Type Control Technology	**IPCC g/mi**	**FTP g/mi**	**Run g/mi**	**Start g/start**	**IPCC g/mi**	**FTP g/mi**	**Run g/mi**	**Start g/start**
Gasoline Passenger Cars								
Low Emission Vehicles	0.028	**0.012**	**0.000**	**0.090**	0.040	**0.013**	**0.009**	**0.032**
Tier 1	0.046	**0.030**	**0.015**	**0.113**	0.048	**0.020**	**0.012**	**0.055**
Tier 0	0.082	**0.054**	**0.042**	**0.092**	0.064	**0.066**	**0.062**	**0.034**
Oxidation Catalyst	0.052	0.042	0.032	0.072	0.113	**0.133**	**0.132**	**0.009**
Non-Catalyst	0.017	0.017	0.013	0.028	0.193	**0.162**	**0.155**	**0.059**
Uncontrolled	0.017	0.017	0.013	0.028	0.217	0.171	0.162	0.062
Gasoline Light-Duty Trucks								
Low Emission Vehicles	0.035	**0.009**	**0.001**	**0.059**	0.048	**0.017**	**0.011**	**0.046**
Tier 1	0.058	**0.067**	**0.041**	**0.200**	0.056	**0.034**	**0.023**	**0.082**
Tier 0	0.102	0.090	0.069	0.153	0.113	**0.071**	**0.062**	**0.072**
Oxidation Catalyst	0.065	0.054	0.042	0.093	0.145	**0.143**	**0.130**	**0.099**
Non-Catalyst	0.021	0.019	0.015	0.032	0.225	0.184	0.175	0.067
Uncontrolled	0.021	0.019	0.015	0.032	0.217	0.195	0.186	0.071
Gasoline Heavy-Duty Vehicles								
Low Emission Vehicles	0.113	0.019	0.002	0.120	0.071	0.034	0.022	0.094
Tier 1	0.139	0.138	0.083	0.409	0.097	**0.047**	**0.024**	**0.163**
Tier 0	0.175	0.183	0.142	0.313	0.121	**0.218**	**0.194**	**0.183**
Oxidation Catalyst	0.111	0.113	0.088	0.194	0.145	**0.208**	**0.179**	**0.215**
Non-Catalyst Control	0.035	0.041	0.032	0.070	0.201	0.403	0.384	0.147
Uncontrolled	0.035	0.043	0.033	0.074	0.435	0.445	0.423	0.162
Diesel Passenger Cars								
Advanced	0.016	0.001	0.001	0.000	0.016	0.001	0.001	-0.003
Moderate	0.016	0.001	0.001	0.000	0.016	0.001	0.001	-0.003
Uncontrolled	0.016	0.001	0.002	-0.001	0.016	0.001	0.002	-0.003
Diesel Light Trucks								
Advanced	0.032	0.002	0.002	-0.001	0.016	0.001	0.002	-0.004
Moderate	0.032	0.002	0.002	-0.001	0.016	0.001	0.002	-0.004
Uncontrolled	0.032	0.002	0.002	-0.001	0.016	0.002	0.002	-0.004
Diesel Heavy-Duty Vehicles								
Advanced	0.048	**0.005**	**0.005**	**-0.002**	0.064	**0.004**	**0.006**	**-0.011**
Moderate	0.048	0.005	0.005	-0.002	0.081	0.004	0.006	-0.011
Uncontrolled	0.048	0.005	0.005	-0.002	0.097	0.004	0.006	-0.011
Motorcycles								
Non-Catalyst Control	0.007	0.007	0.005	0.012	0.209	0.067	0.064	0.024
Uncontrolled	0.007	0.009	0.007	0.015	0.418	0.090	0.085	0.033

Appendix A

Description of Test Data

EPA provided its contractor (ICF) with datasets with test results containing methane measurements:

- -- 13,277 FTP tests on 6,950 vehicles and
- -- 14,636 non-FTP tests on 2,963 vehicles,

and with datasets with test results containing nitrous oxide measurements:

- -- 95 FTP tests on 64 vehicles and
- -- 232 non-FTP tests on 74 vehicles.

The FTP tests that measured nitrous oxide emissions were primarily those performed by EPA, supplemented by tests performed by the University of California at Riverside CE-CERT, Southwest Research Institute (SwRI), and CARB.

The non-FTP tests included a hot running 505 which were used in this study to validate the approach used to separate the start and running emissions as well as several other driving cycles not utilized in this report. Methane tests were performed in various U.S. locations during the period between April 1982 and June 2000. Nitrous oxide tests were performed in various U.S. locations during the period between June 1998 and May 2002.

The analyses performed by ICF were limited to the FTP tests that were performed within the temperature range of 68 degrees to 86 degrees Fahrenheit (i.e., at a nominal temperature of 75° F).

Since the goal of ICF's analyses was to develop separate emission rates for both the running operation and engine starts, the analyses focused on the FTP tests since they contained both of those two types of vehicle operation.

Appendix B

Response to Peer Review Comments from Thomas Durbin

This report was formally peer reviewed by Thomas Durbin, Ph.D., Associate Research Engineer with the College of Engineering-Center for Environmental Research and Technology (CE-CERT) at the University of California-Riverside. In this appendix, comments from Thomas Durbin are reproduced in plain text, and EPA's responses to those comments are interspersed in indented italics.

* *

October 10, 2004

The following is a review of the IFC Consulting document "Update of Methane and Nitrous Oxide Emission Factors for On-Highway Vehicles" and the underlying datasets used in developing this document. This document is being used by the United States Environmental Protection Agency (US EPA) in the development of emissions factors for the EPA MOVES model. This review covers several relevant areas including the dataset completeness, methodology, and report clarity. The suggestions given in this review are to provide EPA guidance in moving forward and improving the emission factors for methane (CH_4) and nitrous oxide (N_2O) from vehicles.

Overall, the report appears to be satisfactory in characterizing CH_4 and N_2O emission factors based on the information provided in the EPA database. The primary concern with the updated emission factors is that there are still some gaps in the EPA database and there is also a need to develop emission factors for some categories by extrapolating data from more broadly tested categories using comparisons of CO_2 emissions. In reviewing the EPA datasets for CH_4 and N_2O, it was found that a number of studies with CH_4 and/or N_2O emissions measurements have not been included. It is suggested that the next step in improving the EPA emission factors for CH_4 and N_2O is to augment the current database with additional information from the literature, especially in under populated categories such as diesel vehicles. In the larger context of greenhouse gases (GHG), the contribution of CH_4 and N_2O emissions is still less than 5% of the total GHG contribution from mobiles sources; therefore, improvements in CO_2 estimates from vehicles should probably remain a higher priority.

RESPONSE: *The analyses for the MOVES2006 version will make use of all the available data.*

For the report itself, some description of how the emission factors will be implemented in the MOVES model would be useful. To provide additional detail to the report, it would be useful to include number of test points available in each vehicle category and a brief discussion of the datasets. A discussion of the criteria used in judging the statistical significance of the available data in particular categories could also be added. Finally, it is suggested that as the emissions factors are improved through the years that the potential effects of other parameters on CH_4 and N_2O emissions be considered. These could include fuel sulfur level, different driving cycles, vehicle mileage/age, and ambient temperature, with fuel sulfur level being one of the most important of these parameters.

RESPONSE: *The implementation of these emission factors is discussed in more detail in the report entitled "MOVES2004 Energy and Emissions Inputs.*

A more detailed commentary on different aspects of the report/underlying datasets is provided below. To address the EPA's primary areas of interest, this review is broken down into four main topics: completeness of data sources, overall methodology and analysis, additional factors to be considered in developing emission factors, and presentation and report clarity.

Completeness of datasets selected. The robustness of the underlying datasets in developing emission factors is essential in the overall accuracy of emissions inventories. The datasets used appear to be obtained from a larger database of emissions testing results maintained by EPA. While this database is sufficient CH_4 emissions for some of the larger categories, some additional data sources need to be considered in other N_2O and CH_4 categories. This is one of the most significant weaknesses of the methodology. Emissions results for CH_4 and N_2O from vehicles are reviewed by Lipman and Delucchi (2002) and in the discussion below.

The available emissions data for CH_4 emissions appears to be large enough for some of the more important categories (i.e., T1, T0, Ocat). The CH_4 data for LEV vehicles is relatively limited, however (7 LDGV and 10 LDGT). Is it possible that information on CH_4 emissions for late model vehicles can be obtained from certification data using the difference between THC and NMHC emissions? Other studies of fuel properties for LEV certified vehicles may also provide information on THC and NMHC emissions for late model vehicles (AAM/AIAM, 2001; Durbin et al., 2003), again using differences in THC and NMHC emissions to get CH_4. In the motorcycle category, The California Air Resources Board (CARB) has done testing on a series of 100 1966-1999 motorcycles (Jones, 2000). This report does not include CH_4 directly, but the CH_4 contribution to THC for motorcycles could be estimated from data of other sources to provide a better emission factor CH_4 for motorcycles.

For N_2O emissions, the database appears to be limited to tests conducted directly by EPA, some of the earlier work from the University of California at Riverside CE-CERT, and smaller number of tests from the Southwest Research Institute (SwRI) and CARB. Several more recent studies should be considered for inclusion, including those by Durbin et al. (2003) and Huai et al. (2002, 2003, 2004) that include approximately 20 LEV LDGVs and 10 LEV LDGTs. The limitations of the LEV N_2O emissions estimates are evident in comparing the emission factors for LDGV and LDGT. Specifically, on the basis of 5 test points, the emission factor for the LDGT is found to be less than that of the LDGVs, contrary to what is found with a more complete review of the literature (Huai et al., 2003). CARB has also characterized N_2O for a fleet of in-use vehicles (Behrentz et al. 2004). The individual vehicle results are not presented in this study, but may be available through CARB. Environment Canada has also collected N_2O emissions for a fleet of 21 1978-1996 vehicles (Graham, 1999). Becker et al. (1999) and Baronick et al. (2000) have conducted studies of 1996 and newer vehicles, although specific vehicle information is not included in the work by Becker et al. Michaels et al. (1998) also reviewed some earlier data sets that are not included in the current N_2O dataset used for this study, although in some cases the previous IPCC values based on these data are still used. Huai et al. (2003b) conducted a more recent review including these data sets as well as some more current information.

RESPONSE: *The analyses for the MOVES2006 version will make use of all the available data.*

The data on CH_4 and N_2O for diesel vehicles is limited to a small number of tests on medium-duty diesel trucks conducted at SwRI. There are some additional sources of data that should be considered for diesel vehicles, although even a more comprehensive literature review yields only a limited number of diesel test records for these specific emissions. Merritt (2003) of SwRI conducted a comprehensive literature review of diesel emissions data as part of Coordinating Research Council's (CRC) project No. AVFL-10A. They identified approximately 10 studies that include either CH_4 and/or N_2O diesel emissions data from vehicles or engines. For CH_4 emissions, several organizations have made measurements on heavy-duty diesel vehicles including West Virginia University (Gautam et al., 2003; Gautam et al., 1996), SwRI

(Ullman et al., 2003) and Ecotraffic of Sweden (Ahlvik and Brandberg, 2000). For light- to medium-duty vehicles, Schaurer et al. (1999) and researchers from Ford (Siegl et al., 1999) and CE-CERT (Durbin et al., 1999) have all made speciation hydrocarbon measurements, although methane emissions are not reported in all of these publications. For light-duty diesel vehicles, N_2O emissions have been measured by Ahlvik (2002), Fanick et al. (2001) of SwRI [which may be in the database], and Oyama and Kakegawa (2000).

RESPONSE: *The analyses for the MOVES2006 version will make use of all the available data.*

In examining the datasets, it is also useful to consider the stratification of the vehicle technology binning structure. The current stratification appears to be sufficient at the present time. As newer LEV II vehicles are introduced into the fleet, these categories should be reflected in the stratification structure. It may also be worthwhile in conducting some sensitivity studies on the older Tier 0 vehicles, since there was considerable evolution of vehicle technology over this time period (early 1980s to mid-1990s). While these vehicles will compose a progressively smaller fraction of the fleet over time, they can still represent a large fraction of the total emissions inventory. It would be useful to further break the Tier 0 group down into roughly 5 year periods based on model year (1980-1985, 1986-1990, and 1990 and newer) and compare the results with the composite emission factor.

RESPONSE: *As more data become available, we shall revisit the selection of model year groupings.*

Analysis and Overall Methodology - The methodologies used in this document are reasonable given the limitations of the datasets provided. As discussed above, there are areas where the EPA database is incomplete and additional data are available. This additional data should be used instead of extrapolating data from CO_2 for certain categories.

RESPONSE: *As more data become available, we shall use those data rather than relying on extrapolations.*

Separating the FTP emissions into start and running emissions. The separation of emissions into start and running emissions is a good idea since each represents an important segment of the emissions inventory. The comparisons of hot running 505s (HR505) and the bag 2 emissions indicate that the subtraction of bag 2 emissions is reasonable for determining start emissions, at least for CH_4 and N_2O.

Presently, the methodology characterizes start emissions as a combination of cold and hot starts. Some analysis should be performed to evaluate the differences between cold and hot start emissions for these pollutants to better understand whether the contribution of these emissions should be considered separately in the model. A quick review of the N_2O dataset by this reviewer indicated that the bag 1 emissions were very similar to those for bag 3 averaged over the entire fleet, but varied considerably from vehicle to vehicle. On this basis, using combined hot and cold start emissions for N_2O is probably adequate for fleet wide emissions. Similar analysis was not done for CH_4 emissions.

RESPONSE: *In estimating the HC, CO, and NOx emissions in the MOVES2006 version, we shall distinguish between hot-start and cold-start emissions. We shall use that opportunity to revisit our estimates of CH_4 and N_2O start emissions to determine whether to also distinguish between hot-start and cold-start for these emissions as well.*

Extrapolation of emission estimates from untested strata using CO2 emissions. While CO_2 and fuel use can be successfully used in some situations to predict emission rates of various pollutants, this relationship depends on a variety of factors such as the vehicle and emissions control technology, the operating conditions, and the emissions standard to which the vehicle is certified to. While relationships between fuel economy and particular emissions may be found under aggressive or off-cycle conditions, under FTP conditions emissions would primarily be related to the control technology required to meet the applicable emissions standards (which are not directly related to fuel economy). Nevertheless, there are some real differences in emissions control technology and emissions standards between passenger cars and trucks and vehicles in different weight classifications that have trends directionally consistent with increasing CO_2 emissions. It is uncertain, however, if these differences would best be obtained from straight comparisons of emissions standards or using CO_2 emissions.

RESPONSE: *In developing the MOVES2006 version of the model, we shall estimate the HC, CO, and NOx emissions. We shall use that opportunity to revisit our estimates of CH_4 and N_2O start emissions to determine whether to base those extrapolations on those estimates of HC, CO, or NOx emissions.*

N_2O emissions for a specific vehicle are not expected to correlate with CO_2 over a range of operating conditions. In fact, N_2O emissions tend to have higher formation rates at intermediate catalyst temperature ranges [250-450°C] that occur when the catalyst is warming up to its operation temperature. Under higher speeds or more aggressive driving conditions, where fuel use would be at a maximum, catalyst temperature would also be at a maximum and N_2O emissions would be low. This has been observed in several studies (Pringent and DeSeote, 1989; Hirano et al., 1992; Odaka et al., 1998; Koike et al., 1999, Huai et al., 2003).

For heavy-duty gasoline vehicles, only one N_2O test record for a Tier 0 truck was found in the database. In the almost complete absence of emissions test data, it is reasonable to expect that these vehicles would have higher N_2O emissions than lighter vehicles due to differences in emissions controls. As such, it seems reasonable N_2O emissions would increase in some proportionally to CO_2 emissions. It is worth noting that the single Tier 0 test record is lower than the emission factor given in Table 18 [55 vs. 183 mg/mi]. A limited number of tests on fairly old technology vehicles are also provided in Dietzmann et al. (1981). These data should probably be considered for comparison or possible inclusion.

For the non-catalyst technologies, it is agreed that previous IPCC N_2O emission factors should be used instead of extrapolating from CO_2 emissions for catalyst-equipped vehicles, since the formation of N_2O is more directly related to the catalyst than combustion conditions. Overall, the values for non-catalyst vehicles may be a little high, since the primary mechanism for forming N_2O is over the catalyst. In deriving the previous IPCC values for non-catalyst vehicles, Michaels et al. (1998) used results from three primary studies (Pringent and De Soete 1989; Dasch, 1992; Urban and Garbe, 1979). Of these studies, Pringent and De Soete (1989) reported FTP emission rates of approximately 50 mg/mi, considerably higher than the results observed in the other studies that were below 5 mg/mi (Dasch, 1992; Urban and Garbe, 1979). Perhaps the Pringent and De Soete (1989) data are outliers. Other studies have reported N_2O emission rates of 15-20 mg/mi for non-catalyst vehicles (Warner-Selph and Harvey, 1990; Robinson, 1991), while Huai et al. (2003) found an emission rate below 10 mg/mi for non-catalyst light-duty truck.

The oxidation catalyst N_2O emission factors are extrapolated from the Tier 0 results using CO_2 emission ratios since the data available in the EPA database was not statistically significant. Earlier estimates by Michaels et al. (1998) in the category, however, indicate that 11 vehicles records were available in the oxidation catalyst category (mostly LDGVs). It seems like using the direct N_2O measurements from oxidation catalysts for at least the LDGVs would be more appropriate than extrapolating the results from only 12 Tier 1 test points using CO_2.

The diesel section is somewhat confusing when the database is cross-referenced with the applicable text on N_2O emissions estimates. The database itself appears to only have 6 records for light-heavy-duty pick-up trucks. The text in section 4.1.5 mentions sanitation truck data that did not appear to be present in the database examined by this reviewer. Since diesel engines are typically not put in pick-up trucks smaller than those in the database, having a separate category for light-duty diesel trucks may not be needed. For light-duty diesel vehicles, Oyama and Kakegawa (2000) found emission rates of about 4-8 mg/mi. Ahlvik (2002) found much higher rates [on the order of 40 mg/mi], but expressed skepticism that these results were too high and could not rule out a mix-up in samples. The experimental values for light-duty diesel vehicles are higher than those obtained from extrapolating CO_2 measurements. For a complete inventory standpoint, however, N_2O emissions from light-duty diesel passenger cars are expected to make a small contribution.

<u>RESPONSE</u>: *The reviewer is correct about the sanitation trucks. There were none in that database. We revised the text by replacing "sanitation" truck with "light heavy-duty" truck.*

For CH_4 emissions, there is statistically significant data for all but the oldest light-duty vehicles, light-duty truck non-catalyst and uncontrolled trucks, and heavy-duty gasoline trucks. These vehicles probably make relatively small contribution to the inventory so estimates based on CO_2 emissions should be sufficient to provide factors in these categories. As discussed above, CARB has conducted some testing on motorcycles (Jones, 2000). It is suggested the THC emissions from this study be extrapolated to obtain the CH_4 estimates for motorcycles as opposed to estimates based on CO_2 emissions from light-duty gasoline cars.

For diesel vehicles, CH_4 emissions generally comprise a small portion of the overall THC emissions. Studies at SwRI on light-heavy-duty and heavy-heavy-duty diesel vehicles have shown CH_4 emissions to generally be below 10 mg/mi, and near background levels compared with the THC (Fanick et al., 2001; Ullman et al., 2003). Gautam et al. (2003) reported higher emission rates of ~40 to 140 mg/mi for a small set of tests on the UDDS in the E-55/59 program, with emissions going up to over 2 grams/mi for the "creep" portion of the CARB heavy-duty cycle. For light- and medium-duty vehicles, values reported by Siegl et al. (1999), Oyama and Kakegawa (2000), and Durbin et al. (1999) range from 1-20 mg/mi.

Statistical Significance – It is mentioned throughout section 4 that statistically significant emission factors could not be obtained for particular emission/technology categories. An examination of the N_2O database by this reviewer, however, indicated that in some of these categories, there was actually either no available data or only a single data point (i.e., N_2O emissions for HDGVs). A better explanation why data were classified as not statistically significant should be given (i.e., number of data points, variability of the data, etc.).

<u>RESPONSE</u>: *We revised the text to include that the reason for the lack of statistical significance was that only a <u>single</u> gasoline-fuel heavy-duty truck produced N_2O FTP emissions.*

Parameters used to characterize emissions.

The main parameters used in the IFC Consulting document for characterizing the emission factors for N_2O and CH_4 include the vehicle technology stratification, running emissions, and start emissions. There are several additional parameters that could be important to characterize for N_2O and CH_4 emission factors in future efforts.

Fuel S Effects

As fuel sulfur levels continue to be reduced nationally, it is important that these effects be evaluated or included in the estimates. A number of studies have shown that decreasing fuel sulfur level leads to significant reductions in N_2O emissions (Baronick et al. 2000; Huai et al, 2002; Michaels et al. 1998; Durbin et al. 2003). In reducing fuel sulfur levels from levels near 300 to levels closer to 30, reductions in N_2O emissions of more than 50% are often found. These changes should be considered in characterizing N_2O emissions in going forward. If possible, it would be useful to add the fuel sulfur level as a parameter in the N_2O database. These fuel sulfur effects would likely be stronger and more important when considering older data sets where higher sulfur fuels were more likely used. For example, measurements made by Ballantyne et al. (1994) on a fleet of Canadian vehicles were performed with a fuel with a 700 ppm sulfur level.

A number of studies have shown that for gasoline vehicles hydrocarbons can increase with fuel sulfur in the range of 5-800 ppm (AAM/AIAM, 2001; Korotney et al., 1995; Rutherford et al., 1995; Benson et al., 1991; Durbin et al., 2003). It is not known, however, if the effects of fuel sulfur on CH_4 have specifically been characterized. It is possible that CH_4 emissions may also increase with fuel sulfur. Since CH_4 emissions are more difficult to oxidize over the catalyst than other hydrocarbons, catalysts are generally not as effective in controlling CH_4 emissions compared to other hydrocarbons. As such, it is anticipated that the impact of fuel sulfur on CH_4 emissions would be smaller than its impact on THC emissions.

RESPONSE: *In estimating the HC, CO, and NOx emissions in the MOVES2006 version, we shall consider the effects on those emissions of the sulfur content of the fuel. We shall use that opportunity to revisit our estimates of CH_4 and N_2O emissions to determine if they are also sensitive to the sulfur content of the fuel.*

Driving cycles

There is no discussion about how emissions factors for different or off-cycle operating conditions would be implemented. For N_2O, emissions are expected to be a stronger function of catalyst temperature as opposed to operating condition. As such, start emissions that are already included are the most critical operating condition in characterizing N_2O emissions. Measurements of N_2O emissions for higher speed or more aggressive driving have generally shown that N_2O emission rates are low under these conditions (Dasch, 1992; Sasaki and Kameoka, 1992; Huai et al., 2002, 2003, 2004). Since there are not significant increases in N_2O emissions under aggressive operating conditions, the influence of operating conditions can be a lower priority parameter. The effects of different driving cycles would most likely track the effects of driving cycles on THC emissions, hence, these effects can probably be estimates based on THC emissions.

RESPONSE: *This analysis (by ICF) was limited to emissions produced over the standard FTP / LA-4 driving cycle. Speed / cycle adjustment factors are being studied for the MOVES2006 version of the model.*

Vehicle Mileage/Catalyst Age

Several studies have shown that vehicles with older catalysts can have higher emission rates of N_2O. These include studies where direct comparisons between older and newer catalysts were made on the same vehicle or under the same operating conditions and other studies where the comparisons were made between sets of newer vs. older vehicles. Jobson et al. (1994) and Odaka et al. (1998, 2000) both showed in laboratory studies that aged catalysts can result in increased N_2O emissions. Odaka et al. (2000) suggested that this could be attributed more to a decline in the ability of the catalyst to decompose N_2O than a reduction in the generation of N_2O. Odaka et al. (1998) found that the effect of catalyst age on

N_2O emission levels depended on the catalyst composition, with Pt/Rh and Pd catalysts with high metal contents showing little differences with catalyst age while Pt/Rh catalysts with low metal contents showed dramatic increases with catalyst age. Some studies have shown that N_2O formation also occurs at higher temperatures with aged compared to new catalysts (Odaka et al., 1998). It has been suggested that this could lead to higher actual N_2O vehicle emissions because a greater proportion of the driving cycle may occur in the higher temperature "window" of formation (Lipman and Delucchi, 2002).

In actual vehicle applications, the effects of catalyst age on N_2O emissions have been mixed. Odaka et al. (1998) found that N_2O emissions for a low Pt/Rh content passenger car increased under stabilized operating conditions after 30,000 miles of operation, but decreased under start conditions. De Soete (1993) found that N_2O emissions increased comparing a catalyst aged to 15,000 miles with a new catalyst. Durbin et al. (2003), on the other hand, found that catalyst age did not have a statistically significant effect on N_2O emissions in comparing 12 vehicles operated with new and aged catalysts. These vehicles were all late model and in the LEV category. In other studies, vehicles with higher mileage/older catalysts also represented older technologies so these data are more difficult to interpret (Ballantyne et al., 1994; Laurikko and Aakko, 1995).

It is expected that CH_4 emissions would also show deterioration with age. Lipman and Delucchi (2002) characterized CH_4 emissions from a variety of sources and observed that most data showed an increase in CH_4 emissions with catalyst age. They found that modern vehicles and fuels (e.g., 1990s vintage vehicles operating on reformulation fuels) showed emissions levels of 50 mg/mi under new conditions, rising to 150 mg/mi when the catalyst was significantly aged. For older three-way catalyst vehicles, they found these vehicles in a "new" condition had emission rates of approximately 100 mg/mi, increasing to 300 mg/mi with higher age.

RESPONSE: *In estimating the HC, CO, and NOx emissions in the MOVES2006 version, we shall consider the effects on those emissions of vehicle age and/or mileage accumulation. We shall use that opportunity to revisit our estimates of CH_4 and N_2O emissions to determine if they are also sensitive to vehicle age and/or mileage accumulation.*

5.1 Ambient Temperature Effects

Ambient temperature is known to have impacts on regulated emissions, with emissions increasing at colder temperatures. Few studies have directly looked at ambient temperature effects on CH_4 and N_2O emissions. Ahlvik (2002) looked at the effects of temperature between –7 and 22°C on N_2O emissions for 2 light-duty gasoline and 2 light-duty diesel vehicles. The lower temperature results only showed a large increase for one of the gasoline vehicles, with slight changes for two other vehicles. Stump et al. (1989, 1990) looked at temperature and oxygenated fuel effects on CH_4 emissions. THC emissions decreased slightly as the temperature was increased from 40 to 90°F, with CH_4 emissions proportionally changing with THC. These results suggest the effects of temperature on CH_4 emissions can be estimated from the effects of temperature on THC.

RESPONSE: *This analysis (by ICF) was limited to emissions produced within the standard FTP temperature range (68 to 86 degrees Fahrenheit). Temperature adjustment factors will be developed for the MOVES2006 version of the model.*

Presentation and Report Clarity. Some additional details and information would help to clarify some of the steps of the methodology and how the emission factors will be implemented.

The level of detail used in describing the data sources is very limited. It would be useful to have some description of the data sources to give the reader an idea of what data may have been included/excluded. In the EPA's "Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-2001" document (US EPA, 2003), a short discussion of data sets is provided in appendix E. Something similar could be added here. For the CH_4 data, it would be useful to include descriptions of some of the larger data sources, since considerably more records are available for CH_4. For N_2O, since data is limited, the specific sources could even be listed as done in the US EPA (2003) document. It would also be useful to have a table of the number of vehicles used in each technology for each of the pollutants, instead of just the information provided in footnote 3 on page 4.

RESPONSE: *Appendix A has been added to this report to provide a brief description of the test data used by ICF to produces these estimated emission rates.*

It would be useful to provide a brief one or two paragraph description of the how the emission factors will be implemented in to the EPA MOVES model. If not, a reference to where more details on the model can be found. How are running and start emissions going to be implemented into the model? How will the running emissions be implemented in terms of the MOVES modal binning structure? Finally, emissions are broken down into g/mi and g/hour, but there is no discussion on how the g/hour would be implemented into the model.

RESPONSE: *The discussion of how these emission rates are incorporated into the MOVES model appears in the MOVES technical report entitled "MOVES2004 Energy and Emissions Inputs."*

A description of the technology categories is provided, but no information is provided on the different weight categories used (i.e., light-duty vs. heavy-duty).

GRAMMAR

1. p 4 – paragraph below equation 1. line 9. There is an extra period after - segments of the FTP.

2. p. 19 – Table 23. Is the first entry under the emission control technology supposed to be non-catalyst instead of moderate?

RESPONSE: *The reviewer is correct on both points. The text has been corrected.*

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