Emissions of Ammonia from Light-Duty Vehicles

Thomas D. Durbin,* Ryan D. Wilson, Joseph M. Norbeck, J. Wayne Miller, Tao Huai, and Sam Rhee

Bourns College of Engineering, Center for Environmental Research and Technology (CE-CERT), University of California, Riverside, CA 92521

ABSTRACT

Emissions of NH_3 were measured with the FTP cycle for 39 vehicles ranging in technology from non-catalyst and Tier 0 vehicles to ULEV vehicles. NH_3 measurements were performed using Fourier Transform Infrared spectroscopy (FTIR). Results showed that NH_3 emissions averaged 54 mg/mi with a range from <4 to 177 mg/mi. NH_3 emissions did not necessarily decline significantly like those of the regulated pollutants with progressive improvements in emission control systems. A subset of 5 vehicles was tested over the US06, NYCC, and a high-speed freeway cycle for comparison with the FTP cycle. NH_3 emissions showed a strong cycle dependence, with increased emissions under more aggressive driving conditions, consistent with the formation of higher NH_3 emissions under richer conditions. The onset of NH_3 emissions typically occurred after catalyst light off, near when the catalyst reached its equilibrium temperature. Initial studies showed that NH_3 emissions decreased as the sulfur content in the fuel was increased.

1.0 Introduction

As ambient air quality standards become increasingly stringent, the role of unregulated vehicle emissions is becoming more important. Ammonia (NH_3) is one compound that has received attention recently. Studies of NH_3 emissions from vehicle exhaust date back to the late 1970s.[1-3] More recently, several studies have indicated that NH_3 emissions from vehicles may be greater than previous thought, although there is a range of estimates for NH_3 emissions. These include studies in tunnels,[4,5,6] remote sensing studies,[7] using chassis dynamometers,[8,9,10] and using dedicated vehicles.[11]

Mobile sources are the third largest component of the NH_3 emissions inventory in the South Coast Air Basin (SoCAB) that surrounds Los Angeles representing approximately 18% of the inventory.[12] Based on tunnel measurements made by Fraser and Cass, the emissions factors were found to be 33.2 tons/day in SoCAB.[12] For comparison, the emission factor for livestock, the largest single contributor, was found to be 60.37 tons/day. [12] From an air quality standpoint, NH_3 is unregulated but it is an important precursor gas that can react in the atmosphere to produce particulate matter (PM), such as ammonium nitrate (NH_4NO_3) or ammonium sulfates (NH_4SO_4, $NH_4(SO_4)_2$). Analysis of ambient PM indicates that ammonium composed from 14.0 to 17.0% of the total fine PM ($PM_{2.5}$) at various locations in SoCAB.[13]

To better quantify the vehicle contribution to the NH_3 inventory, it is important to have a robust database of NH_3 emission rates from vehicles. The objective of this study was to measure the emission levels of NH_3 from an in-use fleet of vehicles. For this project, 39 vehicles were tested over the FTP cycle. This included Low Emission Vehicles (LEVs) that will compose a larger portion of the in-use fleet over the next 5 to 10 years. A subset of 5 of these vehicles was also tested over the US06, New York City Cycle (NYCC), and a high speed freeway cycle for comparison. Additional experiments were also conducted to evaluate the repeatability of NH_3 measurements and the impact of fuel sulfur levels on NH_3 emissions. Measurements were conducted using Fourier Transform Infrared spectroscopy (FTIR), which can measure mass emission rates of compounds like NH_3 in near real-time as shown by researchers at the Ford Motor Company and elsewhere for nearly two decades.[14] The results of this study are described in further detailed in the following paper.

2.0 Experimental Procedures

2.1 Vehicle Recruitment

The 39 test vehicles were recruited from several sources including private owners, the University of California at Riverside campus fleet, and rental car companies. A breakdown of the test vehicles by manufacturer is provided in Table 1 with a more complete vehicle description provided in Appendix A. Although the primary goal of the project was to measure NH_3 in conjunction with CE-CERT's on-going projects, the test matrix shows that a reasonable distribution of the major manufacturers was obtained. This study focused primarily on newer cars with all but 5 of the vehicles being 1990 and newer model years. For the 1990 and newer vehicles, the average age of the test fleet was 1996. The test matrix also included a range of different emissions control technology levels including 14 pre-Tier 1 vehicles, 11 Tier 1 vehicles, 8 TLEV vehicles, 1 NLEV vehicle, 2 LEV vehicles, and 3 ULEV vehicles.

2.2 Protocol for Vehicle Testing

All vehicles were tested over one Federal Test Procedure (FTP) to obtain mass emission rates for total hydrocarbons (THC), non-methane hydrocarbons (NMHC), carbon monoxide (CO), nitrogen oxides (NO_x), and NH_3. Replicate FTPs were performed on 5 of these vehicles. A subset of 5 vehicles was also tested over the US06, New York City Cycle (NYCC), and a high speed freeway cycle. For two vehicles, some initial tests were also conducted to evaluate the potential impact of fuel sulfur levels on NH_3 emissions. The regulated pollutants were measured using the standard techniques as outlined in the Code of Federal Regulations for the FTP (CFR Part 86, Subpart B).

NH_3 emissions were collected using a Pierburg AMA/Mattson FTIR system. The FTIR samples from the dilution tunnel and makes one measurement every three seconds. The minimum detection limits for NH_3 were 4 mg/mi over the FTP cycle. The absorption cell for the FTIR has a volume of 5 liters and the residence time in the cell is approximately 10 seconds. To adjust the model emissions data to correct for this time response, a well-mixed flow cell model is used. The use of a well-mixed flow cell model for analysis of modal emissions data is described in greater detail by Truex et al.[15] A three-second data average is also applied to the data prior to using the well-mixed flow cell model.

All tests were conducted in CE-CERT's Vehicle Emission Research Laboratory (VERL) equipped with a Burke E. Porter 48-inch single-roll electric dynamometer. Sampling was conducted using VERL's 10 inch diameter dilution tunnel and CVS flow rates of 350 SCFM. Since ammonia is a relatively reactive compound, a heating pad maintained at a temperature of 250ºF was wrapped around the transfer tube for some of the experiments to minimize the loss of ammonia through the sampling system. A comparison of tests run with and without the heating pad showed no difference in the observed NH_3 emission levels, however.

All but 5 vehicles were tested with the gasoline in the tank at the time the vehicle was procured for testing. Since the specifications for California Phase 2 gasoline are relatively narrow and must provide equivalent emissions under California's Predictive Model, any effects due to testing with in-tank fuel should be negligible. The other vehicles were tested on California Phase 2 certification fuel (2 vehicles) and industry average RFA gasoline (3 vehicles). For two vehicles, tests were also conducted at two different sulfur levels. These fuels were certification grade California Phase 2 gasoline with nominal sulfur levels of 30 and 330 ppmw. These fuels were obtained from Philips Petroleum Chemical Company in Borger, TX. The vehicles for the fuel sulfur tests were preconditioned using procedures used in previous Auto/Oil research programs.[16]

3.0 Emissions Test Results

A summary of the FTP emission results is provided in Table 2 for the 39 vehicle test fleet. More detailed emissions results for these vehicles are provided in Appendix A. These results show that NH_3 emissions ranged from <4 to 177 mg/mi with an of averaged 54 mg/mi. These NH_3 emission levels are similar to those found in previous studies. Chassis dynamometer tests conducted on a fleet of 75 in-use Canadian and United States (US) vehicles over a hot 505 cycle showed a range in NH_3 emissions from <1 mg/mi to nearly 300 mg/mi.[8] The present results are also very comparable to results obtained in tunnel studies, being slightly lower than those found by Fraser and Cass (116 mg/mi)[4] and Kean et al. (79 mg/mi)[5] and slightly higher than those found by Gertler et al. (15.1 ± 4.3 mg/mi)[6]. Given the differences that can be found in the fleet composition and testing conditions for the various studies, these reported NH_3 emissions rates show relatively good comparability. Overall, the results are consistent with those of previous studies showing that while NH_3 emissions from vehicles are below those of the regulated pollutants, they can still make an important contribution to the overall inventory.

Results of replicate NH_3 measurements are presented in Table 3. In general, the replicates indicate that NH_3 emissions are probably repeatable within 10 to 20%, although for one vehicle the variability appeared to be considerably greater.

A histogram of the NH_3 emissions is presented in Figure 1. These data show that NH_3 emissions for 12 of the 39 vehicles were 10 mg/mi or less. Above this level, there was considerable range in the emission levels, indicating that NH_3 emissions can vary significantly based on vehicle technology and control strategy. The individual vehicle data for some of the highest NH_3 emitting vehicles are presented in Table 4. These data show that, in some cases, NH_3 emissions can have emissions similar to those of other regulated pollutants such as THC and NO_x.

Average emission results for THC, CO, NO_x, and NH_3 are presented in Figure 2 as a function of vehicle certification category. These results show that the emission levels for regulated pollutants have decreased significantly over the years. NH_3 emissions, however, did not necessarily decline as significantly for the range of technology categories tested. As shown in Table 4, the highest NH_3 emitters came from range of vehicle technology categories including Tier 0, Tier 1 and TLEV. It is still important to note, however, that only a few vehicles were tested for the low emission vehicle technology categories and that more data would be needed to provide a more definite comparison of NH_3 emissions for different technology categories. It should also be noted that most of the LEV and ULEV vehicles did have NH_3 emissions near the detection limit.

NH_3 emissions for the US06, NYCC, and the high-speed freeway cycles are presented in Figure 3. Similar to other regulated pollutants, NH_3 emissions were found to increase significantly over the more aggressive driving cycles. This is true even for vehicles that have relatively low levels of NH_3 emissions over the FTP. The results are consistent with previous studies, which have shown that NH_3 emissions can increase significantly under rich operating conditions.[3,11]

NH_3 modal emissions plotted against vehicle speed are presented in Figure 4 for the FTP and in Figure 5 for the US06, NYCC, and the high-speed freeway cycle for one of the test vehicles. The modal emissions show the transient nature of the NH_3 emissions throughout the driving cycle.

The modal data show the onset of NH_3 emissions occurs after catalyst light off, consistent with the formation of NH_3 over the catalyst surface. Experiments conducted on a separate vehicle where the catalyst bed temperature was monitored indicate that NH_3 emissions tend to occur as the catalyst gets closer to its equilibrium temperature rather than during the initial portion of catalyst light off.

Initial tests were conducted on two vehicles with gasoline containing sulfur levels of 30 and 330 ppmw over the FTP and US06. The results of these tests are presented in Table 5. Although the data are limited, for each of the vehicle/cycle combinations, higher NH_3 emissions were observed for each test(s) with the lower fuel sulfur level. Since NH_3 is primarily formed over the catalyst, these results suggest that sulfur could inhibit NH_3 formation on the catalyst by poisoning reaction sites for NH_3 formation.[17] Early engine dynamometer and simulated exhaust gas experiments have shown that increasing SO_2 concentrations in the exhaust suppresses the formation of NH_3.[18,19] Chassis dynamometer measurements on two vehicles, however, showed that decreasing fuel sulfur content resulted in lower NH_3 emissions for one vehicle and had little effect on NH_3 emissions for the second vehicle.[9] The effect of gasoline sulfur levels on NH_3 emissions will be investigated more extensively in two upcoming studies in our laboratory.[20,21]

4.0 Summary and Conclusions

For the present program, a total of 39 vehicles were tested over the FTP with emissions measured for NH_3 using an FTIR. A subset of 5 vehicles was also tested over the US06, NYCC, and high speed freeway cycle. The major results of this study are:

- NH_3 FTP emissions for the vehicles tested ranged from <4 to 177 mg/mi and averaged 54 mg/mi. Of the 39 test vehicles, 12 had emissions below 10 mg/mi while the emissions from the remaining vehicles varied significantly depending on the specific vehicle. NH_3 emissions were comparable to those observed in previous studies and indicate that vehicles could be an important source for NH_3 emissions.

- NH_3 emissions did not necessarily decline significantly like those of the regulated pollutants with progressive improvements in emission control systems.

- NH_3 emission levels increased significantly for the more aggressive US06, NYCC, and high speed freeway cycles. This is consistent with previous studies that have shown increases in NH_3 emissions during periods of richer operation.

- Modal emissions showed that the onset of NH_3 emissions typically occurred after catalyst light off and near when the catalyst reached its equilibrium temperature.

- Initial studies showed that NH_3 emissions decreased as the sulfur content in the fuel was increased over the FTP and US06 cycles.

5.0 Acknowledgments

The authors acknowledge the contribution and support of the following individuals during the course of this project: Dave Martis, Joseph Calhoun, and Ross Rettig and Joe Valdez of the Vehicle Emissions Research Laboratory (CE-CERT) performed the emissions testing on the vehicles. We also thank the United States Environmental Protection Agency for its financial and technical support of this project under cooperative agreement No. CX827692-01-0.

6.0 References

1. Bradow, R.L. and Stump, F.D. (1977) SAE Technical Paper No. 770369.

2. Cadle, S.H., Nebel, G.J., and Williams, R.L. (1979) SAE Technical Paper No. 790694.

3. Cadle, S.H. and Mulawa, P.A. (1980) *Environ. Sci. & Technol*. Vol. 14, p. 718-723.

4. Fraser, M.P., and Cass, G.R. (1998) Detection of Excess Ammonia Emissions from In-Use Vehicles and the Implications for Fine Particle Control. *Environ. Sci. & Technol*. Vol. 32, pp 1053-1057.

5. Kean, A.J., Harley, R.A., Littlejohn, D., and Kendall, G.R. (2000) On road Measurement of Ammonia and Other Motor Vehicle Exhaust Emissions, *Environ. Sci. & Technol*. Vol. 32, pp. 3535-3539.

6. Gertler, A.W., Sagebiel, J.C., and Cahill, T.A., (2001) Measurements of Ammonia Emissions from Vehicles in a Highway Tunnel. Proceedings of the 11th CRC On-road Vehicle Emissions Workshop, San Diego, CA, March.

7. Baum, M.M., Kiyomiya, E.S., Kumar, S., Lappas, A.M., and Lord, H.C. III (2000) Multicomponent Remote Sensing of Vehicle Exhaust by Dispersive Absorption Spectroscopy. 1. Effect of Fuel Type and Catalyst Performance," *Environ. Sci. & Technol.*, vol. 34, pp. 2851-2858.

8. Graham, L. Gaseous and Particulate Matter Emissions from In-Use Light Duty Gasoline Motor Vehicles. Report # 99-67, Environment Canada, Environmental Technology Centre, Emissions Research and Measurement Division.

9. Baronick, J., Heller, B., Lach, G., and Ramacher, B. (2000) Impact of Sulfur in Gasoline on Nitrous Oxide and Other Exhaust Gas Components. SAE Technical Paper No. 2000-01-0857.

10. Klingenberg, H and Schürmann, D. (1989) Unregulated Motor Vehicle Exhaust Gas Components. Report by Volkswagen AG.

11. Shores, R.C. Walker, J., Kimbrough, S., McCulloch, Rodgers, M.O., and Pearson, J.R. (2000) Measurement of Ammonia Emissions from EPA's Instrumented Vehicle. Proceedings of the 10th CRC On-Road Vehicle Emissions Workshop, San Diego, CA, March.

12. Chitjian, M., Koizumi, J., Botsford, C.W, Mansell, G., and Winegar, E. (2000) Final 1997 Gridded Ammonia Emission Inventory Update for the South Coast Air Basin. final Report to the South Coast Air Quality Management District under Contract No. 99025, August.

13. Kim, B.M., Teffera, S., and Zeldin, M.D., (2000) Characterization of PM2.5 and PM10 in the South Coast Air Basin of Southern California: Part 1-Spatial Variations. *J. Air & Waste Manage. Assoc.*, vol 50, pp. 2034-2044..

14. Butler, J.W.; Maker, P.D.; Korniski, T.J.; and Haack, L.P. (1981) On-line Characterization of Vehicle Emissions by FTIR and Mass Spectrometry. SAE Technical Paper No. 810429.

15. Truex, T.J.; Collins, J.F.; Jetter, J.J.; Knight, B.; Hayashi, T.; Kishi, N.; and Suzuki, N. (2000) Measurement of Ambient Roadway and Vehicle Exhaust Emissions-An Assessment of Instrument Capability and Initial On-Road Test Results with an Advanced Low Emission Vehicle. SAE Technical Paper No. 2000-01-1142.

16. Burns, V.R., Benson, J.D., Hochhauser, A.M., Koehl, W.J., Kreucher, W.M., Rueter, R.M. (1991) Description of Auto/Oil Air Quality Improvement Research Program. SAE Technical Paper No. 912320.

17. Ganhdi, H.S. and Shelef, M. (1991) Effects of Sulphur on Noble Metal Automotive Catalysts. *Applied Catalysts*, Vol. 77, pp. 175-186.

18. Ganhdi, H.S., Piken, A.G., Stepien, H.K., Shelef, M., Delosh, R.G., and Heyde, M.E., (1977) SAE Technical Paper No. 770196.

19. Summers, J.C. and Baron, K. (1979) The Effects of SO_2 on the Performance of Noble Metal Catalyst in Automotive Exhaust. *Journal of Catalysis*, Vol. 57, pp. 380-389.

20. Durbin, T.D. additional work to be completed under EPA cooperative agreement CX-827692-01-1, "Investigation of Emission Rates of Ammonia and Other Toxic and Low-Level Compounds as a Function of Gasoline Sulfur Content."

21. Durbin, T.D., Miller, J.W., and MacKay, G.I., "Ammonia Emissions from Late-Model Vehicle," project for the Coordinating Research Council under contract E-60.

Table 1 List of Test Vehicles by Manufacturer

Manufacturer	Passenger Car	LD Truck
GM	3	9
Ford	4	5
Chrysler	3	1
Honda	6	0
Toyota	2	2
Nissan	2	0
Other	1	1

Table 2. Average FTP Emission Results

	THC g/mi	CO g/mi	NO_x g/mi	NH_3 g/mi
Average	0.488	7.259	0.590	0.054
Median	0.183	2.312	0.247	0.046
High	4.938	116.98	3.709	0.177
Low	0.033	0.372	0.058	<0.004

Table 3. Replicate Ammonia FTP Emissions

		NH_3 Emissions (mg/mi)	
	Cycle	**Test 1**	**Test 2**
1992 Tier 0 PC FFV	**FTP**	**118**	**119**
1992 Tier 0 PC FFV	**US06**	**196**	**224**
1993 Tier 0 PC	**FTP**	**36**	**18**
1989 Tier 0 Van	**FTP**	**64**	**52**
1989 Tier 0 PC	**FTP**	**<MDL**	**<MDL**

Table 4. Individual Vehicle Data for the Highest NH_3 Emitting Vehicles

	THC (mg/mi)	**NO_x (mg/mi)**	**NH_3 (mg/mi)**
1996 TLEV SUV	**103**	**535**	**177**
1995 Tier 1 PC	**284**	**235**	**157**
1993 Tier 0 PC	**943**	**1,394**	**155**
1996 Tier 1 PC	**153**	**123**	**144**
1992 Tier 0 FFV PC	**165**	**172**	**119**
1997 Tier 1 Van	**267**	**412**	**118**
1991 Tier 0 PC	**330**	**1812**	**111**
1996 Tier 1 PC	**300**	**258**	**109**
1993 Tier 1 SUV	**203**	**410**	**95**
1998 TLEV LDT	**103**	**233**	**88**

Table 5. Emissions of NH_3 and Regulated Components at 2 Sulfur Levels

Vehicle	Cycle	S Level	THC g/mi	NMHC g/mi	CO g/mi	NO_x g/mi	NH_3 g/mi
1992 Tier 0 FFV PC	FTP	30	0.177	0.138	2.791	0.176	0.118
	FTP	30	0.152	0.119	2.364	0.167	0.119
		Average	0.165	0.129	2.578	0.172	0.119
	FTP	330	0.211	0.161	3.250	0.226	0.086
	US06	30	0.225	0.164	9.984	0.619	0.195
	US06	30	0.289	0.227	11.870	0.599	0.224
		Average	0.257	0.196	10.927	0.609	0.210
	US06	330	0.322	0.246	13.184	0.805	0.161
1997 TLEV PC	FTP	30	0.054	0.051	0.514	0.058	0.038
	FTP	330	0.061	0.057	0.596	0.060	0.005
	US06	30	0.085	0.064	11.710	0.225	0.237
	US06	330	0.093	0.074	10.407	0.216	0.146

Figure 1. Histogram of the NH_3 Emissions

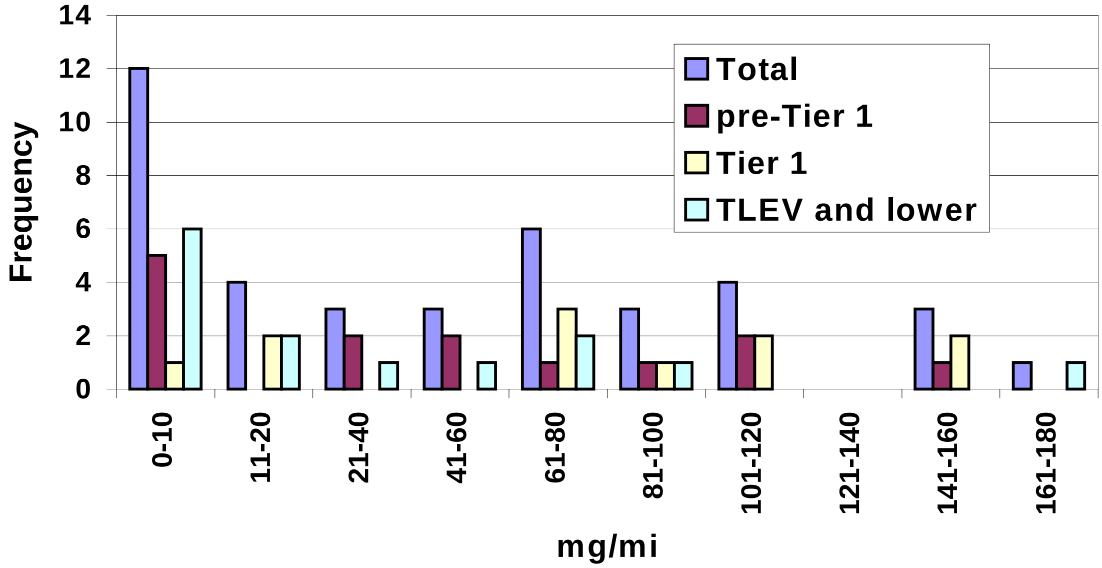


Figure 2. Average Emission Results for THC, CO, NO_x, and NH_3

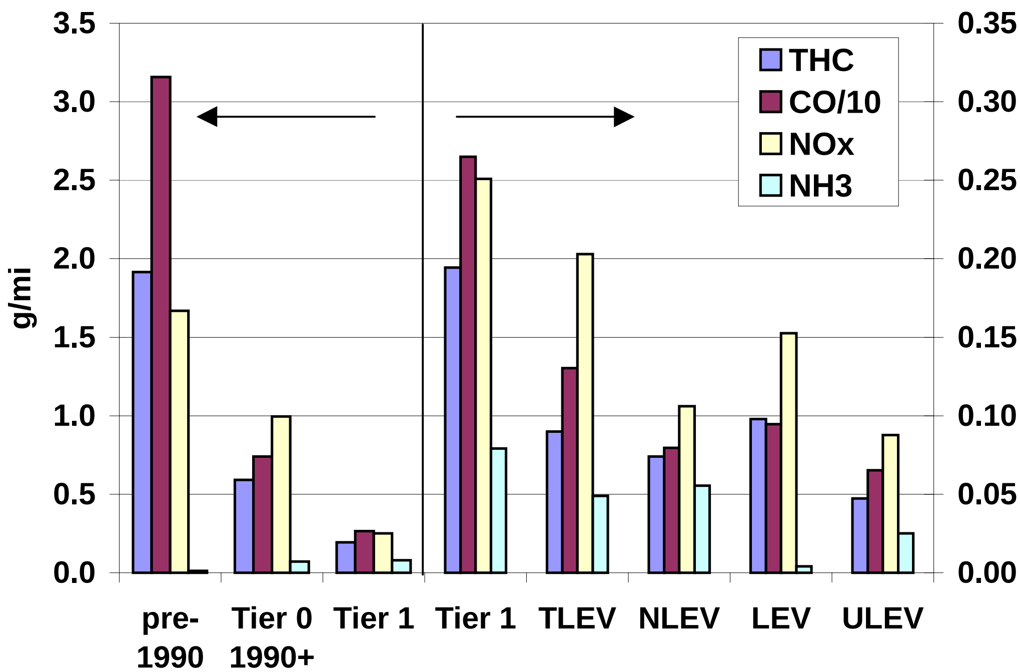


Figure 3. NH_3 Emissions for FTP, US06, NYCC and High Speed Freeway Cycles

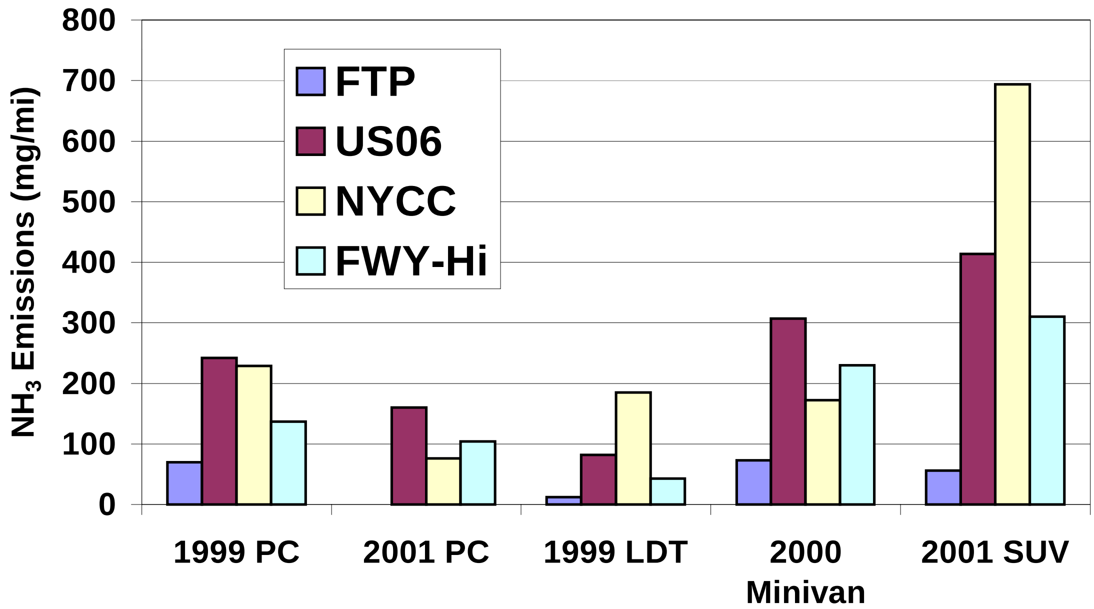


Figure 4. NH_3 vs Speed for FTP Cycle

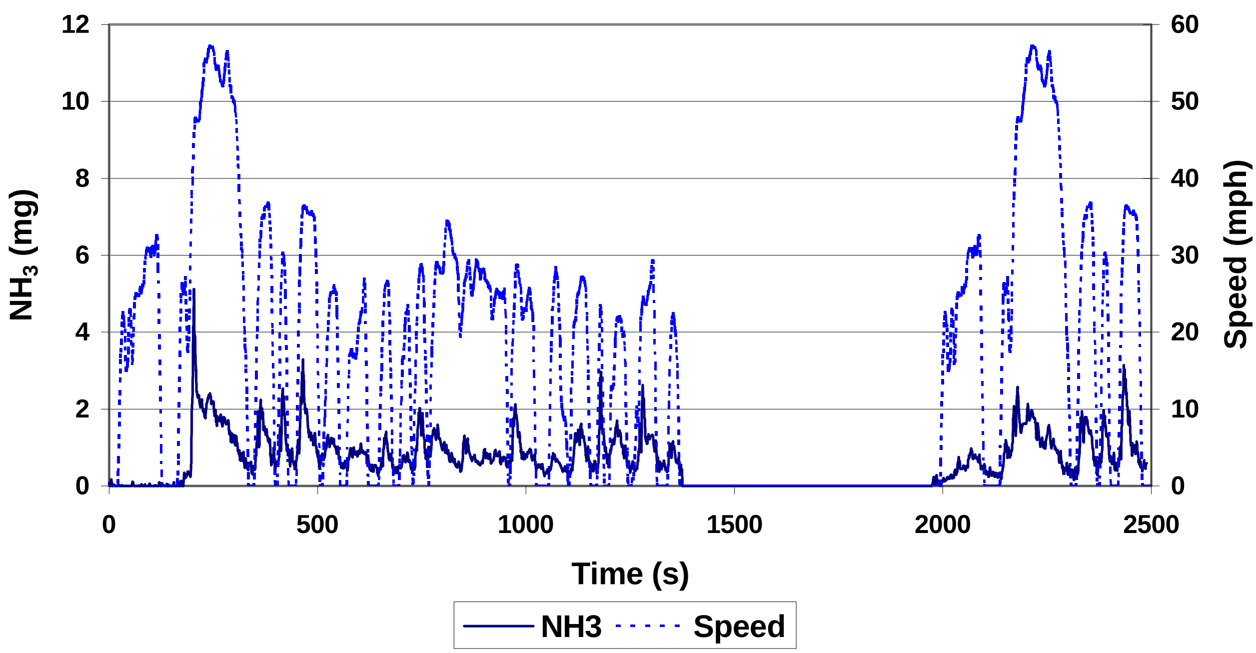
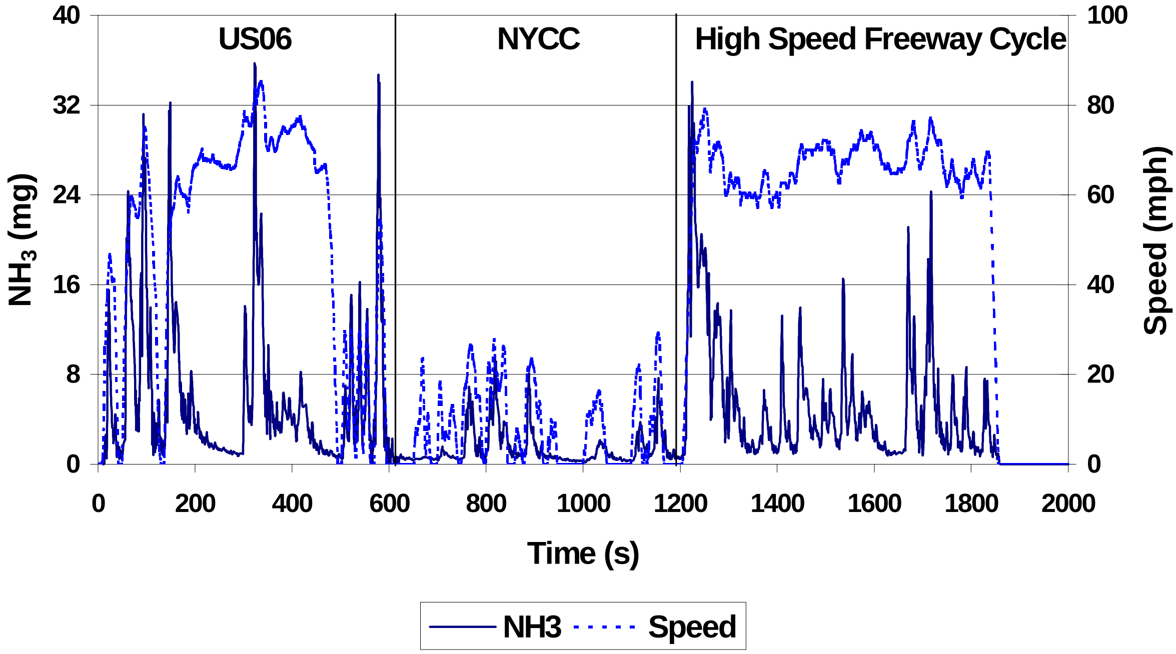


Figure 5 NH_3 vs Speed for US06, NYCC and High Speed Freeway Cycles



Appendix A. FTP Results for Individual Vehicles

Number	vehicle	class	cert	Odometer	Fuel	NH_3 g/mi	THC g/mi	NO_x g/mi	CO g/mi
1	1998 Honda Accord	PC	ULEV	2,402	CA RFG (in-use)	0.001	0.033	0.109	0.461
2	2000 Ford Windstar	LDT	ULEV	26,401	CA RFG (in-use)	0.073	0.036	0.077	0.489
3	2001 Buick LeSabre	PC	ULEV	9,986	CA RFG (in-use)	0.000	0.073	0.077	1.010
					ave	0.025	0.047	0.088	0.653
4	1997 Toyota Camry LE	PC	LEV	110,332	CA RFG (in-use)	0.005	0.122	0.146	0.943
5	1998 Nissan Altima GXE	PC	LEV	22,460	CA RFG (in-use)	0.003	0.074	0.159	0.949
					ave	0.004	0.098	0.153	0.946
6	2001 Suzuki Grand Vitara	SUV	NLEV	10,311	CA RFG (in-use)	0.056	0.074	0.106	0.795
7	1997 Ford Escort	PC	TLEV	5,403	CA RFG (cert)	0.038	0.054	0.058	0.514
8	1999 Toyota Tacoma	LDT	TLEV	30,204	CA RFG (in-use)	0.011	0.132	0.297	1.888
9	1999 GMC SonomaSL	LDT	TLEV	1,677	CA RFG (in-use)	0.000	0.044	0.079	0.426
10	1999 Dodge Stratus	PC	TLEV	19,080	CA RFG (in-use)	0.001	0.100	0.123	0.372
11	1998 Ford Ranger	LDT	TLEV	25,599	CA RFG (in-use)	0.088	0.103	0.233	1.471
12	1997 Honda Accord LX	PC	TLEV	75,132	CA RFG (in-use)	0.062	0.091	0.205	1.211
13	1999 GMC Sonoma	LDT	TLEV	10,610	CA RFG (in-use)	0.012	0.092	0.093	1.284
14	1996 Ford Explorer	SUV	TLEV	38,791	CA RFG (in-use)	0.177	0.103	0.535	3.257
					ave	0.049	0.090	0.203	1.303
15	1997 Dodge 3500 Van	LDT	Tier 1	40,678	CA RFG (in-use)	0.118	0.267	0.412	3.848
16	1996 Honda Civic	PC	Tier 1	58,755	CA RFG (in-use)	0.144	0.153	0.123	1.828
17	1996 Ford F150	LDT	Tier 1	133,524	CA RFG (in-use)	0.015	0.190	0.114	1.876
18	1999 Toyota Tacoma	LDT	Tier 1	27,289	CA RFG (in-use)	0.011	0.175	0.204	2.300
19	1995 Honda Civic	PC	Tier 1	108,008	CA RFG (in-use)	0.157	0.284	0.235	4.466
20	1998 Chevy S10	LDT	Tier 1	29,663	CA RFG (in-use)	0.070	0.194	0.287	5.353
21	1993 Ford ExplorerXLT	SUV	Tier 1	100,887	CA RFG (in-use)	0.095	0.203	0.410	2.959
22	1996 Honda Accord DX	PC	Tier 1	81,237	CA RFG (in-use)	0.076	0.106	0.258	1.479
23	1999 Ford Contour	PC	Tier 1	15,254	CA RFG (in-use)	0.070	0.090	0.152	0.807
24	1996 Ford Taurus	PC	Tier 1	68,154	CA RFG (in-use)	0.109	0.300	0.258	2.282
25	1997 GMC Sonoma	LDT	Tier 1	64,915	CA RFG (in-use)	0.007	0.176	0.306	1.951
					ave	0.079	0.194	0.251	2.650
26	1992 Dodge Spirit FFV	PC	1990+/Tier 0	15,264	CA RFG (cert)	0.118	0.177	0.176	2.791
replicate	1992 Dodge Spirit FFV		1990+/Tier 0		CA RFG (cert)	0.119	0.152	0.167	2.364
27	1994 Chevy Suburban	SUV	1990+/Tier 0	93,986	CA RFG (in-use)	0.046	1.660	2.041	17.029
28	1993 Nissan 240SX	PC	1990+/Tier 0	89,924	CA RFG (in-use)	0.084	0.286	0.617	4.555
29	1991 GMC Sonoma	LDT	1990+/Tier 0	103,245	CA RFG (in-use)	0.068	0.601	0.631	11.619
30	1993 Dodge Intrepid	PC	1990+/Tier 0	139,688	CA RFG (in-use)	0.036	0.528	1.030	4.049
replicate	1993 Dodge Intrepid		1990+/Tier 0		CA RFG (in-use)	0.018	0.609	1.023	4.475
31	1992 Toyota Corolla	PC	1990+/Tier 0	105,418	RFA	0.003	0.305	0.556	2.323
32	1990 Ford Thunderbird	PC	1990+/Tier 0	164,380	RFA	0.035	0.461	0.700	10.529
33	1991 Honda CRX	PC	1990+/Tier 0	166,205	CA RFG (in-use)	0.111	0.330	1.812	5.759
34	1993 Mazda Protégé LX	PC	1990+/Tier 0	106,782	CA RFG (in-use)	0.155	0.943	1.394	7.980
					ave	0.072	0.591	0.994	7.404

Appendix A. FTP Results for Individual Vehicles

Number	Vehicle	class	cert	Odometer	Fuel	NH_3 g/mi	THC g/mi	NO_x g/mi	CO g/mi
35	1989 Chevy G20	LDT	Pre-1990/Tier 0	88,771	RFA	0.064	1.155	0.748	12.021
replicate	1989 Chevy G20			88,771	RFA	0.052	1.355	0.850	11.328
36	1989 Chevy Celebrity	PC	Pre-1990/Tier 0	166,316	RFA	0.000	1.419	1.349	8.534
replicate	1989 Chevy Celebrity			166,316	RFA	0.000	1.492	1.373	9.089
37	1988 Chevy C-20 truck	LDT	Pre-1990/Tier 0	28,547	CA RFG (in-use)	0.000	0.533	0.734	5.241
38	1983 Olds Delta 88	PC	Pre-1990/Tier 0	95,541	CA RFG (in-use)	0.003	1.394	1.741	15.240
39	1968 Chevy C20	LDT	Non-catalyst	85,533	CA RFG (in-use)	0.000	4.938	3.709	116.980
					ave	0.012	1.915	1.669	31.589