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Analysis of Remote Sensing Data to Determine Deterioration Rates for OBDII Equipped Vehicles

Final Report

September 2006

COORDINATING RESEARCH COUNCIL, INC.
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CRC Project Number E-23-8

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Executive Summary

The objective of this project was to compare emissions deterioration rates for OBDII equipped vehicles in areas with inspection and maintenance programs and areas without inspection and maintenance programs using remote sensing measurements made in the same locations two years apart. This study found that single site measurements two years apart from E-23 programs did not allow deterioration rates to be calculated for OBDII equipped vehicles with sufficient precision to accomplish the program objective. By using the very large remote sensing database from the St. Louis, MO inspection and maintenance program, it was possible to determine deterioration rates on OBDII equipped vehicles from measurements made two years apart. From information over four and five years, St. Louis data also showed emission deterioration rates to be lower for newer OBDII equipped vehicles. Also, when looking at average emissions for vehicles of the same age, newer model year OBDII equipped vehicles have lower emissions of NO and CO.

Remote sensing can be used to measure large numbers of vehicles and provides data with lower vehicle selection bias than for laboratory measurement programs which select only a few tens of vehicles. Since 1997 the CRC E-23 program been measuring the change in fleet emissions at specific sites in four cities, all having inspection and maintenance programs. These cities were Los Angeles, CA; Phoenix, AZ; Denver, CO; and Chicago, IL. Two additional cities were selected for two years of measurements, Omaha, NE, and Tulsa, OK. These two cities never had an I/M program and were far from any city that has an I/M program. The latter condition was felt to be important so that Omaha and Tulsa would be unlikely to receive large numbers of vehicles that had been unable to pass I/M inspections. However, this study found that single site measurements two years apart from E-23 programs did not allow deterioration rates to be calculated for OBDII equipped vehicles with sufficient precision to accomplish the program objective.

With the larger numbers of remote sensing measurements made in the St. Louis, MO Gateway Clean Air Program, two year deterioration rates of OBDII equipped vehicles driven there can be obtained with relatively high precision. Using St. Louis data over a four or five year range showed emission deterioration rates are lower for newer OBDII equipped vehicles. Plots of deterioration rates versus model year are “S” shaped; deterioration rates are not a strong function of model year for the newest and oldest OBDII equipped vehicles. When looking at average emissions for vehicles of the same age, newer model year OBDII equipped vehicles have lower emissions of NO and CO. Tailpipe HC is only seen as a function of vehicle age.

The report concludes with a discussion of future applications for remote sensing as vehicle technology improvements result in a fleet of mainly lower emitting vehicles.

Introduction

The objective of this project was to compare emissions deterioration rates for OBDII equipped vehicles in areas with inspection and maintenance programs and areas without inspection and maintenance programs using remote sensing measurements made in the same location two years apart. Remote sensing can be used in areas without inspection and maintenance programs to measure large numbers of vehicles[1]. This provides data with lower vehicle selection bias than for laboratory measurement programs which select only a few tens of vehicles.

The CRC E-23 program has been measuring the change in fleet emissions for a number of years within each of four cities, all having inspection and maintenance (I/M) programs. These cities were Los Angeles, CA; Phoenix, AZ; Denver, CO; and Chicago, IL. For this study two additional cities were selected for two years of measurements, Omaha, NE, and Tulsa, OK. Omaha and Tulsa never had an I/M program and were far from any city that has an I/M program. The latter condition was felt to be important so that Omaha and Tulsa would be unlikely to receive large numbers of vehicles that had been unable to pass I/M inspections in neighboring cities.

E-23 program protocol specifies collecting remote sensing data from at least 20,000 vehicles at a selected location during the same month over a number of years for each city. From 1997 to 2000 measurements were made every year in each city. After 2000, as vehicle technology improved, deterioration rates decreased, and two year intervals were used.

Detecting high tailpipe emitters by remote sensing measurements is more effective when vehicle emissions are high. For example, remote sensing is better able to distinguish high emitting vehicles, vehicles emitting at set multiples of their emission standards, where emissions standards are not as strict[2]. OBDII equipped vehicles have lower emissions than their earlier technology counterparts.[3]

A program to detect low tailpipe emitters by remote sensing is taking place in St. Louis, MO.[4] Two percent of the vehicles identified as low emitting are randomly selected and required to go to an inspection station. Of those vehicles identified twice by remote sensing as low emitting only 34 of 1808 vehicles (1.9%) failed to pass a tailpipe test at the inspection station.[5]

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[1] Wenzel, T., B.C. Singer, R.S. Slott. 2000. Some issues in the statistical analysis of vehicle emissions. J. Transp. Stat. 3(2):1-4.

[2] Slott, R. S., P. McClintock, R. Klausmeier, RSD in Missouri, Part 1, 15th CRC On-Road Vehicle Emissions Workshop, San Diego, California, April 2005

[3] See reports from E-23 or from the large remote sensing programs in Virginia or Missouri.

[4] http://www.gatewaycleanair.com/index.php

[5] "Gateway Clean Air Program Annual RapidScreen Report January – December 2002," Prepared for: Missouri Department of Natural Resources, by Peter M McClintock, Applied Analysis, 891 Tiburon Blvd., Tiburon CA 94920, July 2003, Table IV-2, page 35

Advantages of Remote Sensing

Vehicle emissions measurements which are both accurate and representative of in-use vehicles are difficult to obtain.[6] Remote sensing measures fuel based mass emissions from vehicles on the road. Typical measurements include HC, CO, and NO typically expressed in units of concentrations (parts per million or percent) per standard amount of CO2 produced which can be easily converted to grams per gallon or grams per kilogram of fuel.

Remote sensing measurements are based on an emissions sample representing only about one tenth of a second. Emissions based on this small a sample may be thought to be limited in value[7]. However, remote sensing measurements binned by model year have been found to consistently plot linearly against I/M240 emissions binned by model year in the same area. These linear plots have similar slopes over a number of years in one city and for some other cities[8].

An advantage of remote sensing measurements is that large numbers of vehicles are measured with little selection bias.

Remote sensing can measure emissions from vehicles that would not otherwise be measured. For example, in inspection and maintenance areas, remote sensing has shown that some vehicles that failed their last inspection test continue driving in the area and have high emissions long after that test.[9]

Vehicles measured by remote sensing are “travel weighted.[10]” Vehicles driving more often are more likely to be measured more often.

Remote sensing measurements are usually made at locations where vehicles are under light acceleration with their engines warm and where emission control systems should be operating. At these sites many vehicles with impaired emission control systems are more easily identified. An ideal remote sensing site is an uphill, curved off ramp from a freeway.

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[6] T.P. Wenzel, B.C. Singer, R.S. Slott. 2000. op cit

7 “A 0.1 second measurement period doesn't sound like much in human terms, i.e. one heartbeat. But, in vehicle terms, if a 4-stroke is operating at 1500 RPM (25 Hz), 0.1 seconds is 5-10 cylinders of exhaust depending on whether it is a four- or eight-cylinder engine, which is more than sufficient to measure emissions concentrations. Being mechanical, absent some intervening malfunction or component instability, a vehicle will perform consistently under the same operating conditions.” P. McClintock, personal communication.

[8] S.J. Pokharel, D.H. Stedman, and G.A. Bishop, RSD Versus IM240 Fleet Average Correlations, presented at the 10th CRC On-Road Vehicle Emissions Workshop, March 2000, http://www.feat.biochem.du.edu/assets/reports/RSD_IM240_comparison.pdf

[9] ERG No.: 0147.00.002.002, Baseline Analysis of Enhanced I/M Compliance, Final Report, Prepared for: Air Quality Division, Arizona Department of Environmental Quality, June 28, 2002

[10] This statement is only correct to the extent that the remote sensing sites map the driving behavior of the motorists in the area. For example, if all the remote sensing sites are freeway on-ramps, remote sensing will not map those drivers that do no use the freeway. And if remote sensing is not done at night, the vehicles of people who travel mainly at night will not be equitably incorporated.

Remote sensing measurements made over time in the same location at the same time of year have shown that fleet emissions are decreasing and newer vehicles are staying lower emitting longer[11].

Disadvantages of Remote Sensing

Ideal remote sensing sites are not easily found.

Remote sensing does not measure evaporative emissions.

Vehicle emissions vary with driving conditions and the instant of remote sensing measurement is not representative of all driving conditions. Some vehicles with impaired emission control systems are more easily identified under higher load conditions than are may be experienced at a remote sensing site[12].

Since remote sensing measurements are made on-road, ambient conditions and fuel composition are not controlled. Adjustments can be made to remote sensing measurements if ambient conditions (e.g., humidity) are monitored. Local fuel composition should be taken into account if measurements are being compared in different locations.

When remote sensing has been proposed to identify high emitters, the difficulty of obtaining complete fleet coverage has been raised as a disadvantage. This is not a disadvantage for other applications, for example clean screening or obtaining fuel based emission inventory estimates.

Other Information about Remote Sensing Measurements

The exhaust plume path length and the density of the observed plume are highly variable from vehicle to vehicle, and are dependent upon, among other things, the height of the vehicle's exhaust pipe, wind, and turbulence behind the vehicle. For these reasons, the remote sensor can only directly measure ratios of CO, HC or NO to CO_2. The ratios of CO, HC, or NO to CO_2 are constant for a given exhaust plume. Remote sensing data reported in this study is in units of %CO, HC ppm, and NO ppm in the exhaust gas, corrected for water and excess oxygen not used in combustion. The HC measurement is a factor of two smaller than an equivalent measurement by an FID instrument. These

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[11] S.J. Pokharel, G.A. Bishop, D.H. Stedman and R.S. Slott, Emissions Reductions as a Result of Automobile Improvement, Environ. Sci. Technol., 37:5097-5101, 2003

[12] T. Wenzel and M. Ross, Characterization of Recent-Model High-Emitting Automobiles, SAE 981414, Reprinted From: Advances in General Emissions, (SP-1367), International Spring Fuels and Lubricants Meeting and Exposition, Dearborn, Michigan, May 4-6, 1998. Three vehicles were classified as "Type 2: operates Rich at Moderate Power." These vehicles had much higher CO emissions in a driving cycle with higher loads than 23 kW/t.

percent and ppm are fuel-based mass emissions can be directly and easily converted into grams per kilogram of fuel by simple equations.[13]

Vehicle description in remote sensing measurements is learned from vehicle license plate identification based on a video picture of the vehicle measured. The license plates recorded are read and sent to the local department of motor vehicles which sends back vehicle descriptions based on what is in their records.

Emissions from remote sensing are calculated from a regression of the raw data over about a half second as the plume disperses[14]. Negative emissions values are sometimes recorded[15]. The negative values do not detract from the usefulness of remote sensing measurements. Negative values have been shown to be normally distributed consistent with variation resulting from instrument noise[16, 17]. Raw remote sensing data show that negative slopes can result from one or two negative emissions occurring at high CO_2 in the plume of low emitting vehicles. The apparent negative emissions occur due to a small decrease in the reference signal relative to the pollutant signal.

Based on results from new vehicles, HC emissions measured by remote sensing in E-23 programs have been observed to have an offset which may vary by site and time of day. The reason has not been determined, but is thought to be due to slight variable misalignment of the instrumentation. Some remote sensing instruments have frequent recalibration which may help minimize the offset. When the offset has been observed, the amount of offset has been estimated as the average emissions of the cleanest model year and make of vehicles from each data set. Since the cleanest vehicles emit near zero tailpipe HC emissions under remote sensing conditions (no cold start), “such an approximation will only err slightly towards clean[18].”

When remote sensing measurements are made at sites with high speed and negative load (throttle off) high HC emissions may be seen even for newer vehicles.[19] The delayed

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[13] G.A. Bishop, D.A. Burgard, M.J. Williams, and D.H. Stedman, On-Road Remote Sensing of Automobile Emissions in the Phoenix Area: Year 4, November 2002, November 2003, Prepared for: Coordinating Research Council, Inc., Contract No. E-23-4

[14] Although the emissions are generated in about one tenth of a second, the plume disperses at the measuring site over about half a second.

[15] Recorded negative emissions are due to “negative absorption which is more light than expected on a pollutant channel, or less light than expected on the reference channel.” Personal communication, D. H. Stedman

[16] J.L. Jiménez-Palacios, Understanding and Quantifying Motor Vehicle Emissions with Vehicle Specific Power and TILDAS Remote Sensing, thesis, Massachusetts Institute of Technology, February 1999, sections 6 and 8 show a numerical convolution of a normal distribution (estimated noise distribution) and a gamma distribution (characteristic of skewed vehicle emission data).

[17] S.S. Pokharel, G.A. Bishop and D.H. Stedman, On-Road Remote Sensing of Automobile Emissions in the Phoenix Area: Year 2, Prepared for: Coordinating Research Council, Inc., January 2001, Appendix D.

[18] S.S. Pokharel, G.A. Bishop and D.H. Stedman, On-Road Remote Sensing of Automobile Emissions in the Chicago Area: Year 4, Prepared for: Coordinating Research Council, Inc., August 2001

[19] This was first observed with remote sensing in the 1991 Santa Anita racetrack study. "On-Road Remote Sensing of Carbon Monoxide and Hydrocarbon Emissions During Several Vehicle Operating Conditions," L.L. Ashbaugh, D. R. Lawson, G.A. Bishop, P.L. Guenther, D.H. Stedman, R. D. Stephens, P.J. Groblicki,

high HC tailpipe emissions seen after throttle shut off were also observed on a dynamometer when emissions were measured with a very fast response instrument[20].

One method suggested to adjust for remote sensing site driving conditions is to use the instantaneous power per unit mass of the vehicle, vehicle specific power or VSP. VSP can be estimated using only road grade and speed and acceleration measurements. When VSP is greater than zero, VSP is linearly related to fuel rate[21].

Typically the speed and acceleration measurements used in VSP calculation are those at the time vehicle emissions emerge from the tailpipe. These values of speed and acceleration usually differ from those that occur at the time when these same emissions were generated in the engine. This introduces an element of uncertainty as to which VSP value should be used. However, for at least one typical remote sensing site, no discernable difference in HC or CO emissions and only a slight effect on NO emissions were seen whether speed and acceleration were measured where emissions were generated in the engine or where emissions emerged at the tailpipe[22].

In addition to fuel rate, especially for certain types of high-emitting vehicles, immediate driving history, particularly when load, speed and/or acceleration are large and irregular, can be an important factor influencing vehicle emissions[23, 24]. Extreme irregular driving is usually not a factor at remote sensing sites since the immediate prior driving history of the vehicle is moderated due to traffic and/or road geometry.

One way to estimate remote sensing uncertainties is to compare the average emissions for the newest vehicles. New vehicles would be expected to have similar emissions regardless of where they were measured as long as VSP, driving conditions, fuel composition, and vehicle type were controlled. Emissions from these newer vehicles should be independent of inspection and maintenance programs or owner maintenance practices.

Site to site uncertainty in binned average values for six St. Louis similar remote sensing sites measured in July 2002 was estimated from emissions of newer cars. Using VSP adjusted emission in the VSP range of 1 to 22 kW/t, site to site standard deviations were 4.0, 41, and 3.4 gpg for HC, CO, and NO respectively. Standard errors of the mean for

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J.S. Parikh, B. J. Johnson, S.C Huang, in "PM10 Standards and Nontraditional Particulate Source Controls," AWMA Specialty Conference, Phoenix, AZ, January 1992.

[20] Cambustion Company Ltd., http://www.cambustion.co.uk/

[21] J.L. Jiménez-Palacios, Understanding and Quantifying Motor Vehicle Emissions with Vehicle Specific Power and TILDAS Remote Sensing, thesis, Massachusetts Institute of Technology, February 1999

[22] R.S. Slott, Phoenix 2000 Paired Remote Sensing Readings - Measuring Load Before and After Tailpipe Measurements, 10th CRC On-Road Vehicle Emissions Workshop, San Diego, March, 2000.

[23] T.P. Wenzel, M. Ross, Characterization of Recent-Model High-Emitting Automobiles, SAE 981414, International Spring Fuels and Lubricants Meeting and Exposition, Dearborn, Michigan, May 4-6, 1998

[24] C.E. Lindhjem, A.K. Pollack, R.S. Slott, and R.F. Sawyer, CRC Project E-68, Analysis Of EPA's Draft Plan For Emissions Modeling In Moves And Moves GHG, Prepared for Coordinating Research Council, Inc., February 2004, Section 3

the six remote sensing sites were 0.4, 3.7, 0.3 gpg for HC, CO, and NO[25]. To compare low emitting vehicles' emissions by remote sensing more data are needed in order to reduce the site-to-site noise.

Different remote sensing units may give different results. Some remote sensing campaigns, especially in the early years of measurement by some investigators, did not use adequate quality control and calibration procedures.[26] This should no longer be a problem because the importance of maintaining good quality control is now understood by remote sensing operators. Among modern remote sensing instruments different criteria for accepting or validating measurements may exist in the software.

Parsing and Processing Data

Remote sensing instruments see the plume from tailpipe emissions. The instrument must be aligned to the height of the tailpipe. Remote sensing measurements have been made on both light duty and heavy duty vehicles with tailpipes near the road and on heavy duty diesel vehicles with elevated tailpipes. Typically, remote sensing is carried out to measure gasoline powered vehicles since these have had emission control systems, and the goal of many remote sensing programs is to identify which vehicles have control systems that are or are not working properly.

The concentration of pollutants in the tailpipe plume depends on a number of factors including:

- Whether the vehicle's emission control system is working properly
- Whether the vehicle's fuel delivery system is working properly
- Vehicle type, especially where the emissions standards varied by vehicle type
- Vehicle technology, usually characterized by model year
- Vehicle use, usually characterized by vehicle age
- Driving conditions, usually characterized by VSP
- Cold Start when the catalyst is not at operating temperature
- Ambient conditions, especially humidity which affects NO emissions, and low temperatures which can delay the time for vehicles to be in a warm operating condition. Remote sensing measurements are not made during rain or snow.

Since the goal of this remote sensing project is to characterize the two year deterioration of emissions in the OBDII equipped gasoline vehicle fleet, an effort was made to minimize the effects of other parameters. The variety of vehicle types, fuel composition

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[25] Slott, R.S., and McClintock, P., "Comparing Remote Sensing Emissions Measurements in St. Louis to Emissions Estimates from the MOBILE6 Arterial Roadway Type," 16th CRC On-Road Vehicle Emissions Workshop, San Diego, April, 2006

[26] Eastern Research Group, "Analysis of Historical Remote Sensing and I/M Emissions Data in Arizona," Prepared for: Air Quality Division Arizona Department of Environmental Quality, June 28, 2002. on page ES-4 of this report: 'There is also large variation in average emissions measured by each of the seven vans used (Table 2-4, p. 2-25); in some instances, even when the vans were measuring the same vehicles at the same location at the same time (Table 2-8, p. 2-28). This variation in readings indicates that some of the instruments were not properly calibrated, at least part of the time.

(gasoline and diesel), driving conditions (site location), and HC measurement challenges in a limited selection of sites require data parsing in order to provide a robust data set before investing in further data analyses.

Parsing Data in CRC E-23 Cities and in Omaha and Tulsa

Fuel Composition: Omit diesel fueled vehicles (not possible in Tulsa or Chicago).

Diesel vehicles have different emissions from gasoline vehicles; they typically have low CO and HC but higher NO than similar gasoline vehicles. Arizona, California, Colorado, Nebraska, supply fuel information with license plate information, but Oklahoma and Illinois do not. Fuel information is not associated with VIN. Tulsa and Chicago data may have higher NO levels due to the inclusion of diesel vehicles.

No correction for RFG and California fuel versus the fuel composition in the non-I/M cities was made.

Driving Condition: Include only VSP between 5 and 20 kW/t.

Emissions of CO and especially HC may be high per CO_2 emitted in tailpipe exhaust at very low VSP; however, since the fuel rate under these conditions is low, contribution to mass emissions would be low.

Under high VSP some vehicles are programmed to go into fuel rich conditions resulting in very high CO emissions and suppressed NO emissions, although this is much less of a problem for newer vehicles.

Vehicle Type: Omit vehicles that are not LDGV or LDGT1.

Most DMV data bases do not include standard vehicle type information. Inspection and maintenance records do since the vehicle emissions standards have varied with vehicle type. Vehicle types in the CRC E-23 cities and in Omaha and Tulsa were identified by matching the first eight digits of the VIN[27] (F8VIN) to standard vehicles types in the 2004 Missouri Inspection and maintenance database[28] that were taking their first test.

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[27] Decoding the VIN is shown in Appendix A.

[28] The 2004 Missouri I/M database was chosen because the year was concurrent with the remote sensing data and it was available to the author.

Two problems were encountered[29]. The first eight digits of the VIN are used to describe the vehicle, but they do not unequivocally identify standard vehicle type. This was discovered because the standard vehicle type is listed in the 2004 Missouri I/M database. A small fraction of the F8VIN population was found to have multiple vehicle types. In this report, if a single vehicle type was not associated with a single F8VIN in at least 75% of the vehicles in the 2004 Missouri I/M database, that F8VIN was not used. The second problem is that all combinations of the F8VIN are not in the 2004 MO I/M database. This results in loss of a small amount of data from each city.

No attempt was made to separate passenger cars from light duty trucks. Since the deterioration rates were site specific, the vehicle type distribution was assumed similar over two years for each site.

The results of vehicle type parsing on the total valid remote sensing measurements are shown in Table 1 below. Vehicles were removed for being LDGT2, having a VIN without a 75% unique type, or not having a VIN in the 2004 MO I/M database. This removed between 5% and 13% of the measurements depending on the city.

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[29] An alternative would be use the GVW field to classify vehicles. LDGV and LDGT1 have GVW below 6000 pounds and LDGT2 have GVW between 6001 and 8500 pounds. However, few vehicles have the GVW listed in the MO IM data base. Information from the 2004 MO IM where GVW values were listed is shown in Table 1 below. GVW values are not available from Iowa vehicles measured in Omaha

GVW	GVW Average	GVW Minimum	GVW Maximum	Vehicles with GVW listed	Total Vehicles with first tests
"LDGV "	3,911	1,917	5,420	14	210,707
"LDGT1"	5,125	2,430	6,000	45,625	108,647
"LDGT2"	6,570	6,001	8,500	17,357	33,439
All Grps	5,523	1,917	8,500	62,996	352,793

Similarly, State databases for vehicle licenses have only a small percent of vehicles with GVW listed. For example, Omaha campaign 2004 GVW information received by Denver University and classified by Omaha vehicle type, P and T, for gasoline fueled vehicles is shown in the Table below.

Omaha 2004 License Information		
GVW	"P"	"T"
blank	3,042	1,455
0	8,419	7,084
less than 10	2	0
less than 6001	150	189
6001-8500	180	180
over 8500	0	42

Table 1: Vehicle Type based on the first 8 digits of the VIN in the 2004 MO I/M Database

City	I/M Program	LDGT1	LDGT2	LDGV	VIN but no TYPE	Not in Database	Total
TULSA	No	12539	2284	11948	803	620	28194
PHOENIX	Yes	14691	2050	15456	1435	1142	34774
OMAHA	No	11190	1220	12210	970	366	25956
DENVER	Yes	14250	1073	15453	1085	875	32736
LABREA	Yes	7593	851	14978	318	486	24226
CHICAGO	Yes	9856	529	19281	482	330	30478
TULSA	No	44%	8%	42%	3%	2%	100%
PHOENIX	Yes	42%	6%	44%	4%	3%	100%
OMAHA	No	43%	5%	47%	4%	1%	100%
DENVER	Yes	44%	3%	47%	3%	3%	100%
LABREA	Yes	31%	4%	62%	1%	2%	100%
CHICAGO	Yes	32%	2%	63%	2%	1%	100%

Normalize Site Emissions: Subtract 2003 Vehicle Emissions from other Model Years

University of Denver has observed emissions offset for HC emissions using their instruments. The effect shows up in the inconsistency of HC emissions across locations for newer vehicles as seen in Table 2. The newer vehicles are exempt from I/M so I/M is not a contributing factor to the variation in HC levels between locations. The variation has been attributed to road vibration coupled with slight instrument misalignment[30].

The large increase in HC emissions observed in Omaha was not due to an offset, but was attributed to the driving conditions at the remote sensing site chosen. This section of the report examines remote sensing made at six sites during two years. For some sites the measurements were made in 2003 and 2005, for others the measurements were made in 2002 and 2004. The average values of HC ppm (as hexane) for 2003 for vehicles in both years of measurement in each location are shown in the right hand column of Table 2. It can be seen that Omaha vehicles had unusually high HC emissions, even for the newest vehicles.

Table 2: Average Values of HC ppm (hexane) for 2003 Vehicles

Location	Measured in 2004 or 2005	HC ppm (hexane) Average of 2002/2004 or 2003/2005
Denver	10	12
Chicago	21	21
Phoenix	29	31
Los Angeles	8	17
Tulsa	6	18
Omaha	106	103

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[30] Gary Bishop, personal communication

The Omaha high HC was attributed to many of the vehicles being in high speed cruise mode with the motorists' foot off the accelerator pedal[31]. This was the only site where the average acceleration was near zero for vehicles selected for analysis. The only other site with a low average acceleration was at Denver where the vehicles had a considerably higher road grade to overcome.

The Omaha results show that site selection can strongly influence remote sensing values. Average site speed, acceleration, and VSP values for measurements made between 5 and 20 kW/t VSP for 1996 to 2003 light duty gasoline vehicles and LDGT1 are shown in Table 3. Histograms showing the distribution of Speed, Acceleration, and VSP by location are shown in Appendix B.

Table 3: Average Values of Speed, Acceleration, and VSP (VSP 5 to 20 kW/t)

location	Speed		Accel		VSP		Vehicles	Grade
	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.	selected	degrees
Denver	22.73	4.14	0.13	0.85	10.74	3.31	17,952	4.6
Chicago	23.57	5.40	0.91	0.82	9.53	3.19	14,779	1.5
Phoenix	32.36	5.60	1.08	0.68	14.55	3.89	9,000	1.3
LaBrea	17.21	2.22	1.78	0.81	13.16	3.47	16,740	2
Tulsa	24.45	3.94	0.39	0.67	9.54	3.34	13,710	2.6
Omaha	39.78	8.52	0.01	0.60	13.33	4.12	10,675	2.7

At the Los Angeles site and most sites in St. Louis acceleration increases with increasing average speed. This is characteristic of sites where there is a traffic restriction before the measurement, such as freeway on-ramps with no congestion on the freeway or sites where the measurement is made after a stoplight or a toll booth.

In the 2005 Tulsa measurements, an offset due to instrument misalignment was seen for CO emissions also[32]. This is shown in Table 4 by the change in average %CO for 2003 vehicles in Tulsa between 2003 and 2005.

Table 4: Average Values of %CO for 2003 Vehicles in Tulsa

Year Measured	%CO	Standard Deviation	Observations
2003	0.0425	0.1205	751
2005	0.1088	0.2157	674

By subtracting the 2003 vehicle emissions from other model year emissions, offset effects are minimized, as are the effect of Omaha driving conditions on HC emissions.

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[31] Gary Bishop, personal communication

[32] Don Stedman, personal communication

Two Year Deterioration Rates Single Sites in Six Cities

Chicago, Phoenix, and Omaha were measured in 2002 and 2004. Denver, Los Angeles, and Tulsa were measured in 2003 and 2005. The measurement sites have been described in CRC reports[33]. The two year deterioration in emissions values by vehicle model year and location are in Figures 1 through 3. In order to minimize site specific effects including emission offsets, the average 2003 vehicle emissions were subtracted from each of the model years, which reduces the emissions in 2003 to zero.

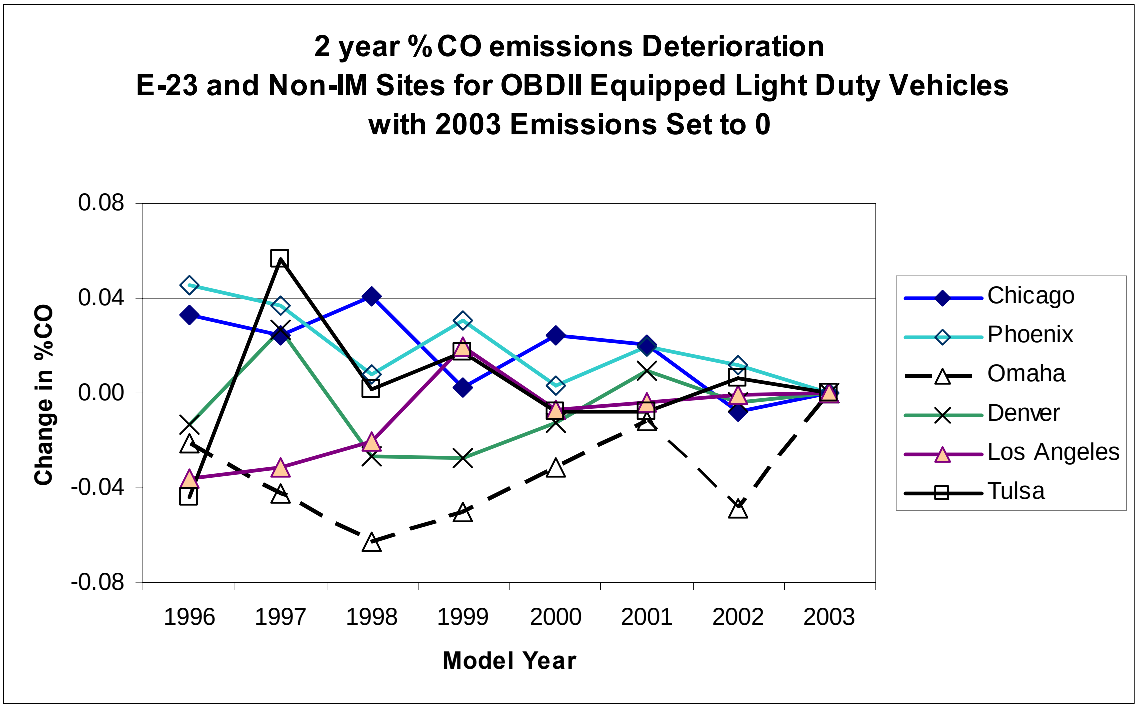

Figure 1: %CO Emissions Deterioration in E-23 Cities with I/M (Chicago, Phoenix, Denver, and Los Angeles) and Cities without I/M (Omaha and Tulsa)

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[33] Some reports have not yet issued.

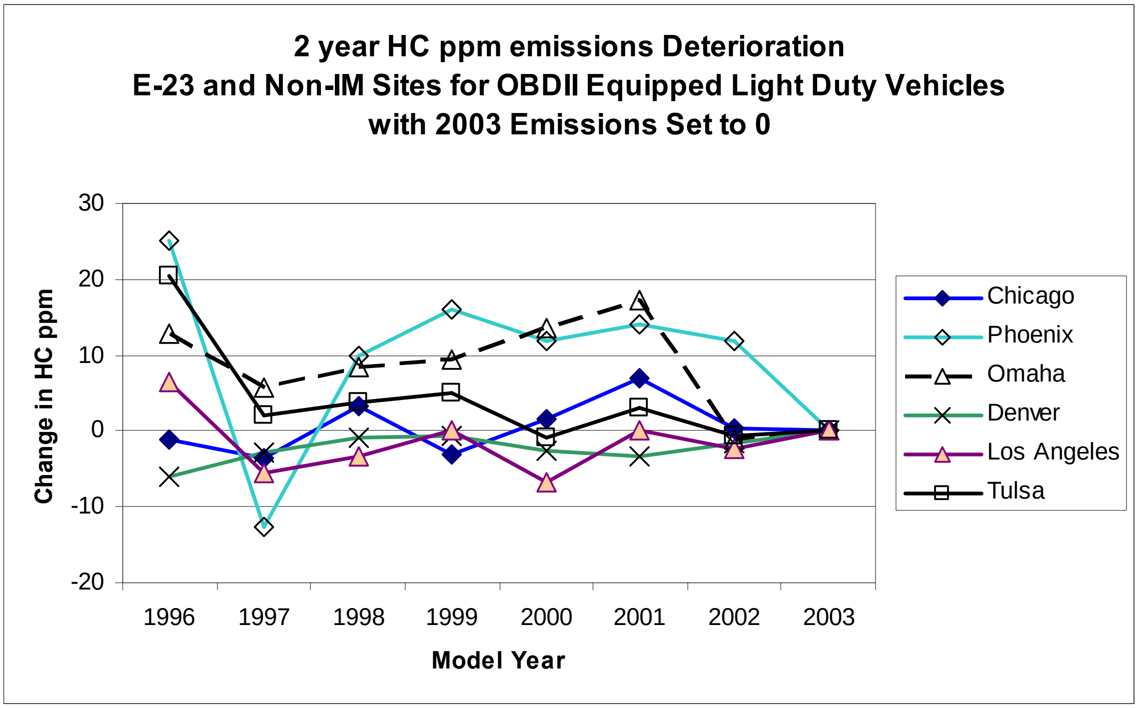

Figure 2: HC ppm Emissions Deterioration in E-23 Cities with I/M (Chicago, Phoenix, Denver, and Los Angeles) and Cities without I/M (Omaha and Tulsa)

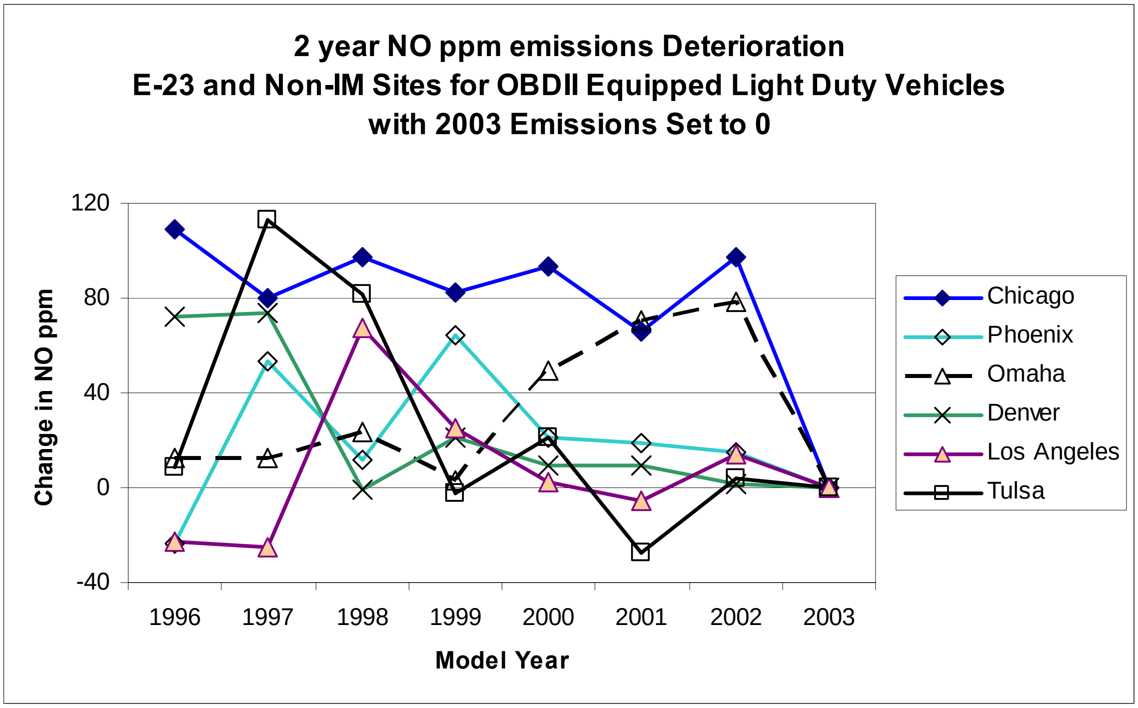

Figure 3: NO ppm Emissions Deterioration in E-23 Cities with I/M (Chicago, Phoenix, Denver, and Los Angeles) and Cities without I/M (Omaha and Tulsa)

Conclusions for Single Site Measurements

Even after parsing the remote sensing data, single site remote sensing measurements made two years apart were not able to characterize emissions deterioration rates for OBDII equipped vehicles with sufficient precision to observe a difference between deterioration rates in cities with and without inspection and maintenance programs.

Two Year Deterioration Rates from Multiple Sites in St. Louis, MO

The single site data two years apart were not sufficient to obtain deterioration rates for OBDII equipped vehicles. What if many more sites were measured two years apart?

The Missouri Department of Natural Resources has been operating a remote sensing based clean screen program since 1999 in St. Louis. The goal of this program is to identify gasoline vehicles with low tailpipe emissions so that the owners can have the option of not having to take their vehicles to a vehicle inspection station for emissions testing. Many remote sensing measurements are made. In 2002, for example, about 5 million measurements were made, with about 3 million on vehicles within the inspection and maintenance program.

Data from this program are used in this report to look at emissions deterioration of OBDII equipped vehicles. The first application of the data is to simulate the ‘single site two years apart’ experiment using many sites. By selecting sites where large numbers of measurements were made in the same month in both 2003 and 205 over 100 “simulated E-23 campaigns” can be extracted from the St. Louis remote sensing data.. Each unique remote sensing site with high measurements in a single month in both 2003 and 2005 is called a site-month.

Data parsing resulted in including only light-duty gasoline vehicles registered in the St. Louis I/M area weighing less than 8500 lbs gross vehicle weight (GVW). Standard Vehicle Types LDGV, LDGT1 and LDGT2 meet this criterion. Further, measurements were only included if the measured grade, speed, and acceleration of the vehicle resulted in a VSP value within the range of 5 to 20 kW/t. To correct for ambient conditions that could lead to cold start operation, all measurements were excluded during the measurement hours for sites where over 5% of newer vehicles were seen to have excessive HC emissions. Extreme negative values of HC or NO emissions (less than 250 ppm) were also excluded. Humidity corrected NO emissions were compared with uncorrected NO emissions.

Tables 5 and 6 describe how the “simulated E-23 campaigns” for St. Louis in 2003 and 2005 were spread over 32 St. Louis sites.[34]

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[34] Site descriptions and information about the St. Louis remote sensing program can be found in “Gateway Clean Air Program Annual RapidScreen Report January – December 2002,” Prepared for: Missouri Department of Natural Resources, by Peter M McClintock, Applied Analysis, 891 Tiburon Blvd., Tiburon CA 94920, July 2003

Table 5 shows the average number of measurements in a month for recent model years for high volume sites in St. Louis. The number of measurements for recent model years is about one quarter of the number of measurements for a typical E-23 campaign. However, there are over 100 site-months in St. Louis so the total number of measurements in St. Louis is about 25 times what is seen in a typical E-23 campaign.

Table 5: "Simulated E-23 Campaigns" in 2003 and 2005 in St. Louis

Model Year	Average Numbers of Measurements per Campaign	Site-Months or Campaigns
1996	255	103
1997	301	104
1998	340	104
1999	391	104
2000	423	104
2001	427	104
2002	439	104
2003	243	104

Table 6 shows the St. Louis remote sensing measurement sites and the number of months that were used in the analysis for each site. A St. Louis site may have multiple 'site-months' if high numbers of measurements were made in more than one month in both 2003 and 2005.

Table 6: Sites and Measurement Months in St. Louis

St. Louis Measurement Sites	Site-Months
3	7
5	5
12	1
13	4
28	2
29	5
37	5
42	5
43	1
45	5
47	2
76	4
87	2
95	1
96	4
100	6
101	2
104	2
105	3
107	5
108	4
112	1
114	7
115	1
118	2
120	5
127	2
139	6
143	1
144	2
163	1
164	1
Total 32 Sites	104

Two year emissions deterioration estimates were calculated by taking the average emissions by model year at a single site-month in 2003 and subtracting the average emissions by model year from the same site-month measured in 2005. Every site-month gave a single estimate of emissions deterioration over two years for each model year, for all three emissions HC, NO, and CO.

The individual two year emissions deterioration estimates showed considerable scatter. However, Figures 4 through 6 show that the mean values of the average emissions from all site-months have regular patterns of slow emissions deterioration in these OBDII equipped vehicles. The individual site-month variation is apparent from the width of the standard deviation whiskers. The large number of site-month estimates reduce the noise as is shown by the width of the standard error boxes.

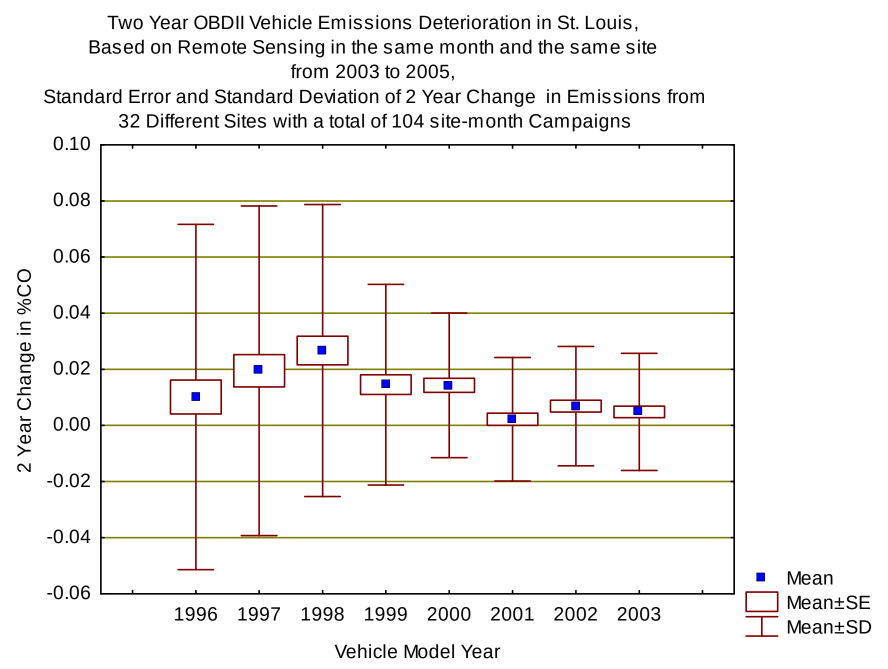

Two Year OBDII Vehicle Emissions Deterioration in St. Louis,
Based on Remote Sensing in the same month and the same site
from 2003 to 2005,
Standard Error and Standard Deviation of 2 Year Change in Emissions from
32 Different Sites with a total of 104 site-month Campaigns

Figure 4: OBDII Vehicle %CO Emission Deterioration in St. Louis

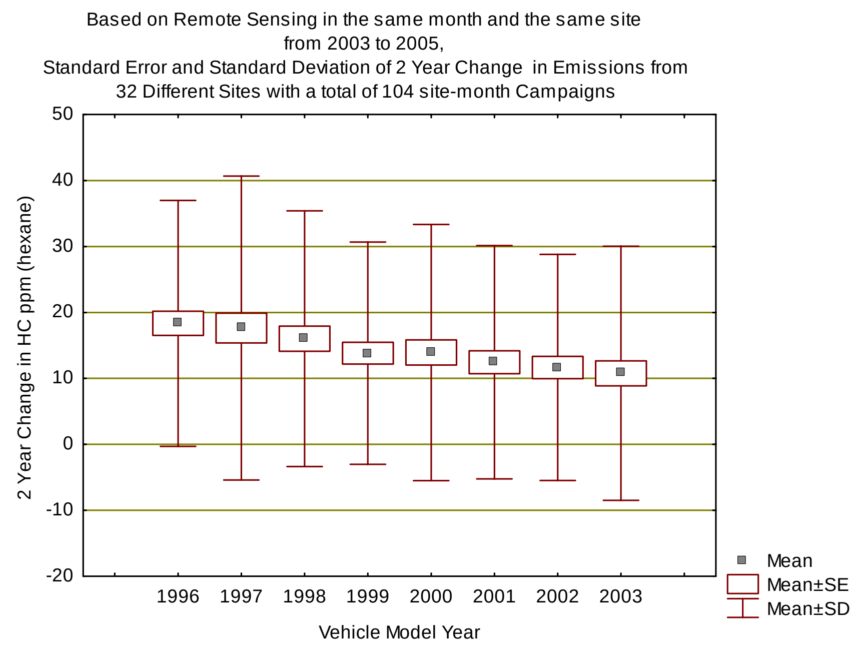

Based on Remote Sensing in the same month and the same site
from 2003 to 2005,
Standard Error and Standard Deviation of 2 Year Change in Emissions from
32 Different Sites with a total of 104 site-month Campaigns

Figure 5: OBDII Vehicle HC ppm Emission Deterioration in St. Louis

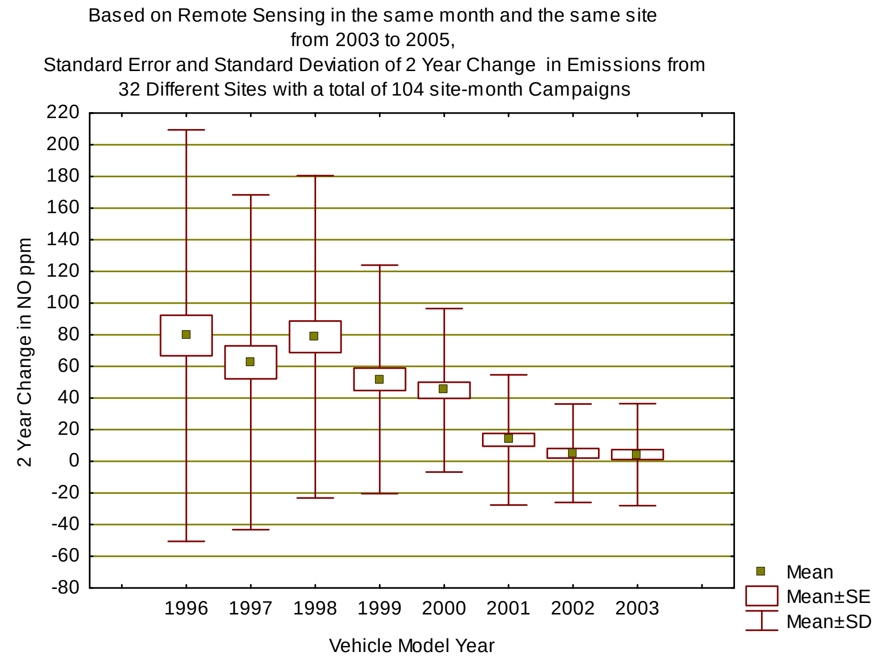


Figure 6: OBDII Vehicle NO ppm Emission Deterioration in St. Louis

Comparing Figure 6 with Figure 7 shows that correcting NO emissions for humidity had only a slight effect on the estimated deterioration rate of the NO emissions for OBDII equipped vehicles.

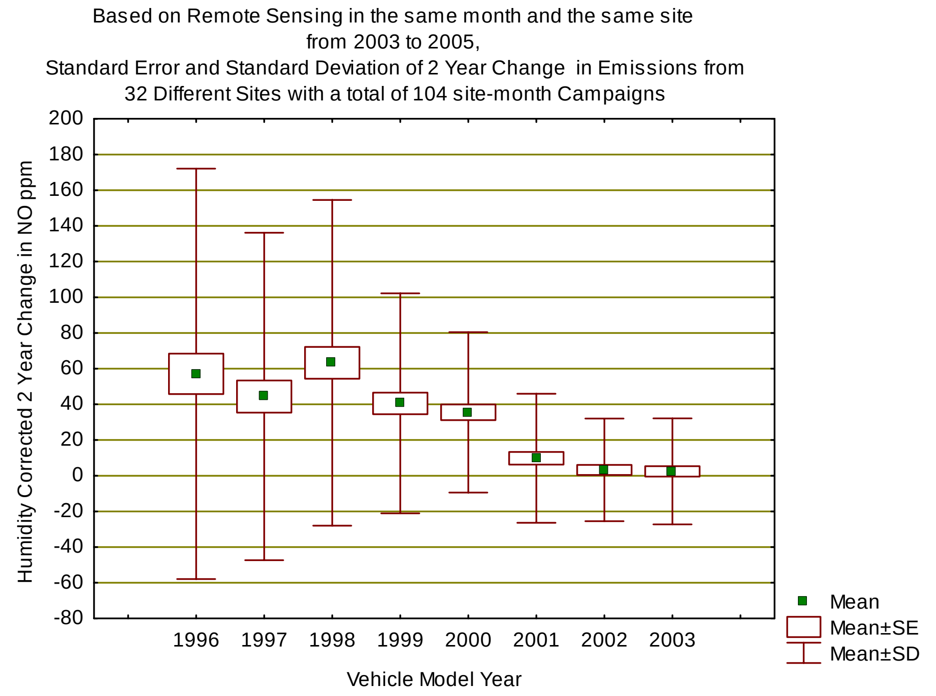


Figure 7: OBDII Vehicle Humidity Corrected NO ppm Emission Deterioration in St. Louis

Deterioration Rates from Multiple Sites over More than Two Years

The deterioration rate estimates in Figures 4 through 7 are based on data two years apart. More information about deterioration rates can be obtained if more of the St. Louis remote sensing data are analyzed. For this analysis multiple remote sensing sites in St. Louis were selected having large numbers of measurements in at least one month from April through September from 2002 to 2005. The statistical analysis used each month's rate of deterioration over this time as a separate estimate of the average deterioration rate.

The calculations assume that any difference in emission values by site and by instrument were confounded by the large numbers of sites. Statistical calculations were made using the software STATISTICA6.1.

In the approach using monthly replicates, the deterioration rate from 2002 to 2005 based on April measurements is assumed to be the same as that based on May, June, July, August, or September measurements. Linear deterioration rates from 2002 to 2005 for each of the months were calculated by plotting in EXCEL and obtaining the slope from linear trend lines for each model year from 1996 to 2003.

When average values of the HC deterioration rates were plotted by model year, an "S" shaped curve is seen with a decreasing deterioration rate from 1996 to 2001.

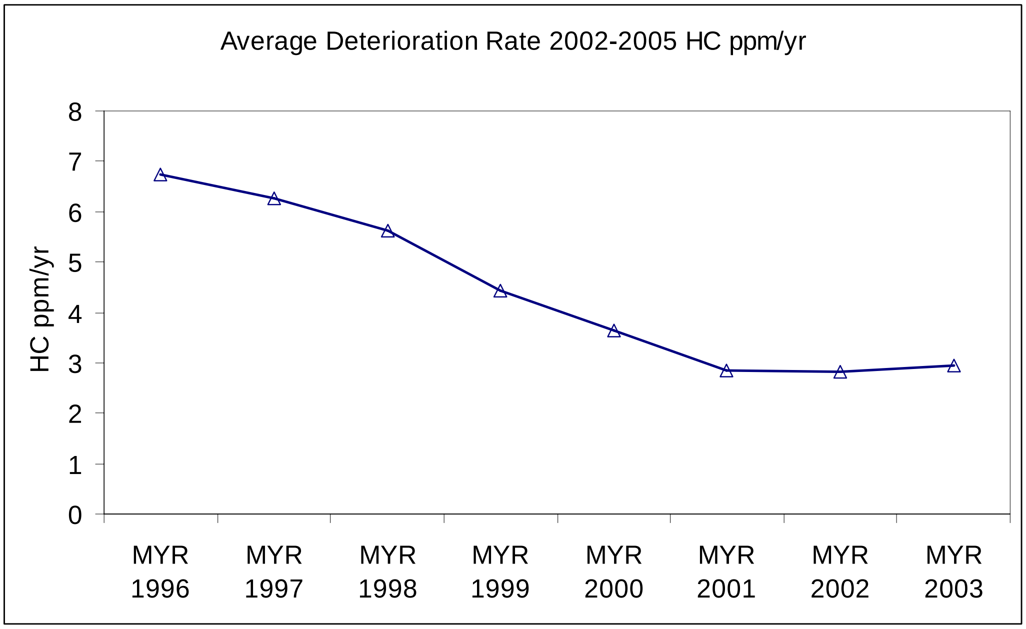


Figure 8: Average Linear Deterioration Rates for HC Emissions by Model Year determined by Remote Sensing Using Monthly Replicates.

To determine whether the trend is statistically significant a one-way ANOVA test was applied. In order for ANOVA to be valid, variances of deterioration rates for individual model years need to be similar. If this were not the case, a few outliers could be responsible for the trend. The Levene test can be used to determine if variances are sufficiently similar. In Figure 9, the variances for model years 1996 and 2003 are seen to be large. A significant difference in the Levene test is observed when either or both of these two model years is included in the analysis. A significant difference ($p<0.05$) in the Levene test shows that variances are not sufficiently similar for a valid ANOVA test.

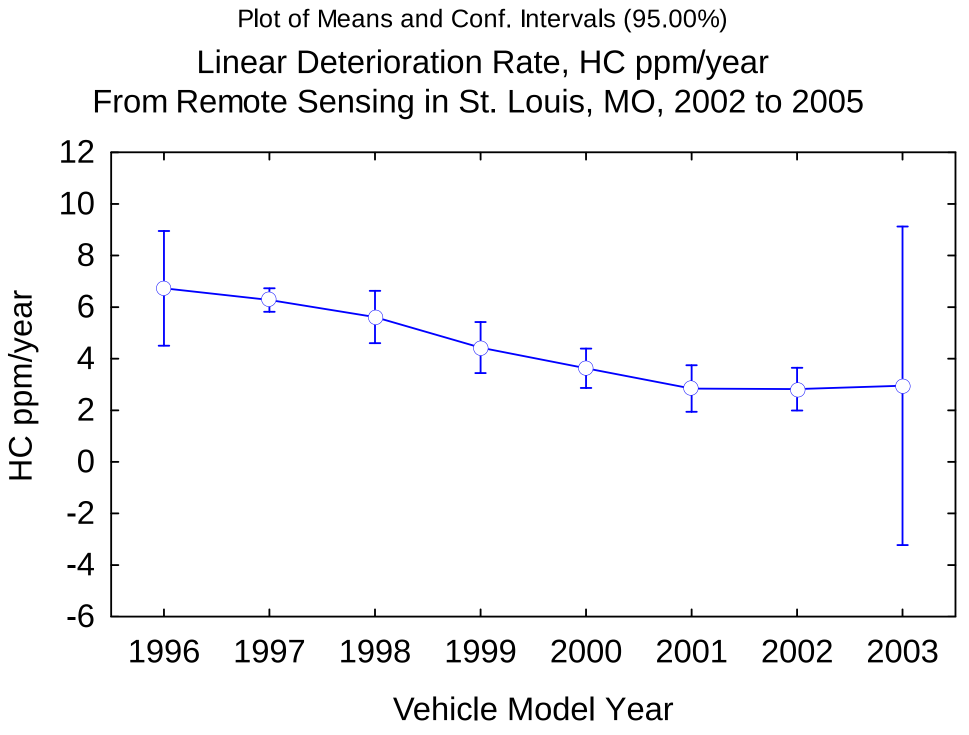


Figure 9: Average Linear Deterioration Rates for HC Emissions by Model Year Showing Variation of the Monthly Replicate Estimates of Linear Deterioration Rates

Omitting model years 1996 and 2003, the variances are sufficiently similar and the observed trend is found to be statistically significant as is shown in Table 7 and illustrated in Figure 10. The abbreviation NS in Table 7 means not significant.

Table 7: Decrease of HC Average Linear Deterioration Rates by Model Year

	ANOVA F	ANOVA p	Levene F	Levene P
Including Model Years 1996 and 2003	2.87	0.016	4.79	0.000
Excluding Model Years 1996 and 2003	19.1	0.000	1.06	0.399 (NS)

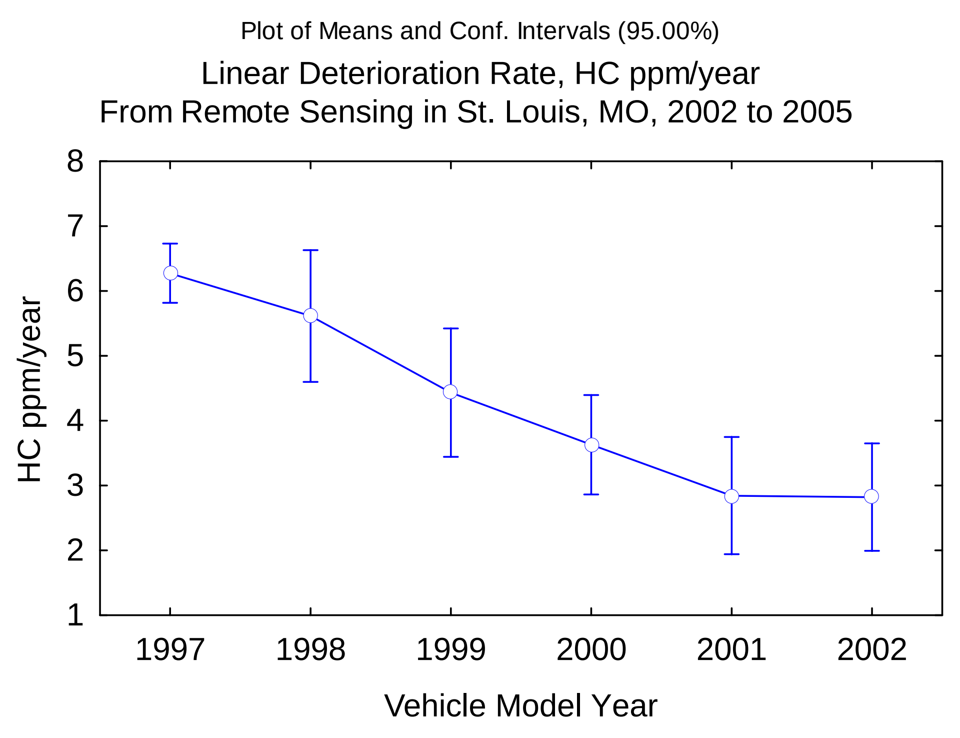


Figure 10: Average Linear Deterioration Rates for HC Emissions by Model Year with Similar Variance in Monthly Replicate Estimates of Linear Deterioration Rates determined by Remote Sensing

Linear deterioration rates used in these calculations are shown in Table 8 below. The large standard deviations for 1996 and 2003 vehicles are indicative of the large variances observed in Figure 9 and the significant differences found in the Levene test for these model years.

Table 8: Linear HC ppm/year Deterioration Rates for 2002 to 2005 by Model Year from Remote Sensing Measurements in St. Louis, MO.

Month	MYR 1996	MYR 1997	MYR 1998	MYR 1999	MYR 2000	MYR 2001	MYR 2002	MYR 2003
APR	9.64	6.98	5.74	5.17	4.03	3.88	2.94	13.20
MAY	7.31	5.75	6.16	2.93	4.16	3.02	2.41	-0.76
JUNE	8.65	6.39	6.52	5.40	3.98	3.45	4.10	4.81
JULY	4.97	6.39	4.71	3.97	4.22	2.74	3.24	-3.97
AUG	4.63	5.89	4.16	4.08	2.69	1.37	1.86	1.24
SEPT	5.17	6.25	6.40	5.05	2.70	2.61	2.38	3.19
Average	6.73	6.28	5.62	4.43	3.63	2.85	2.82	2.95
StdDev	2.12	0.44	0.97	0.94	0.73	0.86	0.79	5.88

Similar calculations were made for NO emissions and are shown Figure 11. The change in deterioration rates with model year once again describes an “S” curve with decreasing deterioration rates between 1997 and 2001. Although the variances of 1996 and 2003 vehicle deterioration rates are larger than the vehicle model years between these extremes, a Levene test does not show a significant difference in the variances. The ANOVA is highly significant with F=40.6 and p<0.000. Data for Figure 11 are shown in Table 9.

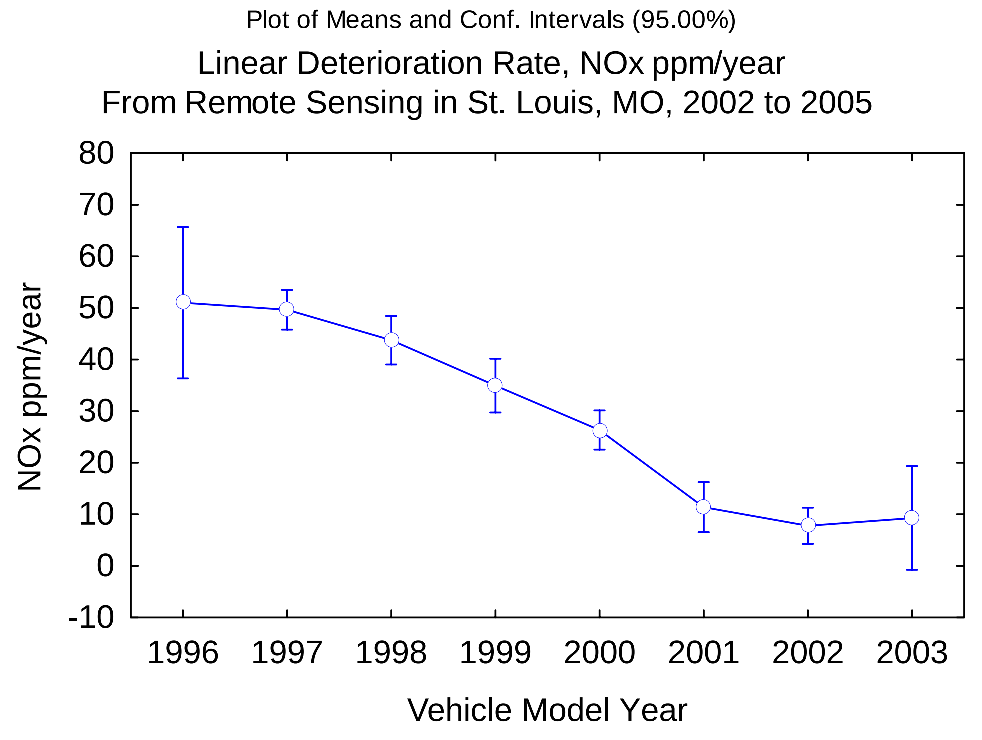


Figure 11: Average Linear Deterioration Rates for NO Emissions by Model Year Showing Variation of the Monthly Estimates of Linear Deterioration Rates determined by Remote Sensing in St. Louis, MO

Table 9: Linear NO ppm/year Deterioration Rates for 2002 to 2005 by Model Year from Remote Sensing Measurements in St. Louis, MO

Month	MYR 1996	MYR 1997	MYR 1998	MYR 1999	MYR 2000	MYR 2001	MYR 2002	MYR 2003
APR	72.1	53.7	47.4	38.7	21.7	6.4	3.6	8.2
MAY	29.7	47.0	43.9	26.3	23.4	5.5	5.1	12.3
JUNE	49.4	47.2	36.7	38.4	27.0	12.5	6.8	16.4
JULY	58.6	49.6	48.1	31.8	31.3	11.8	9.2	17.8
AUG	47.0	54.5	40.2	38.3	25.3	14.8	12.9	-8.8
SEPT	49.3	45.9	46.2	36.2	29.3	17.3	9.2	9.8
Average	51.02	49.65	43.75	34.96	26.33	11.39	7.78	9.29
StdDev	13.99	3.66	4.48	4.97	3.61	4.63	3.34	9.58

Similar calculations were made for CO emissions and are shown Figure 12. The change in deterioration rates with model year once again describes an “S” curve with decreasing deterioration rates between 1998 and 2002. However, the deterioration rate of the 1996 vehicles is lower than that observed for 1997 or 1998 model year vehicles. Although the variances of 1998 and 2003 vehicle deterioration rates are larger than other vehicle model years, a Levene test does not show a significant difference in the variances. The ANOVA is significant with F=9.5 and p<0.000. Data for Figure 12 are shown in Table 10.

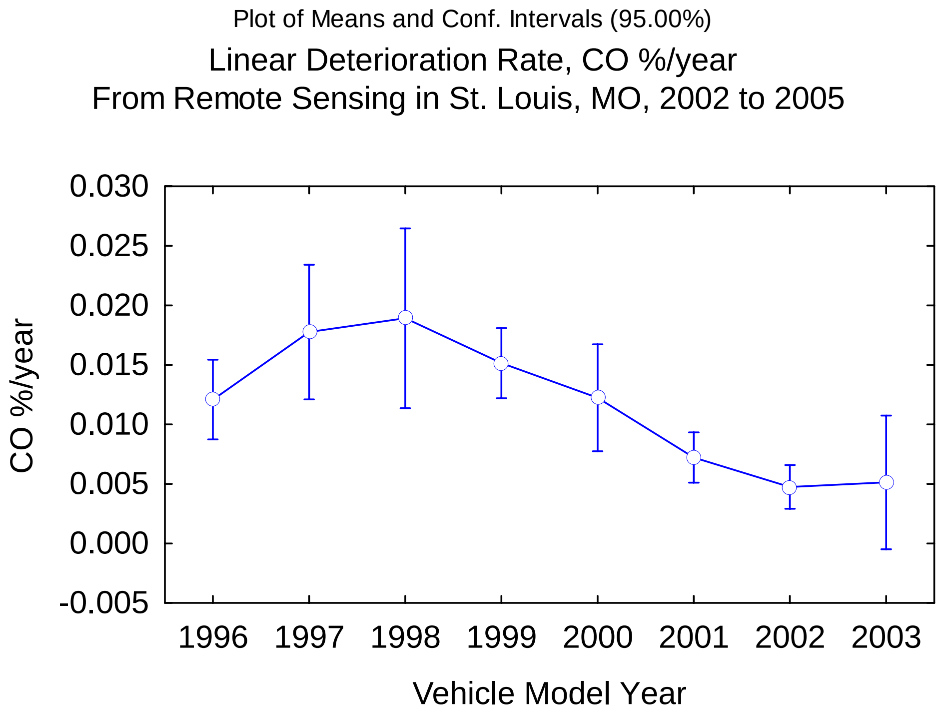


Figure 12: Average Linear Deterioration Rates for CO Emissions by Model Year Showing Variation of the Monthly Estimates of Linear Deterioration Rates determined by Remote Sensing in St. Louis, MO

Table 10: Linear CO %/year Deterioration Rates for 2002 to 2005 by Model Year from Remote Sensing Measurements in St. Louis, MO

Month	MYR 1996	MYR 1997	MYR 1998	MYR 1999	MYR 2000	MYR 2001	MYR 2002	MYR 2003
APR	0.0155	0.0240	0.0045	0.0114	0.0068	0.0045	0.0043	0.0124
MAY	0.0120	0.0179	0.0220	0.0133	0.0163	0.0083	0.0055	0.0048
JUNE	0.0093	0.0094	0.0203	0.0182	0.0118	0.0048	0.0053	0.0013
JULY	0.0164	0.0216	0.0215	0.0151	0.0153	0.0082	0.0015	0.0037
AUG	0.0089	0.0200	0.0209	0.0143	0.0158	0.0090	0.0066	-0.0017
SEPT	0.0104	0.0137	0.0243	0.0186	0.0074	0.0085	0.0053	0.0103
Average	0.0121	0.0178	0.0189	0.0152	0.0122	0.0072	0.0048	0.0051
StdDev	0.0032	0.0054	0.0072	0.0028	0.0043	0.0020	0.0018	0.0053

Emissions at the Same Age, Different Model Year

Multiple regression analysis is used to examine the NO, CO, and tailpipe HC emissions of OBDII equipped vehicles at the same age with different model years. This analysis seeks to see whether vehicle age and vehicle model year are significant factors for OBDII equipped vehicles for determining emissions in the vehicle fleet in St. Louis and, if they are significant, the relative importance of age and model year. Age and model year can be distinguished from each other because emissions were measured over a number of years in the same place using the same type of instruments. If model year were a factor, for example, the average 2002 vehicle measured when it was three years old would be significantly cleaner than the average 1998 vehicle measured when it was three years old.

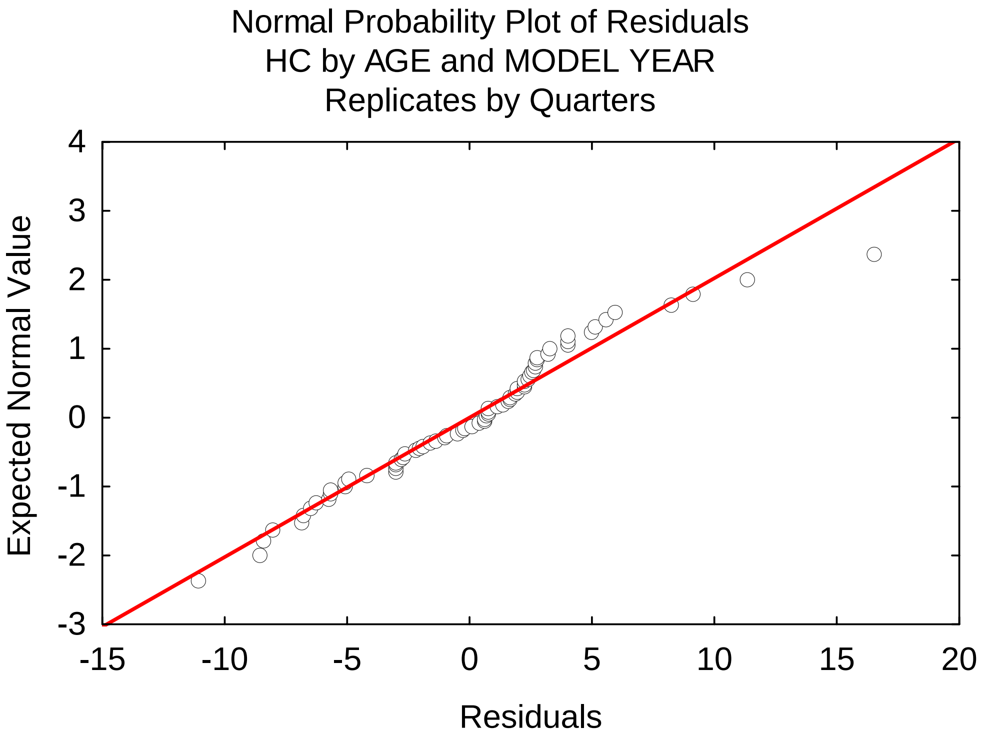
For this analysis two approaches were used. In addition to the monthly replicates, quarterly replicates were also used. For the quarterly replicate approach, multiple remote sensing sites in St. Louis were selected having large numbers of measurements within a quarter of the year from 2001 to 2005. Only three quarters were used, March-May, June-August, and September-November. The winter quarter was excluded since fewer sites qualified and cold starts were more frequent. The statistical analysis used each quarter's rate of deterioration over this time as a separate estimate of the deterioration rate.

The two approaches are somewhat redundant since high volume of measurement sites are used in both. However, the quarterly replicates have more sites and fewer replicates than the monthly replicate approach.

In the monthly analysis vehicles of age 2 through 6 were chosen in order to have four model years at each age. For the quarterly analysis vehicles of age 2 through 7 years were chosen but with only three model years at each age.

Multiple linear regression analysis assumes linear relationships between the variables over the range investigated and normal distributions. For multiple regression analysis to be valid there should be no extreme values in the data (outliers) driving the correlation. Perhaps because the values used are average from many sites, outliers appear not to be a problem in these correlations.

A test of whether gross violations of the assumptions have occurred in the analysis can be made by examining distributions of residuals. Residuals are differences between the observed values and the corresponding values that are predicted by the model and thus represent the variance that is not explained by the model. Plots of residuals versus the expected normal distribution are shown for both analyses for each of the emissions in Figures 13-15.



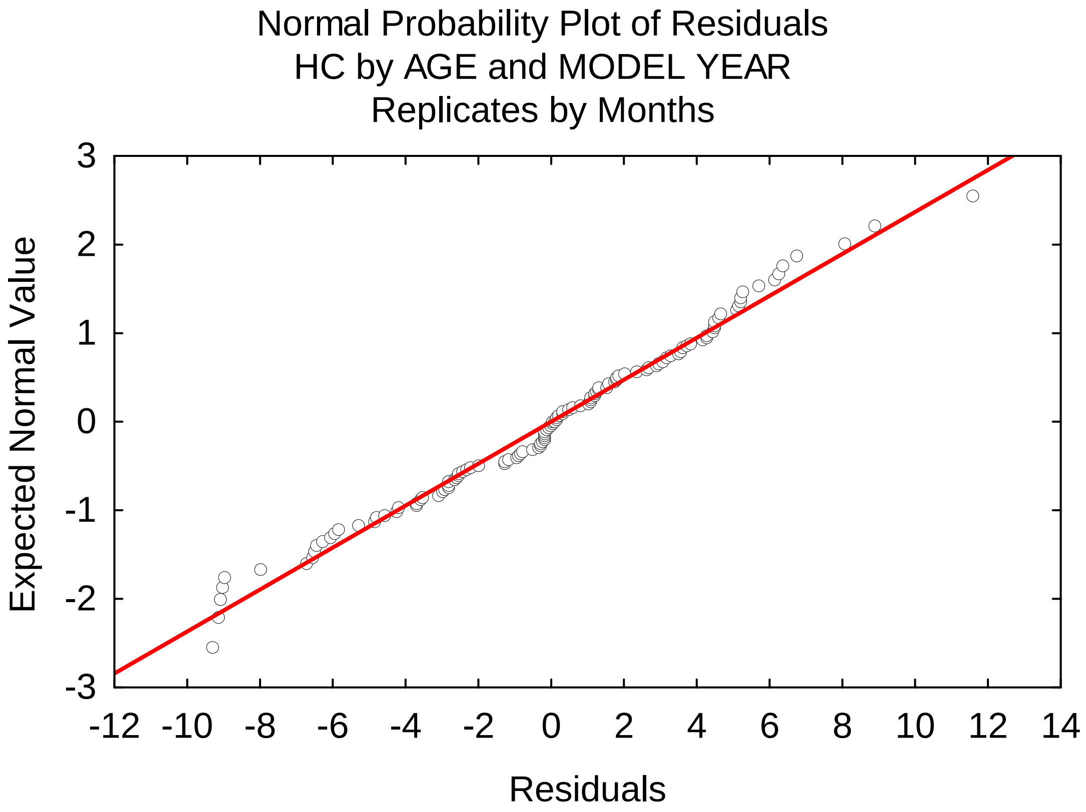


Figure 13: Normal Probability Plot of Residuals, from Multiple Regression of HC ppm by Age and Model Year from Remote Sensing in St. Louis, MO

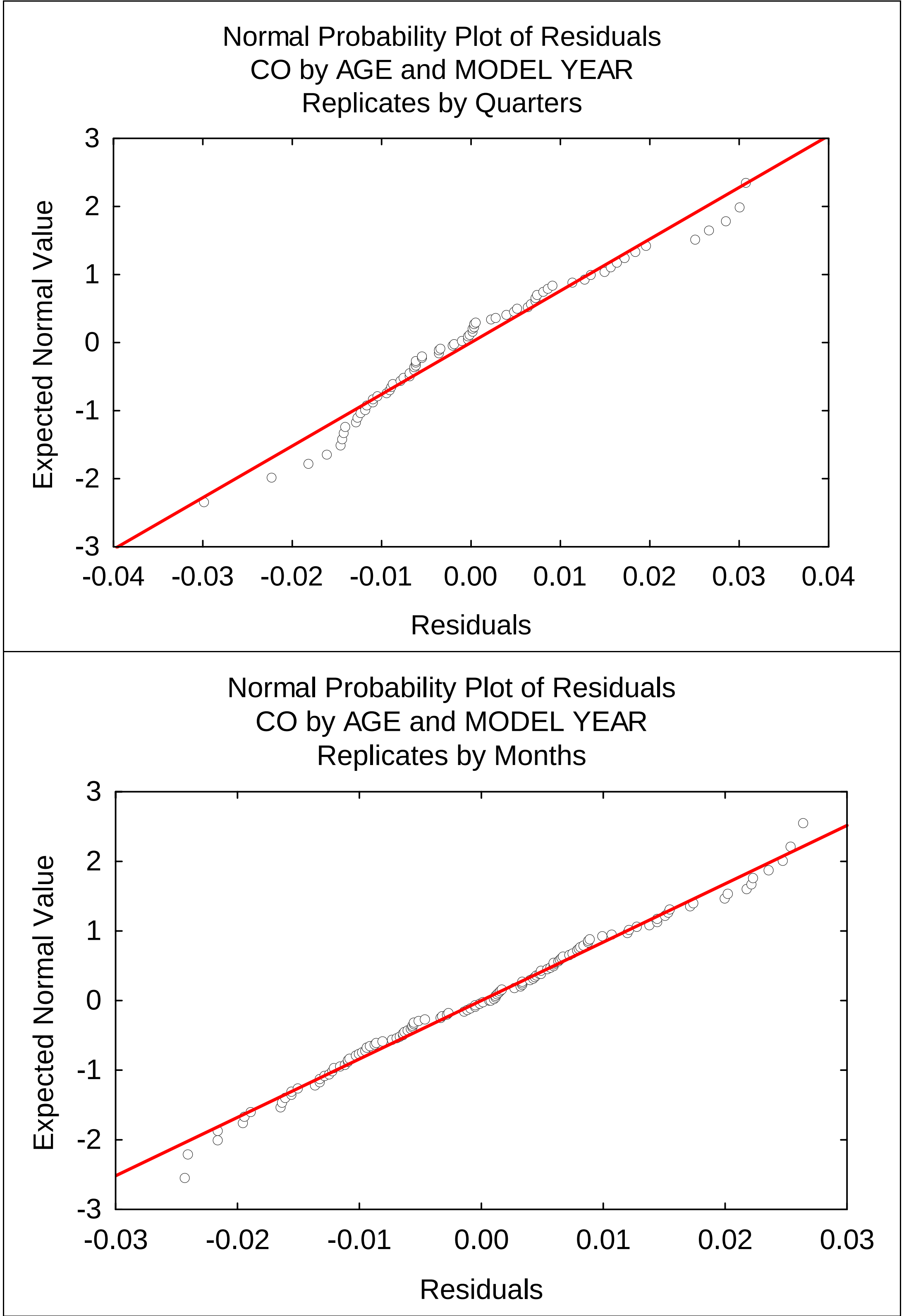
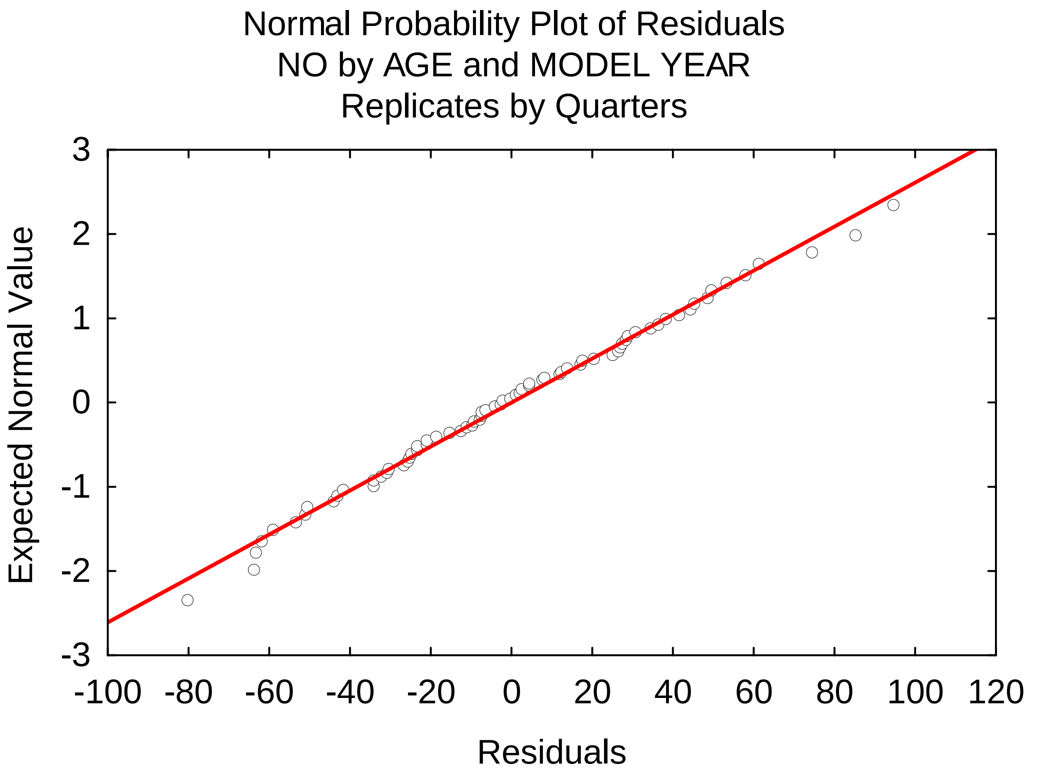


Figure 14: Normal Probability Plot of Residuals, from Multiple Regression of %CO by Age and Model Year from Remote Sensing in St. Louis, MO



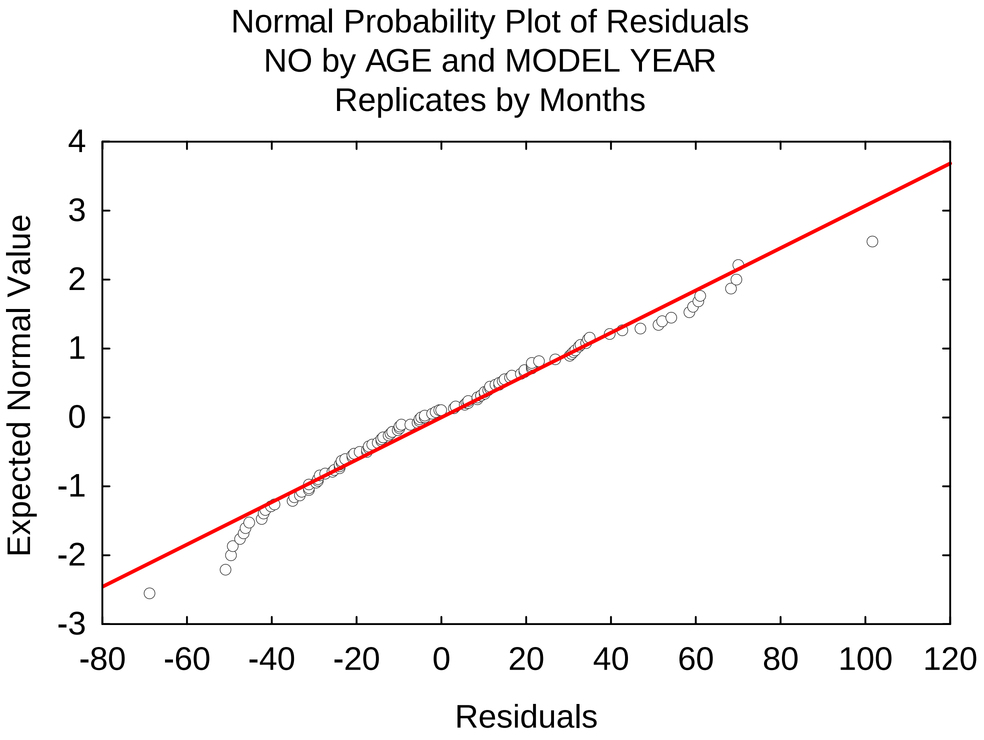


Figure 15: Normal Probability Plot of Residuals, from Multiple Regression of NO ppm by Age and Model Year from Remote Sensing in St. Louis, MO

In multiple regression analysis the beta values indicate the relative importance of different independent variables (age, model year) for explaining the variation in the dependent variable (emissions).

Beta values indicate that model year affects emissions in OBDII equipped vehicles for NO and CO but not for HC. Results are shown in Table 11. Negative beta values indicate that the emissions are decreasing with increasing model year. The abbreviation NS indicates a non-significant correlation. The R^2 value indicates the percent of variation in the dependent variable explained by the independent variables, AGE and MODEL YEAR.

Table 11: Results of Multiple Regression Analysis on emissions of OBDII equipped vehicles categorized by model year and age of vehicle measured by remote sensing in St. Louis from 2002 to 2005

Emission	Replicates	MODEL YEAR beta	MODEL YEAR p value	AGE beta	AGE p value	R^2
NO	Monthly	-0.67	<0.000	0.35	<0.000	0.93
NO	Quarterly	-0.76	<0.000	0.32	<0.000	0.93
CO	Monthly	-0.57	<0.000	0.44	<0.000	0.92
CO	Quarterly	-0.55	<0.000	0.51	<0.000	0.92
HC	Monthly	0.13	0.093 (NS)	0.88	<0.000	0.60
HC	Quarterly	-0.02	0.75 (NS)	0.82	<0.000	0.71

Data for these analyses are shown in Tables 12 through 14.

Plots of emissions classified by both model year and age show that NO and CO emissions are lower for newer OBDII equipped vehicles of the same age based on remote sensing measurements made in St. Louis between 2002 and 2005. However, HC emissions are a function of age, but not of model year. This is shown in Figures 16 through 18. Data for these figures is in Tables 12 to 14.

In Figures 16 through 18 the emission values for the same vehicle model year are slightly offset for different ages in order to prevent overlap of the confidence interval whiskers. The offset in the chart does not indicate a difference in the model year.

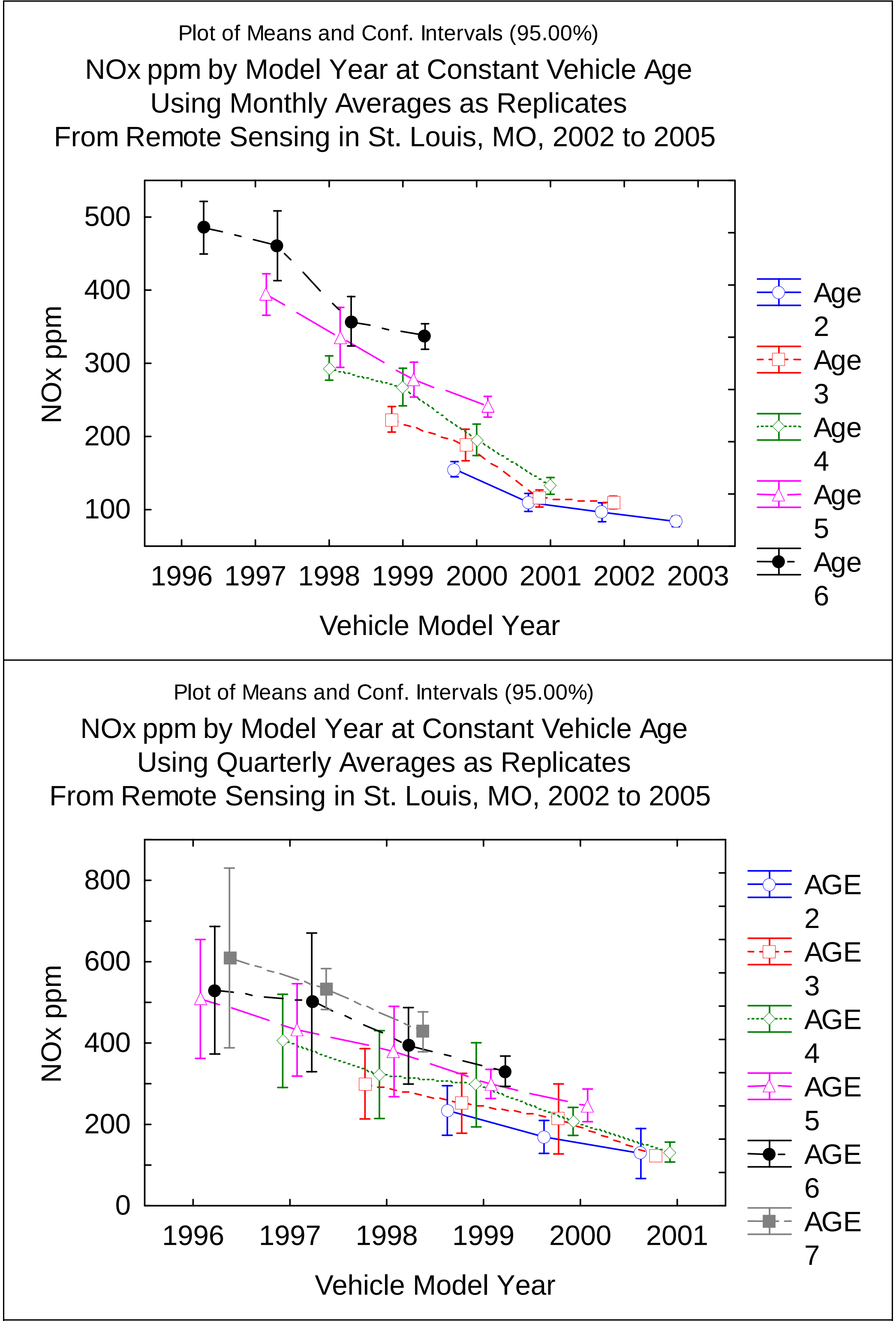


Figure 16: NO Emissions Of OBDII Equipped Vehicles Categorized By Model Year And Age of Vehicle

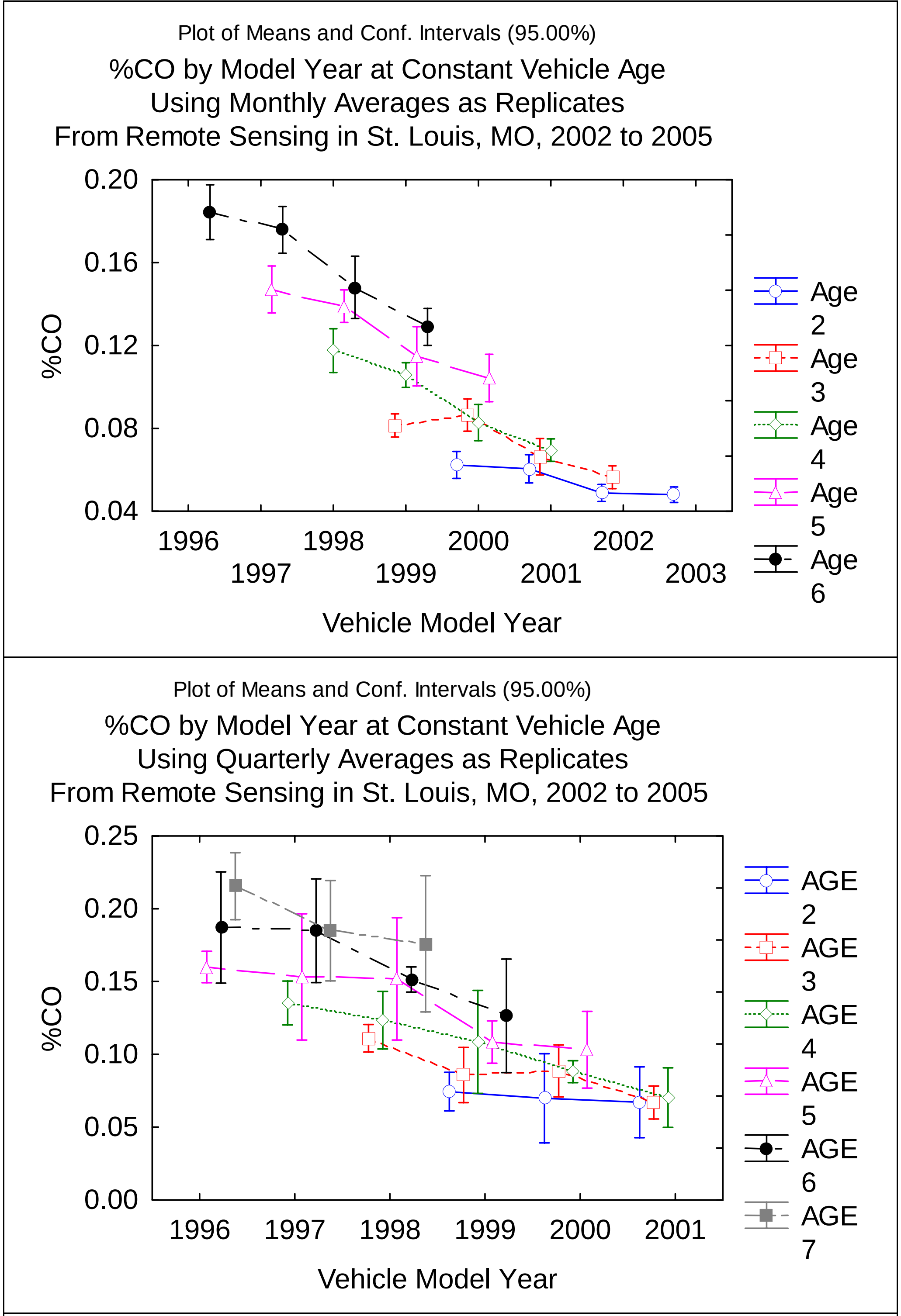
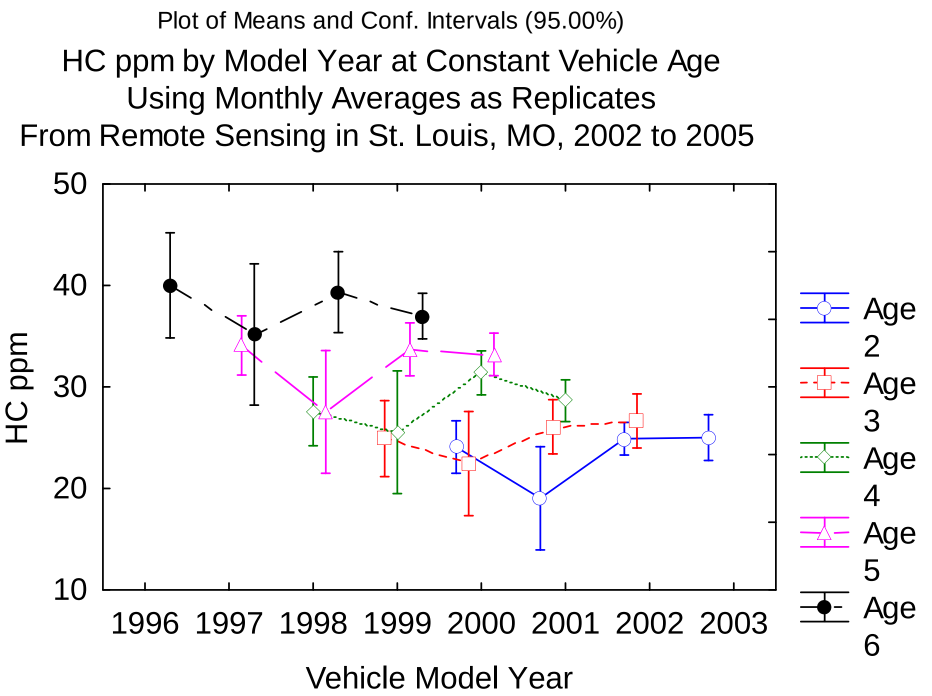


Figure 17: CO Emissions Of OBDII Equipped Vehicles Categorized By Model Year And Age of Vehicle



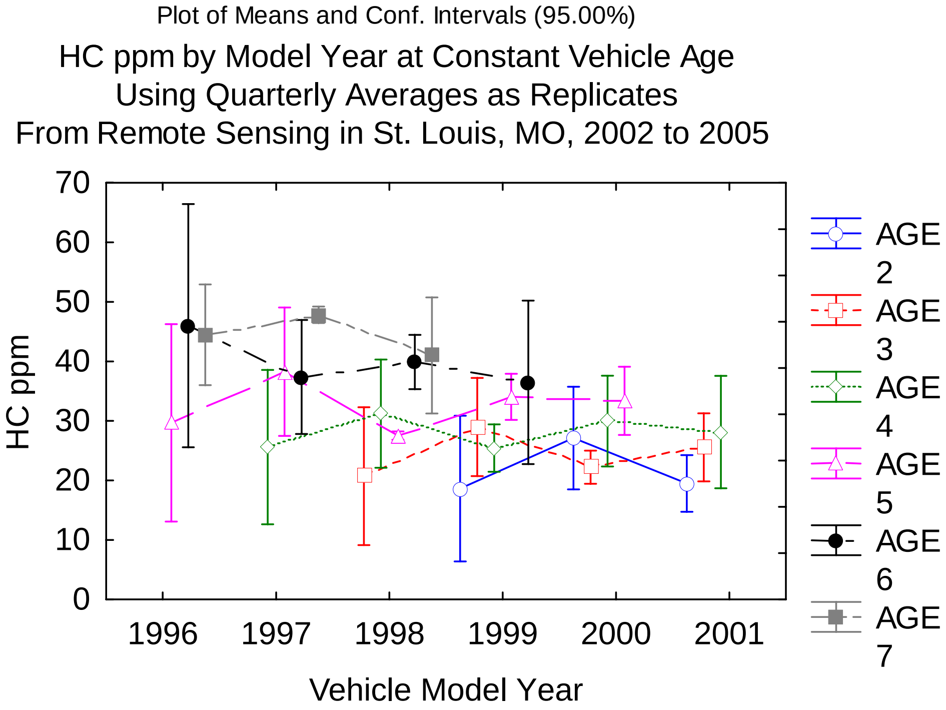


Figure 18: HC Emissions Of OBDII Equipped Vehicles Categorized By Model Year And Age of Vehicle

Table 12A: Average NO ppm from Remote Sensing in St. Louis, MO, by Year and Month Measured at Multiple Sites for OBDII Equipped Vehicles, Model Years (1996 to 2003)

Year	Month	1996	1997	1998	1999	2000	2001	2002	2003
2002	Apr	487.7	405.6	289.8	211.8	155.9	107.5	94.2	53.6
2002	May	530.8	417.5	300.8	242.0	166.5	105.7	88.1	34.5
2002	Jun	471.3	388.7	287.0	211.9	150.9	89.1	71.7	26.3
2002	Jul	446.9	356.5	279.6	218.5	144.0	90.5	84.5	25.4
2002	Aug	455.8	371.1	282.1	210.0	146.9	85.5	74.9	110.7
2002	Sep	520.5	425.7	322.2	247.0	167.4	99.3	91.1	66.6
2003	Apr	617.6	517.3	375.0	295.9	211.8	130.3	113.3	80.3
2003	May	565.7	462.6	330.9	279.4	185.1	108.3	98.4	90.0
2003	Jun	550.0	469.8	350.1	268.9	197.1	110.9	92.3	76.6
2003	Jul	520.6	450.2	313.4	242.1	176.8	103.4	86.3	56.8
2003	Aug	472.5	381.0	271.8	234.5	155.5	94.8	84.5	69.6
2003	Sep	529.8	483.9	371.6	285.5	204.3	111.8	100.7	64.0
2004	Apr	586.8	526.6	352.9	278.2	180.9	133.7	93.2	66.6
2004	May	516.1	492.6	328.0	248.7	169.3	105.0	79.7	59.1
2004	Jun	526.8	448.5	325.1	263.9	197.9	103.8	86.8	68.6
2004	Jul	621.3	500.2	389.2	283.1	220.0	116.3	105.3	82.9
2004	Aug	552.6	508.8	346.7	276.0	187.0	112.4	112.9	82.6
2004	Sep	622.3	514.2	403.4	316.6	218.0	120.2	101.2	76.1
2005	Apr	738.3	581.4	455.1	346.5	238.6	127.7	112.8	85.6
2005	May	646.5	564.2	448.0	339.9	249.8	125.3	111.4	85.9
2005	Jun	643.6	553.3	417.5	341.4	240.6	133.0	96.2	83.6
2005	Jul	608.8	505.2	414.5	311.0	233.9	125.7	108.7	76.2
2005	Aug	585.9	510.3	391.3	324.0	220.8	128.9	108.4	77.2
2005	Sep	654.0	568.7	465.5	357.4	260.5	154.0	121.5	95.0

Table 12B: Average NO ppm from Remote Sensing in St. Louis, MO, by Year and Quarter Measured at Multiple Sites for OBDII Equipped Vehicles, Model Years (1996 to 2001)

Year	Quarter	1996 avg	1997 avg	1998 avg	1999 avg	2000 avg	2001 avg
2001	Mar-May	502.3	384.3	290.7	221.7	148.9	100.0
2002	Mar-May	542.7	438.8	308.9	254.8	167.8	101.6
2003	Mar-May	665.4	528.8	393.8	312.0	227.6	124.4
2004	Mar-May	609.0	532.9	365.2	289.3	193.3	121.0
2005	Mar-May	657.8	528.1	417.7	324.4	239.9	126.9
2001	June-Aug	452.9	373.4	270.5	218.7	153.2	95.4
2002	June-Aug	461.3	383.9	287.4	221.3	153.6	93.1
2003	June-Aug	506.9	421.9	328.9	250.4	174.0	106.1
2004	June-Aug	571.6	512.6	378.2	292.9	207.5	120.4
2005	June-Aug	608.7	520.5	415.0	319.9	235.3	125.9
2001	Sept-Nov	570.1	458.1	338.2	262.6	176.8	112.1
2002	Sept-Nov	585.5	474.7	371.1	280.3	186.3	122.4
2003	Sept-Nov	655.7	549.8	414.6	329.7	238.8	155.1
2004	Sept-Nov	648.2	553.0	436.3	315.8	221.0	127.5
2005	Sept-Nov	661.3	581.1	450.5	347.8	265.3	143.5

Table 13A: Average %CO from Remote Sensing in St. Louis, MO, by Year and Month Measured at Multiple Sites for OBDII Equipped Vehicles, Model Years (1996 to 2003)

Year	Month	1996	1997	1998	1999	2000	2001	2002	2003
2002	Apr	0.164	0.136	0.128	0.080	0.059	0.048	0.036	0.008
2002	May	0.178	0.135	0.102	0.073	0.056	0.042	0.033	0.026
2002	Jun	0.199	0.163	0.111	0.082	0.062	0.052	0.041	0.053
2002	Jul	0.186	0.154	0.115	0.090	0.066	0.050	0.058	0.036
2002	Aug	0.183	0.143	0.122	0.084	0.058	0.049	0.043	0.053
2002	Sep	0.196	0.152	0.127	0.080	0.073	0.045	0.041	0.019
2003	Apr	0.231	0.185	0.139	0.114	0.090	0.063	0.048	0.033
2003	May	0.207	0.155	0.144	0.098	0.075	0.050	0.043	0.037
2003	Jun	0.226	0.176	0.149	0.107	0.088	0.064	0.041	0.036
2003	Jul	0.195	0.183	0.136	0.108	0.097	0.068	0.045	0.040
2003	Aug	0.208	0.175	0.127	0.100	0.085	0.060	0.046	0.035
2003	Sep	0.216	0.181	0.139	0.107	0.083	0.057	0.043	0.039
2004	Apr	0.187	0.164	0.141	0.097	0.071	0.056	0.041	0.029
2004	May	0.194	0.156	0.138	0.099	0.094	0.070	0.050	0.034
2004	Jun	0.210	0.166	0.134	0.130	0.086	0.056	0.049	0.044
2004	Jul	0.241	0.187	0.174	0.118	0.089	0.076	0.050	0.038
2004	Aug	0.179	0.168	0.153	0.124	0.079	0.068	0.053	0.039
2004	Sep	0.214	0.188	0.149	0.121	0.078	0.072	0.049	0.042
2005	Apr	0.231	0.223	0.142	0.123	0.088	0.065	0.052	0.051
2005	May	0.222	0.195	0.177	0.118	0.104	0.063	0.049	0.043
2005	Jun	0.235	0.197	0.184	0.135	0.102	0.070	0.056	0.046
2005	Jul	0.225	0.224	0.174	0.137	0.120	0.075	0.061	0.049
2005	Aug	0.222	0.212	0.183	0.124	0.113	0.076	0.063	0.046
2005	Sep	0.231	0.195	0.205	0.137	0.099	0.068	0.057	0.053

Table 13B: Average %CO from Remote Sensing in St. Louis, MO, by Year and Quarter Measured at Multiple Sites for OBDII Equipped Vehicles, Model Years (1996 to 2001)

Year	Quarter	1996 avg	1997 avg	1998 avg	1999 avg	2000 avg	2001 avg
2001	Mar-May	0.165	0.130	0.107	0.071	0.054	0.037
2002	Mar-May	0.176	0.138	0.120	0.082	0.061	0.049
2003	Mar-May	0.212	0.170	0.147	0.101	0.088	0.061
2004	Mar-May	0.195	0.169	0.151	0.102	0.087	0.062
2005	Mar-May	0.221	0.202	0.158	0.109	0.093	0.066
2001	June-Aug	0.157	0.134	0.111	0.071	0.058	0.047
2002	June-Aug	0.181	0.150	0.118	0.081	0.065	0.051
2003	June-Aug	0.208	0.185	0.138	0.100	0.082	0.062
2004	June-Aug	0.225	0.194	0.148	0.112	0.091	0.071
2005	June-Aug	0.235	0.211	0.174	0.138	0.114	0.080
2001	Sept-Nov	0.158	0.142	0.115	0.081	0.060	0.043
2002	Sept-Nov	0.205	0.172	0.133	0.095	0.084	0.061
2003	Sept-Nov	0.226	0.199	0.171	0.125	0.096	0.078
2004	Sept-Nov	0.207	0.192	0.155	0.112	0.086	0.068
2005	Sept-Nov	0.244	0.198	0.196	0.132	0.102	0.065

Table 14A: Average HC ppm from Remote Sensing in St. Louis, MO, by Year and Month Measured at Multiple Sites for OBDII Equipped Vehicles, Model Years (1996 to 2003)

Year	Month	1996	1997	1998	1999	2000	2001	2002	2003
2002	Apr	30.5	29.2	22.3	21.3	20.0	16.0	15.8	-18.2
2002	May	40.5	35.1	28.9	27.9	25.7	21.8	21.3	30.6
2002	Jun	41.6	35.5	28.3	22.4	22.5	21.5	17.6	14.0
2002	Jul	44.7	36.5	31.8	28.5	26.5	24.3	22.5	41.3
2002	Aug	40.1	35.9	28.6	28.0	25.8	24.6	23.0	21.8
2002	Sep	42.6	32.4	25.8	21.4	23.9	20.9	18.8	16.1
2003	Apr	50.6	47.9	39.0	35.2	29.9	26.9	27.5	23.5
2003	May	37.6	29.8	23.6	20.1	16.3	12.5	10.4	10.3
2003	Jun	41.1	33.7	26.9	24.5	23.2	18.2	15.1	16.0
2003	Jul	39.8	33.8	26.0	23.0	20.6	17.0	15.3	17.3
2003	Aug	36.0	30.4	23.7	21.1	19.0	18.1	15.7	17.8
2003	Sep	43.1	35.5	26.2	29.4	25.7	21.5	19.2	16.5
2004	Apr	50.5	45.9	44.9	34.7	29.7	25.9	24.7	26.3
2004	May	53.5	43.5	43.2	33.7	34.7	30.5	27.5	28.9
2004	Jun	51.5	42.5	36.6	30.1	29.4	25.4	24.2	26.2
2004	Jul	50.2	48.7	36.7	33.0	33.1	24.7	23.4	17.1
2004	Aug	45.9	43.9	36.0	37.7	30.8	23.0	23.9	23.3
2004	Sep	47.7	47.3	38.6	33.0	30.7	27.0	25.8	23.1
2005	Apr	62.7	53.2	39.4	38.7	33.5	29.3	26.6	24.8
2005	May	59.5	49.7	42.9	33.1	33.5	25.8	23.6	21.9
2005	Jun	66.9	53.9	46.7	38.5	33.7	30.6	28.3	26.6
2005	Jul	57.8	52.8	43.9	38.4	36.4	30.9	30.6	28.1
2005	Aug	52.2	51.0	38.4	36.1	30.9	27.5	26.4	24.1
2005	Sep	58.3	49.3	42.9	37.0	31.2	27.8	24.5	24.5

Table 14B: Average HC ppm from Remote Sensing in St. Louis, MO, by Year and Quarter Measured at Multiple Sites for OBDII Equipped Vehicles, Model Years (1996 to 2001)

Year	Quarter	1996 avg	1997 avg	1998 avg	1999 avg	2000 avg	2001 avg
2001	Mar-May	29.2	23.8	20.5	17.8	14.7	11.5
2002	Mar-May	40.9	35.7	28.3	27.3	24.9	21.7
2003	Mar-May	46.8	41.5	27.8	26.5	23.5	21.6
2004	Mar-May	54.7	47.5	41.9	35.2	31.8	27.0
2005	Mar-May	52.7	48.9	36.5	30.1	30.7	23.9
2001	June-Aug	23.2	21.5	16.1	14.2	13.1	11.3
2002	June-Aug	41.6	35.8	30.0	26.8	25.4	22.9
2003	June-Aug	40.6	33.9	27.6	23.6	21.7	19.2
2004	June-Aug	53.1	48.5	39.4	34.6	31.6	26.7
2005	June-Aug	61.1	51.5	43.1	39.2	34.9	31.1
2001	Sept-Nov	36.6	31.5	25.5	23.9	20.4	17.6
2002	Sept-Nov	55.5	43.3	35.3	32.8	31.1	28.0
2003	Sept-Nov	46.0	36.7	27.2	26.2	21.4	17.8
2004	Sept-Nov	47.8	47.5	38.4	32.3	26.4	22.9
2005	Sept-Nov	62.3	53.1	43.4	40.1	34.5	29.3

Conclusions for Multiple Site Measurements

Large number of remotes sensing measurements can be used to obtain average deterioration rates of OBDII equipped vehicles and to determine if newer vehicles of the same age are cleaner and deteriorate more slowly. The results are for fuel based mass emissions and are valid for driving conditions under which the remote sensing measurements were made.

The results for 2001-2005 measurements on 1996 to 2003 vehicles show that emission deterioration rates are lower for the newer OBDII equipped vehicles. Plots of deterioration rates versus model year are “S” shaped, with deterioration rates are not a strong function of model year for the newest and oldest vehicles. The tailing off of deterioration rates with model year for the older OBDII equipped vehicles could be due to the repair of these vehicles in the St. Louis area.

The results of the analyses also show that for NO and CO, but not for HC, newer model year OBDII equipped vehicles at the same age are lower emitting.

Discussion of Remote Sensing Applications as Vehicles Become Cleaner

This report examines the use of remote sensing to measure OBDII equipped vehicles. Most of these vehicles are very low emitting so many measurements were required to characterize the average emissions and the average deterioration rates. One might ask what the value of remote sensing is in the era of cleaner vehicles.

Remote sensing can identify high emitting vehicles. As high emitting vehicles become rarer, the relative cost effectiveness of a remote sensing high-emitting vehicle identification program becomes greater compared to testing all vehicles. Also, as most vehicles get cleaner, the ability of remote sensing to identify vehicles that are always high emitters should become easier.

One could increase the accuracy of remote sensing by an order of magnitude for HC, CO, NO, and include HCHO monitoring if mid IR range lasers (quantum cascade lasers) were to drop in cost sufficiently. Availability of inexpensive mid-IR range lasers would allow inexpensive commercial instruments similar to Aerodyne’s TILDAS devices. Another possible way to improve individual vehicle remote sensing accuracy would be to be better able to adjust measurements for ambient conditions, background levels, and driving variability. Instrument improvements that have already occurred include automatic, frequent calibration to standards.

New applications exist for remote sensing with currently available technology for measuring tailpipe SO_2, NO_2, NH_3, and possibly HONO. High SO_2 emissions indicate whether diesel truckers are using a cheaper substitute fuel instead of low sulfur diesel. NO_2 is formed when PM traps are regenerated. Plumes have been measured where NO_2 is 50% of the NO emissions. Remote sensing is being used on a pilot study in Japan to determine the extent of this problem. NH_3 is formed from gasoline fueled catalyst equipped vehicles by over reduction of NO and from diesel fueled vehicles using urea as part of NO emission suppression.[35] The contribution of vehicle generated NH_3 to ammonium sulfate and ammonium nitrate production in urban areas is not well understood.

Even if RSD does not have the signal to noise level to accurately detect the variations in individual vehicle emissions at the ZEV or SULEV level it is still appropriate for estimating on-road vehicle emissions inventories by a fuel based method. This is because the signal to noise ratio improves by the square root of the number of measurements and when you can easily make 5000-10,000 fuel based mass emission measurements per day you can get useful signal to noise ratios as is seen from E-23 studies and even better in programs that generate many more measurements such as those in Virginia and Missouri.[36]

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[35] As vehicles of newer model years are observed we see less and less NO of which a larger and larger fraction is NH3 up to 50% from the newest model years. Personal communication, D. H. Stedman, 5 July 2006

[36] Don Stedman and Peter McClintock contributed to this section.

Appendix A: VIN information

From
http://www.vehicleidentificationnumber.com/vehicle_identification_numbers_vin_detail.html

The first character vehicle identification number (VIN) serial number identifies the country from which the vehicle was manufactured. First vehicle identification number digit: U.S.A.(1 or 4), Canada (2), Mexico (3), Japan (J), Korea (K), England (S), Germany (W), Italy (Z)

Second vehicle identification number digit specifies the manufacturer. Audi (A), BMW (B), Buick (4), Cadillac (6), Chevrolet (1), Chrysler (C), Dodge (B), Ford (F), GM Canada (7), General Motors (G), Honda (H), Jaguar (A), Lincoln (L), Mercedes Benz (D), Mercury (M), Nissan (N), Oldsmobile (3), Pontiac (2 or 5), Plymouth (P), Saturn (8), Toyota (T), Volvo (V).

Third vehicle identification number digit indicates the vehicle type or manufacturing division.

Fourth through eighth vehicle identification number digit reveals the vehicle features such as body style, engine type, model, series, etc.

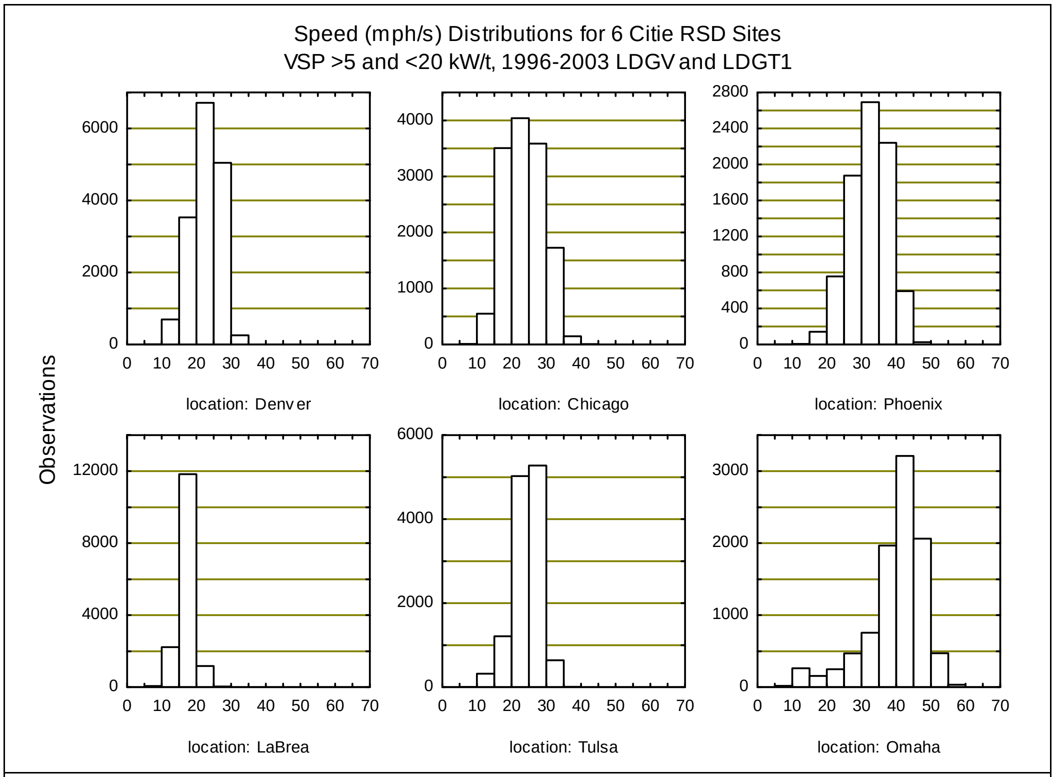
The ninth vehicle identification number digit is a VIN accuracy check digit, verifying the previous VIN numbers.

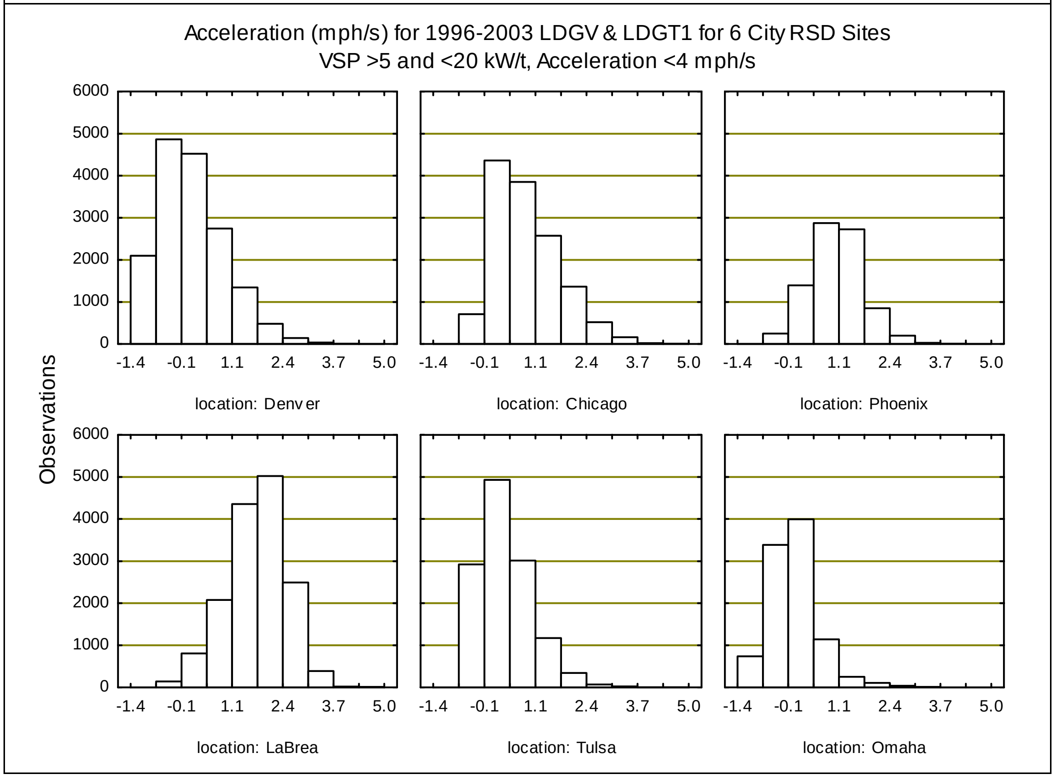
Tenth vehicle identification number digit tells the model year. 1988 (J), 1989 (K), 1990 (L), 1991 (M), 1992 (N), 1993 (P), 1994 (R), 1995 (S), 1996 (T), 199 7(V), 1998 (W), 1999 (X), 2000 (Y) 2001(1), 2002 (2), 2003 (3)

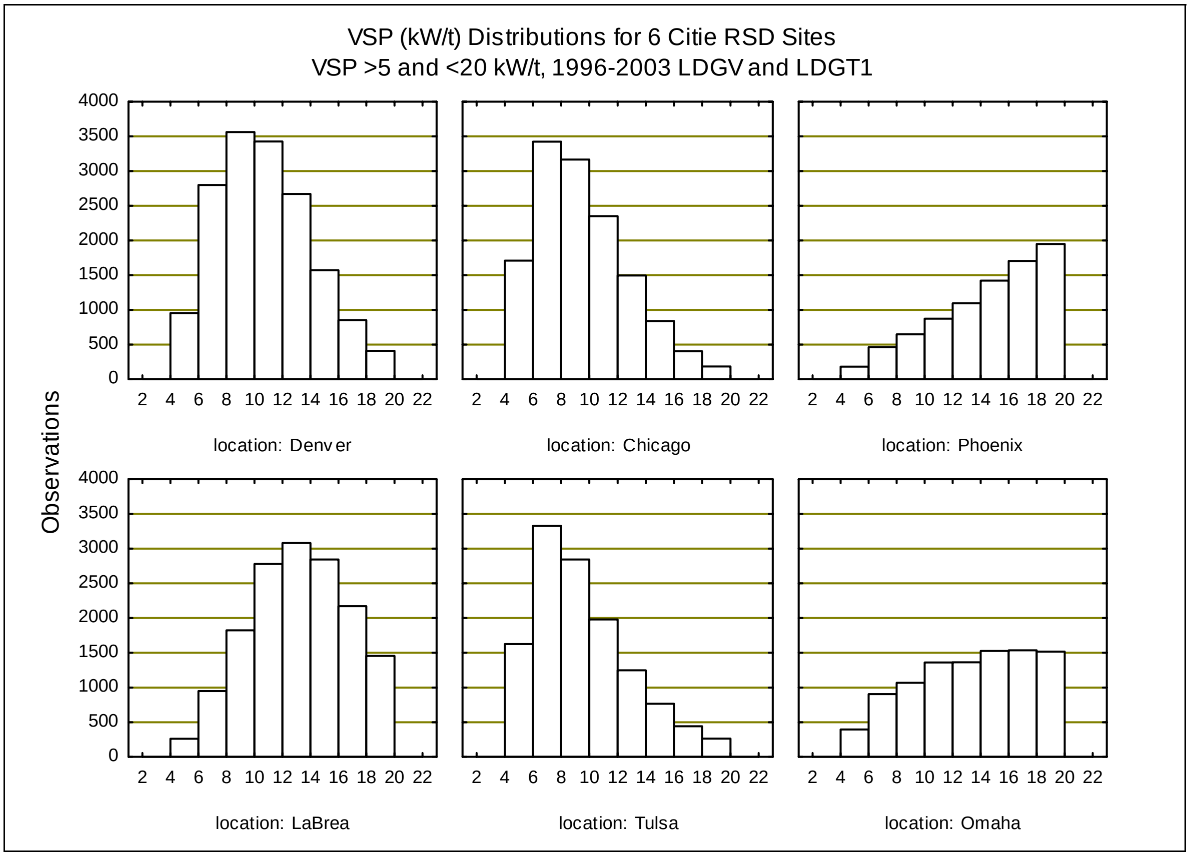
Eleventh vehicle identification number digit reveals the assembly plant for the vehicle.

The twelfth to seventeenth vehicle identification number digits indicate the sequence of the vehicle for production as it rolled off the manufacturer's assembly line.

Appendix B: Histograms of Speed, Acceleration, and VSP for 6 Cities






VSP (kW/t) Distributions for 6 Citie RSD Sites
VSP >5 and <20 kW/t, 1996-2003 LDGV and LDGT1
Observations
0
500
1000
1500
2000
2500
3000
3500
4000
2 4 6 8 10 12 14 16 18 20 22
location: Denv er
location: Chicago
location: Phoenix
location: LaBrea
location: Tulsa
location: Omaha