REMOTE SENSING MEASUREMENT OF REAL WORLD VEHICLE HIGH-EXHAUST EMITTERS

Interim Report

CRC Project No. E-23

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Table of Contents

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PowerPoint Presentations:

EXECUTIVE SUMMARY

REMOTE SENSING MEASUREMENT OF REAL WORLD VEHICLE HIGH-EXHAUST EMITTERS

Scope and Objectives

The objectives of this project are to follow vehicle emissions using remote sensing measurements of on-road vehicles at selected sites to identify trends over a five-year period, and use the information to estimate high exhaust emitter populations. The answers to two questions are important to these objectives:

- How do fleet emissions change from year to year?
- How do fleet emissions differ from site to site?

Background

Investigators have used remote sensing of on-road emissions to find the fraction of vehicles that are high hydrocarbon and carbon monoxide emitters, and have shown that a small fraction of on-road cars are responsible for a large fraction of the mobile emissions. There has been, however, little information from single sites over a period of years to examine trends in vehicle emissions as vehicle technology changes. CRC is interested in long-term monitoring at several sites to examine the influence of new technology, use of enhanced inspection/maintenance programs, and the use of on-board diagnostic systems.

Additional data, collected under the E-23 protocol, are being contributed by other organizations for analysis in E-23. Remote sensing measurements made in 1999 as part of the California Inspection and Maintenance Review Committee Smog Check II Evaluation and earlier measurements made in Denver by the University of Denver have been analyzed with the E-23 measurements. EPA is supplying data collected in Raleigh/Durham, NC, and Georgia Institute of Technology will be supplying data from Atlanta and other locations in Georgia supported through a state program. Data have been promised from the Missouri Rapid Screen program. CRC has established a multi-year phased contract to collect data in Los Angeles, Phoenix, Denver, and Chicago.

Interim Results

Data

Through 2001, the program has accumulated 4 years of RSD at the same Chicago site, and 3 years of E-23 RSD plus 2 earlier years of University of Denver RSD at the same Denver site. Los Angeles data gathering has been more difficult. Three years of data were obtained at Riverside, though the most recent fleet does not look like earlier years, perhaps due to intervening construction at the Riverside site. Starting in 2001, E-23 measurements were made at La Brea in Los Angeles, but this site was used once before for California Smog Check remote sensing. In Phoenix, measurements were made at three different sites over three years, but in each of two years two sites were used.

The North Carolina data has not yet been analyzed. The Georgia Tech data available had not collected using E-23 protocol until 1999, and then only in a limited study. However, 2000 and later data should be collected under E-23 protocol. No Missouri data have been received, but data should arrive after Missouri's reports are issued.

Analysis

Analysis for the project has resulted in a way to quantitatively analyze NOx remote sensing results. Using a limited load range (estimated as "vehicle specific power", based on speed, acceleration, and road grade) fleet NO emissions can be compared at different sites. Also, the onset of power enrichment can be detected for different model years and vehicle types. The technique was described in a poster session at the 2001 CRC On-Road Vehicle Emissions Workshop and published in an SAE paper in September

2001. Vehicle specific power estimates were used to filter remote sensing CO and HC readings, removing vehicles from the analysis that could be driving in power enrichment or in deceleration. Clean vehicles in either of these driving modes could appear as high emitters based on remote sensing measurements.

How do fleet emissions change from year to year?

Currently, the four and five year data sets from Chicago and Denver provide the best records for monitoring the change of emissions with time. In Chicago, NO and CO fleet emissions decreased from 1997 to 2000. HC emissions decreased only slightly during that time. In early 1999, Chicago converted from a Basic (idle) inspection and maintenance program to an Enhanced (loaded mode) program. The E-23 remote sensing measurements could be used to estimate the additional emissions benefit of the more sophisticated inspection program. For the model years tested in the program, a 7% $\pm$ 2% CO, a 14% $\pm$ 6% HC, and a 2% $\pm$ 3% NO benefit was estimated for the Enhanced over the Basic program based on the vehicles measured at the E-23 site. Both CO and HC emissions decreased from 1996 to 2000 in Denver. The reduction, at constant vehicle age, was most noticeable in the older vehicles. In both Chicago and Denver, the percent of vehicles with emissions above cut points 1%, 2%, and 3% CO decreased from the first year of measurement to the most recent. Newer vehicles are showing slower emissions deterioration than older vehicles.

Site to site correlation was examined using the IMRC California remote sensing data. Sites in Los Angeles and sites in Sacramento were consistent. However, the three Sacramento sites showed much lower CO and HC emissions deterioration than the three Los Angeles sites.

Load corrected NO emissions were similar in Phoenix, Denver, Chicago, and four of the seven California sites. The other three California sites had a lower response of NO to load. Two of these three California sites were high load sites. Further research is required to explain the lower NO emission response to estimated load at these three sites.

Future

Due to the slower rate of deterioration of new vehicles, the timing between measurements at the same site has been increased from one year to two.

The benefit of inspection and maintenance programs based on OBDII cannot be determined from data collected within the program because OBDII is a pass/fail test. EPA is considering funding additional E-23 cities that do not have inspection and maintenance (I/M) programs to compare emissions deterioration in 1996 and newer vehicles that are equipped with OBDII systems between locations with I/M programs and locations with no I/M program.

The response of NO emissions to load at high load sites will be examined using measurements made in 2000 in Phoenix. Measurements were made using two remote sensing instruments in Phoenix in 2000 so that two measurements per vehicle were made, where the same vehicle would be under different loads each time it was measured.

Large numbers of additional remote sensing measurements made under E-23 protocol are expected from Georgia Tech and from Missouri.

Summary

E-23 is progressing well. Denver and Chicago sites continue to provide useful data on how fleet emissions are changing. Trends from Phoenix and Los Angeles (La Brea) should become clear with additional measurements. Opportunities for site to site correlation will be enhanced when Atlanta and St. Louis data are received.

This interim E-23 report has been assembled so that all parties can see the results in the first part of this written report. Background on remote sensing, and analysis of remote sensing follows the results. The current status of the project is in Appendix A and the E-23 protocol for data gathering is in Appendix B. Graphical presentations of the results are shown in five PowerPoint presentations. Looking at these presentations is highly recommended to appreciate the trends and uncertainties in the data.

Results

E-23 uses on-road remote sensing measurements to understand the changes in vehicle fleet emissions over time. This interim report will discuss analysis on measurements made as part of the E-23 project in four cities: Denver, Phoenix, Chicago, and Los Angeles. Additional data obtained using E-23 protocol will also be analyzed. The additional data were gathered in Denver prior to the start of E-23 in 1995/1996 and 1996/1997 by Denver University, and was measured in six California locations in 1999 for the California Inspection and Maintenance Review Committee.

The answers to two questions are important to the E-23 objective:

- How do fleet emissions change from year to year?
- How do fleet emissions differ from site to site?

To see how emissions change year to year, E-23 measurements are made in the same site and at the same time of the year over a number of years. Two of the E-23 sites, Chicago and Denver, already have four years of remote sensing measurements. These sites will be used in this report to examine change in CO and HC emissions.

To see how emissions differ from site to site, HC, CO, and NO emissions in 1999 are compared between the seven sites in California. The NO emissions are also compared to the two sites in Phoenix and the Chicago and Denver sites.

Results of the analysis are shown graphically in five presentations. A summary of the conclusions from the analysis follows:

1) Presentation for the September 2001 SAE Fuels and Lubricants Conference: Interpreting Remote Sensing NO Measurements [Analysis based on Cars identified by Vehicle Identification Number (VIN)]
   a) E-23 Phoenix 1999 NO emissions at Site 2 differed in magnitude and in relation to VSP (a surrogate for load) from what had been observed on other individual vehicles and many fleet measurements
      i) NO emissions were high
      ii) NO emissions were independent of VSP between 0 – 15 kW/t.
   b) Vehicle types and vehicle age were found to interact with Vehicle Specific Power[1] (VSP)
      i) For both the low and high load sites, vehicle type ratios (cars/trucks) were different at different VSP (cars appeared to accelerate more quickly than trucks).
      ii) At the high load site, Site 2, average car age was found to be lower at higher VSP (newer cars appeared to accelerate more quickly than older cars).
      iii) Load-based corrections based on individual vehicles should not be applied to vehicle fleets without checking for interactions between vehicle type and vehicle age with load.

[1] Vehicle Specific Power is described in E-23 Reports, e.g. "On-Road Remote Sensing of Automobile Emissions in the Chicago Area: Year 3," Sajal S. Pokharel, Gary A. Bishop and Donald H. Stedman, April 2000, page 8.

   c) NO emissions were analyzed for cars grouped by age in 5-year bins and by load in 5 kW/t. VSP bins. NO emissions at Phoenix Site 2 were found to be similar by age and by VSP to NO emissions measurements for cars at the Phoenix 1998 site, and the Chicago, and Denver sites.
   d) The change of NO emissions with age was modeled by a simple equation.
2) Analyzing Fleet NO Measurements at E-23 Sites (Analysis based on Cars identified by VIN)
   a) %NO versus VSP 1999
      i) Chicago, Phoenix Site 2, and Denver have similar NO emissions for 3, 8, and 13 year age bins, VSP 0-15 kW/t.
      ii) Phoenix Site 1 in 1999 and Riverside, CA, NO emissions were low, and could not be explained yet.
   b) %NO emissions trends
      i) Chicago NO emissions decreased from 1997 to 2000.
      ii) Insufficient information from E-23 measurements in other cities to draw conclusions.
         (1) Only two years of measurement in Denver; emissions appear to decrease with model year.
         (2) Multiple site changes and only two years of measurement in Phoenix
         (3) Riverside data not understood yet, and only two years of measurement; emissions appeared to increase for cars, but still lower than Chicago or Denver or Phoenix (1998 or Site 2 in 1999).
3) California Sites: CO, HC, and NO emissions at seven sites in California in 1999 [Analysis based on MVD registration classification 'P', ~ 93% of which are cars identified by VIN]
   a) The three sites in Los Angeles compared to the three sites in Sacramento showed that vehicles in Los Angeles had higher CO and HC emissions than vehicles in Sacramento.
      i) CO measurements from cars at VSP 5-20 kW/tonne were found to be higher at three sites in Los Angeles than at three sites in Sacramento. A San Jose site was intermediate.
      ii) HC measurements from cars at VSP 5-20 kW/tonne were also found to be higher at the three Los Angeles sites than the three Sacramento sites. The San Jose site was intermediate.
   b) NO emission remote sensing measurements found four of the seven 1999 California sites to be similar to sites in Phoenix, Denver, and Chicago, and three others to be lower.
      i) NO emissions from cars at VSP 0 to 15 kW/tonne at four of the sites were similar to NO emissions from cars in Denver, Phoenix, and Chicago.
      ii) Cars in three of the sites, one in Sacramento, one in Los Angeles, and the San Jose site had lower NO emissions, the NO emissions were less sensitive to VSP.
   c) A comparison of the 1999 fleet CO emissions versus vehicle age with emissions measured in 1993 across North America, shows that the 1999 CO emissions were lower and deteriorated more slowly with increasing age.
4) Analyzing Car CO and HC Emissions in Chicago (Analysis based on Cars identified by VIN)
   a) Average car CO emissions decreased from 1997 to 2000 for all age groups
      i) %CO versus VSP behaved as expected, with little effect of VSP from 5 to 20 kW/t.
   b) Percent of measurements of 1 to 8 year old cars with >1% CO decreased steadily from 1997-2000.
      i) Percent of measurements decreased over the four year time period for each of the following cut points:
         (1) %CO >=1% and <2%,
         (2) %CO >=2% and <3%, and
         (3) %CO >=3%
   c) Deterioration of car %CO by model year was difficult to detect between 1997 and 2000.
      i) Recent model years, 1994-1997, showed no deterioration.
      ii) Some model years, 1991-1992, and possibly 1993, did have deterioration of average %CO emissions.

        iii) Little deterioration seen in cars 1988-1990. This could have occurred due to greater survival of the better-maintained cars, or through the I/M program. A similar low deterioration rate for 1989 model vehicles was also seen in Denver.
    d) Average car HC emissions decreased slightly from 1997 to 2000 for all age groups.
        i) For 1-5 year old cars, and 6-10 year old cars, average %HC emissions were independent of VSP from VSP 5-20 kW/t.
        ii) For 11-15 year old cars, average %HC emissions were much higher at negative loads, and continued to decrease with increasing VSP to 15 kW/t.
5) Analyzing Vehicle CO and HC Emissions in Denver (Analysis based on vehicles identified by DMV classifications "PAS" & "LTK", which represent almost all vehicles measured by remote sensing)
    a) Average PAS & LTK vehicle CO emissions decreased from 1996 to 2000 for all age groups.
        i) The most noticeable drop was for 16-20 year old vehicles, probably due to fleet turnover.
        ii) As expected, VSP between 5 and 20 kW/tonne had little effect on CO emissions.
    b) The percent of measurements of 1 to 8 year old PAS & LTK vehicles with >1% CO decreased from 1996-2000.
        i) Percent of measurements decreased over the four year time period for each of the following cut points but not to the extent seen in Chicago:
            (1) %CO >=1% and <2%,
            (2) %CO >=2% and <3%, and
            (3) %CO >=3%
    c) Average deterioration of average PAS & LTK %CO by model year was easy to detect in most model years between 1996 and 2000. The difference between Denver and Chicago observations could be due to the inclusion of light duty trucks in the Denver analysis set.
        i) Of the recent model years, 1993-1996, only the 1996 model year showed very low deterioration.
        ii) Vehicles in model year 1989 had low deterioration from 1996 to 2000, similar to what was seen in Chicago.
    d) Average LTK and PAS vehicle HC emissions decreased from 1996 to 2000 for all age groups
        i) %HC versus VSP behaved as expected, with little effect of VSP from 5 to 20 kW/t except in older vehicles, which had higher %HC that decreased with VSP similar to what was observed in Chicago.

Introduction

E-23 uses on-road remote sensing measurements to understand the change in vehicle fleet emissions over time. Measurements have been made in four cities: Denver, Phoenix, Chicago, and Los Angeles. The project will analyze other remote sensing measurements made using E-23 protocols. Additional data were gathered in Denver prior to the start of E-23 in 1995/1996 and 1996/1997 by Denver University, in six California locations in 1999 for the California Inspection and Maintenance Review Committee, and an on-going program of remote sensing is taking place in Raleigh-Durham, North Carolina, by EPA. In addition, the Air Quality Laboratory (AQL) at Georgia Institute of Technology has shared data they have obtained with the project. These data include a large number of measurements made in many cities, but especially in a number of sites in the Atlanta area, since 1993 as part of a large remote sensing project for the State of Georgia and EPA. AQL measurements up to 1999 did not measure speed, acceleration, and road grade.

Two factors are important to the E-23 objective: how do fleet emissions change from year to year, and how do fleet emissions differ from site to site. To see how emissions change year to year, E-23 measurements are made in the same site and at the same time of the year. Two of the E-23 sites, Chicago and Denver, already have reported measurements for four years. These sites will be used in this report to examine change in CO and HC emissions.

To see how emissions differ from site to site, NO emissions in 1999 are compared between the seven sites in California, two sites in Phoenix and the Chicago and Denver sites.

Reports are written on each of the E-23 remote sensing campaigns. The Coordinating Research Council website, www.crcao.com, has information on obtaining these reports. Recent reports are available directly from this site. Data and other reports are available at the University of Denver website, www.feat.biochem.du.edu. An up-to-date summary of remote sensing is in the recent NRC report, "Evaluating Vehicle Emission Inspection and Maintenance Programs," which can be located through www.nas.edu. A more detailed review of remote sensing is in the EPA draft guidance document on the use of remote sensing to evaluate inspection and maintenance programs. This document will soon be posted on the EPA website, http://www.epa.gov/otaq/epg/remote.htm, or can be obtained by contacting Jim Lindner at EPA (contact information at the EPA website).

Remote sensing measures emissions by finding the ratio of the pollutant to the amount of CO2 in the exhaust plume. Since this is a concentration measurement rather than a mass emission measurement, remote sensing emissions are related to grams of pollutant per gram of fuel. Mass emission measurements are usually reported in grams per kilometer for a specific driving cycle. The remote sensing measurement takes place in about a ½ second. This is in contrast to dynamometer tests during which vehicle emissions are measured over a variety of driving modes.

Vehicle exhaust emissions depend on a number of factors. The most important are the design of the vehicle, the condition of emission control equipment, and the driving mode of the vehicle.

The design (and identification) of the vehicle is obtained in remote sensing from a video frame of the measured vehicle's license plate. The local Department of Motor Vehicles (DMV) matches the license plate to its registration database. The DMV supplies the vehicle identification number (VIN) and information about the vehicle, which may include information about the owner and the current I/M status. The VIN can be decoded to supply additional information about the vehicle including the engine size and the emission control equipment on the vehicle.

When vehicles have high on-road emissions and are not in a driving mode that could produce such emissions in a well-maintained vehicle, emission control equipment has likely deteriorated or is broken. The driving modes under which a 'clean' vehicle could produce high emissions include: cold-start, when the engine and catalytic converter have not reached operating temperature, at low load HC concentrations in the plume may be high, and during fuel enrichment, when the vehicle purposely operates with extra fuel. Fuel enrichment only occurs when certain vehicles are under high loads.

Vehicle emissions change depending on the load on the vehicle. Jimenez and McClintock[2] developed an equation to estimate vehicle specific power (VSP) in units of kW/metric ton. VSP is a surrogate for vehicle load and can be calculated using only measurements that can be obtained from the side of the road: vehicle speed, acceleration, and road grade.

Emission systems of older vehicles deteriorated gradually over time with age, with the amount and type of driving, and depending on the amount of maintenance. Newer vehicles have more

[2] Jimenez, J. L. and P. M. McClintock, 1999 "Vehicle Specific Power: A Useful Parameter for Remote Sensing and Emission Studies," 9th CRC On-Road Vehicle Emissions Workshop

robust and sophisticated vehicle emission controls and fuel delivery systems. With newer vehicles, less maintenance is required. Emission deterioration is more likely to occur as a result of a component breaking. Since 1996 light duty vehicles sold in the United States are equipped with an on-board computer/sensor system that will alert the motorist to emission related problems. These vehicles may show even more resistance to emission deterioration.

Background

Remote sensing in Denver from 1989 to 1995 had given an early indication that emissions of newer vehicles were deteriorating more slowly[3]. This observation was not reflected in the EPA emissions computer model, MOBILE, used at the time. Slower deterioration rates were confirmed by analysis of full IM240's from inspection and maintenance data in Colorado and other emissions measurements[4]. The new version of MOBILE, MOBILE6, has much lower rates of emission deterioration.

Immediate roadside testing of vehicles identified by remote sensing as high emitters has shown that remote sensing has a high probability of identifying vehicles that are emitting high levels of CO and exhaust HC. Arizona attempted to use remote sensing as a way to catch high emitters on the road. However, the program was recently dropped after a number of years because of political pressures and a high cost to identify and confirm a high emitter ($300/high emitter).[5] In the Arizona remote-sensing high-emitter identification program, a considerable time lag took place from when remote sensing identified a vehicle, and when the vehicle was inspected. Intermittent malfunctions or repairs/adjustments between the RSD measurement and any confirmatory I/M test would reduce the correlation between the two measurements.

Model year averaged remote sensing readings correlate exceptionally well with full inspection and maintenance loaded mode tests. New vehicle models have very low emissions. This led to the proposal to use remote sensing as a device to "clean screen" vehicles. Missouri and two counties in Colorado are starting to use remote sensing for this purpose. Vehicles achieving low remote sensing readings on a number of days in a period of time prior to their planned conventional emission test may be excused from taking an inspection test in these programs.

The recent NRC report points out that remote sensing has been underutilized in inspection and maintenance programs.[6] One reason for this has been the lack of standardization in remote sensing quality control and data reporting. An early accomplishment of E-23 was to produce a remote sensing protocol that detailed how remote sensing sites should be described, what data should be obtained, and how data should be reported. This protocol was developed from a series of evening meetings held during two years of CRC On-Road Workshops. Meeting attendance included most researchers, contractors, consultants, and regulators who were gathering remote sensing data, analyzing it, or considering using remote sensing results in regulations. The protocol was drafted and revised, and has been sent to all participants. The protocol is used in E-23 data collection. The current version of the protocol is in Appendix B.

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[3] Slott, R.S. 1996. Remote Sensing at the Speer Off Ramp, Denver, CO, 1989-1995, Preprint extended abstract, American Chemical Society, New Orleans, LA. March 24-26, 1996. Analysis of remote sensing measurements showed emissions of newer vehicles were deteriorating more slowly than older vehicles

[4] National Research Council, Modeling Mobile Source Emission, 2000

[5] This number was lower than the cost of finding high emitters in the then operating I/M program.

[6] National Research Council, Evaluating Vehicle Emissions Inspection and Maintenance Programs, July 2001.

Another reason for the hesitation in the use of remote sensing results is the uncertainty about the quantitative significance of a measurement made over only about ½ second during which there is no control over the driving mode of the vehicle. VSP correlates second-by-second dynamometer emissions better than speed or acceleration. Fleet measurements of HC, CO, and NO follow general patterns with respect to VSP when regressed against model year. VSP is being considered as a correlating parameter in a future version of EPA's vehicle emission inventory model.

Use of VSP can identify measurements taken during low or negative load when the mass of emissions is low (contribution to the inventory is low), but the *concentration* of HC emissions can be high. Under high VSP some well-maintained vehicles can go into enrichment, resulting in high levels of CO and suppressing NO emissions. NO emissions increase steadily from low VSP to about 15 kW/tonne or 20 kW/tonne. This portion of the NO VSP function has been used to estimate the NO emission control deterioration rate from E-23 remote sensing in Illinois[7].

Objectives

The objectives of this project are to follow vehicle conditions and emissions using remote sensing measurements of on-road vehicles at selected sites to identify trends over a five-year period, and to use the information to estimate high exhaust emitter populations.

Due to the slower rate of deterioration of emissions of newer vehicles, the time of the project has been increased, with a slower frequency of remote sensing campaigns.

The status of data collection, reports issued, and plans is in Appendix A.

Remote Sensing Measurements

Remote sensing of vehicle exhaust was first reported in 1989[8]. Emissions in vehicle exhaust were detected by spectroscopic measurements. Although emissions concentrations in the exhaust plume change rapidly as the plume disperses, the ratio of the individual emissions stays the same over the time of measurement. The concentration of CO_2 can be used as a standard. Other emissions concentrations can be obtained as a ratio of their concentration to that of CO_2. A computer can calculate the best slope of the ratio pollutant to CO_2 from many spectroscopic readings taken in the approximately ½ second of total measurement time. Combustion equations translate emissions measurements into percent, or weight of emissions per weight of fuel used.

The accuracy of remote sensing measurements has been estimated by comparing exhaust emissions measured on-board a vehicle to those measured external to the vehicle using remote sensing equipment. Studies of this type have shown that a remote sensor is capable of CO measurements correct to within ±5% of the values reported by an on-board gas analyzer, and within ±15% for HC[9 10]. The NO remote sensing measurements have increased in accuracy. In

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[7] Slott, R. S. , 11th CRC On Road Workshop, April 2001, poster session.
[8] Stedman, D. H., "Automobile Carbon Monoxide Emissions," Environ. Sci. Tech. 23 (2) 147-148. 1989.
[9] Lawson, D.R.; P. J. Groblicki, D. H. Stedman, G. A. Bishop, P. L. Guenther, *J. Air & Waste Manage. Assoc.* 1990, *40*, 1096.
[10] Ashbaugh, L.L.; D. R. Lawson, G. A. Bishop, P. L. Guenther, D.H. Stedman, R. D. Stephens, P. J. Groblicki, J. S. Parikh, B. J. Johnson, S. C. Haung, "On-road remote sensing of carbon monoxide and hydrocarbon emissions during several vehicle operating conditions." Presented at Environmental Source Controls, Phoenix, AZ, 1992.

a recent study the instrument used by the University of Denver, measuring a late model, low-emitting vehicle indicated a detection limit of 25 ppm for NO, with an error measurement of ±5% of the reading at higher concentrations[11].

The driving mode of vehicles undergoing remote sensing measurements is not well characterized. However, site selection can limit the range of driving modes experienced by most vehicles to a reasonable range of load under hot running conditions[12]. Exhaust emissions certification tests are based on measurements made while a vehicle is on a dynamometer. The vehicle undergoes different, known driving modes. These include cold start, warm start, idle, accelerations, decelerations, and cruising at various speeds. Dynamometer tests used in inspection and maintenance programs attempt to mimic or be correlated with the hot running portion of the exhaust emissions certification tests.

Current emissions models adjust emissions estimates according to average speeds. The speed correction factors depend also on vehicle driving patterns. Jimenez has found that load is a better classification parameter than speed for predicting emissions. Speed correction factors need to be associated with specific vehicle driving patterns. Jimenez derived a vehicle load term, vehicle specific power (VSP), which can be approximated by measurements of speed, acceleration, and road grade. [13]

McClintock reported on the variation of emissions with VSP based on remote sensing measurements in Denver made by RSTi from April 1997 to March 1998.[14] CO measurements are fairly insensitive to VSP over the range 5 to 20 kW/tonne. At higher VSP, CO increased. The new vehicle certification test used at that time had a maximum load of 23 kW/tonne. Above that load some vehicles were programmed to go into fuel enrichment to achieve higher power. Fuel enrichment leads to high concentrations of exhaust CO.

HC concentrations can be high at negative VSP during deceleration. However, the amount of HC emitted is small under these conditions. Remote sensing measurements of HC that are not corrected for VSP can be misleadingly high. HC measurements can also increase at high load due to fuel enrichment. Since remote sensing instruments are calibrated for aliphatic hydrocarbons, and are not sensitive to aromatic and olefinic hydrocarbons, HC measurements

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[11] Pokharel, S. S., G. A. Bishop, and D. H. Stedman, "On-Road Remote Sensing of Automobile Emissions in the Chicago Area: Year 3," Coordinating Research Council, Inc., Contract No. E-23-4, April 2000. To get an idea of what 25 ppm NO may mean in grams/mile emissions, refer to the correlation between IM240 grams/mile and on-road percent emissions in Figure 1 of Stedman, D. H., G. A. Bishop, P. Aldete, R. S. Slott, 1997 "On-Road Evaluation of an automobile emission test program." Environ. Sci. Technol. 31:927-931. Figure 1 shows the correlation between on-road percent emissions at a remote sensing site in Denver with the Colorado IM240 measurements. A reading of 0.15 %NO is about equivalent to 2 grams/mile. On this basis, 25 ppm is equivalent to about 0.03 grams/mile as IM240.

[12] Hot running conditions are driving modes where the catalyst is fully warmed up.

[13] Jiménez-Palacios, José Luis, "Understanding and Quantifying Motor Vehicle Emissions with Vehicle Specific Power and TILDAS Remote Sensing", Submitted to the Department of Mechanical Engineering In Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Mechanical Engineering, Massachusetts Institute of Technology, February 1999.

[14] McClintock, P., "Remote Sensing Measurements of Real World High Exhaust Emitters,"CRC Project No. E-23 - Interim Report, Coordinating Research Council, Inc., March 12, 1999.

need to be increased by about a factor of two.[15] HC emissions over the range 5 to 20 kW/tonne are also not strongly dependent on VSP.

NO emissions are very dependent on VSP. From 0 to about 15 kW/tonne, NO is almost linearly related to VSP. For 13-year-old cars in Chicago, between 0 and 15 kW/tonne VSP, average NO increased from 0.04% to 0.10% in 1997. At higher load, NO may increase or decrease. The average NO emissions for the 13-year-old cars in Chicago in 1997 decreased above 15 kW/tonne, while 3-year-old cars in Chicago in 2000 had average NO emissions that increased from below 0.01% to just above 0.04% when VSP increased steadily from 0 to 25 kW/tonne. A decrease in NO would occur if a vehicle had fuel enrichment. At very high loads NO will continue to increase.

Second-by-second emissions measurements made when vehicles are on dynamometers show emissions vary by driving mode. However, vehicles that have broken emissions control components or malfunctioning fuel metering equipment, show much higher emissions than a well maintained vehicle under almost all hot running driving modes. This has led to the suggestion of the use of remote sensing for detecting low and high emitting vehicles.

Vehicle emissions and emissions distributions

Vehicle emissions of new vehicles meet or exceed new vehicle emissions standards. However, as vehicles age, some vehicles have broken emission control equipment or fuel delivery/engine operation malfunctions, which lead to higher emissions. The probability of this occurring increases with vehicle age and has been observed to decrease with model year. Although vehicle emissions are deteriorating more slowly,[16] some fraction of vehicles in each model year have high emissions.

Since a small percent of the vehicles can have a large effect on the average emissions, to understand changes in fleet emissions, measurements on a large number of vehicles are required. The greater the skewness, the larger the number of measurements is needed.

Analysis of vehicle emissions

A number of factors are important when analyzing vehicle emissions.[17] The fleet should be randomly sampled. The measurements should reflect vehicle emissions on the road. Ideally, motorists would not be aware their emissions are being measured. If the motorist were aware, the accuracy of the measurement may be compromised. The penalty or benefit the motorist may incur as a result of the measurement influences the amount of bias if the motorist is aware of the test. Motorists may adjust their vehicle, fuel, or driving behavior to bias the result in their favor.

Remote sensing has advantages over other vehicle emission tests. However, remote sensing also has drawbacks. A comparison of tests used to obtain tailpipe emissions is shown in Table 1.

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[15] Singer, B. C., D. Littlejohn, J. Ho, and T. Vo, "Scaling of infrared remote sensor hydrocarbon measurements for motor vehicle emission inventory calculations," Environ. Sci. Tech 32(21) 3241-3248, 1998.
[16] McClintock, P., "Options for Future Changes to I/M Programs," Presentation to Regional Air Quality CO Maintenance Plan Subcommittee, Denver, May 1999.
[17] Wenzel, T., B. C. Singer, R. S. Slott, "Some issues in the statistical analysis of vehicle emissions." J. Transportation Statistics, 3(2) 1-14, 2000.

Table 1: Comparison of Tests for Measuring Tailpipe Emissions			
Test	Loaded Mode Emissions Test Conducted at I/M Test Station.	Roadside Pullover Loaded Mode Emissions Test	Remote Sensing
Sample	All vehicles complying with I/M program	Stratified random sample.	Sampled randomly at selected site(s).
Number of Measurements	Millions/year in most programs currently	Thousands/year in a large program	Tens of thousands/week (research) to millions/year for a monitoring or clean screening program.
Prepared for test	Motorist aware of test; failure leads to cost and inconvenience	Motorist can refuse to be tested	Not prepared for test; if motorist penalized as a result of the test, steps can be taken to obscure license plate, etc.
Driving mode	Load depends on test, all vehicles tested at about the same load.	Load depends on test, all vehicles tested at about the same load.	Different vehicles measured at different loads.
Units of measurement	Converted to gram/mile, same as certification test	Converted to gram/mile, same as certification test	Grams/kilogram of fuel. Can be used as part of a fuel based inventory.
Location	Measured at test only or test and repair stations	Limited sites. Large state roadside test program only in California.	Current technology has limited good remote sensing sites for optimum driving modes.

Since vehicle emissions distributions are skewed, there are at least three ways to analyze data. One is to transform the data into a near normal distribution, for example with a log transform. This method undervalues the high emitter population, and assumes that the trends in the lower emitter population are consistent with those in the high emitter population. The second is to use the average of a large number of vehicles or measurements within multiple bins of the variables of interest; for example, bins of vehicle age and bins of VSP for NO emissions. With a sufficiently large number of vehicles in each bin, the bin averages are normally distributed. The uncertainty associated with the averages of the variables of interest can be treated statistically as a normal distributed function. The third method compares the data on the distribution of emissions.

Valid Readings

In order to identify the vehicle measured by remote sensing, the license plate must be recorded and matched with a database, usually from the State Department of Motor Vehicles. Because of various factors, a remote sensing reading may or may not be considered valid; for example, the exhaust plume size of the vehicle may be too small.

When only a small percent of the readings result in measurements used in the analysis, one must be careful that use of the valid readings does not introduce bias into the analysis. For example, if the better maintained vehicles had more easily read license plates, or were more likely to be matched, this could bias the results.

Measurement objectives for E-23 sites are to have 20,000 valid measurements during one week of the year at the same time each year. Seasonal variability of emissions has been observed in both inspection data and remote sensing data. This could be due to fuel change, humidity, or, in the case of inspection data, differences in conditioning of the vehicle prior to testing.

Use of remote sensing measurements

Remote sensing measurements have been used to estimate vehicle emissions in a number of cities. Some of the reports are mentioned here. Remote sensing measurements were consistent with ambient CO readings showing a reduction of CO in Mexico City after vehicles were equipped with catalysts.[18] Remote sensing CO measurements showed emissions deterioration was decreasing for newer vehicles in Denver between 1985 and 1989 as vehicle technology improved.[19] Remote sensing measurements in California showed that test station data from the old decentralized Smog Check program over-predicted the amount of emissions reduction that was taking part in the program.[20] Remote sensing has been used to estimate a fuel-based emissions inventory,[21] to estimate the effectiveness of the Denver inspection and maintenance program,[22] and to gain insight into the Arizona[23] and California[24] inspection and maintenance programs. Remote sensing has been especially useful in pointing out that many vehicles that failed an initial inspection test and never passed were still driving (and emitting) in the I/M area.[25] Also, remote sensing is the only way to estimate the emissions reductions associated with pre-inspection repairs made in anticipation of an inspection.[26]

Multi-site remote sensing measurements: year to year and site to site consistency

In order to make quantitative judgements from remote sensing at more than one site, site effects need to be understood. Because of changes in fleet composition and the relatively uncontrolled nature of remote sensing measurements, it is a challenge to compare remote sensing measurements from one site to another, or at the same site from one year to another. Two of E-23's four sites, Chicago and Denver, show excellent year to year and site to site correlation. Sites

[18] Klausmeier, R. and D. Pierce, "Audit Of Vehicle Emission Control Programs [in Mexico City]," ICF, November, 2000

[19] Slott, R.S., 6th CRC On-Road Workshop, March 1996, San Diego, CA, and "Remote Sensing at the Speer Off-Ramp, Denver, CO, 1989-1995," at the Symposium honoring Donald Stedman at the ACS meeting in New Orleans, March 24-28, 1996.

[20] Klausmeier, R. and C. Weyn, "Using Remote Sensing Devices (RSD) to Evaluate the California Smog Check Program," report for the California Bureau of Automotive Repair, Engineering and Research Branch, October 2, 1997.

[21] Singer, B. C., and R. A. Harley, 1996 "A fuel based motor vehicle emission inventory." J. Air Waste Management Assoc. 46 (6) 581-593.

[22] Stedman, D. H., G. A. Bishop, P. Aldete, R. S. Slott, 1997 "On-Road Evaluation of an automobile emission test program." Environ. Sci. Technol. 31:927-931.

[23] Wenzel, T., in press, Evaluating the Long Term Effectiveness of the Phoenix IM240 Program. Environmental Science and Policy.

[24] IMRC (California Inspection Maintenance Review Committee) 2000. Smog Check II Evaluation. California Inspection Maintenance Review Committee, Sacramento, CA. June 19, 2000. Available: http://www.epa.gov/otaq/im.htm

[25] Wenzel, T., 1999 "Evaluation of Arizona's Enhanced I/M Program" 9th CRC On-Road Workshop. And Wenzel, in press, Reducing Emissions from In-Use Vehicles: An Evaluation of the Phoenix Inspection and Maintenance Program using Test Results and Independent Emissions Measurements. Environmental Science and Policy.

[26] ibid.

in the other two cities, Phoenix and Los Angeles, have proven to be difficult to analyze and have been less consistent year to year and to other sites.[27]

Major factors affecting fleet emissions include the age of the vehicle fleet, the load distribution, and the vehicle type. Socioeconomic factors of vehicle owners also influence vehicle fleet emissions[28]. Road disruptions or changes in the positioning of the remote sensing units can cause a shift in driving patterns. Ambient conditions, fuel changes, and local emission control programs, such as I/M programs, influence fleet emissions.

At some sites the composition of the fleet can change with VSP. Cars tend to be concentrated at higher VSP, which could be an indication that VSP estimates load differently for cars and trucks. VSP includes a term for the drag coefficient of the vehicle. Jimenez and McClintock used an average drag coefficient for many vehicles, including multiple models, model years, and types. Improved accuracy would be expected if separate coefficients were used when calculating VSP for different vehicle types (pick ups, cars, SUVs, minivans, etc.), model years, or even models. At a high load site (Phoenix, 1999, Site 2[29]) newer cars were concentrated at higher VSP compared to older cars. This load/age interaction effect was especially important for interpreting NO emissions.

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[27] Data in Atlanta and other cities, gathered by researchers at the Georgia Institute of Technology Air Quality Laboratory (AQL) did not include speed and acceleration measurements. Attempts were made to select sites where vehicles would be in light acceleration. Although not funded as part of E-23, AQL has generously made the data available to E-23, and plans to start using the E-23 protocol in future remote sensing measurements. Since CO emissions are not very dependent on load, useful conclusions about CO emissions are possible. Preliminary analysis of 1998 Atlanta measurements, however, showed that CO emissions in some of the Atlanta sites were significantly lower or significantly higher than at other sites, independent of model year. AQL has decided to review all the data on a site-by-site basis by the end of the 2001.

[28] Stedman, D. H., G. A. Bishop, S. P. Beaton, J. E. Peterson, P. L. Guenther, I. F. McVey, Y. Zhang, "On-Road Remote Sensing of CO and HC Emissions in California," Contract No. A032-93, Air Resources Board, February 1994, page 34.
Wenzel, T., 1997. I/M Failure Rates by Vehicle Model. Paper presented at the Seventh CRC On-Road Vehicle Emissions Workshop, San Diego, CA, April 1997, and personal communication, May 2001. Analysis of AZ IM240 emissions by I/M station, model year and model indicated higher emissions at the I/M station in a low income neighborhood than at the station in a high income neighborhood, holding both vehicle age and model constant. Similar results were found in Colorado and Wisconsin.
Rodgers, M., 2000, I/M Analysis. Presented at the workshop of the Committee to Review the Effectiveness of Vehicle Emission Inspection and Maintenance Programs, Irvine, CA, February 2000.

[29] Slott, R. S., D. H. Stedman, S. S. Pokharel, SAE Fuels and Lubricants Meeting, September 2001.

Appendix A: Status of E-23 on August 1, 2001

CRC E-23	01-Aug-01										
Year	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Chicago		1	2	3	4		5		6		7
Data Collection		Sept	Sept	Sept	Sept						
Report or status		Aug-98	Oct-99	Apr-00	final draft						
VIN decoding		received	received	received	received						
Denver	#	#		1	2	3	#	4		5	
Data Collection	Jan	Jan		Jan	Jan	Jan	Jan - possible				
Report or status				Dec-99	Mar-01	1st draft					
VIN decoding				received	received						
LA Riverside				1	2	3	road construction				
Data Collection				July	June	July					
Report or status				Apr-00	Mar-01	plate reading					
VIN decoding				received	received						
LA la Brea				*		4		5		6	
Data Collection				Oct - not E-23		Oct					
Report or status				need complete plate matching		Permission to measure requested					
VIN decoding											
Phoenix*			1a	2b	3bb	#	4b		5b		6b
Data Collection			Nov	Nov	Nov	Nov - possible					
Report or status			Nov-99	Jan-01	plate matching						
VIN decoding			received	received							

Footnotes:
Measurements made according to E-23 protocol but not funded by E-23. If measured, available for inclusion in E-23 analysis.
* Measurements made at different sites in 1998 and from 1999 on. Two sites on the same ramp were used in 1999 and 2000.

Appendix B: E-23 Measurement Procedures

A data definition/dictionary is required. The data definition/dictionary explains in detail the codes, units and other information about each field. See appendices in CRC-23-4, "On-Road Remote Sensing of Automobile Emissions in the Los Angeles Area: Year 1" for examples of reporting validation criteria, temperature & humidity, and calibration frequency. See the data from this report on the CRC E-23 CD "DU Databases + Reports 4/14/00" for examples of the database format.

Category	Mandatory	Desired
Site Description	1. Include in the report a road map with features affecting traffic flow 2. Report any change in the position of the light source, detector, etc., from previous year(s). The site should be set up the same as in the previous year(s). 3. Report any change in traffic flow from previous year(s). 4. Report the altitude of the site and the road grade. Include a field in the database showing the road grade in percent for all measurements. 5. Picture of site (digital) including all cones, etc., that would influence motorists' driving patterns.	1. Note whether motorists change driving behavior as a result of the remote sensing measurements. Compare motorist behavior with previous years' measurements.
Instruments	1. Report a description of remote sensing equipment used; report any changes from previous year(s). 2. Name of operator and van. If more than one operator or van are used, key and record which operator and/or van was used for each measurement. 3. Calibration procedures and frequency. Frequency at least twice per day. Report the times of calibration.	
Measurements	1. Report remote sensing: %CO2, %CO, %NO, %HC, maximum CO2, and all error terms; restarts; report negative emission numbers. Include a field showing whether HC is reported as propane or hexane (P or H) 2. Report Speed, acceleration. 3. Report Time and date of measurement. 4. Report license plate: record all plates including in-state, out-of-state (OS); dealer plate (D); paper plate (PP); obscured plate (OP), and no plate visible (NVP). 5. Report hourly temperature, barometric pressure, and relative humidity. 6. Describe how plume strength is determined and flagged and report criteria for rejecting measurement attempts.	1. General wind direction and speed. 2. Any other factors that could affect measurements, such as when there was water on the road.

Database Format	Use format and units described in LA 1998 report.	Appreciate if field names could be reduced to 8 letters to fit in SAS.
DMV Data	1. Report date DMV data returned from DMV. 2. Report how current the DMV data in that file are (i.e., when was the most recent DMV update to the file received by the investigators, especially for vehicles that have changed ownership). 3. Report VIN, Model Year, Make, Model, Fuel Type, Vehicle Type (define terms used by DMV), Zip Code if available.	1. VIN decoded data. 2. Other information supplied by DMV.
Report Changes That Could Affect Analysis	1. Fuel. 2. I/M program.	1. Local economy. 2. Site socioeconomics.

Interpreting Remote Sensing NOx Measurements

Robert Slott, Consultant,

Donald Stedman and Saj Pokharel,
University of Denver

Fall Fuels & Lubricants Meeting

San Antonio, TX

September 24-27, 2001

Paper # 2001-01-3640

Acknowledgements

Project sponsor: Coordinating Research Council

- Data collected by Prof. Donald Stedman's group at University of Denver
  - Reports available at http://www.crcao.com
  - Data at http://www.feat.biochem.du.edu/
- VINs decoded by Eastern Research Group

Analyzing Vehicle Tailpipe Emissions

- Fleet emissions increase with age
- Possibility of sampling bias
- Emissions higher when catalyst cold
- Emissions depend on load
- Emissions may vary when vehicles measured under same conditions at different times
- Different model years & vehicle types have different standards & control technologies

Paper # 2001-01-3640

CRC E23 Project

Monitor how on-road vehicle tailpipe emissions (HC, CO, NOx) are changing with time

- Use remote sensing
- Measurements in at least 4 cities
  - Chicago, Phoenix, Los Angeles, Denver
- Large number (20,000) of measurements at same time of the year at each location
- Uniform QC/QA and data reporting

Paper # 2001-01-3640

Remote Sensing

Measures concentrations of CO, HC, NO, CO2 in automobile exhaust

- Accurate
- Measured over ~ ½ second
- Vehicle identified by video frame of license plate matched to registration records
- Related to grams/gallon, not grams/mile
- Limited numbers of suitable sites

Paper # 2001-01-3640

Calculate Vehicle Load

Vehicle Load estimated as Vehicle Specific Power (VSP) from

- Speed, Acceleration, and Road Grade
- Typical Values of VSP
  - No Load = 0 kW/tonne
  - Deceleration = <0 kW/tonne
  - ASM Test = 5 to 9 kW/tonne
  - Upper limit of FTP = 23 kW/tonne

Paper # 2001-01-3640

NO Vehicle Emissions

NOx emissions very sensitive to VSP (load) under typical driving conditions

- NOx emissions vs VSP for individual vehicles
  - From low VSP ~ 0 kW/tonne, where NOx is low,
  - NOx increases until VSP = 15 to 20 kW/tonne
  - Then decreases if fuel enrichment employed
  - And increases again at higher VSP

Paper # 2001-01-3640

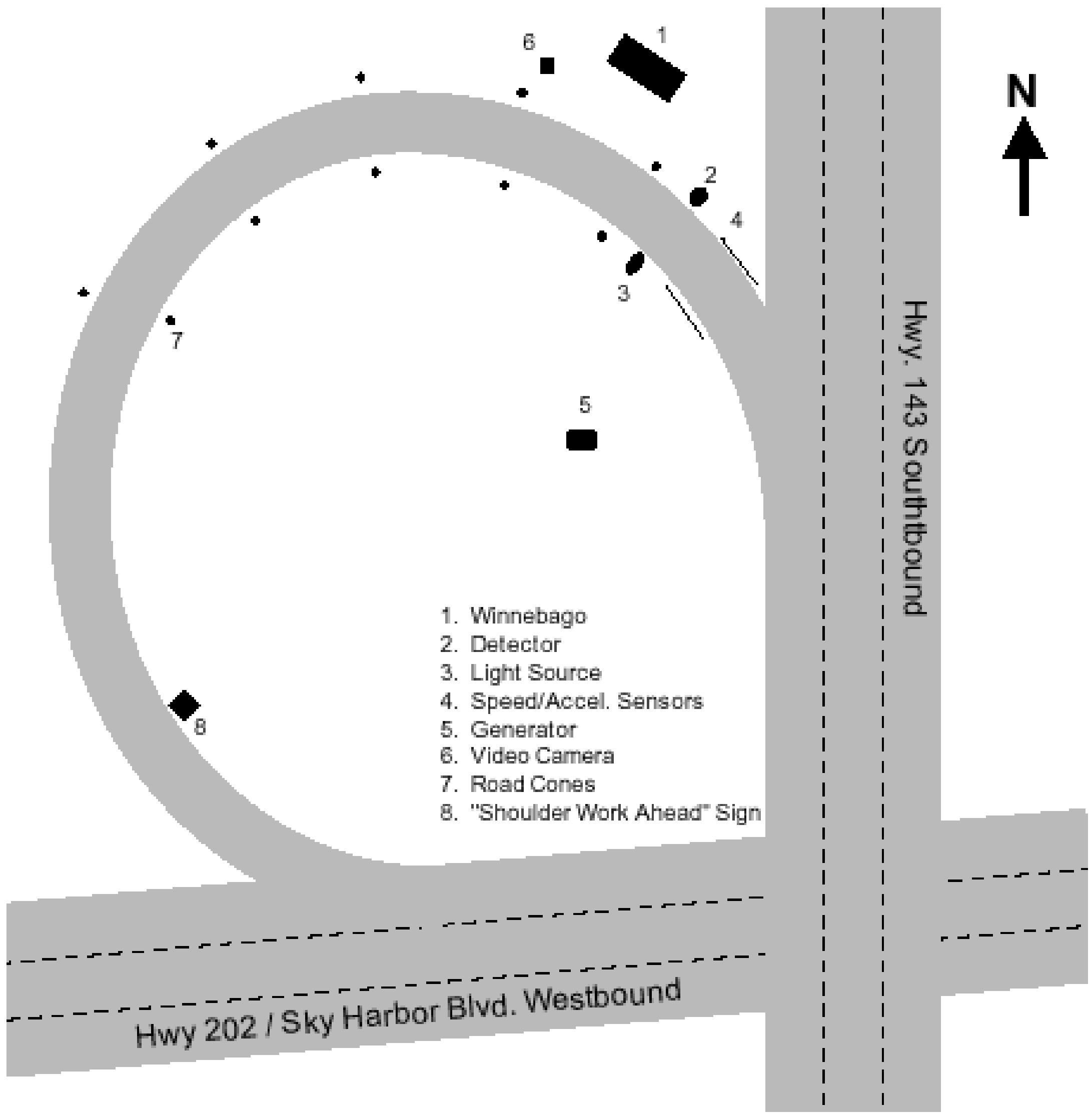
Three Phoenix Remote Sensing Sites

- In 1998, a high speed, low load site gave low percent valid readings due to small exhaust plumes.
- In 1999, two sites were used. These were at different positions on the same on-ramp.
  - **Site 1**: Free flowing traffic, no reason to rush; Trucks observed to dawdle, cars moved faster.
  - **Site 2**: Entry to highway, vehicles accelerate.
    - Two sites measured on different days.
    - Same model year distribution, similar fleet

Paper # 2001-01-3640

Phoenix 1999

Sites at uphill exit ramp from Hwy 202 / Sky Harbor Blvd. Westbound to Hwy 143 Southbound, Site 2: at top of ramp as shown, Site 1: ¼ way down the ramp.



%NO and VSP Phoenix 1999

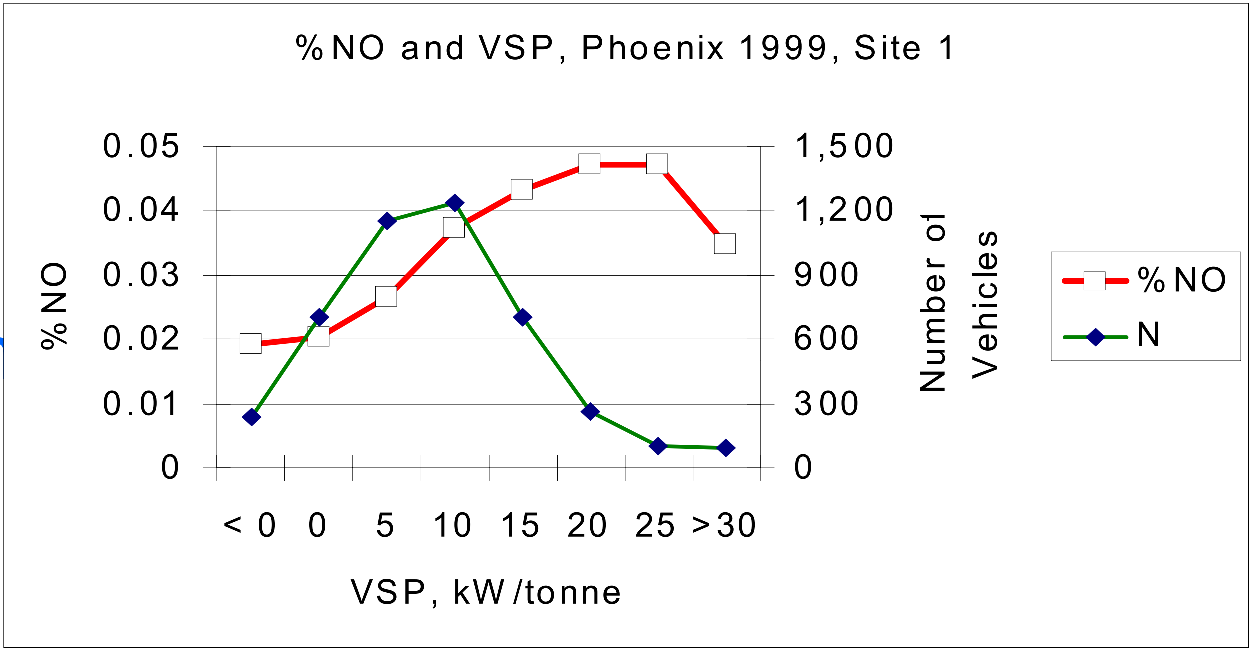
Site 1 on top

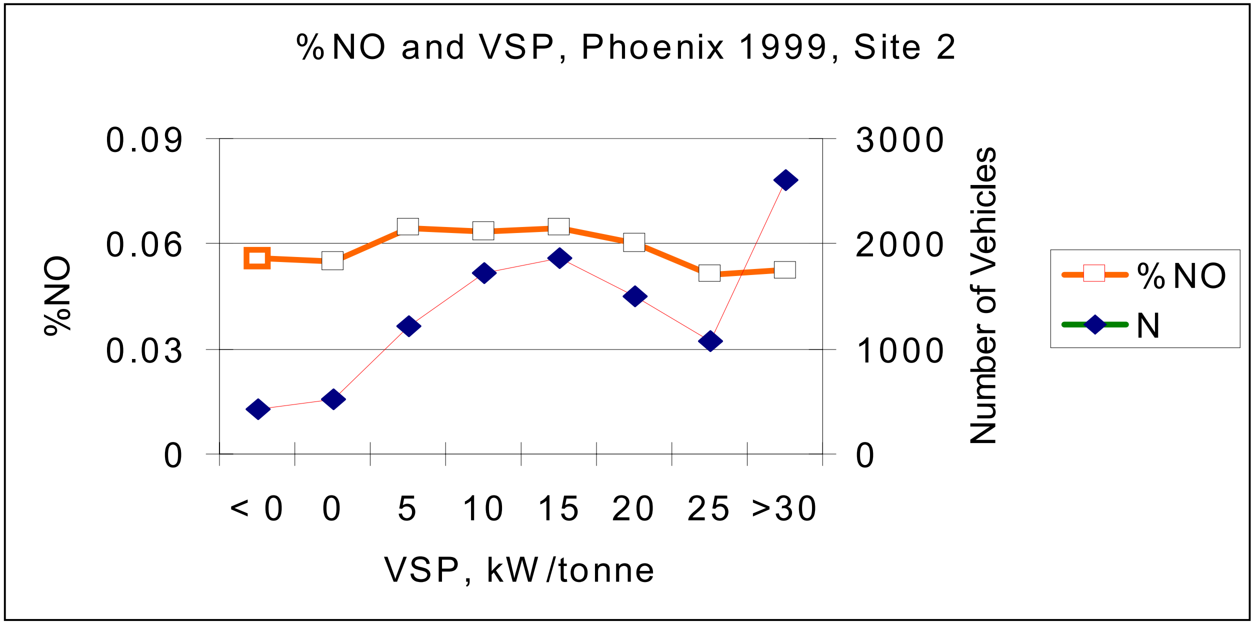
Site 2 at bottom

Average %NO & Number of vehicles measured

on y-axis,

VSP on x-axis.





NOx Emissions in Phoenix

- Phoenix 99 NOx measurements appear to be independent of VSP at Site 2 (high load site).
- %NO is a strong function of vehicle age and load interacted with vehicle age at Site 2.
- Fleet NO emissions analysis needs to take into account age, load, and vehicle type.
  - Data from three Phoenix Sites binned into
    - 5 kW/tonne bins (Bin 5 = VSP from 2.5 to 7.5)
    - 5 year age bins (Bin 3 years = 1 to 5 years)
    - analysis on CARS as defined in the VIN.

Paper # 2001-01-3640

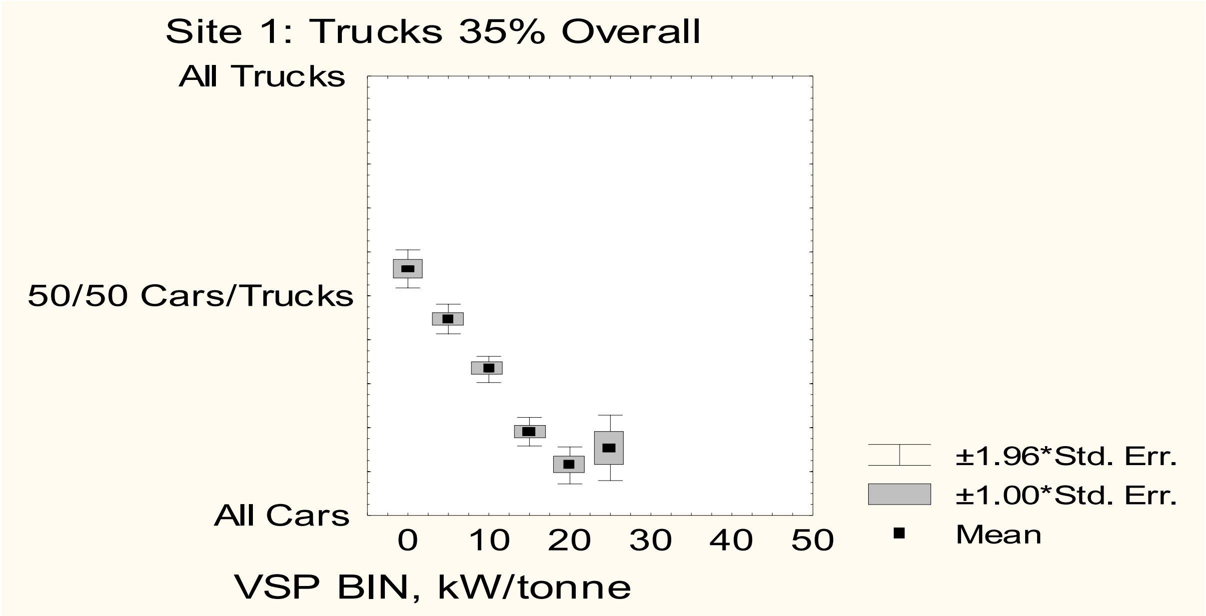
% Trucks
Phoenix 1999
Site 1 on top

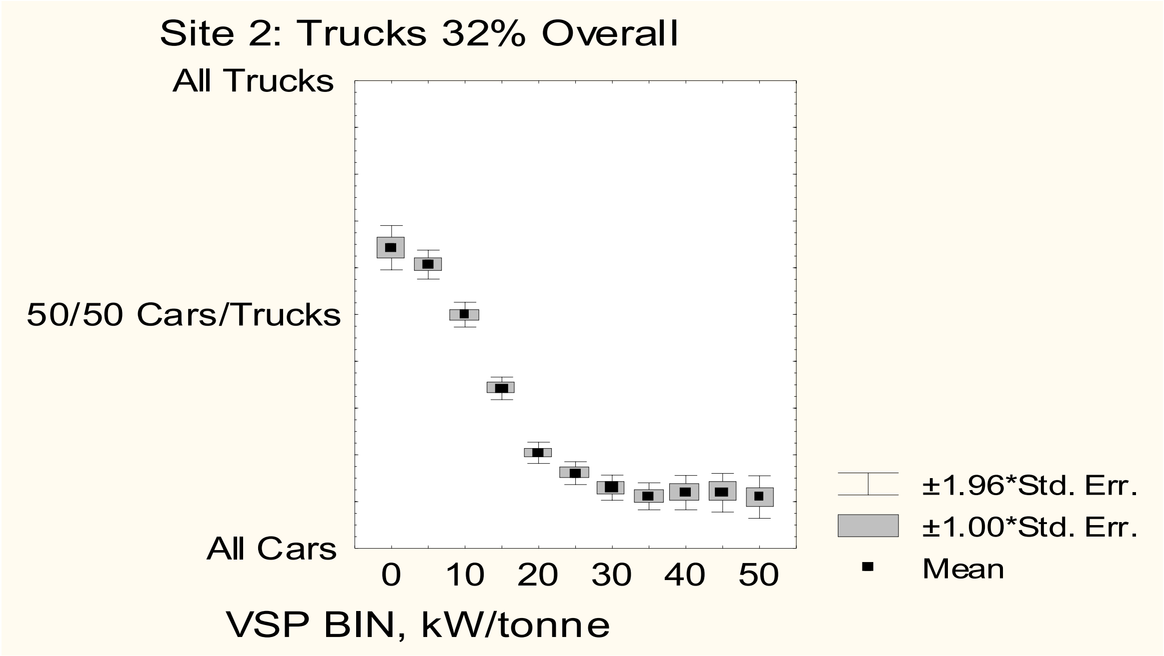
Site 2 bottom

In both sites vehicle type interacts with VSP.

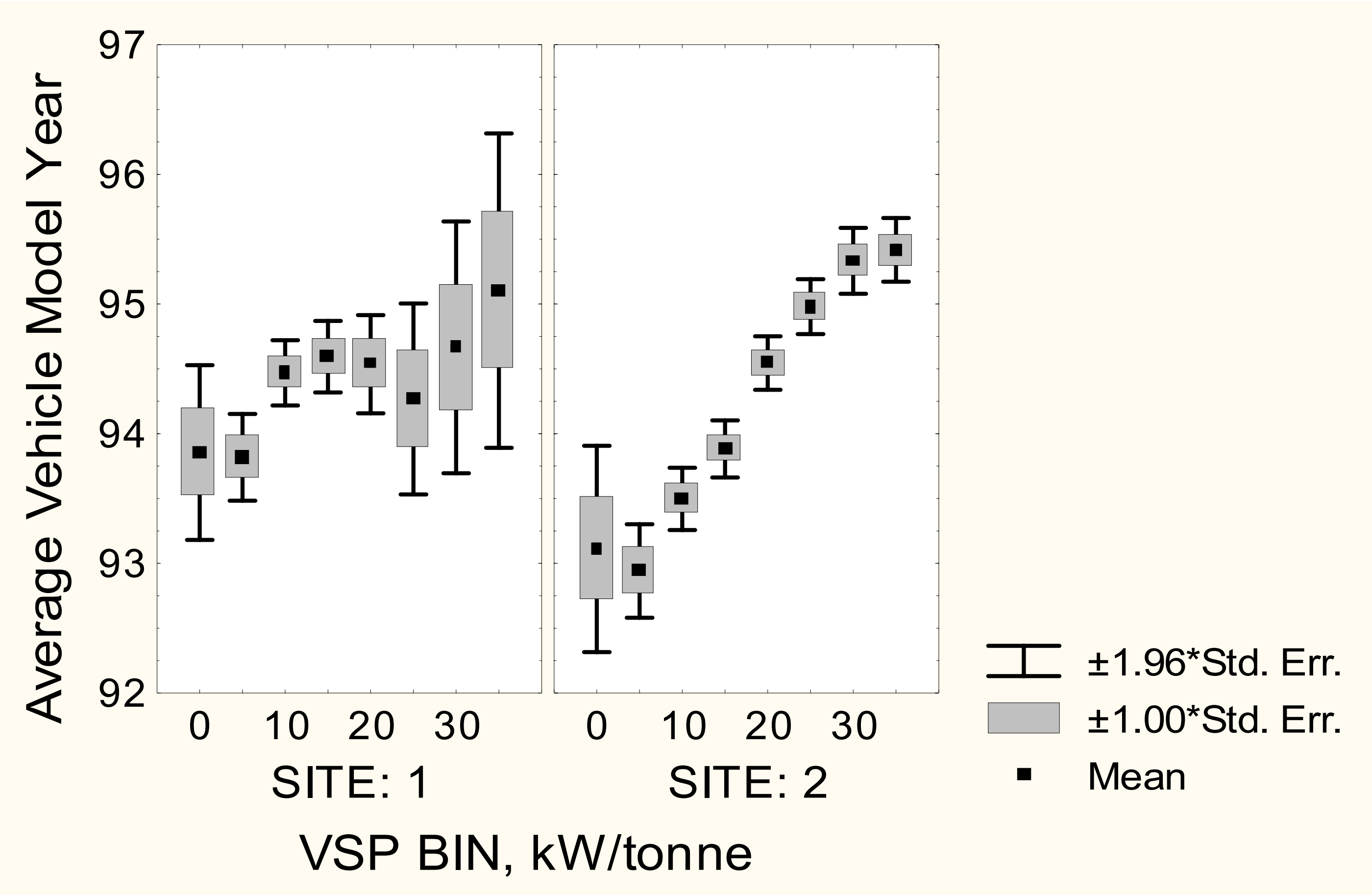
%Trucks on the y-axis

VSP on x-axis.





Model year vs VSP, Phoenix 99 Sites

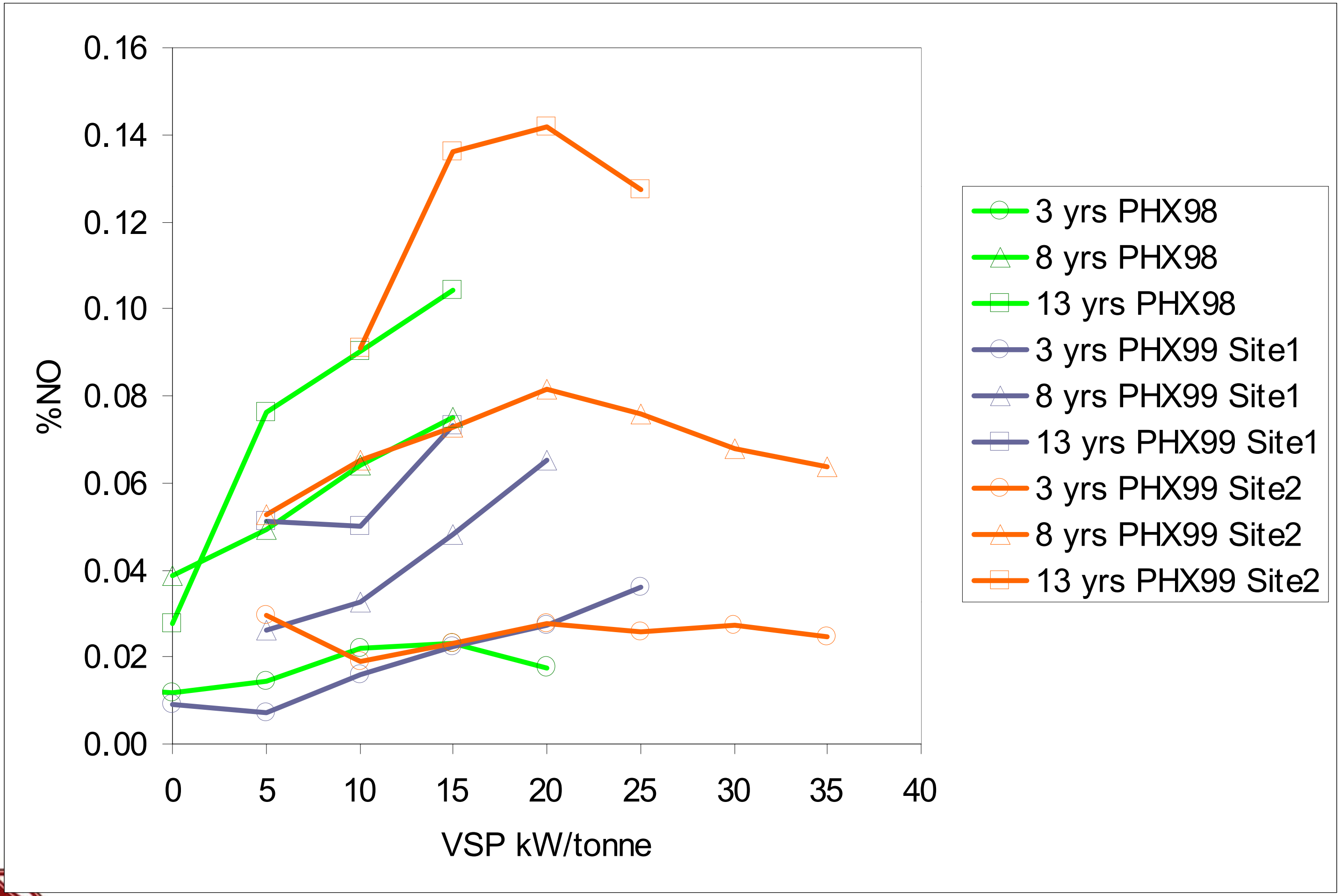


Vehicle age is much more dependent on load at Site 2.

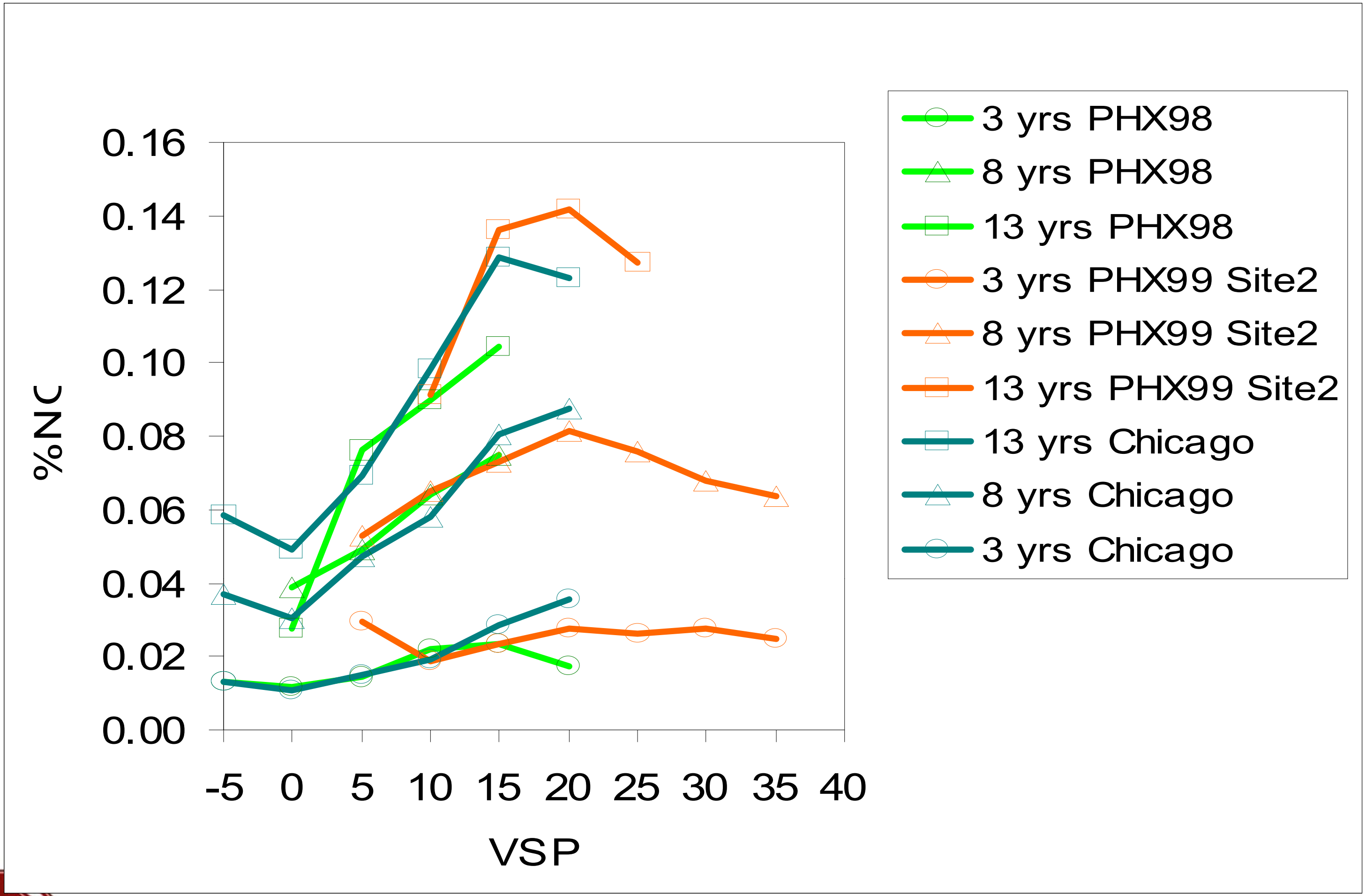
Phoenix Site Comparisons, Cars Only

- Which Phoenix site in 1999 was giving a typical NO vs VSP relationship when binned for age as well as VSP?
  - Comparing the two Phoenix 99 Sites with the Phoenix 98 Site, Site 2 in Phoenix 99 was more similar to Phoenix 98 Site than Site 1.
  - [Phoenix 98 Site] and [Phoenix 99 Site 2] are similar in their NO vs VSP relationship to Chicago 99 remote sensing measurements.

Phoenix 1998 & 1999, Cars Only

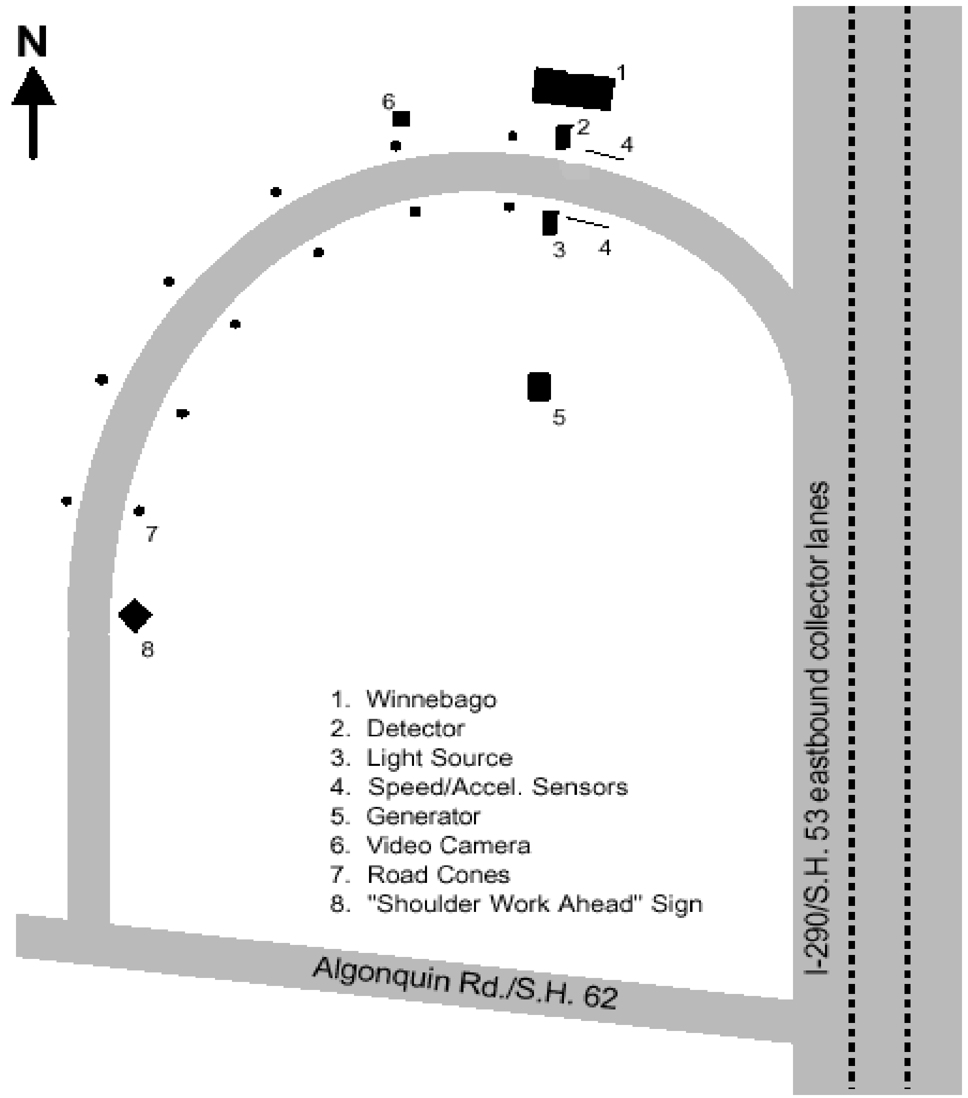


Phoenix 98-99 & Chicago 99, Cars

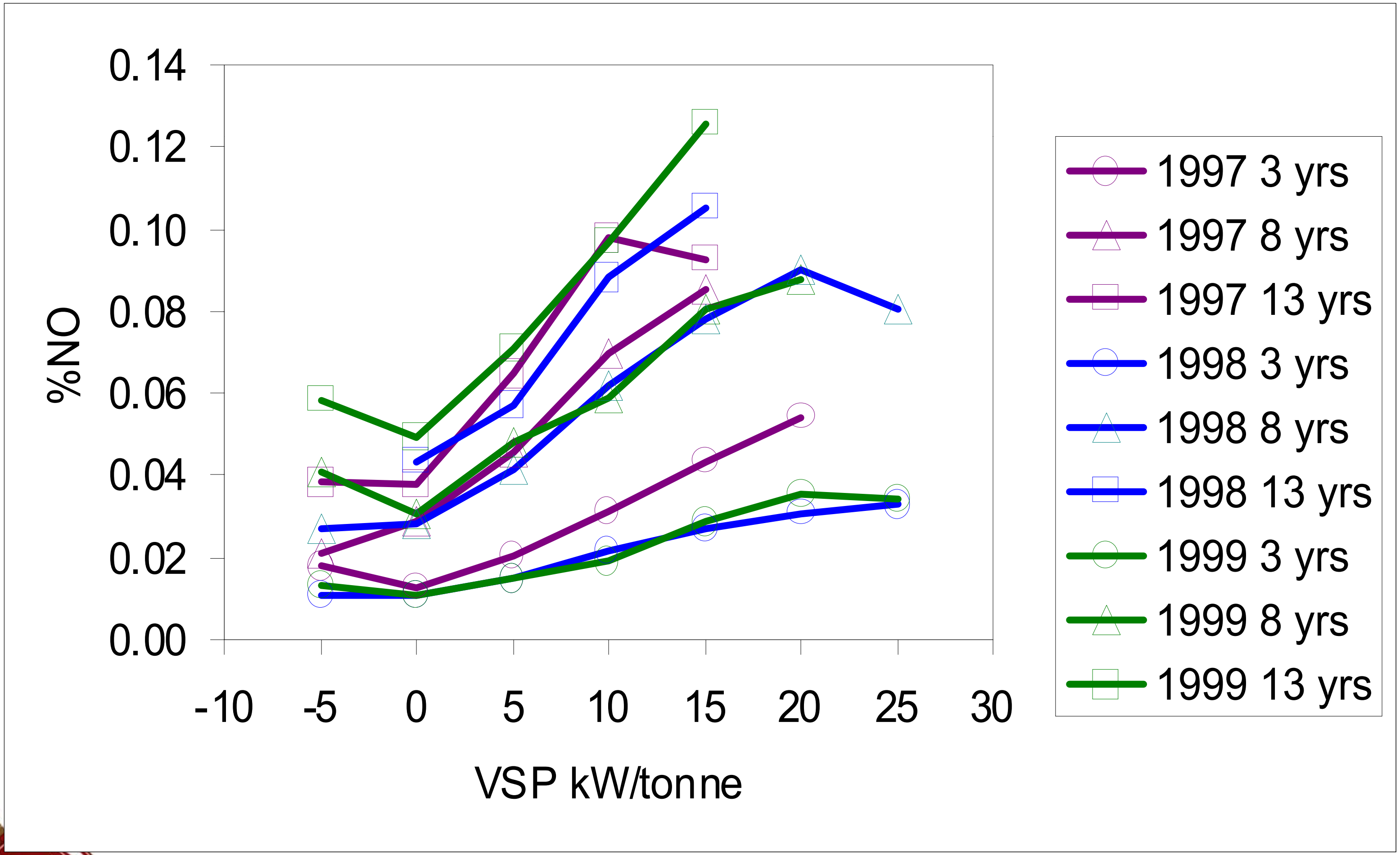


Chicago Remote Sensing Site

On-ramp from Algonquin Rd. to eastbound I-290 (S.H. 53) in northwest Chicago



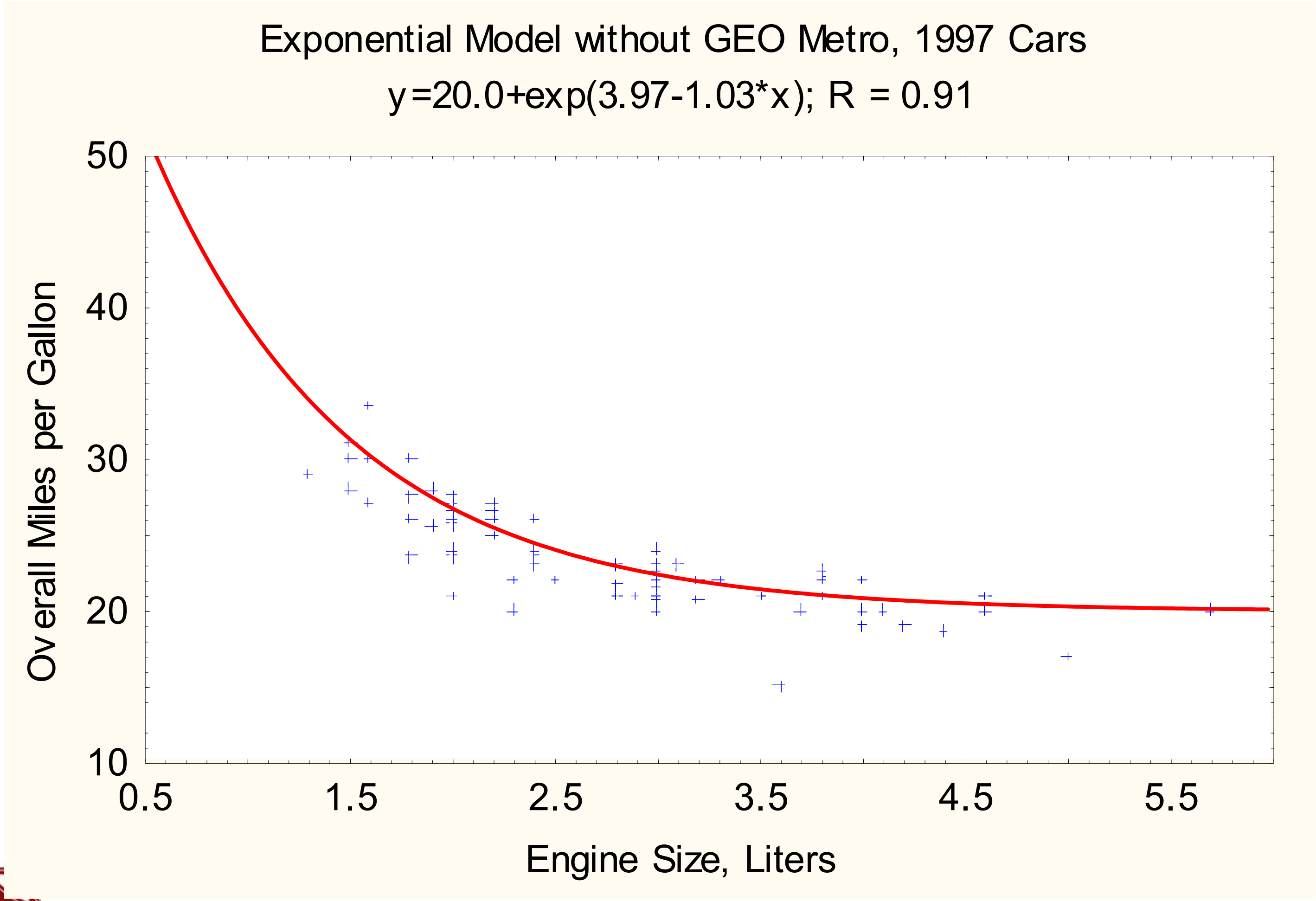
Chicago 1997-1999, Cars



Adjusting %NO to gpm NO

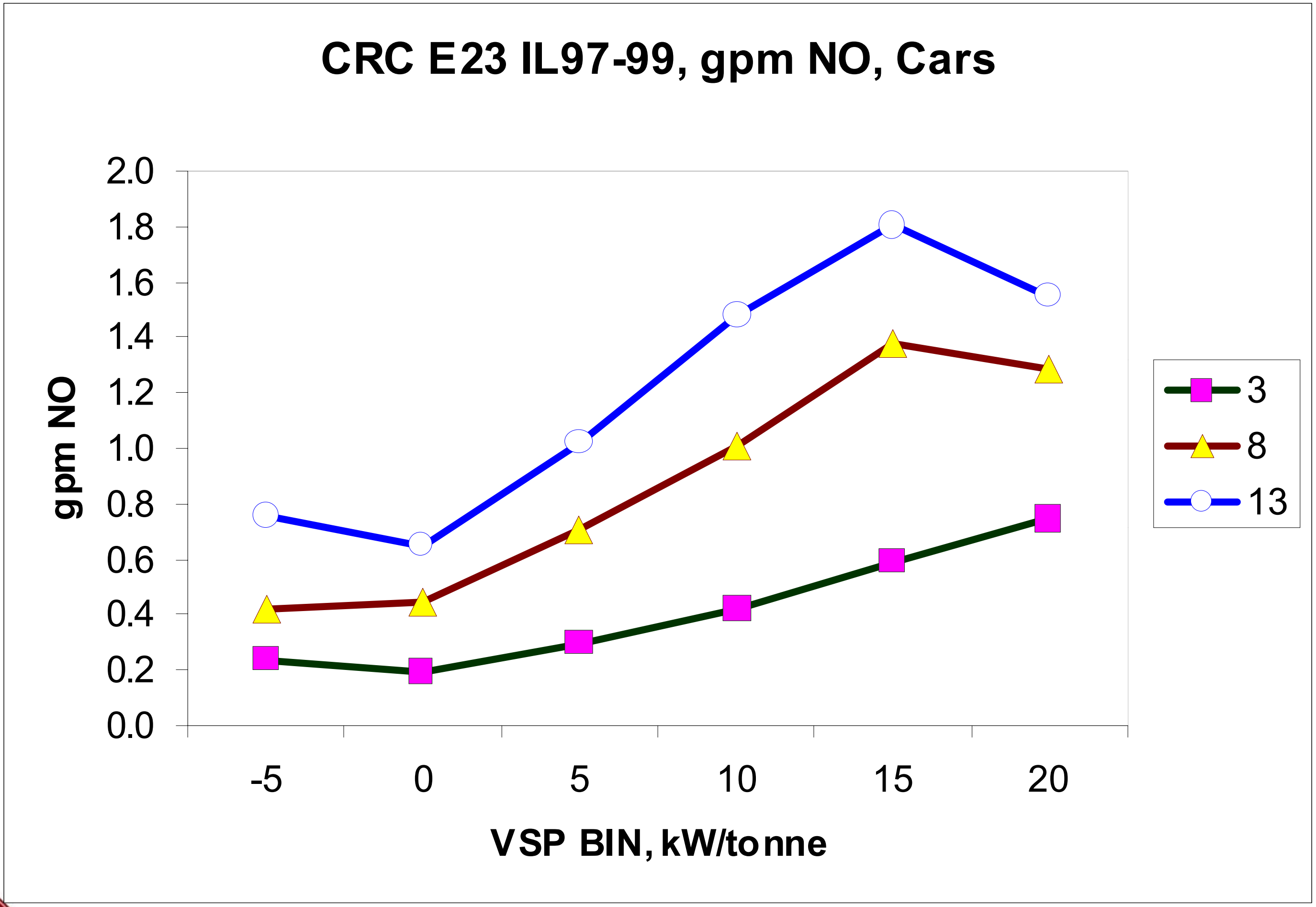
- In Chicago, the change of %NO vs VSP by measurement year from 1997 to 1999 was small compared to the change of %NO seen in any of these years due to vehicle age.
- Combined %NO data by vehicle age (from 1997, 1998, and 1999 measurements) was converted to grams/gallon, and then, using a correlation based on engine size and 1997 vehicles' fuel economy, to grams/mile (gpm).

Gram/mile (gpm) for CARS 1997



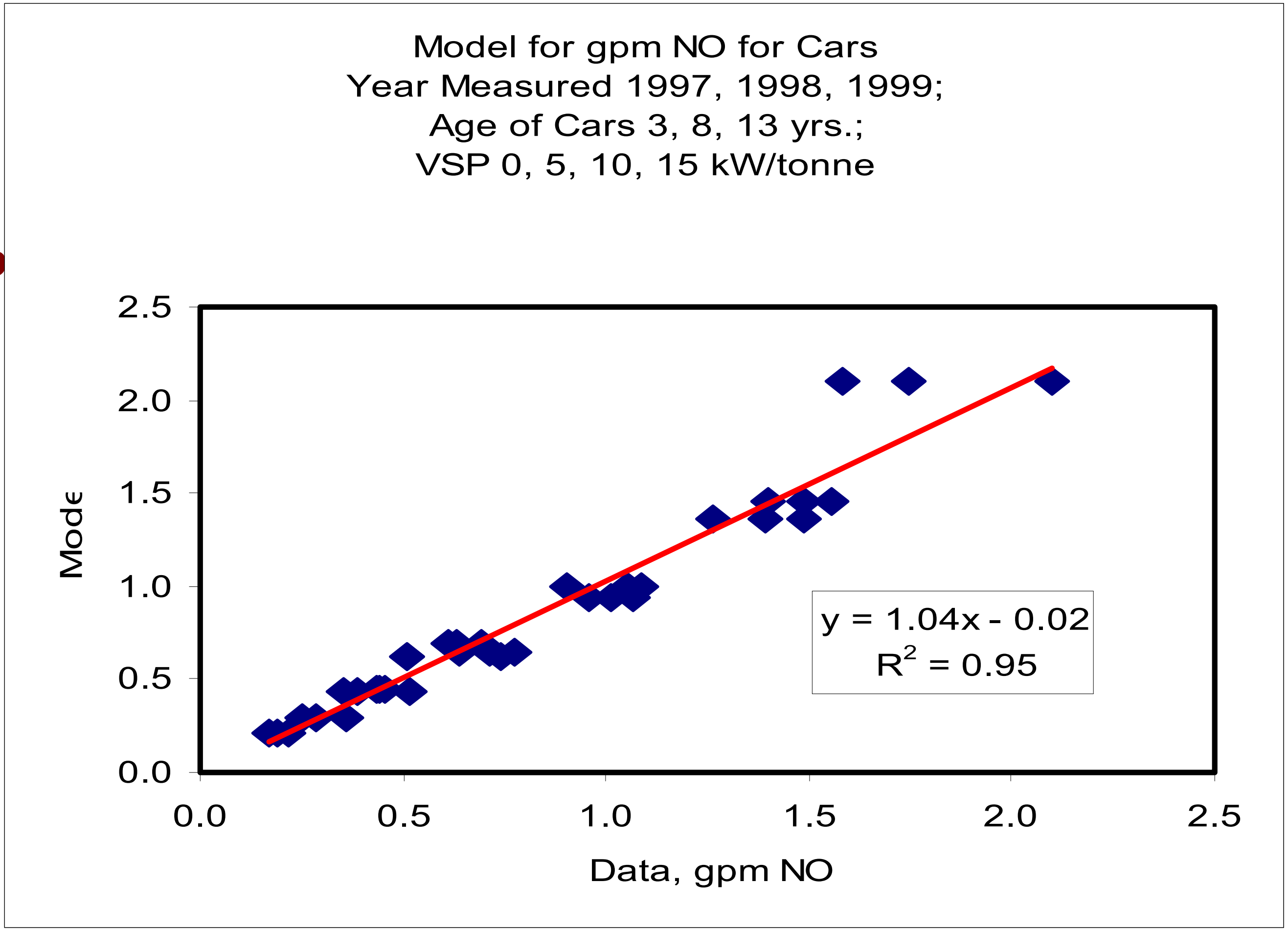
Correlation between engine size and mpg weighted vehicles based on frequency they were seen in 1997 remote sensing measurements.

NO gpm for 3, 8, 13 year Age Bins



Model vs Data in gpm NOx

gp



Modeled gpm NOx in Chicago

- Chicago 97-99 remote sensing NO emissions, binned by load and vehicle age, and converted to gpm using average fuel economy, can be modeled from VSP = 0 to 15 kW/tonne, and age = 1 to 15 years, by a equation based on age and VSP.
- Two points off the line are due to older vehicles (measured in 97 & 98) at 15 kW/tonne. This could be explained if some of these older vehicles have gone into fuel enrichment at 15 kW/tonne, suppressing NO formation.

Status of E23 Measurements

Year	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Chicago September		1	2	3	4		5		6		7
Report		X	X	X							
Denver January	#	#		1	2	3	#	4		5	
Report				X	X						
LA Riverside July				1	2	3	road construction				
Report				X	X						
LA la Brea October				#		4		5		6	
Report											
Phoenix November			1	2	3	#	4		5		6
Site			98	1 & 2	1 & 2		2		2		2
Report			X	X							

 # Not E23 Project but measurements conducted under E23 protocol and available for analysis

Interim Report

Analyzing Fleet %NO Emissions at E-23 Sites

CRC E-23
December 17, 2001

Bob Slott

%NO Remote Sensing Measurements

- Controlling NO emissions are important to reduce both ozone and particulate matter.
- Little is known about NO emissions for on-road vehicles.
  - %NO remote sensing technology developed recently.
  - NO emissions sensitive to load, analysis must be load corrected.
    - Jimenez and McClintock developed load equations depending only on speed, acceleration, and road grade.
      - Parameter calculated is vehicle specific power, VSP.
      - VSP allows estimates of load from measurements of on-road vehicles.
    - Remote sensing campaigns have begun to measure speed, acceleration, and record road grade only in the last few years.
    - Confirmation of VSP equations applicability to all on-road remote sensing sites is at an early stage.

Analysis Methodology

- NO emissions are dependent on:
  - Model year or age of the vehicle,
    - vehicle technology
    - emission control deterioration.
  - Load.
  - Vehicle type (CARS, TRUCKS, etc), especially when different types of vehicles were built to different standards or when different types have different use and maintenance patterns.
- Analysis based on numerical average from a set (a bin) of remote sensing measurements.
  - All measurements were averaged (rather than averaging all measurements per vehicle) to better reflect fleet emissions.
  - Averages of sufficiently large sample (~50+) are normally distributed or near normal and confidence limits can be applied.
  - Measurements were grouped into AGE x VSP bins with at least 50 cars per bin.

Dividing the Fleet

- Earlier analysis of E-23 %NO emissions in Chicago and Phoenix *(Slott, R. S., CRC 11th On Road Workshop, poster presentation)* showed:
  - » 1997-1999 measurements in Chicago showed little effect of %NO on model year independent of vehicle age.
  - » Phoenix 1999 measurements showed Vehicle Type and Vehicle Age were a function of VSP, especially at high load sites.
    - > Cars were concentrated at higher VSP and Trucks were concentrated at lower VSP
    - > Newer Cars were concentrated at higher VSP and Older Cars were concentrated at lower VSP
  - » Therefore, VSP adjustments should not be applied to the whole fleet.
    - > Vehicle type and vehicle age should be separated out.
  - » To obtain sufficient numbers of vehicles in a bin, bins were made up of CARS x 5 year AGE BINS x 5 kW/tonne VSP BINS

    5 year age bins (3 year bin has years from 1 to 5)

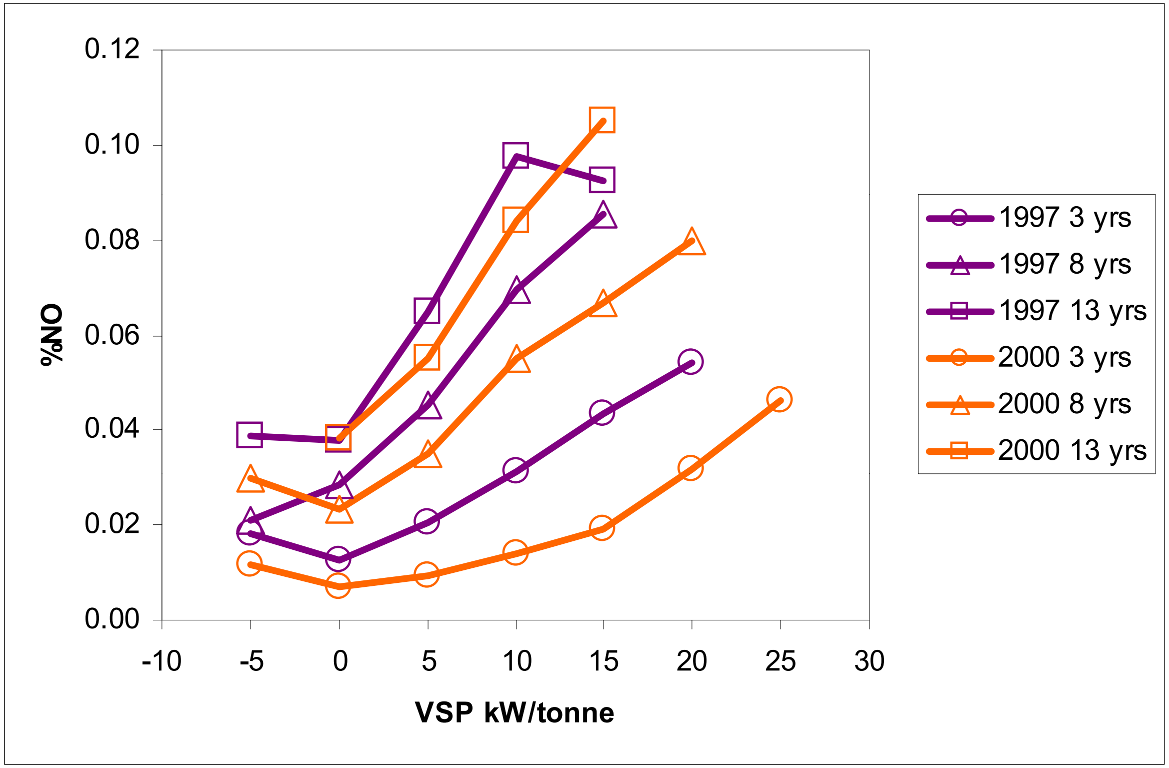
    5 kW/metric ton load bins (5 kW/tonne bin from 2.5 to 7.5)

Sites and Vehicles

Study	City	Site	slope	Month
E23	Chicago	on-ramp from Algonquin Rd. to southbound I-290.	2.7%	September
E23	Denver	interchange ramp for northbound I-25 to westbound 6th Avenue in central Denver.	8.0%	January
E23	Phoenix 1998	uphill exit ramp from I-10W to US 143N in Tempe, AZ	3.7%	November
E23	Phoenix 1999 Site 1	uphill exit ramp from Hwy 202/Sky Harbor Blvd. Westbound to Hwy 143 Southbound in Phoenix	2.9%	November
E23	Phoenix 1999 Site 2	same as Site 1, but close to the entrance of the Hwy 143, causing much more acceleration	3.7%	November
E23	Riverside	exit ramp from northbound 91 to westbound 60, almost identical to sampling site in Denver	8.0%	June/July

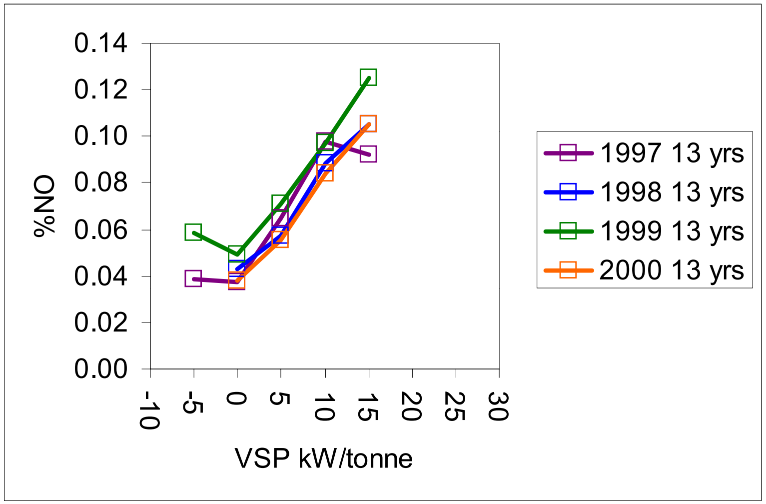
Vehicles used in this analysis were classified as cars by VIN.

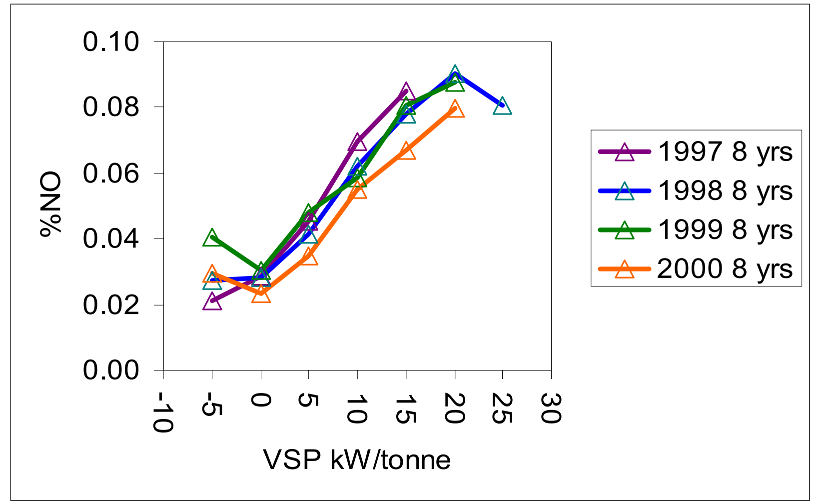
Car Remote Sensing NO in Chicago 1997-2000



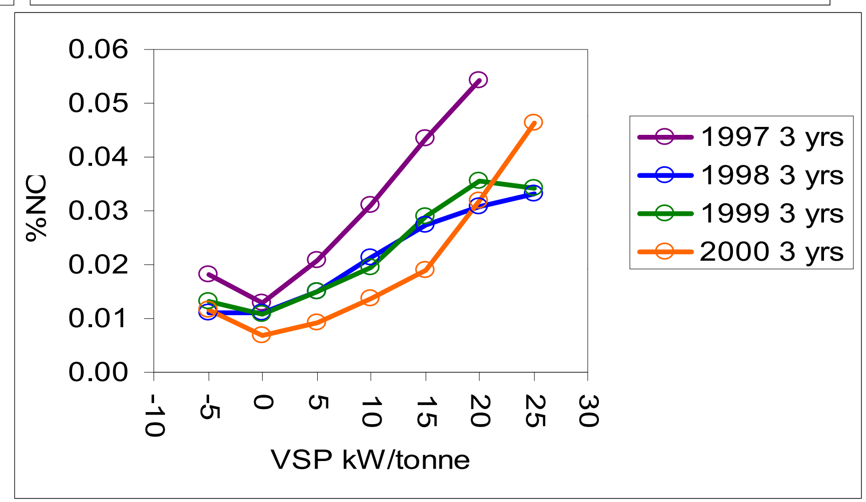
- %NO trends, Cars Chicago from 1997 to 2000:
  - Emissions increase with VSP from 0 to 15 kW/tonne
  - Emissions increase with vehicle age.
  - Emissions decrease from 1997 to 2000

Cars Remote Sensing, Chicago 1997 through 2000

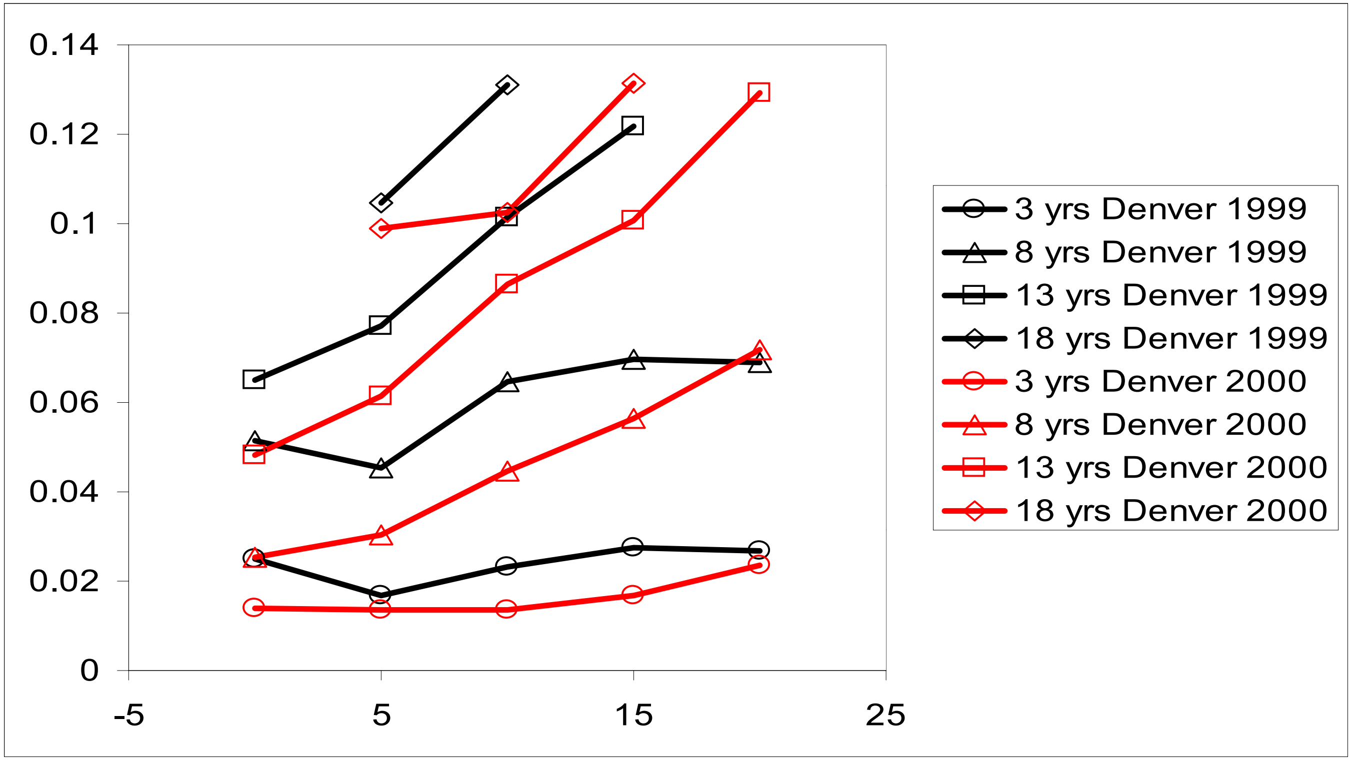




%NO vs VSP relationships were very consistent from year to year in Chicago from 1997 to 2000.
Most improvement seen in newer cars.

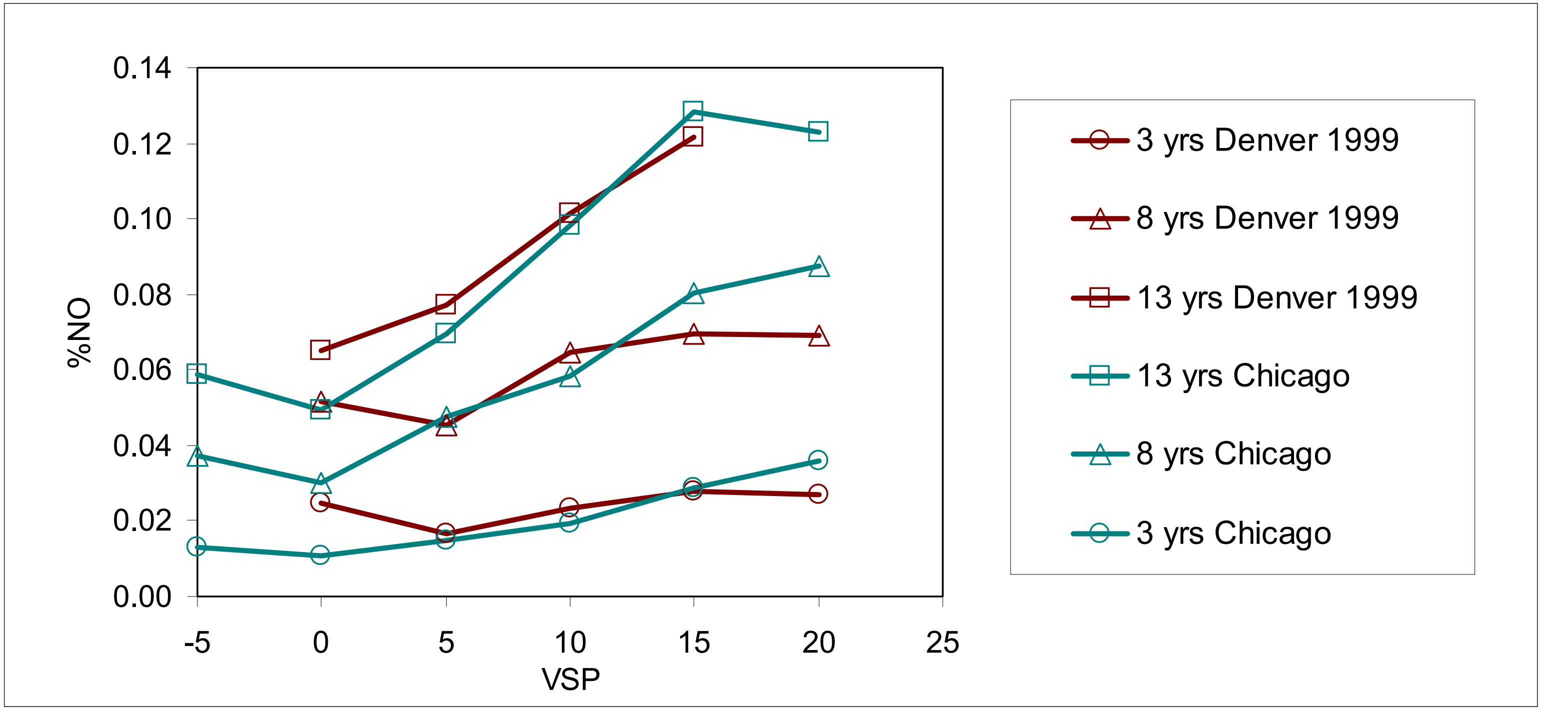


Car Remote Sensing NO in Denver 1999-2000



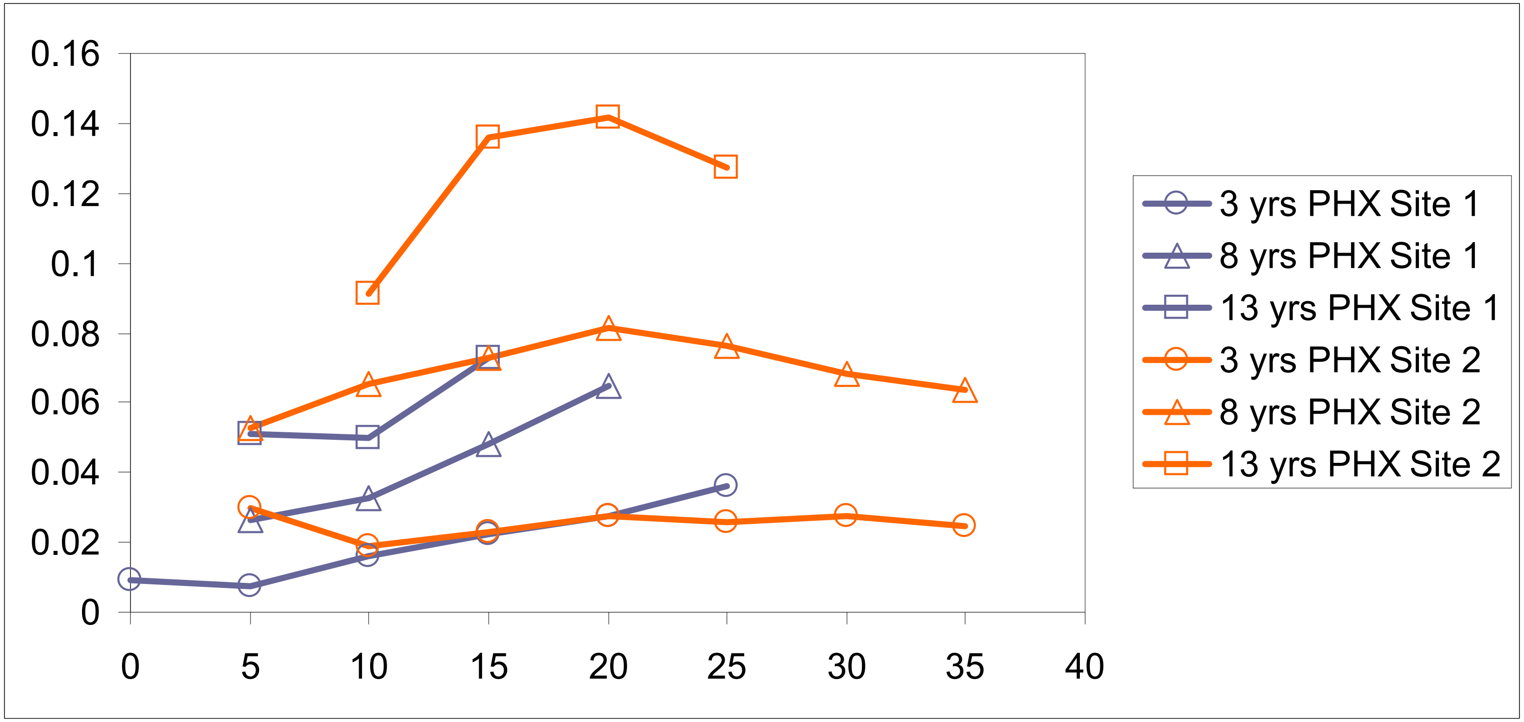
- %NO trends in Denver:
  - Emissions increase with VSP from 0 to 20 kW/tonne
  - Emissions increase with vehicle age.
  - Emissions decreased from 1999 to 2000

Car NO Remote Sensing Denver & Chicago, 1999



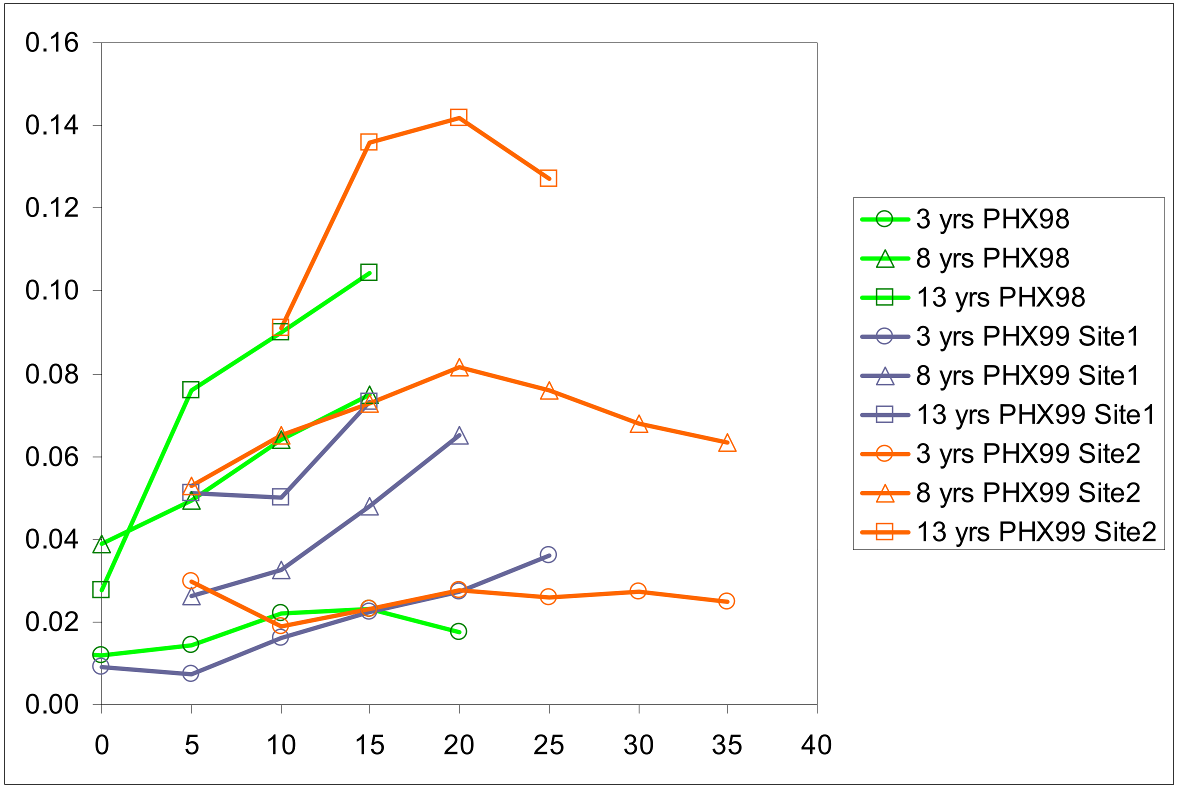
- Site Comparison: Chicago and Denver
  - Same trends
    - in rate of deterioration
    - in response to load

Car Remote Sensing NO in Phoenix 1999



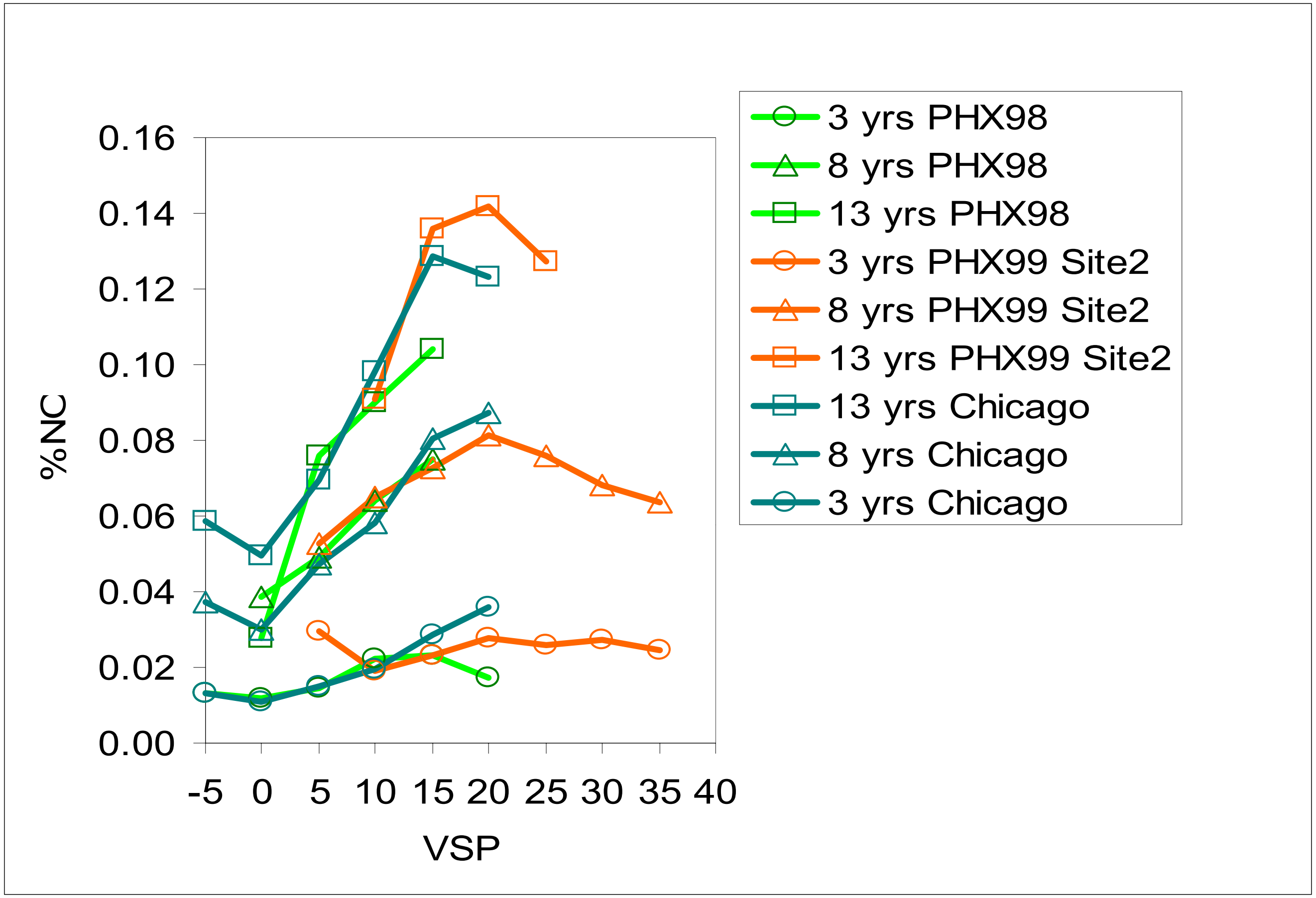
- Site Comparison: 1999 Phoenix Sites at different points on same ramp
  - Site 1 vehicles under low load, many exhaust plumes too small to measure
  - Site 2 vehicles were accelerating rapidly
  - %NO emissions were much lower for older Cars at same VSP at Site 1

Car Remote Sensing %NO Phoenix 1998-1999



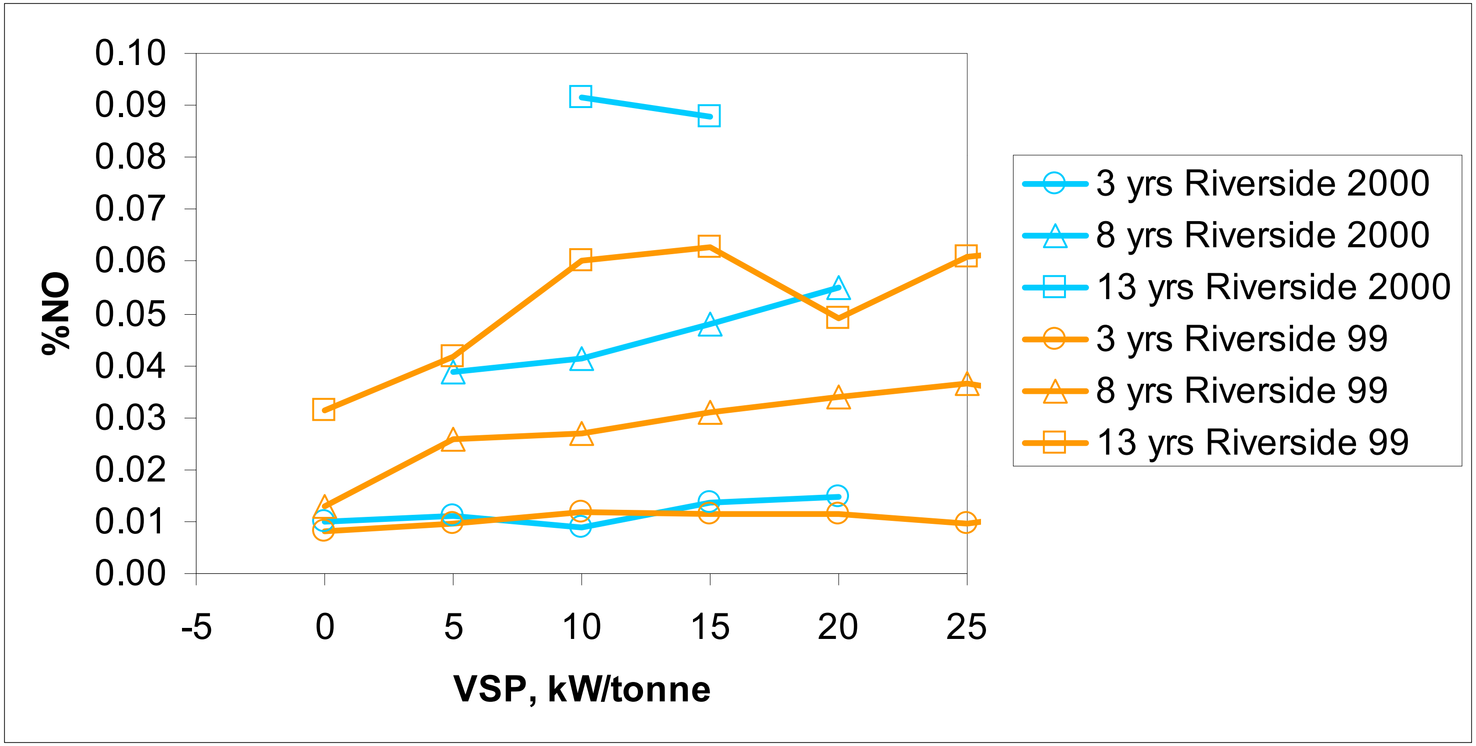
- Site Comparison: Phoenix 1999 Sites and Phoenix 1998 Site
  - %NO versus VSP in 1998 at lower load is in line with 1999 Site 2.
  - No explanation for the results at 1999 Site 1.

Car Remote Sensing NO in Phoenix and Chicago 1999



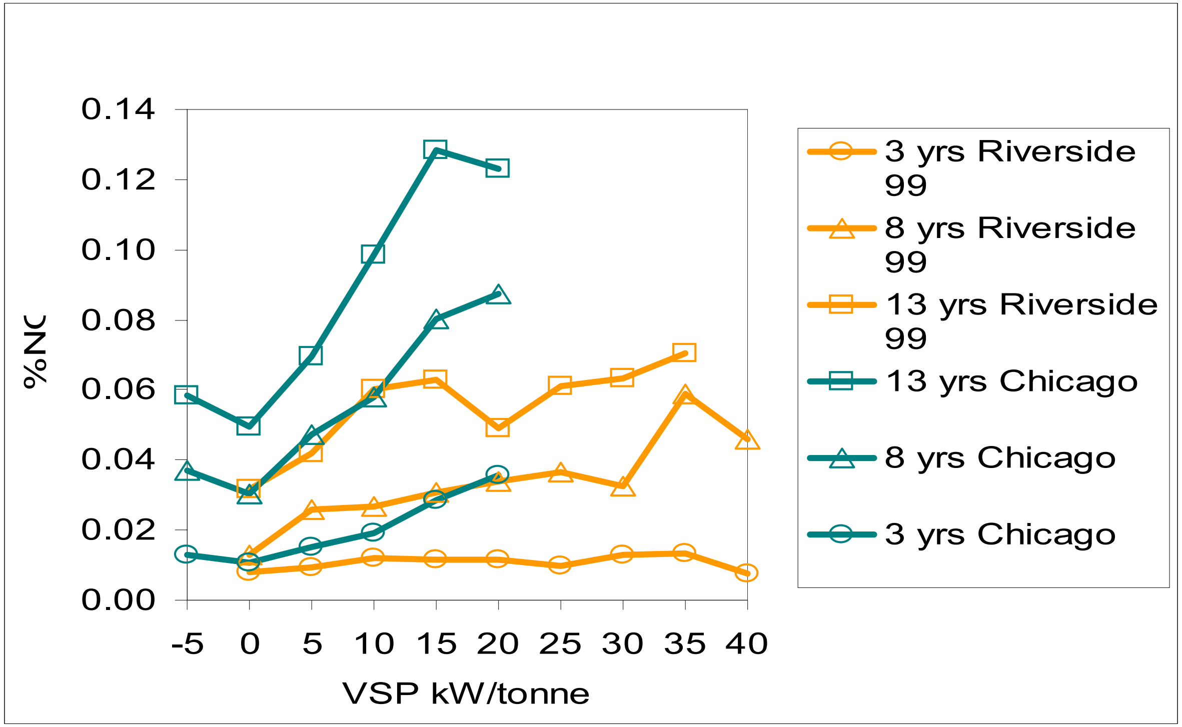
- Site Comparison Phoenix and Chicago:
  - %NO versus VSP at Phoenix sites 1998 and 1999 Site 2 are similar to measurements in Chicago

Car Remote Sensing NO in Riverside 1999-2000



- %NO at Riverside, CA:
  - Emissions increase only slightly with VSP from 0 to 15 kW/tonne
  - Emissions increase from 1999 to 2000 for older Cars.
    - Far fewer cars measured in 2000 (2,500) than in 1999 (8,500)

Car NO Remote Sensing Chicago and Riverside 1999



- Site Comparison: Chicago and Riverside
  - %NO emissions in Riverside much lower than %NO emissions in Chicago.
  - No explanation as for Riverside %NO versus VSP.
  - See results from seven California sites for more information.

Summary of %NO Emissions at E-23 Sites

- 1999 Car %NO emissions at Chicago, Denver, and Phoenix Site 2 are similar.
  - %NO emissions at Phoenix 1999 Site 1 and at Riverside are different. The reasons for the difference are not yet understood.
- Car %NO emissions are decreasing from 1997 to 2000 in Chicago.
  - Only two years of data available from other cities
    - Emissions appear to be decreasing in Denver.
    - Riverside data is not understood.
    - Too many site changes in Phoenix

Vehicles used in the Analysis

- Vehicles in this analysis had valid speed, HC, CO, and NO emissions and were classified as "P" in the California's DMV vehicle registration database.
  - California classifications are "P", "T", and "M". P and T classifications were 99.98% of the vehicles measured.
  - Cross-checking VIN and California classifications in a sample of over 17,000 measurements, 93% of P vehicles were CARS.

TYPE	P	T
BUS	0%	1%
CAR	93%	3%
INC	0%	4%
MPV	4%	23%
TRK	1%	63%
VAN	2%	7%
	100%	100%

City	Car Measurements with Valid Speed, HC, CO and NO Emissions	
Los Angeles	riverside	10,001
Los Angeles	labrea	9,130
Los Angeles	la710	6,693
San Jose	san jose	19,556
Sacramento	sac99	1,938
Sacramento	sac80	7,851
Sacramento	sac50	8,612
	Total	63,781

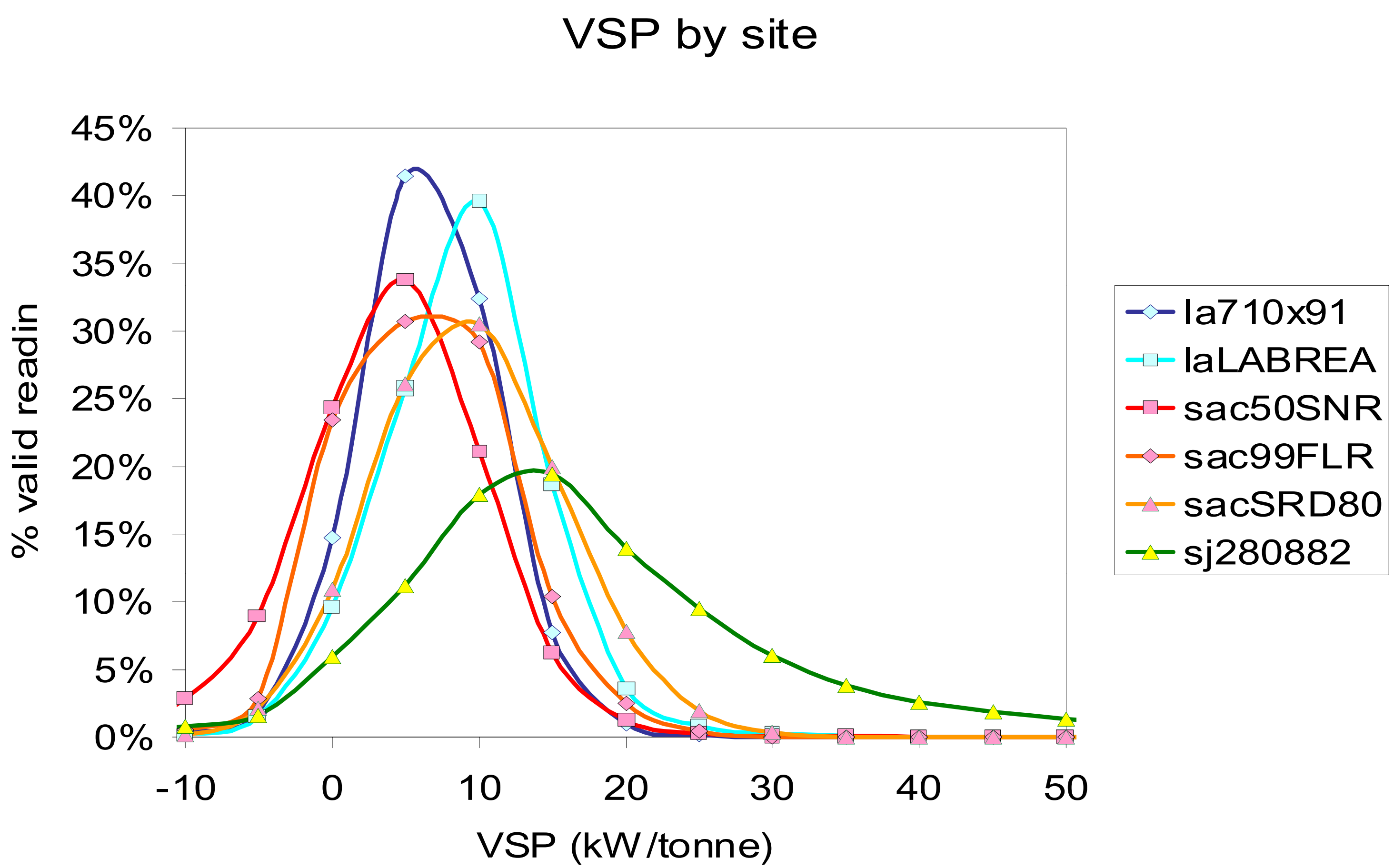
Sites

Study	City	Site	road grade	Month
E23	Riverside, Los Angeles	exit ramp from northbound 91 to westbound 60, almost identical to sampling site in Denver	8.0%	June/July
IMRC	Los Angeles	Interstate 710 and State Highway 91 interchange	3.7%	November
IMRC	Los Angeles	entrance ramp to eastbound Freeway 10 from LaBrea	3.1%	November
IMRC	Sacramento	50 E to Sunrise N	3.3%	October
IMRC	Sacramento	Arden Way W to Business 80 W	3.0%	November
IMRC	Sacramento	99 S to Florin Rd. E	4.5%	November
IMRC	San Jose	280 N to 880 N	3.7%	November

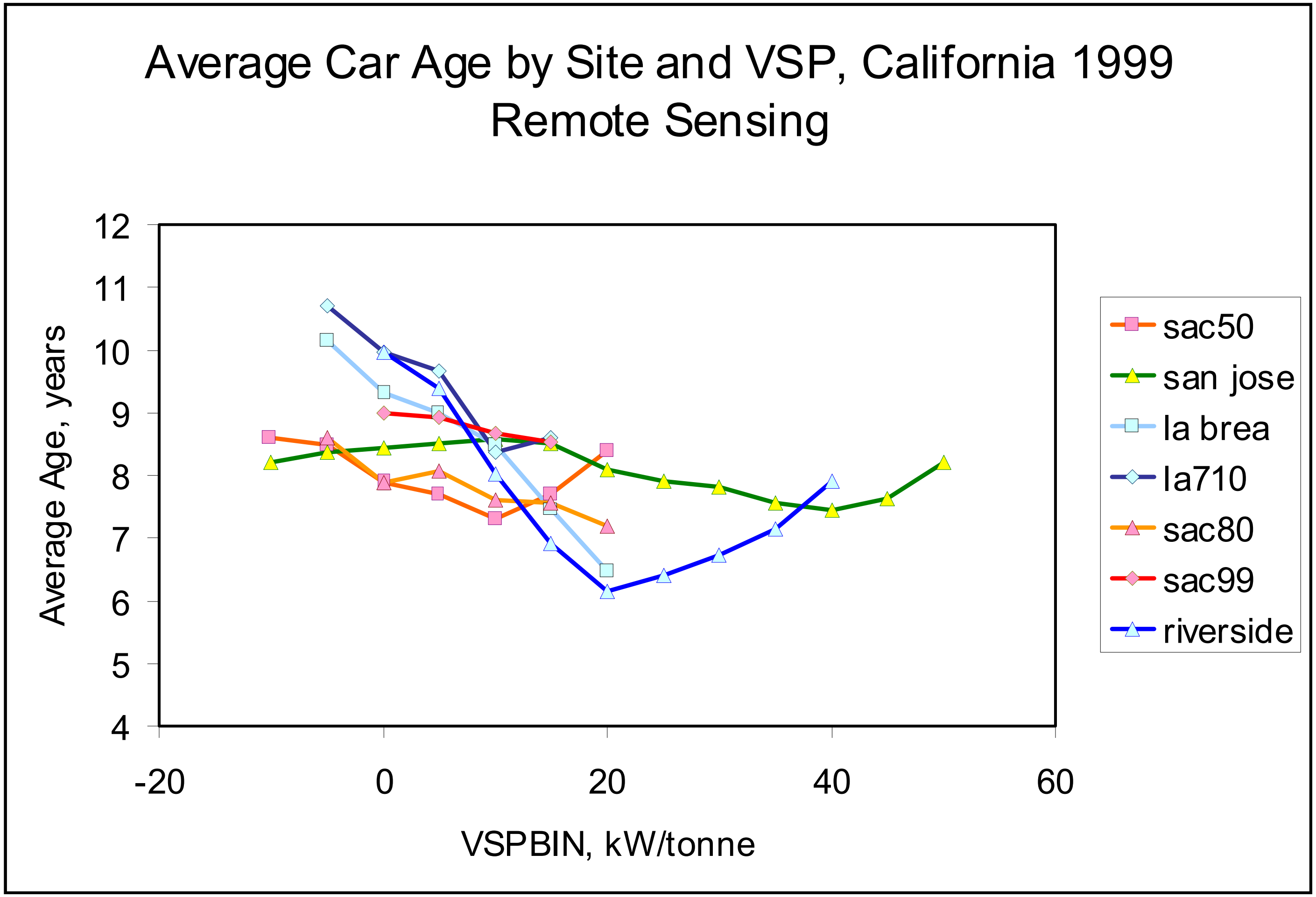
Los Angeles, San Jose, and Sacramento 50E were measured by Denver University people. The other two Sacramento sites were measured by ESP.

Load Distribution of IMRC Sites, All Vehicles,

From Brett Singer, LBL



Car Age and VSP at California Sites
Car Age differs more at different VSP in Los Angeles Sites



California 1999 Sites - CO and HC Analysis

- Remote sensing measurements for E-23 (Riverside) and the Inspection Maintenance Review Committee report on the evaluation of California's I/M program.
  - » All measurements made under E-23 measurement protocol.
  - » Details of the remote sensing analysis can be found in Appendix F of the IMRC report available on the internet.
- Data for this analysis limited to Cars, with VSP between 2.5 and 17.5 kW/tonne
  - » Avoids fuel enrichment
  - » Avoids increase in emissions during deceleration
- Measurements were grouped into Age Bins (3, 8, 13, 18 years)
- The average %CO or %HC regressed with Age Bins by site.
  - » Only Age Bins with >=50 observations were accepted.
  - » The regression line is only valid between the Age Bins; the relationship between emissions and age is not linear for all ages.

Regression of Average %CO for CA 1999 Sites

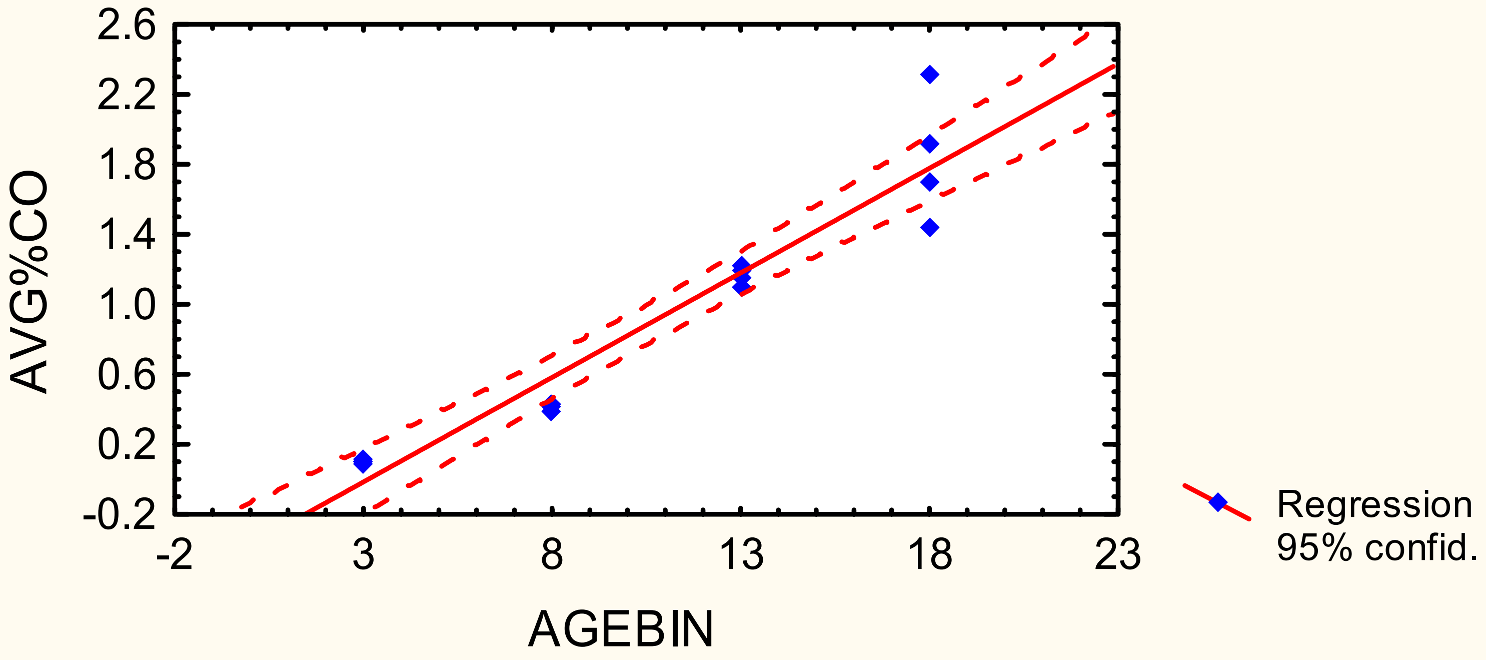
AGEBIN vs. AVG%CO (Casewise Missing Data deletion)

AVG%CO = -0.37 + .119 * AGEBIN

Correlation: r = .96

Variation from 4 random subsets, >=50 obs. per cell

Riverside 1999, Cars, VSP 2.5-17.5 kW/tonne



1999 Remote Sensing, Cars, California

AVG%CO = a + b * Age in years

Location	Site	a	b	R2
LA	rvrside	-0.37	0.119	0.92
LA	labrea	-0.29	0.109	0.92
LA	la710	-0.28	0.098	0.90
SJ	san jose	-0.14	0.066	0.98
SAC	sac99	-0.081	0.053	0.83
SAC	sac80	-0.026	0.046	0.98
SAC	sac50	-0.024	0.042	0.94

- The three Los Angeles Sites had higher rates of emissions deterioration.
- The three Sacramento Sites had lower rates.
- The San Jose Site rate of emissions deterioration was in between that of Los Angeles and Sacramento.

1999 Remote Sensing, Cars, California

AVG%HC = a + b * Age in years

Location	Site	a	b	R2
LA	labrea	-0.001	0.0029	0.88
LA	riverside	-0.001	0.0028	0.94
LA	la710	-0.001	0.0023	0.86
SAC	sac80	0.000	0.0017	0.81
SJ	san jose	0.005	0.0016	0.85
SAC	sac99	-0.002	0.0011	0.88
SAC	sac50	0.017	0.0010	0.72

- The three Los Angeles Sites had higher rates of emissions deterioration.
- The Sacramento Sites had lower rates.
- The San Jose Site rate of emissions deterioration was in between that of Los Angeles and Sacramento.

Vehicle Emissions in Los Angeles and Sacramento, Other Reported Information

- CO emissions of older Los Angeles (model year 1983 and older) vehicles were about 10% higher than Sacramento vehicles of the same age, based on initial ASM5015 vehicle inspection data (VID) from June 1998 to July 1999. (Wenzel, presentation to the IMRC, January 14, 2000). However, this data also showed that all Sacramento vehicles' HC emissions were about 5% <u>higher</u> than HC emissions from Los Angeles vehicles.
- BAR ARB roadside tests reported in CARB A032-093, February 1994, led to the remark on page 77: "Vehicles measured in northern California have lower CO emissions, for equivalent model years, and may have lower HC emissions than vehicles in southern California".

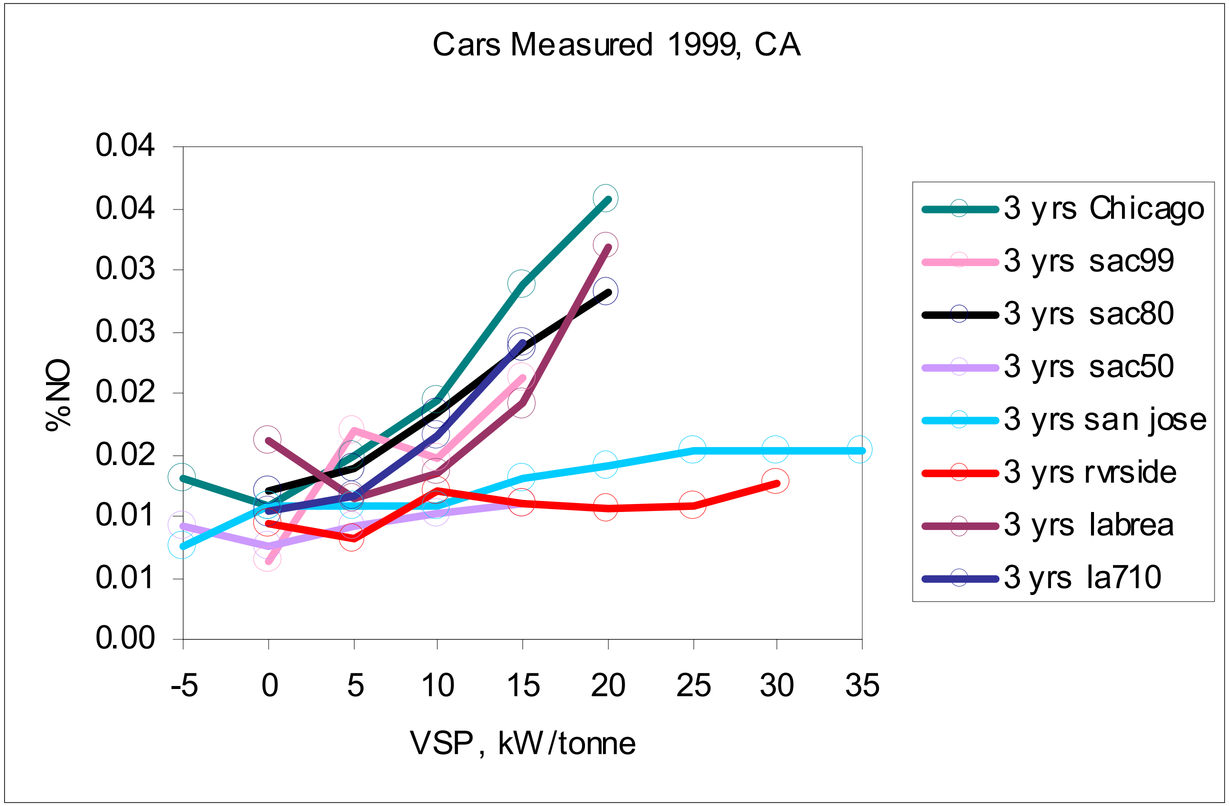
NOx Measurements

- Earlier analysis of E-23 %NO emissions in Chicago and Phoenix *(Slott, R. S., CRC 11th On Road Workshop, poster presentation)* showed:
  - » Phoenix 1999 measurements showed Vehicle Type and Vehicle Age were a function of VSP, especially at high load sites.
    - > Cars were concentrated at higher VSP and Trucks were concentrated at lower VSP
    - > Newer Cars were concentrated at higher VSP and Older Cars were concentrated at lower VSP
  - » Therefore, VSP adjustments should not be applied to the whole fleet.
    - > Vehicle type and vehicle age should be separated out.
  - » To obtain sufficient numbers of vehicles in a bin, bins were made up of Vehicle Type = CARS x 5 year AGE BINS x 5 kW/tonne VSP BINS

    5 year <u>age bins</u> (3 year bin from 2 to 5 years [year 1 missing because of use of one year old registration data], 8 year bin from 6 to 10 years, 13 year bin from 11 to 15 years, etc.)

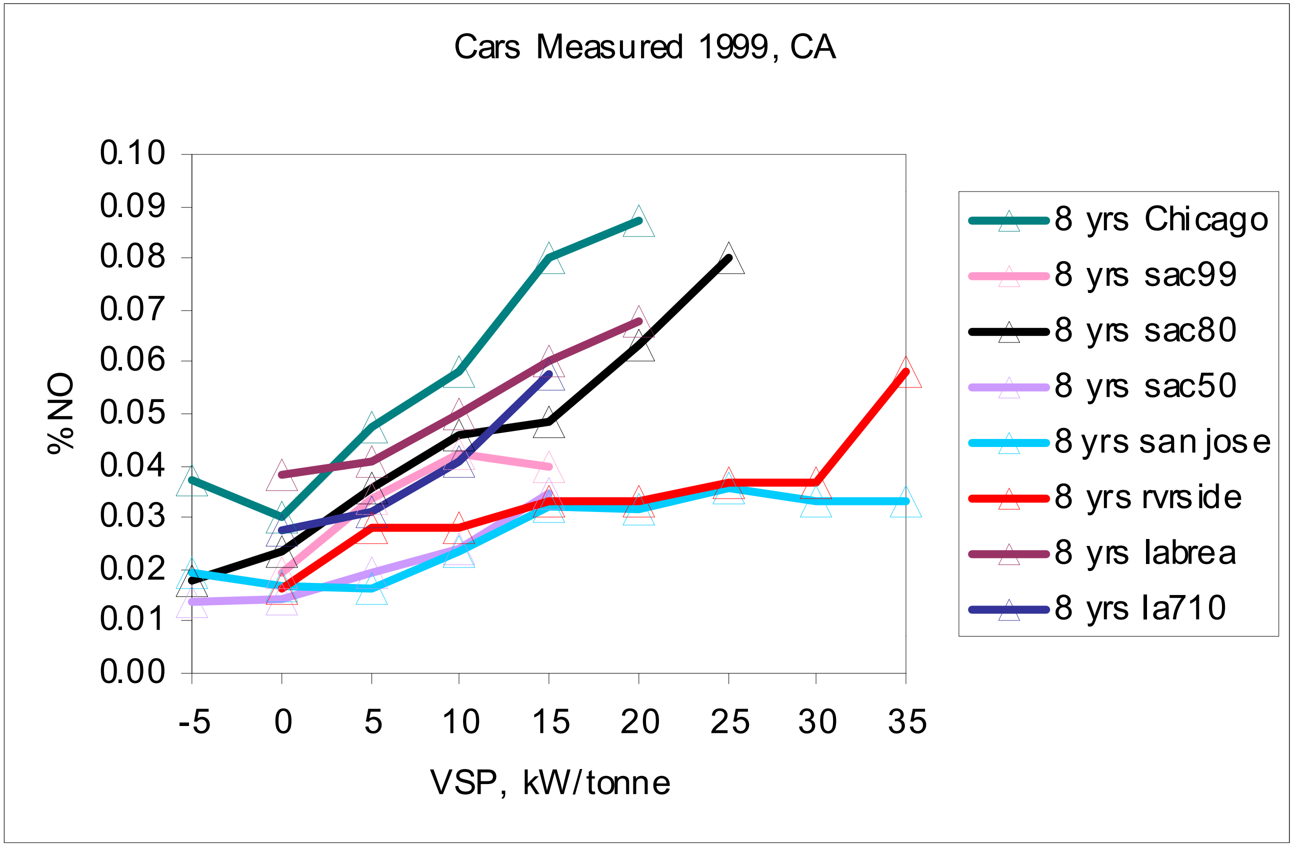
    5 kW/metric ton <u>VSP bins</u> (5 kW/tonne bin from 2.5 to 7.5)

Car Remote Sensing %NO All California Sites 1999



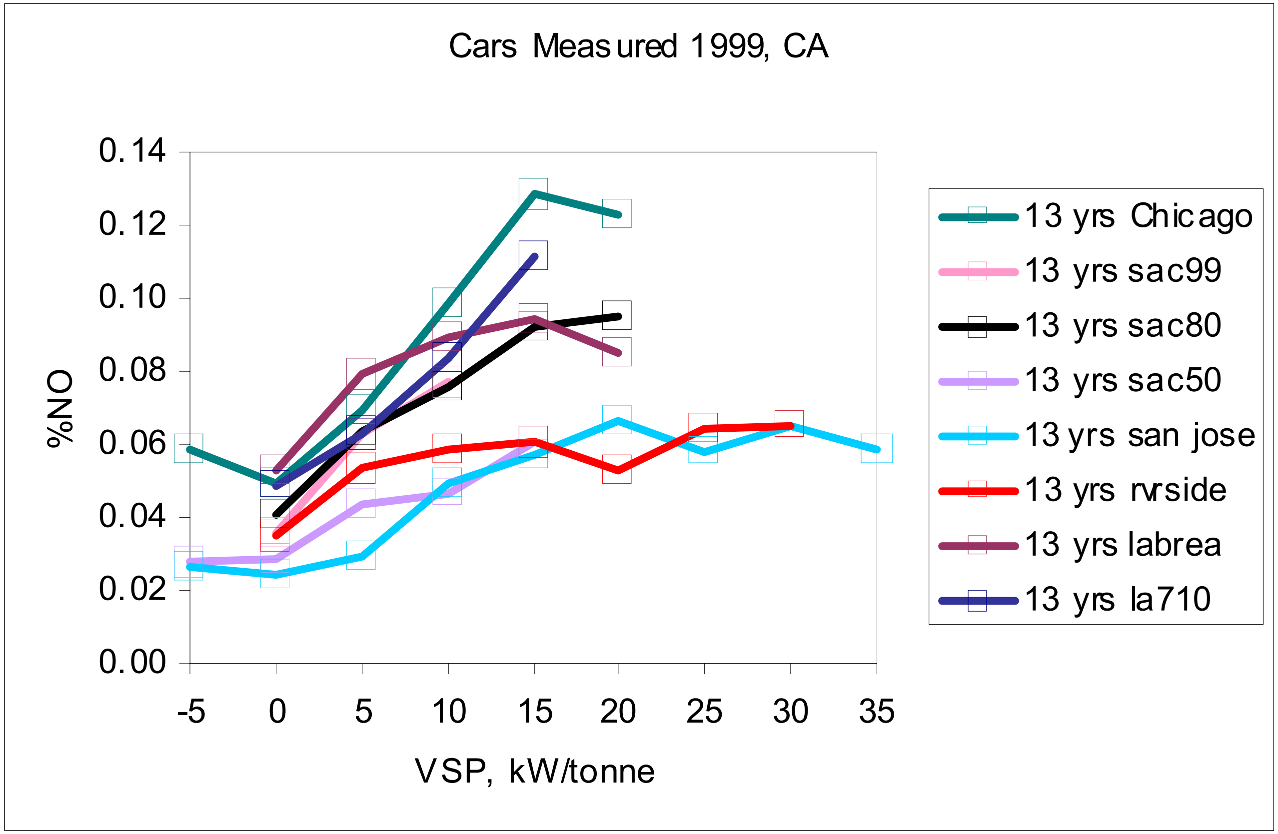
- %NO trends:
  - 3 year age bins
  - Two separate groups of %NO versus VSP in California
    - one similar but slightly lower than %NO in Chicago
    - one much lower than %NO in Chicago, and less sensitive to VSP

Car Remote Sensing %NO All California Sites 1999



- %NO trends:
  - 8 year age bins
  - Two separate groups of %NO versus VSP in California
    - similar to results for 3 year age bins

Car Remote Sensing %NO All California Sites 1999



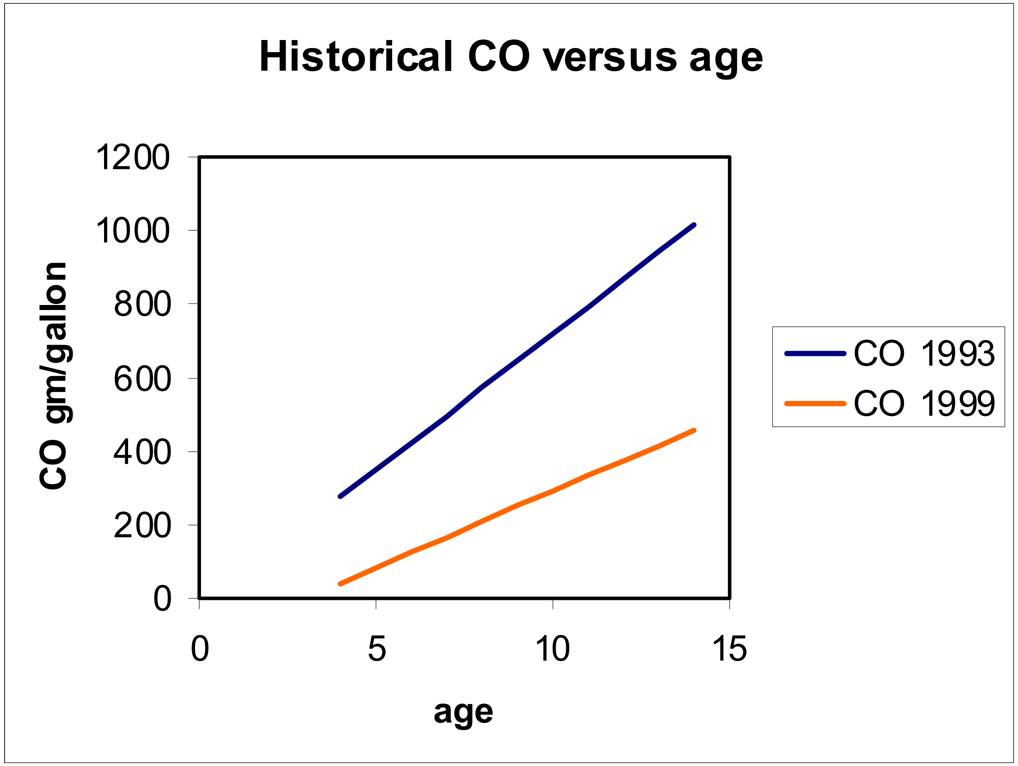
- %NO trends:
  - 13 year age bins
  - Two separate groups of %NO versus VSP in California
    - similar to trend for 3 and 8 year age bins.

Remote Sensing in California in 1999

- Results
  - Remote sensing data say that Los Angeles average CO and HC vehicle emissions are deteriorating faster than Sacramento average CO and HC vehicle emissions. San Jose average CO and HC vehicle emissions are deteriorating at a rate in between Los Angeles and Sacramento.
  - NO versus VSP, a measure of load, by site and by age show three sites, one in Los Angeles, one in Sacramento, and one in San Jose, with average NO vehicle emissions that are considerably lower and less sensitive to VSP, than average NO vehicle emissions from four other sites measured in California in 1999.
    - The other four sites have NO versus VSP emissions that are similar, possibly slightly lower, than Chicago [and Phoenix and Denver].
    - Currently, there is no explanation for why the three sites should be lower and less sensitive to VSP.

CO Emissions are Cleaner and Staying Cleaner

from Don Stedman



- CO 1993: results of analysis of 56,000 measurements from 20 sites in North America, P.L. Guenther, G.A. Bishop, J.E. Peterson and D.H. Stedman, Science of the Total Environment, 146/147, 297-302, 1994.
- CO 1999: results from California presented by R.S. Slott for CRC E-23, Sept. 2001.

Interim Report

Analyzing Fleet %CO & %HC Emissions in Chicago

CRC E-23
December 17, 2001
Bob Slott

%CO & %HC Remote Sensing Measurements

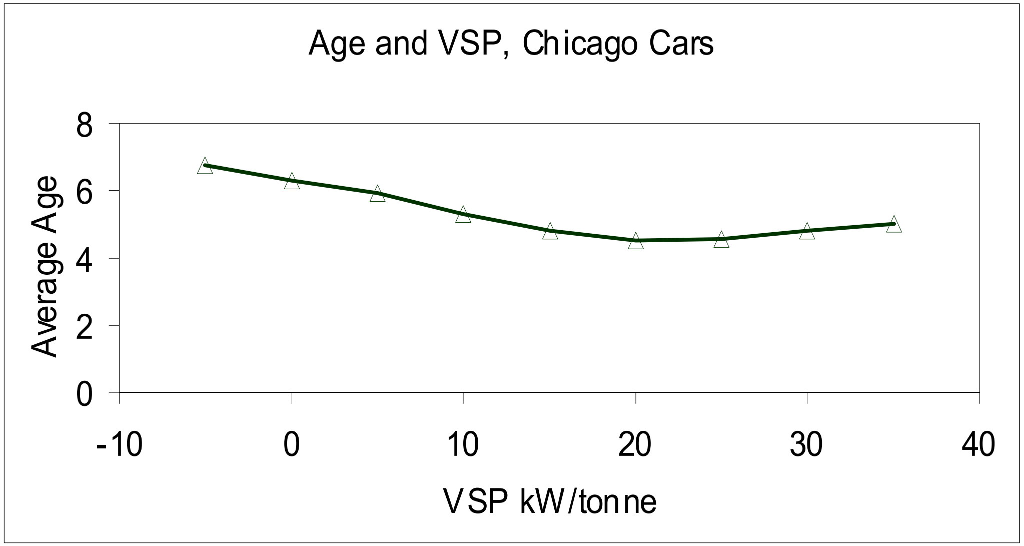
- CO was the first tailpipe pollutant to be measured by on-road remote sensing.
  - Vehicles with high CO emissions under normal driving loads are likely to have emission control malfunctions.
- Motor vehicle exhaust is responsible for almost all CO in urban areas.
  - Many areas in the Mountain States are in CO non-attainment or are close to being in non-attainment.
- HC measurements are based on propane or hexane. Conversion to concentration of "%CH2" requires multiplying by 3 or 6 AND multiplying again by 2.
  - The last multiplication is to correct for the hydrocarbons that are not seen to the same degree as propane or hexane by the NDIR detector.
- Chicago switched from basic to enhanced I/M on 02/01/1999.

Analysis Methodology

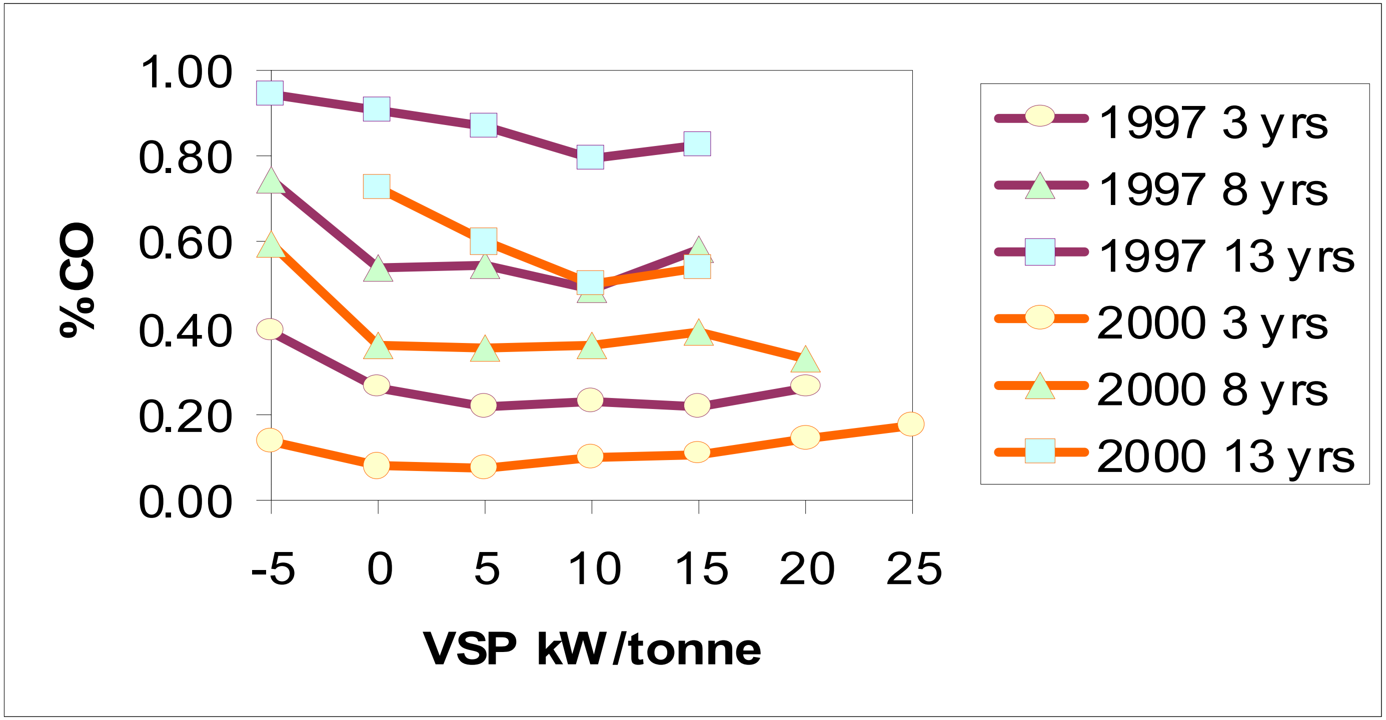
- CO and HC emissions are dependent on:
  - Model year or age of the vehicle,
    - vehicle technology
    - emission control deterioration.
  - Load as measured by VSP.
  - Vehicle type (CARS, TRUCKS, etc), especially when different types of vehicles were built to different standards or have different use and maintenance patterns.
- Analysis based on numerical average from a set (a bin) of remote sensing measurements.
  - All measurements were averaged (rather than averaging all measurements per vehicle) to better reflect fleet emissions.
  - Averages of sufficiently large sample (~50+) are normally distributed or near normal and confidence limits can be applied.
  - Measurements were grouped into AGE x VSP bins with at least 50 cars per bin.

- Chicago remote sensing:
  - » **vehicles in this analysis were cars as identified in the VIN**
- The average age of the car fleet measured was very similar between 1997 and 2000.
- The average age of the cars did not change much with VSP.

Cars	Average Age	Observations
1997	5.4	11,624
1998	5.6	15,071
1999	5.6	14,656
2000	5.7	13,633
All Years	5.5	54,984

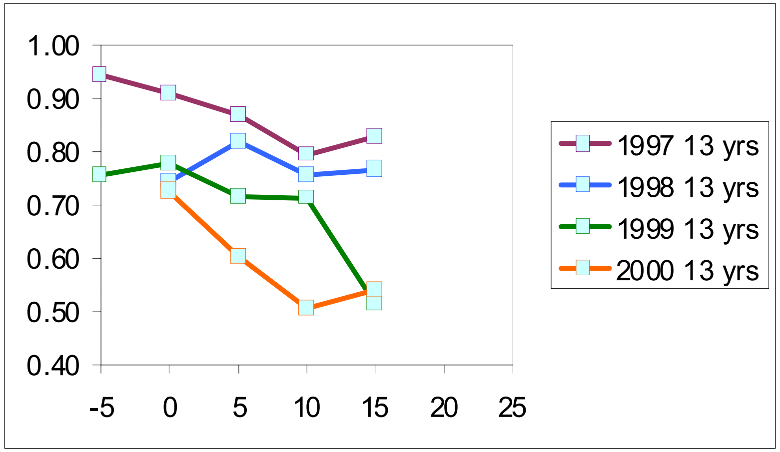


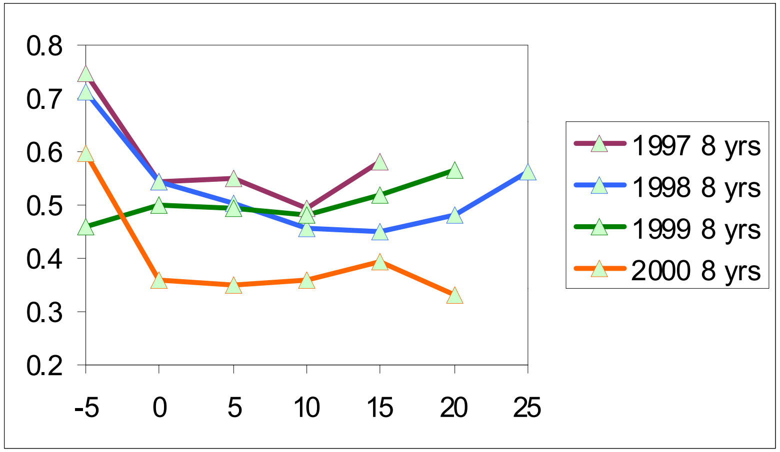
Cars Remote Sensing CO, Chicago



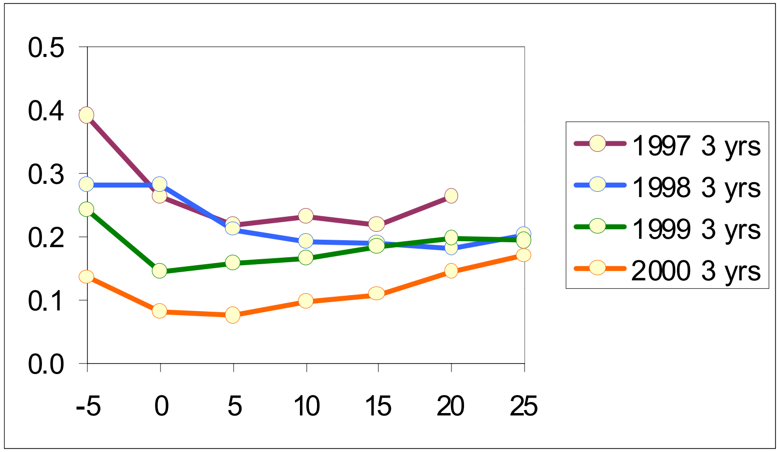
- %CO emissions have decreased from 1997 to 2000 in Chicago.
- As expected, VSP has little effect on %CO emissions from VSP 5 to 20 kW/tonne

Cars Remote Sensing CO, Chicago

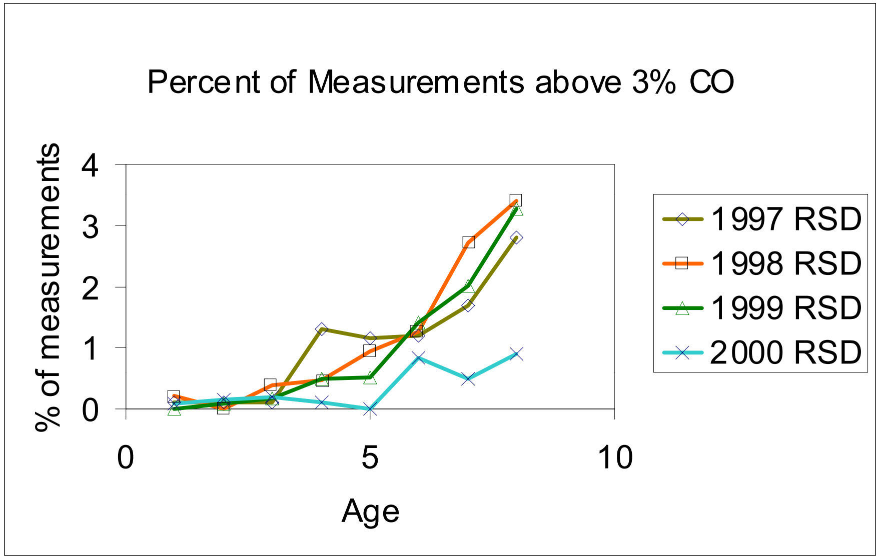


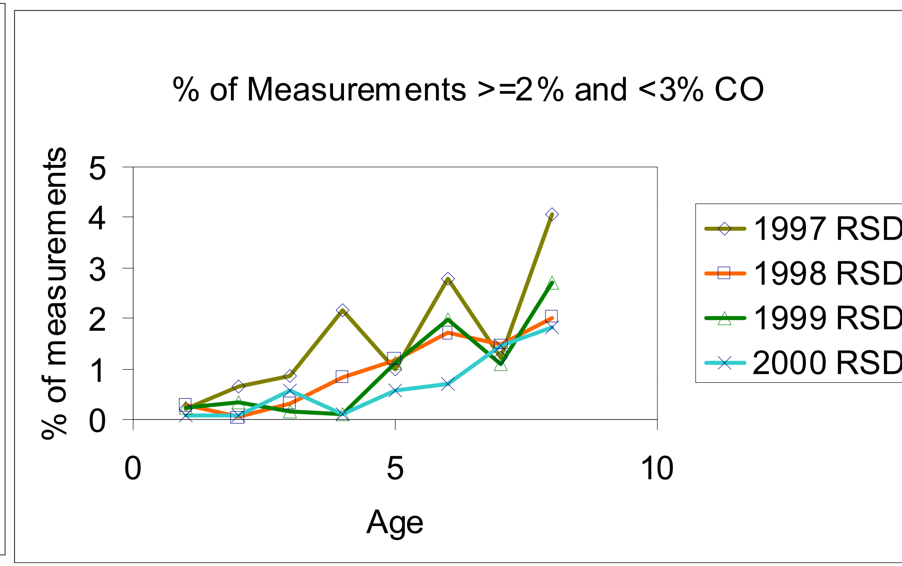


%CO in 1998 and 1999 are bracketed by those in 1997 and 2000

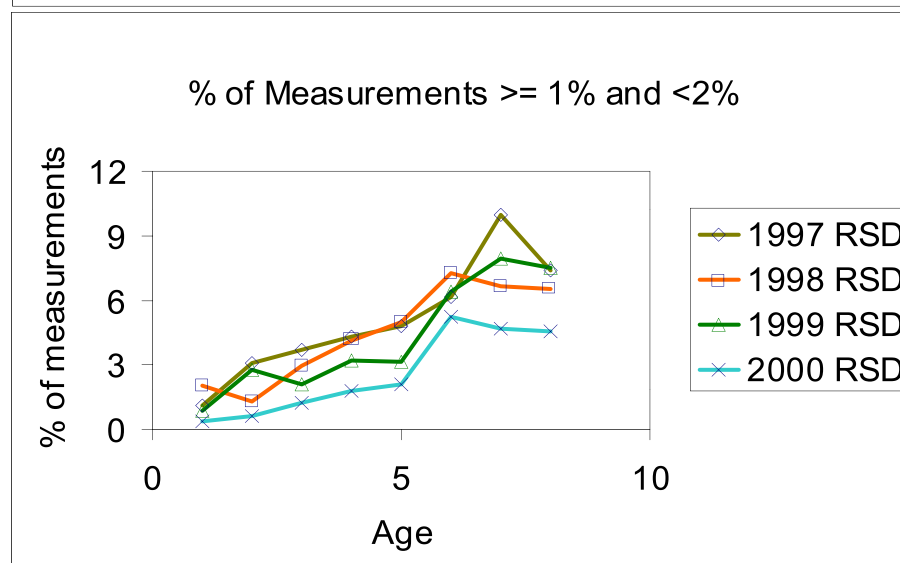


Change in Emissions Distributions, VSP 5-20 kW/t





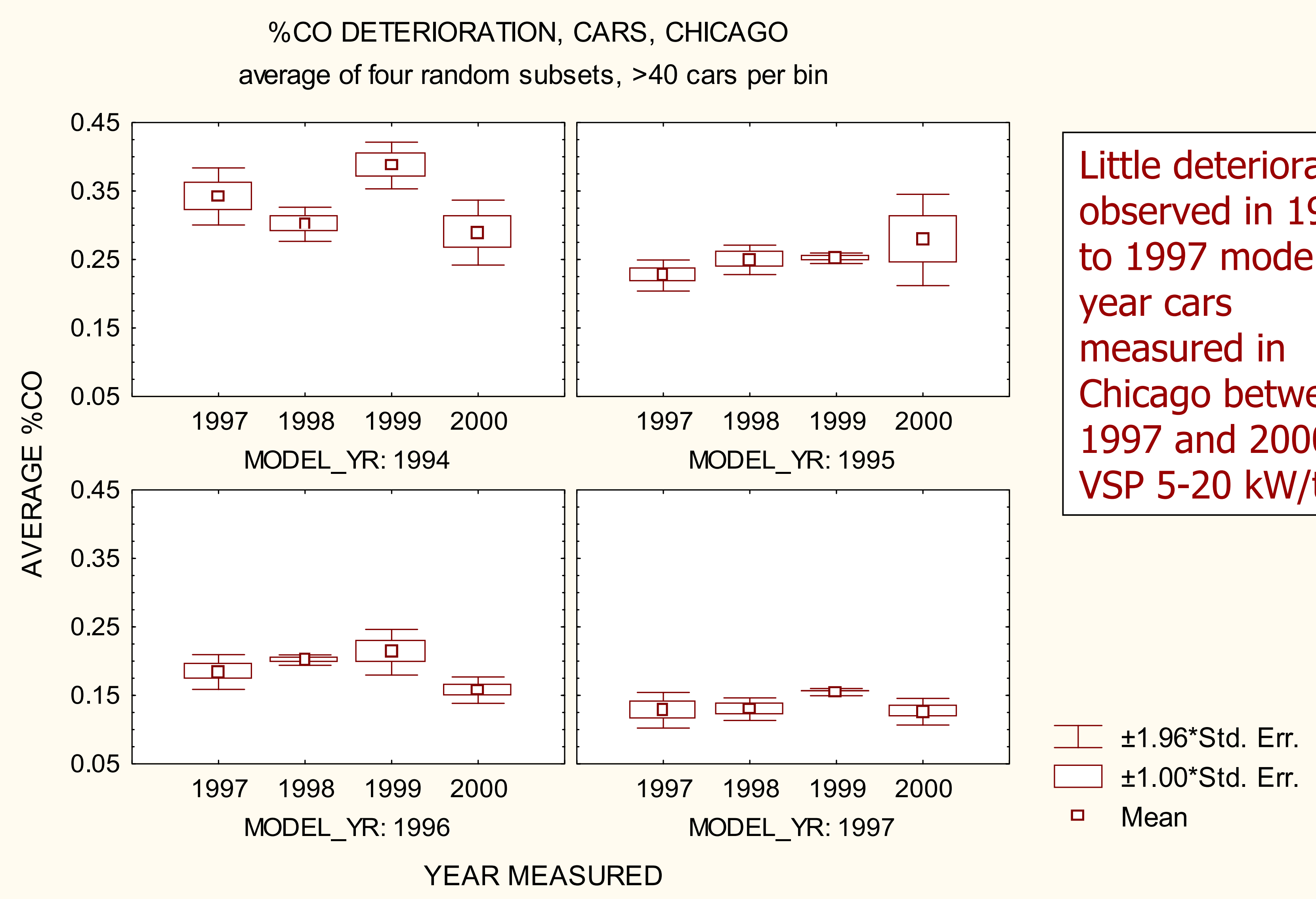
Another way to see the change in emissions with time is to look at the emissions distributions.
Reduction in the percent of CO emissions higher than 3%, between 2 and 3%, and between 1 and 2% took place between 1997 and 2000 for cars in Chicago.



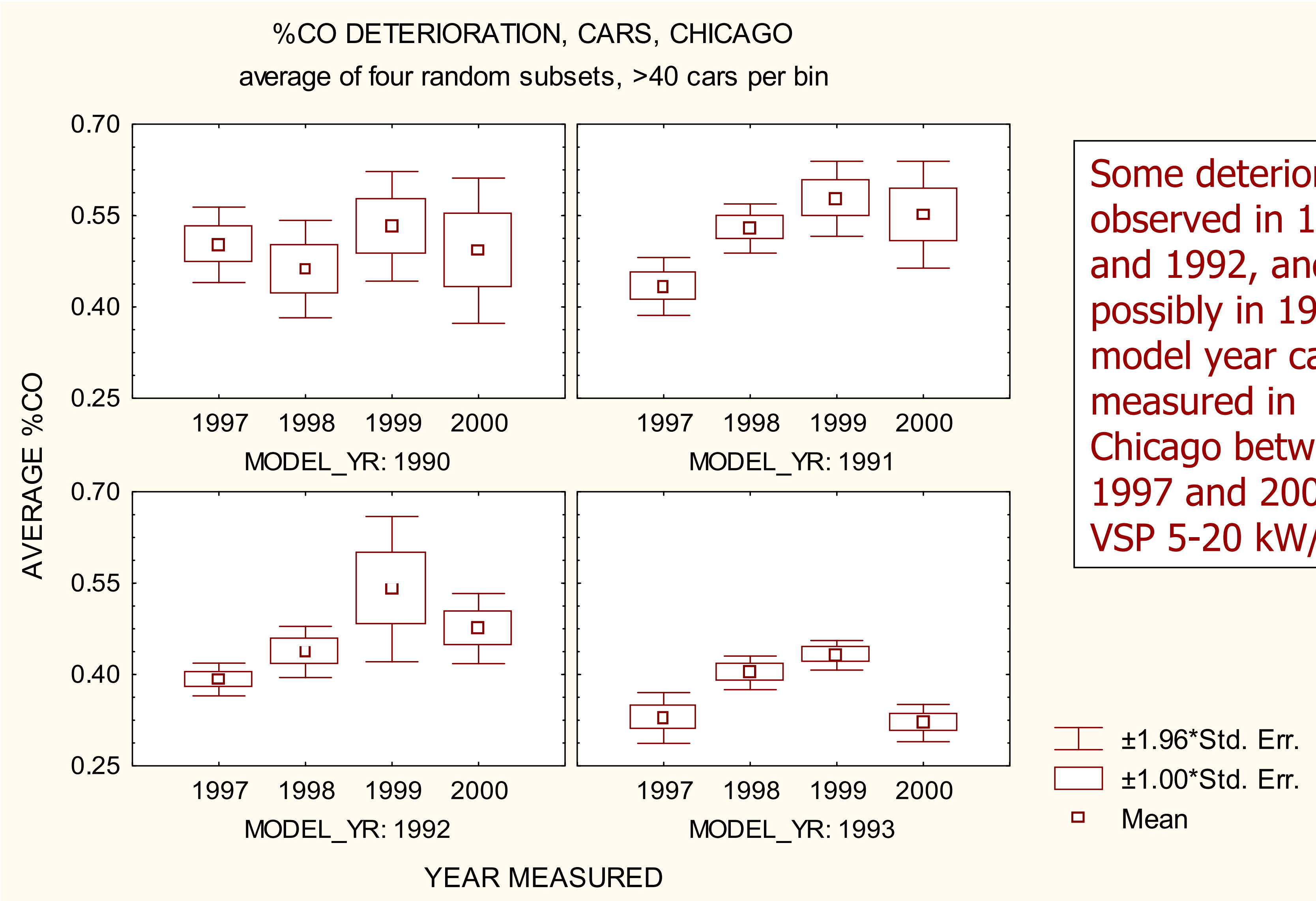
Analysis of %CO Deterioration

- Why CO emissions were selected for deterioration measures.
  - CO remote sensing is the most reliable.
  - No change in sensor over the time.
  - CO emissions are insensitive to VSP from 5 to 20 kW/tonne, resulting in larger samples for each model year at each measuring year.

- How analysis was performed:
  - Average %CO was obtained for four random subsets of each model year in each measurement year.
  - Model years were chosen that had 200 observations in each measurement year.
  - The average %CO was plotted for each model year in each measurement year, the variation in the subsets gives an estimate of the uncertainty of the average %CO.



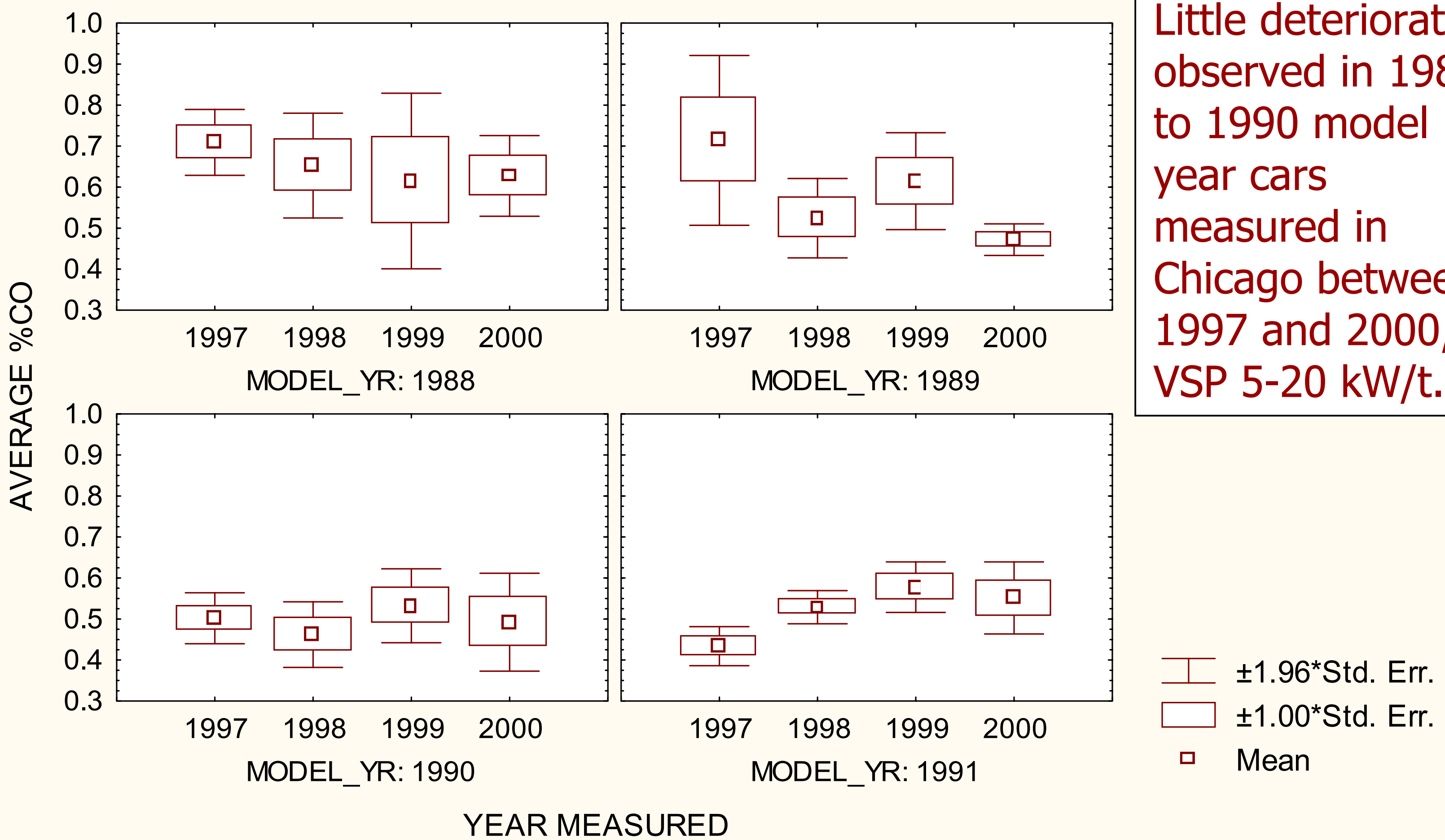
Little deterioration observed in 1994 to 1997 model year cars measured in Chicago between 1997 and 2000, VSP 5-20 kW/t.



Some deterioration observed in 1991 and 1992, and possibly in 1993 model year cars measured in Chicago between 1997 and 2000, VSP 5-20 kW/t.

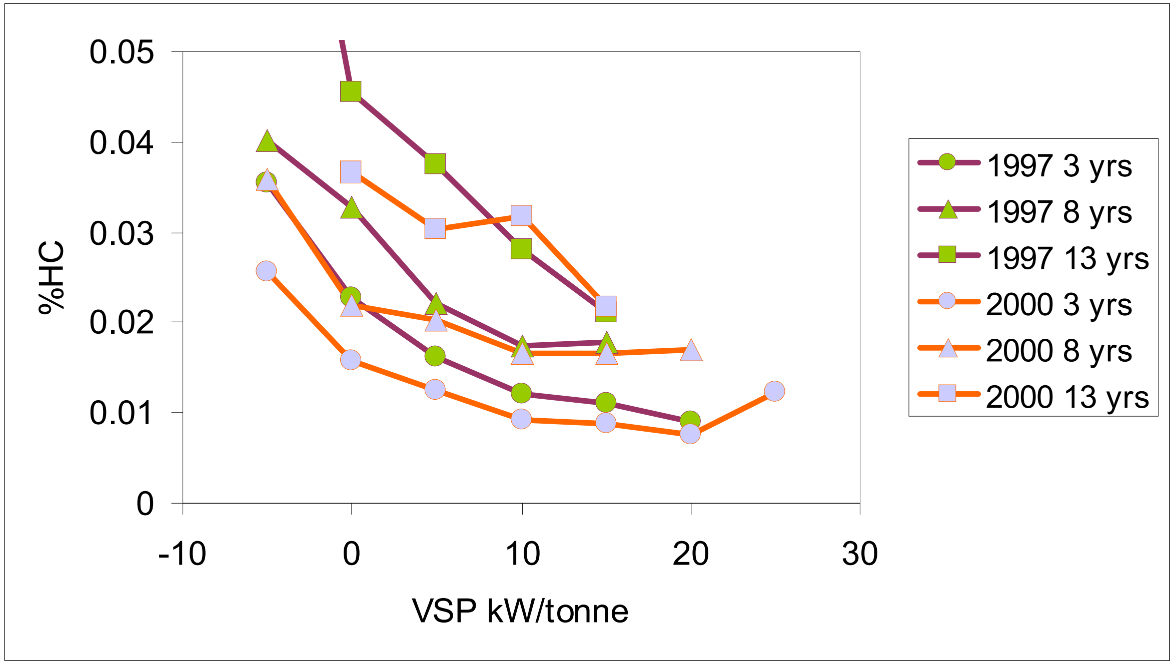
%CO DETERIORATION, CARS, CHICAGO

average of four random subsets, >40 cars per bin



Little deterioration observed in 1988 to 1990 model year cars measured in Chicago between 1997 and 2000, VSP 5-20 kW/t.

Cars Remote Sensing HC, Chicago



- %HC emissions have decreased slightly from 1997 to 2000.
- As expected, higher %HC occurs at negative load. Under negative load, the amount of HC emitted is small, although its concentration can be high.
- %HC emissions are seen to decrease somewhat with increasing VSP from VSP of 5 to 20 kW/tonne. The trend is greater in older vehicles.

Interim Report

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CRC E-23
December 17, 2001
Bob Slott

%CO & %HC Remote Sensing Measurements

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- Motor vehicle exhaust is responsible for almost all CO in urban areas.
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- HC measurements are based on propane or hexane. Conversion to concentration of “%CH2” requires multiplying by 3 or 6 AND multiplying again by 2.
  - The last multiplication is to correct for the hydrocarbons that are not seen to the same degree as propane or hexane by the NDIR detector.

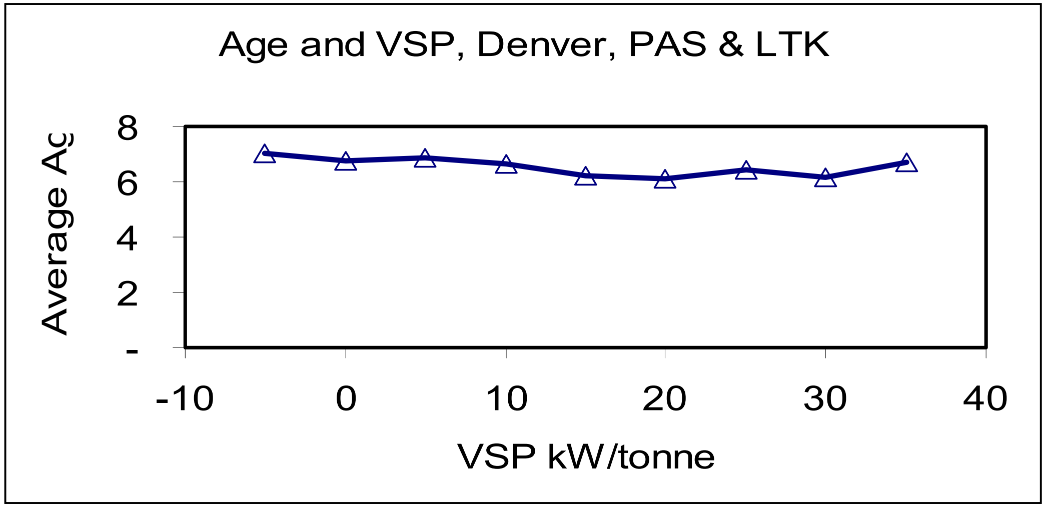
Analysis Methodology

- CO and HC emissions are dependent on:
  - » Model year or age of the vehicle,
    - > vehicle technology
    - > emission control deterioration.
  - » Load as measured by VSP.
  - » Vehicle type (CARS, TRUCKS, etc), especially when different types of vehicles were built to different standards or have different use and maintenance patterns.
- Analysis based on numerical average from a set (a bin) of remote sensing measurements.
  - » All measurements were averaged (rather than averaging all measurements per vehicle) to better reflect fleet emissions.
  - » Averages of sufficiently large sample (~50+) are normally distributed or near normal and confidence limits can be applied.
  - » Measurements were grouped into AGE x VSP bins with at least 50 cars per bin.

Vehicles used in this Analysis

- Vehicles used in the this analysis were PAS and LTK vehicles as classified by the Colorado MVD.
- The average age of the car fleet measured was very similar between 1996 and 2000.
- The average age of the cars did not change much with VSP.

LTK & PAS	Average Age	Observations
1996	6.63	21,446
1997	6.53	27,316
1999	6.51	20,430
2000	6.50	17,668
All Years	6.55	86,860



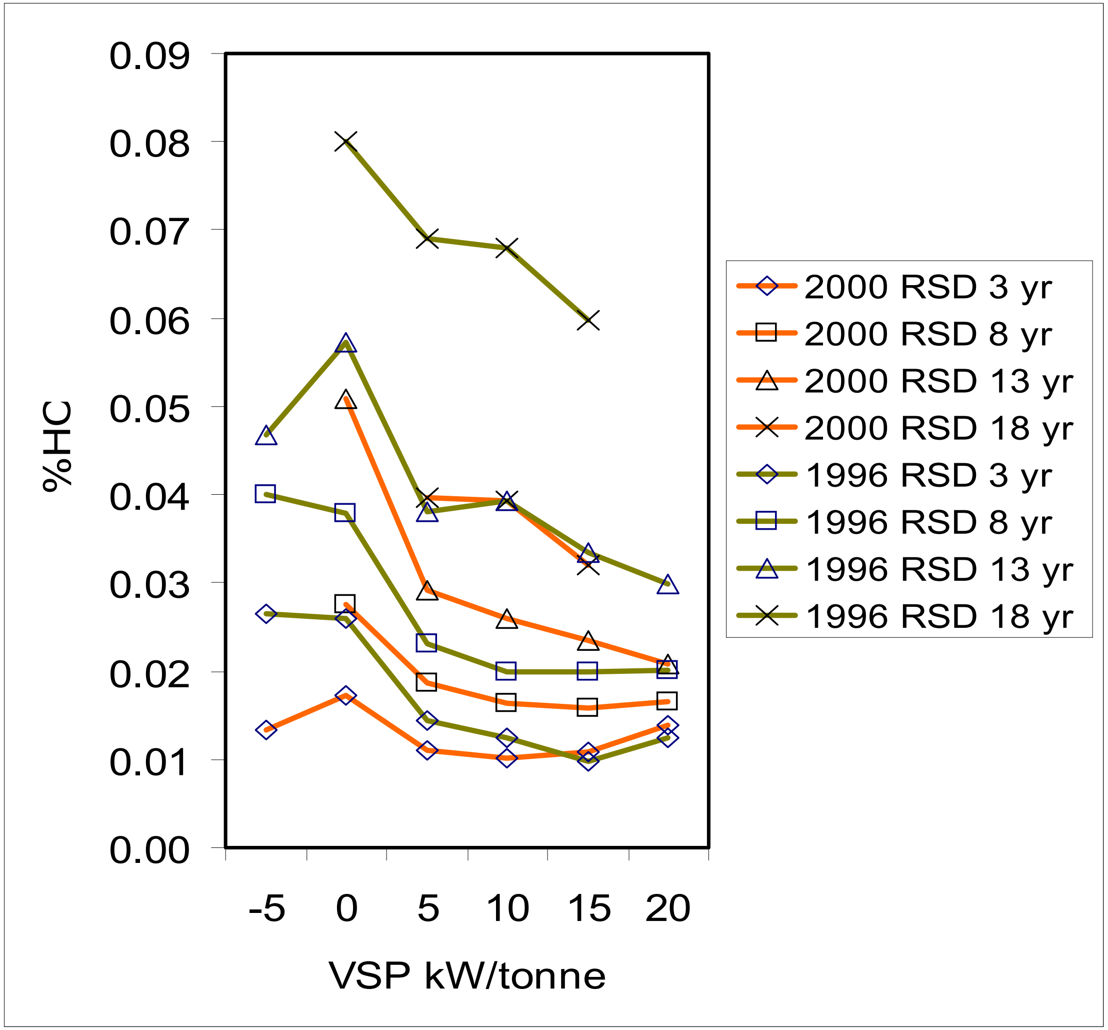
PAS and LTK Vehicle Classifications

- Vehicles used in the this analysis were PAS and LTK vehicles as classified by the Colorado MVD.
- PAS and LTK vehicles were over 99% of the vehicles measured, and were a mix of VIN classifications.
- PAS and LTK classifications were compared to VIN types in a sample of over 22,000 remote sensing measurements:
  - CARS compose only 2/3 of the PAS classification

TYPE	PAS	LTK
BUS	0%	0%
CAR	66%	1%
INC	1%	5%
MPV	24%	1%
TRK	2%	93%
VAN	7%	0%

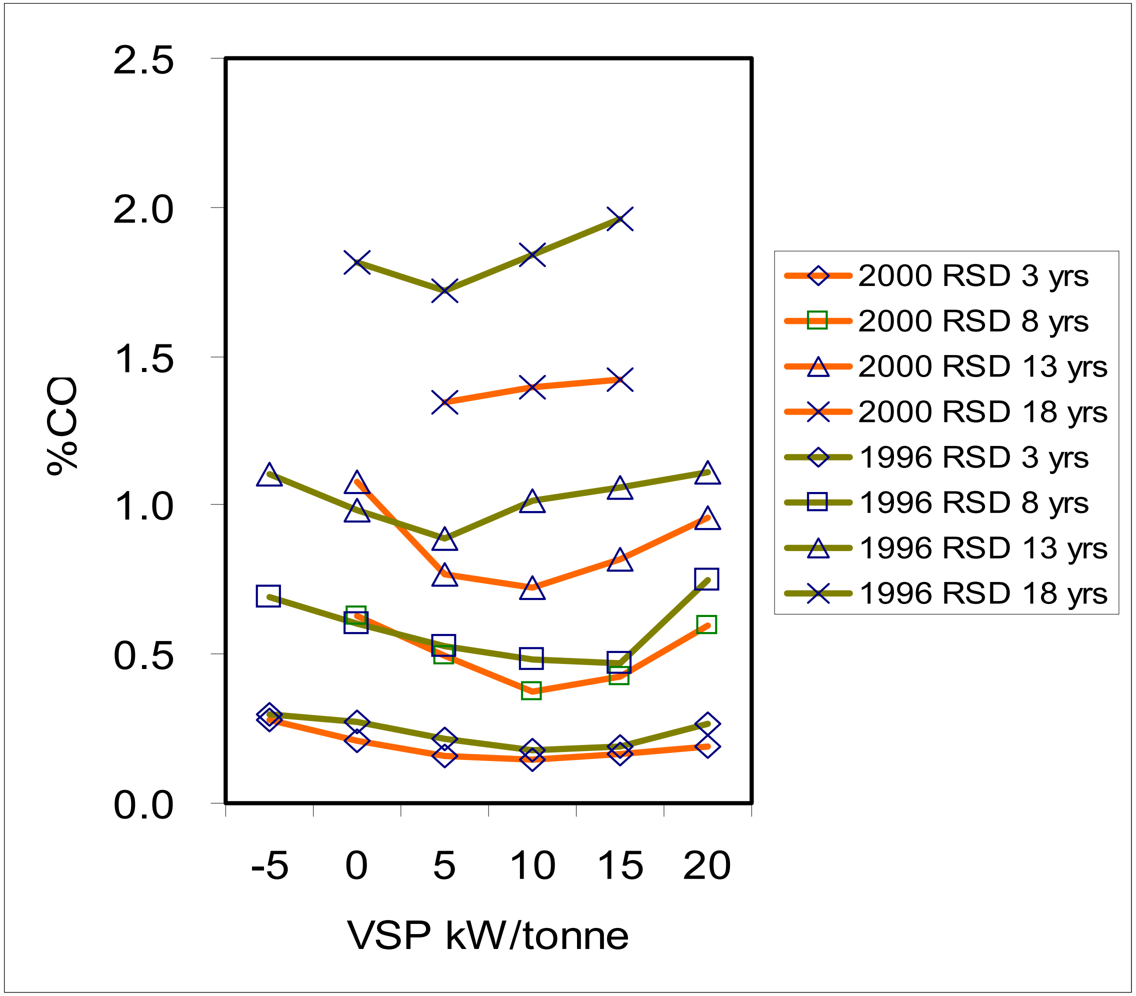
PAS & LTK Remote Sensing HC, Denver

- %HC emissions have decreased from 1996 to 2000 in Denver.
- The largest improvement is in the oldest vehicles, probably due to fleet turnover.
- VSP has little effect on %HC emissions from VSP 5 to 20 kW/tonne except in older vehicles where %HC continues to decrease with VSP.

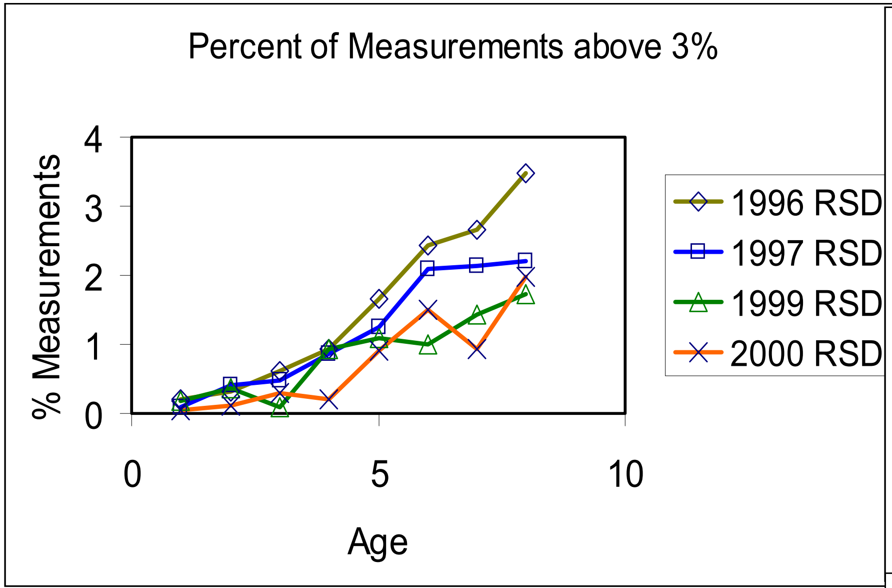


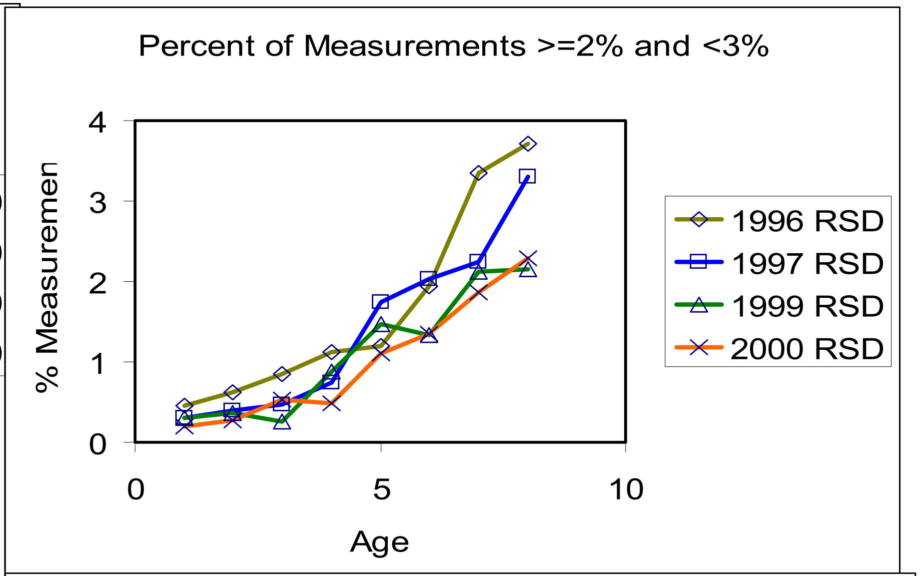
PAS & LTK Remote Sensing CO, Denver

- %CO emissions have decreased from 1996 to 2000 in Denver.
- The largest improvement is in the oldest vehicles, probably due to fleet turnover.
- As expected, VSP has little effect on %CO emissions from VSP 5 to 20 kW/tonne

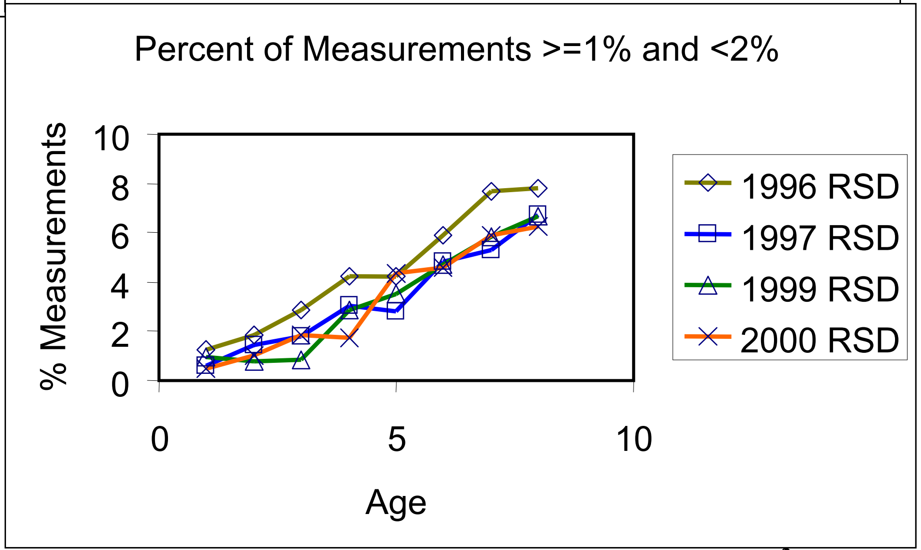


Change in Emissions Distributions, VSP 5-20 kW/t





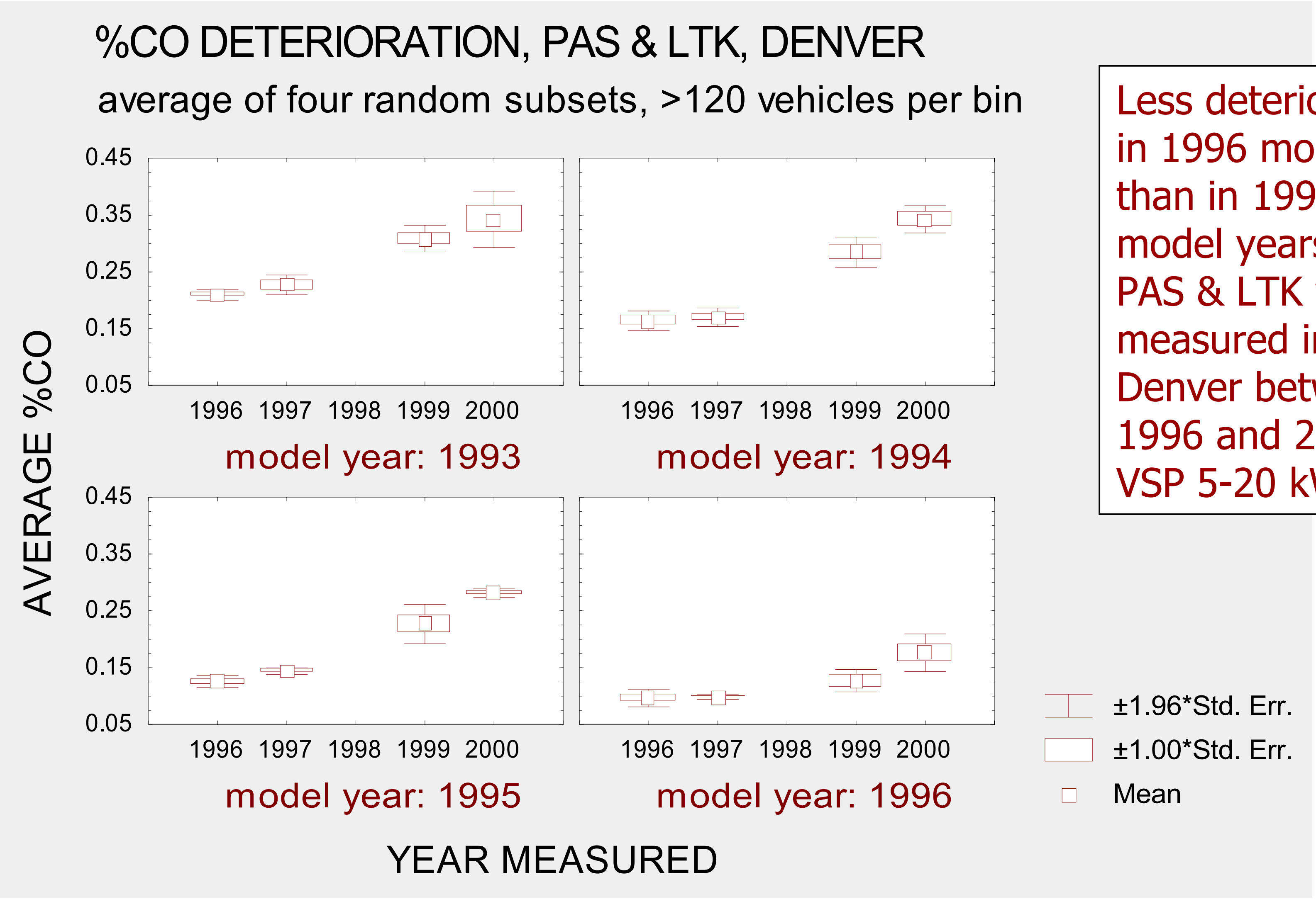
Another way to see the change in emissions with time is to look at the emissions distributions.
Reduction in the percent of CO emissions higher than 3%, between 2 and 3%, and between 1 and 2% took place between 1996 and 2000 for PAS & LTK in Denver.



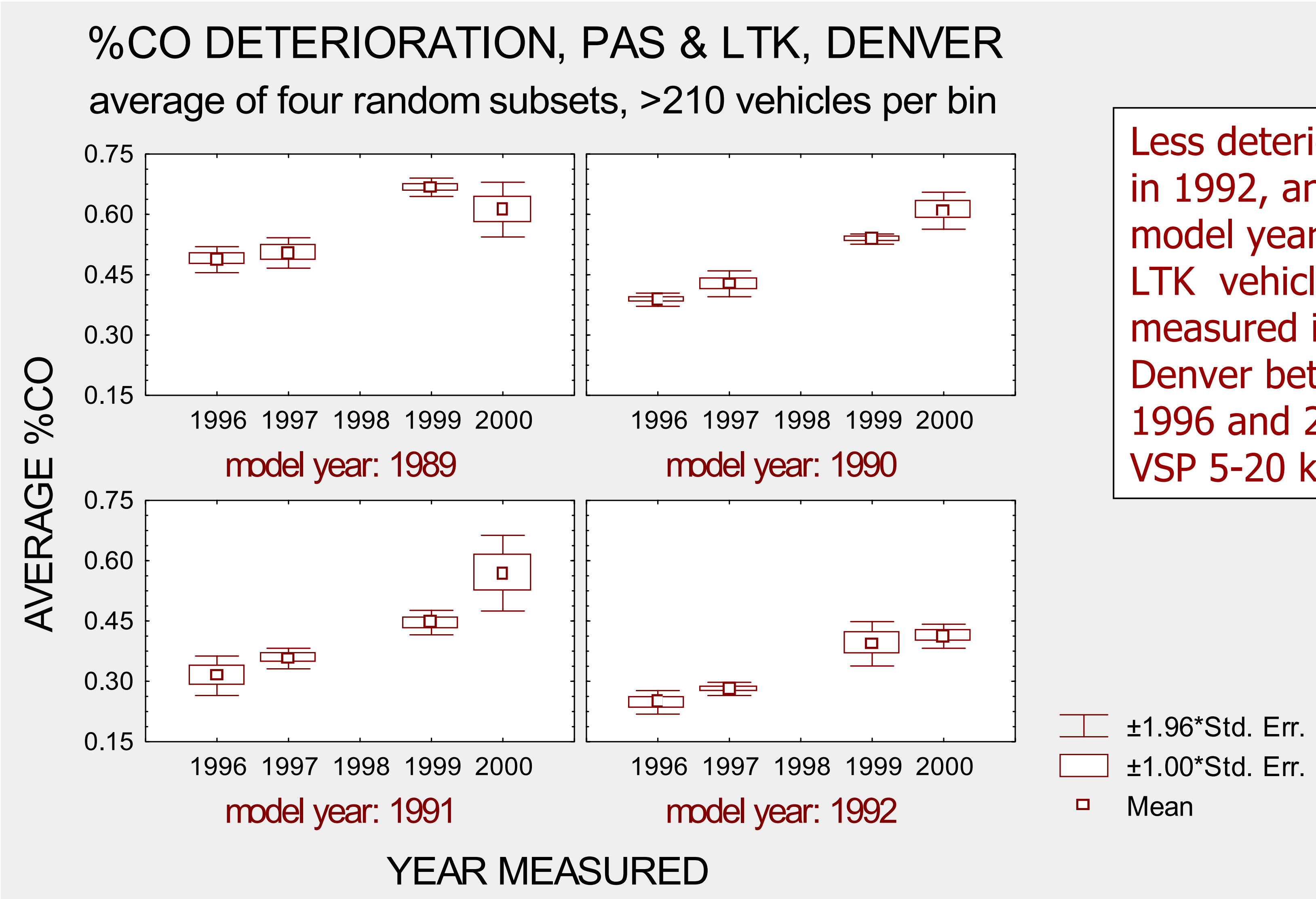
Analysis of %CO Deterioration

- Why CO emissions were selected for deterioration measures.
  - » CO remote sensing is the most reliable.
  - » No change in sensor over the time of measurements.
  - » CO emissions are insensitive to VSP from 5 to 20 kW/tonne, resulting in larger samples for each model year at each measuring year.

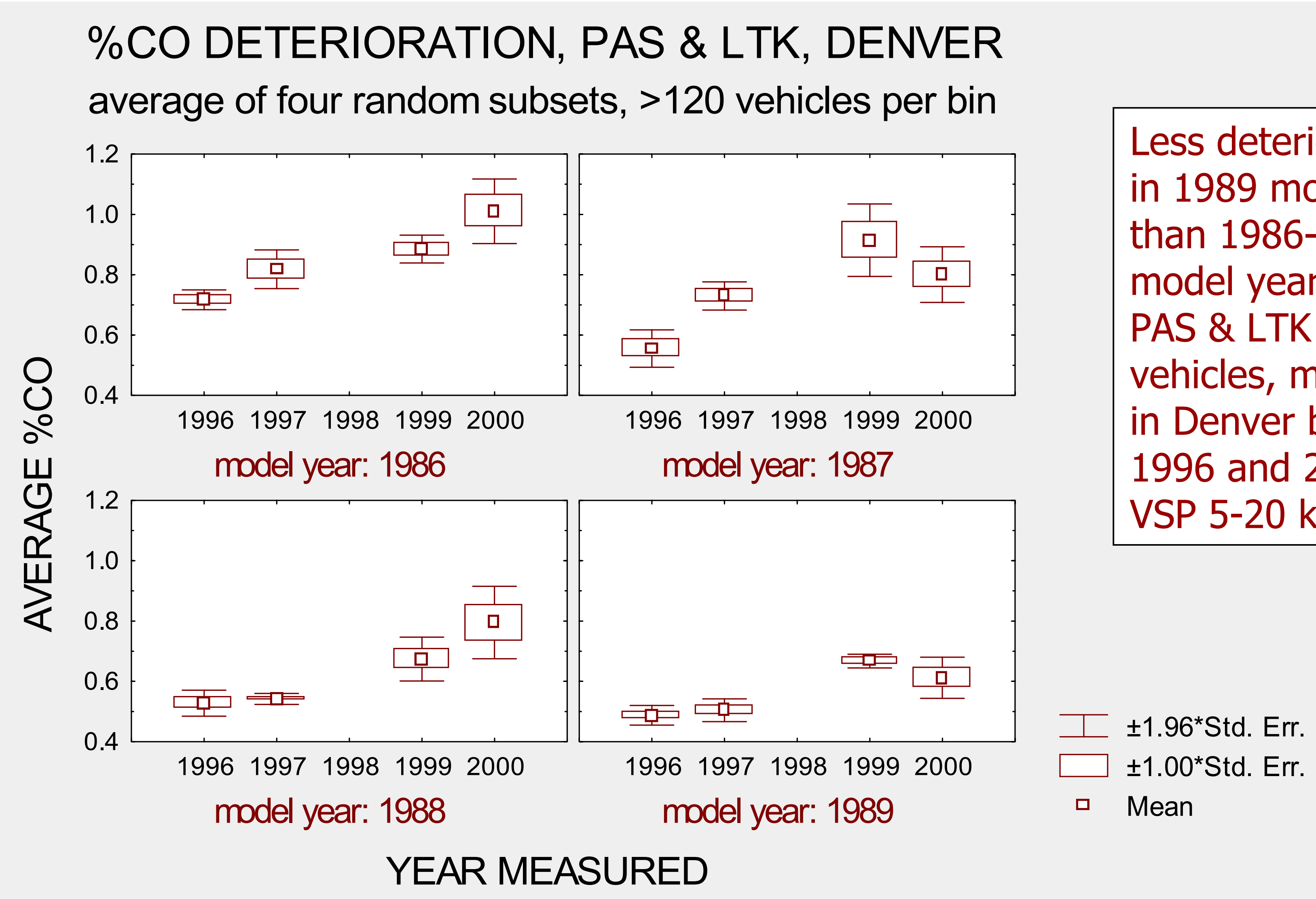
- How analysis was performed:
  - » Average %CO was obtained for four random subsets of each model year in each measurement year.
  - » Model years were chosen that had 200 observations in each measurement year.
  - » The average %CO was plotted for each model year in each measurement year, the variation in the subsets gives an estimate of the uncertainty of the average %CO.



Less deterioration in 1996 model year than in 1993-1995 model years of PAS & LTK vehicles measured in Denver between 1996 and 2000, VSP 5-20 kW/t.



Less deterioration in 1992, and 1989 model year PAS & LTK vehicles measured in Denver between 1996 and 2000, VSP 5-20 kW/t.



Less deterioration in 1989 model year than 1986-1988 model years for PAS & LTK vehicles, measured in Denver between 1996 and 2000, VSP 5-20 kW/t.