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ABSTRACT

Remote sensing nitric oxide (NO) measurements are difficult to analyze because load varies among on-road vehicles measured by remote sensing and NO emissions are dependent on load. Remote sensing NO measurements were made on passenger cars in 1997, 1998, and 1999 in Chicago, IL at a site where few vehicles had loads greater than those encountered in the FTP. Passenger car NO emissions could be modeled by an equation with an age term and a load term for measurements made under moderate load. Onset of decreasing NO emissions with increasing load was observed to occur at lower load for older technology vehicles. Light duty vehicles were measured by remote sensing at two sites on the same ramp in Phoenix, AZ. A large proportion of the vehicles at one of the sites was under loads far in excess of those experienced in the FTP. NO could not be characterized by a single valued function of age and load for both Phoenix sites even though the fleet at the two sites was very similar. Reasons for this are discussed.

INTRODUCTION

Remote sensing of vehicle tailpipe exhaust offers a way to monitor fleet and individual vehicle fuel specific mass exhaust emissions. Remote sensing has been used to evaluate the effect on CO and HC emissions of inspection maintenance programs, fleet turnover, and to identify individual vehicles for scrappage or for further inspection. Remote sensing measurements are made only over a short time, typically a half a second and are expressed in gm/gallon units, which are less sensitive to the vehicle operating conditions than the more conventional gm/mile. However, operating conditions change considerably during a vehicle trip. For CO and HC, the variation in emissions with load is not large for warm running vehicles operating under low to moderate loads. If remote sensing measurement sites are carefully chosen, the variation in load for CO and HC emissions can be adjusted or ignored. Emissions of NO, on the other hand, are sensitive to load. Any analysis of NO on-road measurements must take load into account.

MEASUREMENTS

INSTRUMENTATION - The remote sensor used in this study was developed at the University of Denver for measuring the pollutants in motor vehicle exhaust.[1,2] The instrument consists of a non-dispersive infrared (IR) component for detecting carbon monoxide, carbon dioxide (CO_2), and hydrocarbons, and a dispersive ultraviolet (UV) spectrometer for measuring nitric oxide. The source and detector units are positioned on opposite sides of the road in a bi-static arrangement. Colinear beams of IR and UV light are passed across the roadway into the IR detection unit, and are then focused onto a dichroic beam splitter, which serves to separate the beams into their IR and UV components. The IR light is then passed onto a spinning polygon mirror, which spreads the light across the four infrared detectors: CO, CO_2, HC and reference. The UV light is reflected off the surface of the beam splitter and is focused into the end of a quartz fiber-optic cable, which transmits the light to an UV spectrometer. The UV unit is then capable of quantifying nitric oxide by measuring an absorbance band at 226.5 nm in the UV spectrum and comparing it to a calibration spectrum in the same region. The exhaust plume path length and density of the observed plume are highly variable from vehicle to vehicle, and are dependant 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, termed Q, Q' and Q'' respectively, are constant for a given exhaust plume, and on their own are useful parameters for describing a hydrocarbon combustion system. Measured emissions are reported as %CO, %HC and %NO in the exhaust gas, corrected for water and excess oxygen not used in combustion. They can be directly converted to mass emissions per gallon or per kilogram of fuel.

Quality assurance calibrations were performed twice daily in the field unless observed voltage readings or meteorological changes were judged to warrant more frequent calibrations. A puff of gas containing certified amounts of CO, CO_2, propane and NO was released into the instrument's path, and the measured ratios from the instrument were then compared to those certified by the cylinder manufacturer (Praxair). These calibrations account for day-to-day variations in instrument sensitivity and variations in ambient CO_2 levels caused by local sources, atmospheric pressure and instrument path length. Since propane is used to calibrate the instrument, all hydrocarbon measurements reported by the remote sensor are as propane equivalents.

Studies sponsored by the California Air Resources Board and General Motors Research Laboratories have shown that the remote sensor CO measurements are correct to within ±5% of the values reported by an on-board gas analyzer, and within ±15% for HC.[3,4] The University of Denver has tested the NO channel used in this study. Tests involving a late-model low emitting vehicle indicate a detection limit at 3σ of 25 ppm for NO, with an error measurement of ±5% of the reading at higher concentrations. Appendix A of data reports on the web gives a list of criteria for valid or invalid data.

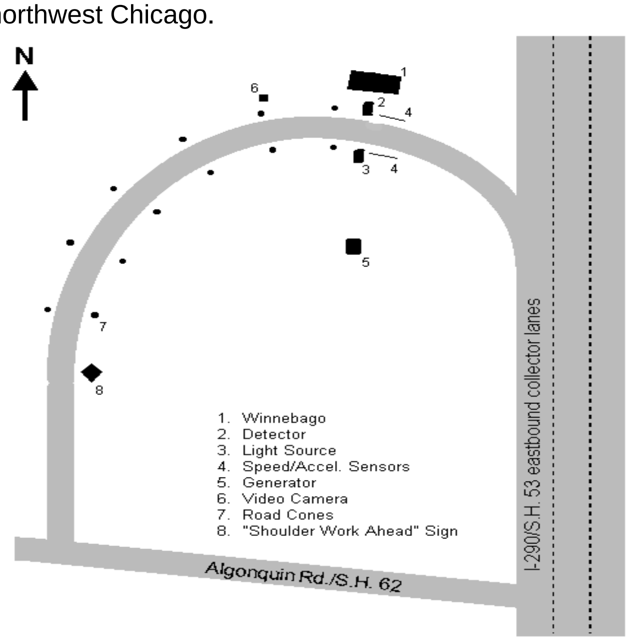
The remote sensor is accompanied by a video system to record a freeze-frame image of the license plate of each vehicle measured. The vehicle's emissions, as well as a time and date stamp, are also recorded on the video image. The images are stored on videotape, so that license plate information may be incorporated into the emissions database during post-processing.

A device to measure the speed and acceleration of vehicles driving past the remote sensor was also used in this study. The system consists of a pair of infrared emitters and detectors (Banner Industries) which generate a pair of infrared beams passing across the road, 6 feet apart and approximately 2 feet above the surface. Vehicle speed is calculated from the time that passes between the front of the vehicle blocking the first and the second beam. To measure vehicle acceleration, a second speed is determined from the time that passes between the rear of the vehicle unblocking the first and the second beam. From these two speeds, and the time difference between the two speed measurements, acceleration is calculated, and reported in mph/s.

MEASUREMENTS – Remote sensing measurements were made as part of the Coordinating Research Council's E23 Project. This project is looking at the change in fleet emissions over time by making remote sensing measurements in the same location and at the same time of the year in a number of cities over a series of years. At least 20,000 valid measurements are targeted for each year of measurement at each site. Data from two measurement locations were used in this report. Individual vehicle identification numbers were obtained from the respective state department of motor vehicles. Individual vehicle characteristics were determined by decoding the VIN. Eastern Research Group carried out the VIN decoding,

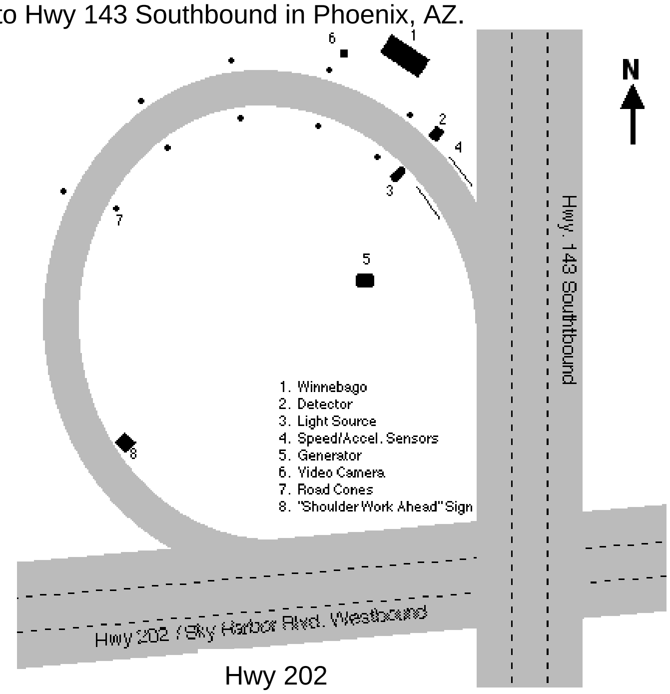
Chicago - The measurement location was the on-ramp from Algonquin Rd. to eastbound I-290 (S.H. 53) in northwest Chicago. This highway is officially designated as an east/west thoroughfare, but traffic is actually travelling in a north/south direction at Algonquin Rd. A map of the measurement location is shown in Figure 1. The on-ramp serves both eastbound and westbound traffic on Algonquin Rd., and has an uphill grade of approximately 2.6%. Measurements were made for 5 consecutive weekdays, from Monday, Sept. 15 to Friday, Sept. 19, 1997; on four consecutive weekdays, from Monday, September 21 to Thursday, September 24. 1998, and on four consecutive weekdays, from Monday, September 20 to Thursday, September 23. 1999.

Figure 1: The measurement location was the on-ramp from Algonquin Rd. to eastbound I-290 (S.H. 53) in northwest Chicago.



Phoenix – Measurements were made for 5 consecutive weekdays, from Monday, Nov. 15 to Friday, Nov. 19, conducted on the uphill exit ramp from Hwy 202 / Sky Harbor Blvd. Westbound to Hwy 143 Southbound in Phoenix, AZ. This intersection is just east of Sky Harbor Airport, and the ramp consists of a rather large loop approximately a mile long. The first two days of measurements were made at a location earlier on the ramp than indicated in Figure 2, and the uphill grade was 3.3%. On the third day, measurements were made at the location in Figure 2, which was as far up the ramp as possible; there the road grade was 3.0%. This new location was used for the remaining days. Measurements were generally made between the hours of 6:00 and 16:30, except for Monday, which consisted of afternoon measurements only.

Figure 2. The measurement location was on the uphill exit ramp from Hwy 202 / Sky Harbor Blvd. Westbound to Hwy 143 Southbound in Phoenix, AZ.



VEHICLE SPECIFIC POWER (VSP)

VSP EQUATION - An equation for determining the instantaneous power of an on-road vehicle has been proposed by Jimenez [5],

$$VSP=4.39 \cdot sine(slope) \cdot v + 0.22 \cdot v \cdot a + 0.0954 \cdot v + 0.0000272 \cdot v^3$$

where VSP is the vehicle specific power in kW/metric tonne, slope is the slope of the roadway in degrees, v is vehicle speed in mph, and a is vehicle acceleration in mph/s. VSP represents the power to mass ratio of the vehicle at an instant of time. The components of the right hand side of the equation describe the various forces on the vehicle, including frictional and aerodynamic drag.

VSP AND EMISSIONS - Using second by second data, VSP has been shown to represent engine out emissions from dynamometer data far better than speed or acceleration alone.[6] The reason proposed for this correlation of emissions with VSP is that fuel flow is seen to correlate very well to VSP, much better than with either speed or acceleration.

VSP AND DRIVING CONDITIONS - Vehicles are designed to pass emission requirements set by the EPA. Prior to 1997 light duty vehicles were certified for emissions on the Federal Test Procedure (FTP) dynamometer test cycle. Vehicle emission control equipment is designed to reduce engine out emissions to meet these requirements under the simulated driving conditions specified by the EPA. The maximum VSP on the FTP is 23 kW/tonne.

NO emissions are observed to increase with increasing VSP until a commanded enrichment event takes place. Commanded enrichment is any extra fuel, beyond what is necessary to maintain a stoichiometric air-fuel ratio, that is deliberately delivered to the engine via a command from the engine calibration through the electronic engine control system to the electronic fuel injection system. Commanded enrichment is typically used whenever the engine is under high loads, such as those that occur during hard accelerations or pulling a loaded trailer. The extra fuel provides the engine with a power gain and is also used to cool the engine and catalyst.[7]

Jimenez[6] found that VSP was able to accurately predict the onset of fuel enrichment with increasing load. For many pre-1997 vehicles, this takes place at 23 kW/tonne. He hypothesized that vehicle manufacturers may have designed the fuel delivery system to avoid fuel enrichment up to the maximum load of the certification test.

EPA became concerned about excessive CO and HC emissions during commanded enrichment and recognized that the FTP did not cover high load events typical of normal driving. So in December 1996, EPA modified light-duty vehicle certification requirements to take into account more aggressive driving behavior than was observed on-road in a series of studies.[8] The revised requirements specified the US06 Driving Cycle, which has a peak VSP of about 55 kW/tonne. This regulation has decreased the use of commanded enrichment in more recent vehicles.

Dynamometer settings for vehicle emissions inspection tests operate under conditions milder than experienced during the FTP driving cycle. The IM240 test does not exceed the FTP in VSP and the ASM test operates with VSP below 10 kW/tonne. On the road, a typical light-duty vehicle accelerating from 0 to 60 mph in 15 seconds has a VSP of 33 kW/tonne, and a similar vehicle operating at 60 mph going up a 4% grade, will experience the same VSP as the maximum in the FTP, 23 kW/tonne.[6]

VSP TO ADJUST FLEET EMISSIONS – Jimenez proposed adjusting emissions measured in one driving cycle or remote sensing measurement campaign to another test cycle by reweighting the VSP emission distribution curve.[5] Such a method would be useful to correlate remote sensing measurements made at one site and time with another and also to relate remote sensing measurements with dynamometer inspection tests. Use of this methodology assumes that fleet composition (model year, vehicle type) would not change with changing VSP.

CHICAGO: MEASUREMENTS OVER 3 YEARS

Remote sensing NO measurements in Chicago were analyzed for passenger cars using model year bins and VSP bins.

The emission data included in this analysis had valid HC, CO, and NO measurements, and valid speed and acceleration measurements. The vehicle's VIN showed fuel was not diesel, vehicle type was a CAR, engine size was between 1.5 and 5.5 liters, age was between 1 and 15 years old, and VSP was between –7.5 and +22.5 kW/tonne. This data set gave a relatively homogeneous fleet of vehicles that were measured over three years.

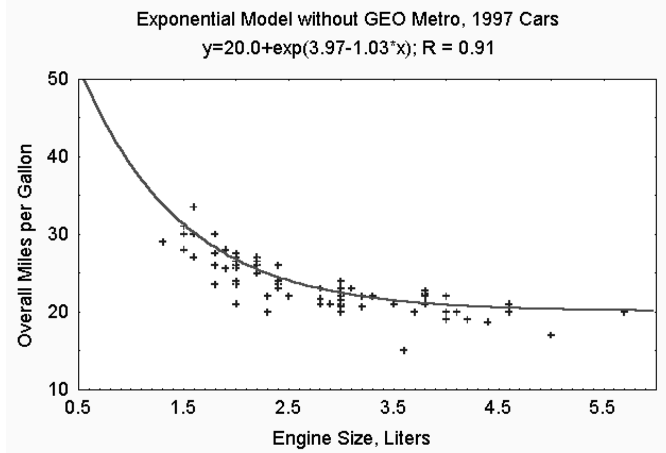
Since cars are designed to meet gram/mile emission standards, the %NO remote sensing data was converted to gram/mile (gpm). Grams per gallon (gpg) is proportional to %NO as measured by remote sensing.[5]

$$\text{gpg NO} = \frac{5900 \times [\%\text{NO}]}{15 + 0.285 \times [\%\text{CO}] + 2.87 \times [\%\text{HC}]}$$

The equation is based upon carbon balance in the fuel and requires the reported %HC to be multiplied by a factor of approximately two[9] to take into account the fact that the NDIR does not measure all typical HC with 100% efficiency.

Engine size was correlated with fuel economy for engines larger than 1.5 liters for 1997.[10] The fuel economy and engine size data were weighted by the frequency with which 1997 vehicle models were seen in 1997 remote sensing. This eliminated some of the vehicle models such as Ferrari's, and gave more weight to popular models. Overall miles per gallon can be related to engine size in liters for vehicles with engine size 1.5 to 5 liters with r^2 equal to 0.83 and is shown in

Figure 3. Correlation of overall miles per gallon with engine size for 1997 passenger cars.



Grams per gallon NO was converted to grams per mile using the following formula,

$$\text{gpm NO} = \frac{[\text{gpg NO}] \times (1 + 2 \times [\%\text{CO}])}{20.0 + e^{(4 + (-1.03) \times [DISP])}}$$

where the term with [%CO] corrects for mpg loss due to incomplete combustion[11] and the engine size in liters, [DISP], converts grams/gallon to miles/gallon for engine sizes between 1.5 and 5 liters.

Increasing vehicle age and increasing VSP up to 20 kW/tonne shows increasing gpm NO, independent of the year measured from 1997 to 1999. Therefore, the three years were combined and were binned into three 5 year age bins (centered at 3, 8, and 13 years) and six VSP bins (centered at –5, 0, 5, 10, 15, and 20 kW/tonne). The larger amount of data obtained by combining the three years allowed for exclusion of all bins containing under 50 vehicles. Since emissions are dominated by a small fraction of broken vehicles, large bin sizes are needed for valid statistics.

Figure 4, a plot of gpm NO versus VSP for the three age bins, shows a nearly linear ramp from VSP bin 0 to VSP bin 15. This can be modeled by an equation,

$$\text{gpm NO} = (0.173 \times [\text{AGEBIN}] - 0.033) \times e^{(0.37 \times [\text{VSPBIN}])}$$

The final model, derived from the data, fits the binned data on a point by point basis with r^2 = 0.91 as shown in Figure 5. The two points at the top of Figure 5, that are lower than predicted by the model, represent the older vehicles at the higher load. This falling off in NO emissions is most likely due to some of the older vehicles running rich at the higher loads. The newer vehicles do not show this break, and continue to follow the model.

Figure 4. Gram per mile NO increases with (VSP) from 0 to 15 kW/tonne for passenger cars binned in three age groups, 0 to 5 years, 6 to 10 years and 11 to 15 years, Chicago, 1997-1999.

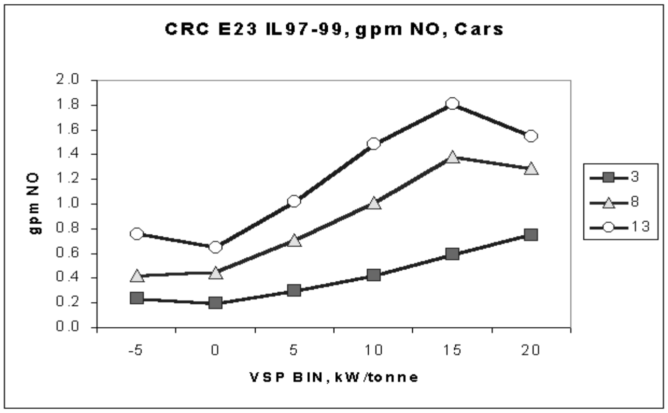
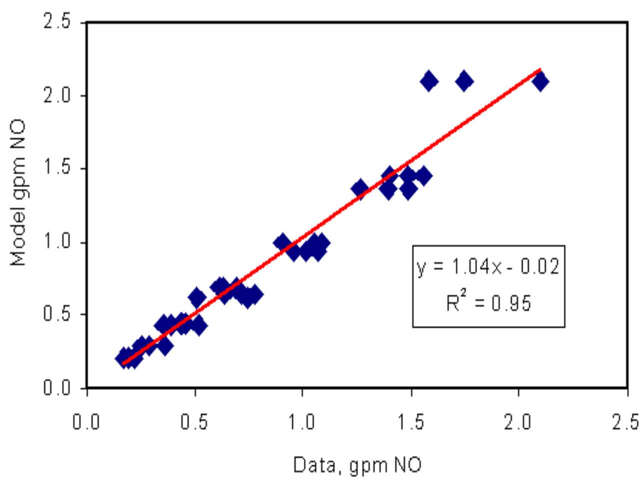


Figure 5. Modeled gpm NO versus data, Chicago 1997, 1998, 1999. Age of cars: 3,8,13 yrs; VSP: 0,5,10,15 kW/tonne.



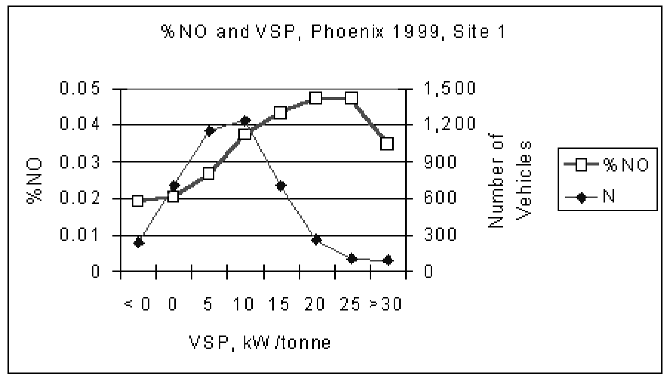
PHOENIX: MEASUREMENT UNDER HIGH LOAD

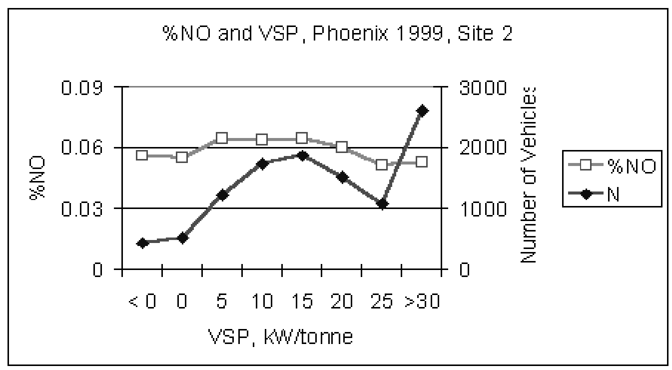
The first two days of the CRC E23 measurements in Phoenix in November 1999 were made while vehicles were slowly cruising on a freeway off ramp about a half minute after leaving the freeway [Site 1]. At this site too many vehicle measurements had invalid readings due to small emission plumes that result from vehicles slowing down to look at the remote sensing equipment, and the lack of any pressing need for motorists to accelerate. On the third day, the equipment was moved up the same ramp to a point near the exit of the ramp on to another freeway [Site 2]. Plume strength improved and invalid measurements decreased, because many of the vehicles were accelerating hard to get on the freeway.

Measurements used in the analysis of Phoenix data include gasoline fueled vehicles with model year 1984 or later and having valid speed, acceleration, NO, HC, and CO remote sensing measurements. The data were binned in VSP bins that were 5 kW/tonne wide. The VSP bins are centered at the bin label so a VSP bin of 20 kW/tonne includes readings from 17.5 to 22.5 kW/tonne. Almost all bins had more than 25 vehicles per bin.

UNUSUAL VSP NITRIC OXIDE RELATIONSHIP - VSP corrected NO emissions at Site 2 did not follow a normal pattern of fleet emissions as a function of VSP. NO emissions were high at both low VSP and high VSP compared to observations at Site 1 as shown in Figure 6. Other E23 sites, Chicago 1997, 1998, 1999, Phoenix 1998, and Los Angeles, 1999, which were not high load sites, all showed NO versus VSP relationships similar to Site 1 in Phoenix 1999.

Figure 6. %NO and number of vehicles (N) as a function of load in Phoenix in 1999 at two different sites.

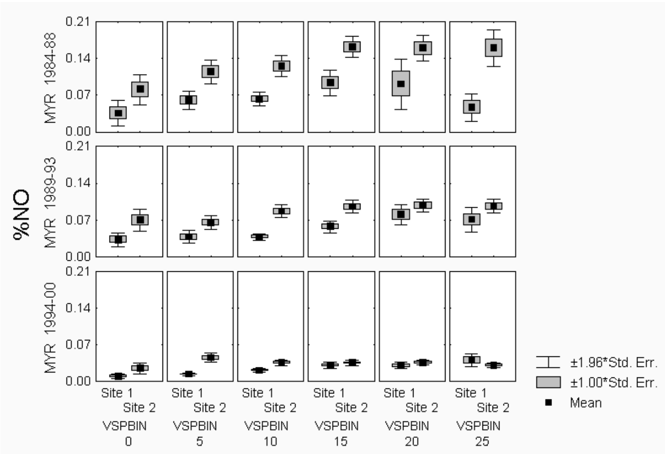




The fleet measured at Site 2 should have been similar to that at Site 1 since the ramp was the same, only the measurement days were different. The model year distributions of the fleet at the two sites were very similar as expected.

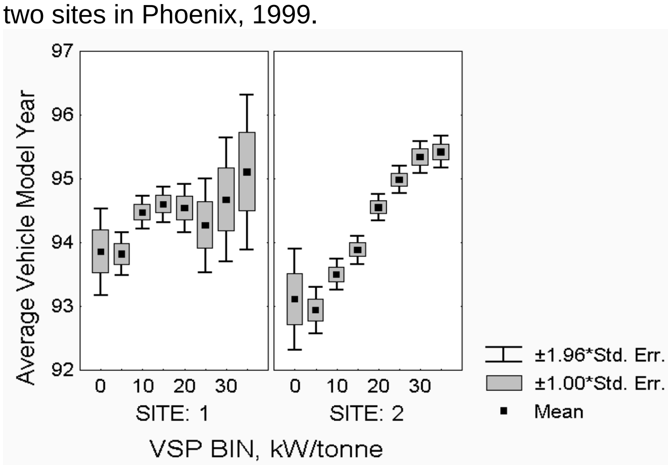
A comparison of %NO versus VSP for different vehicle model year bins is shown in Figure 7. Except for the newer vehicles at higher VSP, all model year groups are higher in Site 2 at all VSP levels. However, for each of the model year groups, the %NO increases with increasing VSP, while for Site 2 in Figure 3 the relationship between %NO and VSP is flat.

Figure 7. %NO by model year bin and VSP bin at two sites in Phoenix, 1999.



SHAPE OF THE %NO VSP CURVE -The %NO VSP behavior for Site 2 could be explained if the fleet composition at Site 2 were a function of VSP. Figures 8 and 9 show that this is the case. The hard acceleration, high load conditions at Site 2 result in concentrating trucks and older vehicles at the low VSP levels, and concentrating cars and newer vehicles at the higher VSP levels. While this trend is also observed at Site 1, the effect at Site 2 is more pronounced, especially for average vehicle model year.

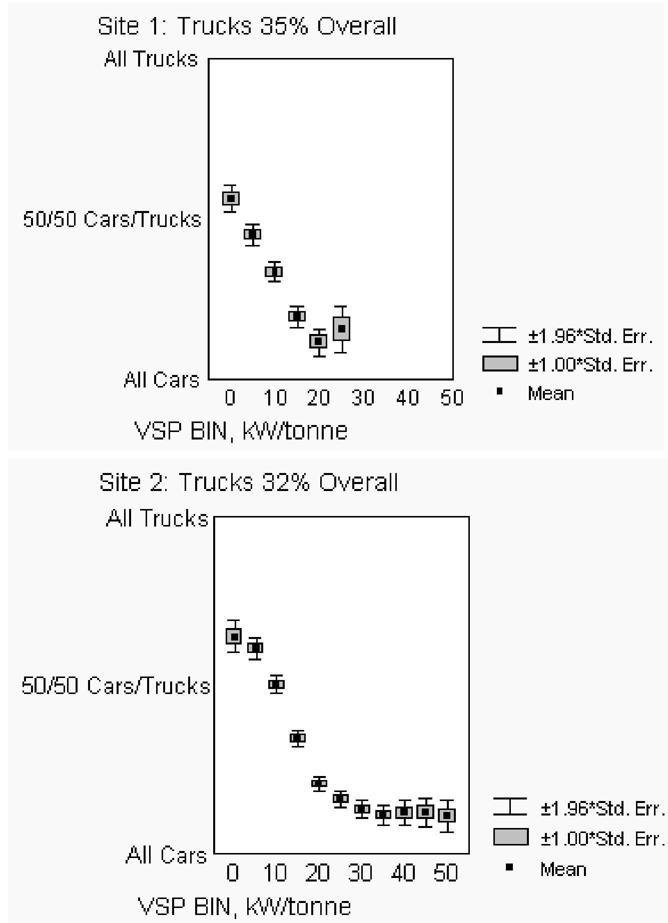
Figure 8. Average model year as a function of load at two sites in Phoenix, 1999.



By concentrating trucks and older vehicles at low VSP levels, and concentrating cars and newer vehicles at high VSP levels, the shape of the %NO emissions versus VSP flattens out. Trucks and older vehicles raise the %NO at low VSP and the cars and newer vehicles drop the %NO at higher VSP relative to what would be seen in the %NO dependence on VSP for individual vehicles.

LEVEL OF %NO AT SITE 2 - While the change in the fleet composition as a function of VSP explains the change in the shape of the %NO and VSP curve, it does not explain the increase in %NO as a function of VSP observed at the high load site.

Figure 9. Percent of Trucks as a function of load in Phoenix in 1999 at two different sites.



In these campaigns speed and acceleration and NO were measured at essentially the same time. Speed and acceleration should be measured where combustion in the engine produces the measured NO coming out of the tailpipe. Measurement of speed and acceleration should be made ~ 5 to 15 meters earlier from where the tailpipe NO is measured. The effect of late speed and acceleration measurement should cause the low load Site 2 NO versus VSP curve to shift left. This was not observed.

If there is a lag in the response of the vehicle to the accelerator pedal being depressed, the engine could be producing more NO, but speed and acceleration have not yet increased. VSP, calculated from the motion of the vehicle, may not yet be in equilibrium with engine conditions, and would be underestimated. This may be part of the explanation for high NO at high and moderate VSP at Site 2.

CONCLUSION

Remote sensing NO measurements can be analyzed quantitatively at moderate load sites. At such sites, fleet gpm NO, binned by vehicle age and vehicle specific power, can be modeled to show the effect of age and load between 0 and 15 kW/tonne VSP. At higher VSP levels, the gpm NO does not increase as rapidly for older vehicles. This is believed due to the onset of commanded fuel enrichment.

At remote sensing sites with many vehicles under loads in excess of those experienced in the FTP, VSP and age alone could not explain measured NO emissions. At these high load sites the fleet composition changes markedly with VSP. Newer cars are concentrated at higher VSP, and older cars and trucks are concentrated at lower VSP. Even after correcting for the fleet change, the NO emissions are higher than expect from the relationship of NO and VSP at low load. This could be due to a lag in the response time of the vehicle to what is taking place in the engine under high load.

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ADDITIONAL SOURCES

Raw data for both sets of measurements are available on the web at www.feat.biochem.du.edu.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

CRC: Coordinating Research Council
EPA: Environmental Protection Agency
FTP: Federal Test Procedure
IR: Infrared
NDIR: Non-Dispersive Infrared
SH: State Highway
UV: Ultraviolet
VIN: Vehicle Identification Number
VSP: Vehicle Specific Power