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Cross Border In-Use Emissions Study For Heavy Duty Vehicles, Nogales, AZ

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Executive Summary

This pilot project was designed to capture data and information related to in-use emissions from commercial trucks crossing the US-Mexico border at Nogales, Arizona. Technologies capable of measuring in-use truck emissions are becoming increasingly important as heavy duty vehicles account for a greater portion of the mobile emissions inventory due to controls on light duty vehicles. The next generation of heavy duty vehicle regulations, which begin in 2007, will necessitate the use of sensitive new emissions control equipment for new vehicles and ultra low sulfur fuel for the entire fleet. The ability to monitor in-use heavy duty vehicle emissions can help ensure that projected benefits are realized, and can help inform the development of potential mitigation/corrective actions.

The US-Mexico border presents a unique opportunity to gather data on in-use truck emissions in an area which is projected to experience explosive growth in heavy duty vehicle traffic over the next several decades. Already, there are 4.5 million truck crossings into the United States from Mexico each year, and emissions from these trucks impact air quality in the border region. Cross border traffic can also impact air quality along interstate trucking routes, which often encompass major metropolitan areas that already experience air pollution concerns or have degraded air quality.

By quantifying emissions from the cross border truck fleet this pilot project will help policy makers in the US and Mexico identify ways to improve emissions inventories along the Nogales border and prepare for the projected increase in truck traffic volume. The project also explored the potential for new emission control strategies such as gross emitter identification for heavy duty vehicles.

Pilot Project Description

The purpose of the pilot was to utilize a suite of existing and emerging technologies capable of measuring in-use truck emissions to characterize emissions at the Nogales border crossing. Data were collected over a four week period during the peak traffic season at the Nogales border crossing. The technologies included Portable Emissions Monitors (PEMs), opacimeters, and the emerging technology of heavy duty remote sensing (HDRSD). PEMs measurements were also compared to HDRSD results as one measure of consistency. A PEMs unit was installed in a subset of 42 trucks and gathered emissions data for hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NOx) while the trucks were operated in service from the border crossing site to their local destination. Opacimeters were used to test the same subset of trucks for total light obscuration (smoke) using the SAE J1667 snap-acceleration procedure. HDRSD measured the instantaneous emissions of HC, CO, NO[1] and fine particulate matter ($PM_{2.5}$) from over 15,000 truck crossings.

The goals of the pilot project were multi-fold; including:

- to provide information on the average in-use emissions levels of a commercial truck fleet crossing the US-Mexico border during the study period

[1] Nitric oxide (NO) is a sub-set of total NOx emissions. For typical diesel vehicles total NOx mass is generally composed of 75% - 90% NO and 10% -25% nitrogen dioxide (NO_2). For all of the trucks tested by PEMS in this project NO represented 80% – 85% of total NOx mass.

- to demonstrate and evaluate the application of HDRSD technology as an emissions screening tool for commercial trucks
- to compare HDRSD emissions measurements with other recognized emission measurement methods, i.e., PEMs and opacimeters
- to identify possible emissions levels for "gross emitter" cut points, and
- perform an initial investigation as to the feasibility and emission reduction benefits of a gross-emitter identification program for heavy duty vehicles using HDRSD

HDRSD as an Emissions Screening Tool

The HDRSD technology performed well as an emissions screening tool, demonstrating the capability to capture emissions and vehicle data snapshots from a large number of trucks in a short time frame. HDRSD recorded emission readings for over 15,000 commercial truck crossings during the three week period, capturing valid exhaust gas measurements for 84% of the trucks passing the sensors, and achieving a combined validity rate (valid gas, valid speed/acceleration, and valid license tag) of 63% in this debut study. These rates are typical of those obtained from light duty RSD operations but should improve in future HDRSD deployments.

For NO and HC there was good general agreement between the average emissions rates (g/gal) calculated for the cross border fleet from the collected HDRSD and PEMs data, both for individual trucks and averages by vehicle vintage. Averages of screened HDRSD readings from a single truck generally matched both total cycle PEMS averages (representing mixed driving), as well as the average of PEMS data from a typical 20-second vehicle acceleration event.

For CO, the HDRSD calculated averages were generally only half the PEMS total cycle averages. This can be explained by the fact that for many of the PEMS-tested trucks much of the total CO mass was emitted in infrequent, short-duration CO "spikes", during which the CO emissions rate was ten times or more higher than during the rest of the drive cycle. In fact, for some of these trucks over 50 percent of total CO mass was emitted in less than 10 percent of driving time. NO and HC emissions did not generally show this type of behavior. For the type of emissions distribution observed for CO, short duration emissions measurements such as those collected by HDRSD are less likely to be representative of average emissions over a longer drive cycle, however, they may still be useful for identifying unusual malfunctions that result in consistently elevated CO emissions. More study with typical CO elevating malfunctions are required to establish the latter. CO emissions are typically low from diesel engines but elevated CO levels may be indicative of elevated PM emissions.[2]

These comparisons between PEMS and HDRSD results are illustrative only since the PEMs sample size was orders of magnitude smaller. Also, PEMS data was collected from only a few of the newest trucks; no meaningful comparisons could be drawn between PEMS and HDRSD results for 1999 and newer vehicles[3].

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[2] R.L. McCormick, et. al., "Quantifying the Emissions Benefits of Opacity Testing and Repair of Heavy Duty Vehicles"; Environ Sci Technol. 2003 Feb 1;37(3):630-7

[3] Recent testing has shown that there is typically also some variance between PEMS measurements and measurements made in an engine test cell with laboratory-grade analyzers. See: D. Carder, et al, "Comparison Study of In-Use Emissions Measurement Systems for Heavy-Duty Diesel Engines", 16th CRC On-road Vehicle Emissions Workshop, San Diego, CA, March 2006.

As with other remote sensing programs, only HDRSD data taken when the vehicle engine was under load (ie. while accelerating) are useful for screening purposes. Deployment strategies that maximize the number of vehicles that are accelerating as they pass the HDRSD equipment will enhance the utility and cost effectiveness of future HDRSD screening programs.

Comparing HDRSD with Other Emissions Testing Technologies

HDRSD is an emerging technology currently undergoing validation studies and comparison studies with more developed testing technologies. One goal of this pilot project was to directly correlate the results from PEMs and HDRSD for CO, NO, and HC.

While the comparisons of PEMS and HDRSD fleet averages discussed above provide preliminary evidence that the two technologies can give the same value for average emissions rates from individual trucks and truck groupings, the data used for comparison was not collected at the same point in time. PEMS data was collected from each truck over a 20-40 minute period, while multiple HDRSD readings were taken from the same and other trucks over a four-week period.

In order to complete a more direct comparison between the technologies a supplemental data set was compiled using four trucks of varying ages equipped with PEMs and passing through the HDRSD equipment multiple times. This experiment yielded a data set of matched pairs of emissions measurements taken by each technology from the same truck at the same time. Once time alignment issues were addressed this data set was used to make direct correlations between PEMS and HDRSD for each pollutant.

The correlations showed very good agreement between the HDRSD and PEMs measurements of NO and CO, but no correlation between HDRSD and PEMS measurements for HC was shown in this experiment. However, both PEMS and HDRSD consistently measured HC emissions from all four tested trucks as being very low.

Give the limited range of NO, CO and HC emissions rates in the data set, additional correlation work is merited, using a set of trucks with a wider range of emissions rates, to more fully evaluate the exact range over which HDRSD measurements for NO, CO, and HC are accurate, and how this would effect high emitter identification.

No correlation was possible for the HDRSD particulate (smoke factor) measurements in this study since PEMs does not measure particulate emissions[4].

A comparison was also made between the HDRSD-measured smoke factor and exhaust opacity as measured with a traditional opacimeter using the SAE J1667 snap-acceleration procedure.[5] This analysis was not a direct correlation since the measurements with each technology were not made at the same time. This analysis was akin to the general comparison of fleet averages for NO, HC, and CO discussed above.

[4] Other on-going projects are attempting to correlate HDRSD smoke factor measurements against PM mass measurements made using other technologies, including a study comparing results from a Tapered Element Oscillating Microbalance (TEOM) taken during testing with vehicles mounted on a chassis dynamometer.

[5] Oge, M.T.; “Guidance to States on Smoke Opacity Cutpoints to be used with the SAE J1667 In-use Smoke Opacity Test Procedure”, US Environmental Protection Agency, February, 1999.

The HDRSD particulate measurement is based on total light obscuration at a narrow frequency band, similar to traditional opacity testing, but because HDRSD also measures the concentrations of the major carbon-containing combustion products in the exhaust (CO_2, CO, HC) these can be used to calculate a "smoke factor" that is theoretically proportional to the fuel-specific PM mass emissions rate of the engine (i.e. PM mass per unit of fuel burned). By contrast, measurement of exhaust opacity with a traditional opacimeter yields an absolute measurement that does not account for exhaust dilution, flow rate, fuel input, or engine activity.

Traditional opacimeters use green (or red) light wavelengths to measure the amount of light obscured by particles in the vehicle exhaust. The finest particles produced by diesel engines are much smaller than green light wavelengths and therefore generally do not obscure the light beam (ie. are not detected by the opacimeter). The HDRSD technology uses a shorter ultraviolet wavelength. Opacity measurements using this shorter wavelength are much more sensitive to the smaller particles than those of the longer wavelength used in a traditional opacimeters.

In addition, properly screened HDRSD data can yield information on PM emissions rates while the engine is under load, when diesels are known to produce the most PM mass. By comparison, the SAE J1667 procedure used for traditional opacity testing uses engine inertial load, which varies depending on how the driver revs the engine.

Despite the fact that traditional opacity testing is currently used to flag high emitters in a number of heavy-duty vehicle I/M programs, a direct relationship between opacity and PM mass emission rates has not been demonstrated. For this reason, a strong relationship between traditional opacity measurements and HDRSD-measured smoke factor was not expected, and none was seen.

Additional correlation work is merited, using a set of trucks with a wider range of PM emissions rates, to evaluate the relationship between HDRSD smoke factor measurements and traditional gravimetric PM measurements.

Characteristics of the Cross Border Truck Fleet at Nogales

The tested fleet was composed of mainly Mexican trucks, which were likely to cross the border only once per week during the data collection period. The Mexican fleet had the highest number of new (post-2002) vehicles (12 percent versus one percent of US trucks). The dual-plated fleet, which is a short-haul drayage fleet captive to the border region, though smaller in number made the greatest number of trips per vehicle during the program deployment, with each truck typically crossing the border almost once a day. While much smaller, the dual plated fleet made almost as many total trips during the study period as the Mexican fleet (41percent of the total). The US fleet was the smallest, and only accounted for 10 percent of total trucks and 14 percent of total trips. Approximately 95 percent of the trucks that crossed the border during the study period were large, Class 8 trucks.

Please note that this study examined a border crossing with significant seasonal variation in total truck traffic, and collected data during the peak traffic season. The type and distribution of vehicles seen in this study may not be representative of year round traffic at Nogales, and may not be representative of truck traffic at other border crossings.

Average In-Use Emissions of Cross Border Trucks at Nogales

All three technologies were used to examine average in-use emissions levels of the cross border commercial truck fleet at Nogales. The emissions profiles showed that NO emissions were

relatively flat through vintage year 2002, after which they were marginally lower – but not as low as would be expected based on EPA certification standards (2.5 g/bhp-hr for trucks built after 2002 compared to 4.0 or 5.0 g/bhp-hr for older trucks). The average NO emissions rates hovered around 100 grams/gallon.[6] There were relatively few US-plated post-2002 trucks in the tested fleet. The majority of post-2002 trucks were Mexican-plated; the Mexican NOx standards did not drop in 2002 in parallel with US standards.

Both HC and smoke emissions from post-1992 trucks were lower than from earlier vintage year trucks. Trucks manufactured before 1993 had average emission rates of 15-30 grams/gallon HC, while trucks manufactured after 1992 averaged around 10 grams/gallon HC –approximately half the emissions levels for older trucks. Smoke (fine particle) emission rates in trucks manufactured before 1993 averaged around 12 grams/gallon, and average smoke emission rates dropped to half this level for post-1992 trucks.

Overall, there were few clear emissions distinctions between the US, Mexican, and dual plated fleets of any vintage, with the exception of CO emission rates, which appear higher for US trucks manufactured after 1992 .

Identifying Potential Gross Emitting Vehicles

The HDRSD technology flagged a number of potential gross emitters of HC, CO, NO and PM emissions by identifying individual vehicles with emissions rates significantly higher than those from the rest of the fleet. These potential gross emitters included US, Mexican and dual plated trucks. As with light-duty remote sensing programs, only trucks that had crossed the border multiple times with multiple valid HDRSD measurements were analyzed, in order to add greater certainty to HDRSD identification of gross emitters.

Year	Emission Standards for New Heavy-Duty Diesel Engines (g/bhp-hr)							
	CO		HC		NOx		PM	
	Mexican	US	Mexican	US	Mexican	US	Mexican	US
1988	No standards	15.5	No standards	1.3	No standards	10.7	No standards	0.60
1990		15.5		1.3		6.0		0.60
1991		15.5		1.3		5.0		0.25
1993	15.5	15.5	1.3	1.3	5.0	5.0	0.25	0.25
1994	15.5	15.5	1.3	1.3	5.0	5.0	0.10	0.10
1998	15.5	15.5	1.3	1.3	4.0	4.0	0.10	0.10
2002	15.5	15.5	1.3	1.3	4.0	2.5	0.10	0.10

Table ES.1 US and Mexican New Engine Emission Standards

In this pilot, for discussion purposes, a truck was considered a potential 'gross emitter' if its fuel specific emissions rates were consistently greater than the majority of tested trucks. The cut

[6] Assuming that diesel fuel has an energy content of approximately 128,000 btu per gallon, and assuming average diesel engine efficiency of 33%, burning a gallon of fuel in a diesel engine will produce approximately 16.6 bhp-hr. Therefore, to calculate approximate brake-specific emissions rates (g/bhp-hr) the g/gallon rates can be divided by 16.6. In-use g/bhp-hr results are not, however, expected to exactly match EPA certification standards due to likely differences between the EPA certification test cycle and in-use duty cycles.

points were selected using dual criteria; 1) examination of the point in the distribution curve where emissions clearly increased, and 2) examination of applicable engine certification standards.

As shown in Table ES.1, for NO_x, the US certification standard in the late 1980's was 10.7 grams per brake horse power hour (g/bhp-hr), while Mexican trucks were unregulated. This standard was subsequently was reduced to 5 g/bhp-hr in the mid-1990s and then to 4 g/bhp-hr in the late-1990s for both US and Mexican trucks. In 2002 the US reduction to 2.5 g/bhp-hr NOx was not matched by the Mexican emissions standards. HC and CO standards were 15.5 g/bhp-hr and 1.3 g/bhp-hr, respectively and remained so through the 1990's. The standard for PM for most of the trucks tested in this project was either 0.6 g/bhp-hr or 0.25 g/bhp-hr. For both US and Mexican trucks the PM standard was reduced to 0.1 g/bhp-hr beginning in the 1994 model year, but relatively few of the tested trucks were newer than 1994.

In many cases, the preliminary cut points chosen by evaluating the emissions distribution curves are more than two times the expected rate based on the relevant certification standard.

Much more data needs to be collected and analyzed to verify the accuracy of HDRSD measurements and to determine emissions levels that would indicate that a truck of a specific vintage was a high emitter in need of maintenance. If a State were interested in adopting a gross emitter identification and repair program as an emission control strategy, agreements would need to be reached with authorities on exactly what emissions levels would be appropriate as gross emitter cut points. Nonetheless, the preliminary cut points chosen after review of HDRSD data collected in this pilot project yielded the following results:

- Using a cut point of 20 grams/gallon (~ 1.2 g/bhp hr) for PM, HDRSD found that 13 percent of trucks could be considered potential gross emitters and they were responsible for 40 percent of particulate emissions.
- Using a cut point of 144 grams/gallon[7] for NO, HDRSD found that 10 percent of the trucks could be considered potential gross emitters and they were responsible for 19 percent of the NO emissions.
- Using a cut point of 44 grams/gallon (~ 2.6 g/bhp hr) for HC, HDRSD found that 3 percent of the trucks could be considered potential gross emitters and they were responsible for 12 percent of the total HC emissions.
- Using a cut point of 258grams/gallon (~15.5 g/bhp hr) for CO, HDRSD found that 1.5 percent of the cross border fleet could be considered potential gross emitters and they were responsible for12 percent of the total CO emissions. While this is equivalent to the current certification standard, this standard is very lenient and well functioning diesel engines never approach this level of CO emissions. If a cut point of twice the standard was used (516 g/gal) none of the border trucks would be considered a gross emitter.

The PEMs unit identified a few older vehicles with high HC emissions, but determining whether these should be considered gross emitters is complicated by the fact that there were no HC emissions standards in place when they were built. PEMS did not identify any potential gross emitters for CO or NOx. The sample size of 27 vehicles was almost two orders of magnitude

[7] A cut point of 144 g/gal NO is equivalent to approximately 10.7 g/bhp-hr of NO. This is also equivalent to approximately 11.9 – 14.3 g/bhp-hr of NO_X , since NO_X emissions from a diesel engine are generally 75% - 90% NO.

smaller than the sample of HDRSD-tested vehicles analyzed for gross emissions. Given the small sample size it would not be expected to fully represent the entire border fleet.

Two of the 40 vehicles tested for opacity had average opacity levels that exceed the cut points used in most current diesel I/M programs (40% opacity for post-1991 vehicles). Some individual vehicles exhibited a wide spread in the measured opacity values of individual snap acceleration tests.

Feasibility and Potential Emissions Reductions from a Gross-Emitter Identification Program

With regard to the physical and operational feasibility of a gross emitter identification program for heavy duty vehicles at a border crossing, this project demonstrated that HDRSD is very promising as an emissions screening tool. During the pilot project every northbound truck leaving the border compound was screened by HDRSD. Valid gas measurements were obtained from 84 percent of these trucks. The HDRSD set-up did not delay any trucks, or cause any back-ups within the compound. A road-side emissions screening program for trucks using HDRSD technology would be one way to identify gross emitters without adding further delay at already congested border sites.

To date, most applications of remote sensing emissions measurement have targeted light-duty vehicles (cars, light trucks). This study has demonstrated that remote measurement of exhaust emissions from heavy-duty trucks, while possible and promising, is more challenging given the physical design and operating characteristics of trucks compared to cars. Relevant issues include high- versus low-mounted exhaust and its effect on mounting of the HDRSD equipment, as well as the need to avoid HDRSD measurements during transmission shifts (which are more frequent during low-speed acceleration for trucks than for cars).

The siting and set-up of HDRSD must be carefully planned to maximize data collection efficiency, and in many cases it will almost certainly be necessary to collect multiple HDRSD readings from the same truck to identify gross emitters, not unlike light-duty vehicles. The Nogales border site proved to be ideal for collecting multiple HDRSD readings, but less ideal with respect to consistently measuring trucks that were accelerating, and avoiding transmission shift points during data collection. Not all truck corridors will have the same characteristics, and additional work is required to evaluate the best HDRSD deployment and set-up strategies for a variety of situations.

Despite these limitations, this pilot project indicated the potential for large emissions reduction benefits from a gross emitter identification program. Specifically, the HDRSD results indicate that:

- 50 percent of CO emissions are produced by less than 20 percent of vehicles;
- 40 percent of HC emissions are produced by less than 20 percent of vehicles;
- 40 percent of NO emissions are produced by less than 25 percent of vehicles, and
- 50 percent of smoke emissions are produced by 20 percent of vehicles.

These numbers suggest that a gross emitter screening program might be an effective emission control strategy at the Nogales border, since a relatively small number of the vehicles are responsible for emitting a sizable portion of the emissions. Repair of identified gross emitting

vehicles is likely to reduce their emissions, though the actual utility of such a strategy must be verified by follow-up studies which further evaluate vehicles flagged by HDRSD to confirm their emissions levels and the effect of repair actions.

It should also be noted that while there appear to be few technical or physical barriers to such a gross emitter screening program there are significant institutional issues that would need to be worked out. For light duty vehicles RSD is sometimes used to screen for gross emitters – which are then verified by a more traditional I/M testing method (ie. ASM tail pipe testing) before imposing enforcement.

For heavy-duty vehicles the only method currently used to identify gross emitters in state or local I/M programs is traditional opacity testing with the SAEJ1667 procedure. Because no correlation between HDRSD smoke factor and opacity was expected or demonstrated in this project it would not be possible or meaningful to screen using HDRSD and then verify using opacity testing. As such, the ability to integrate HDRSD directly into existing I/M programs is limited at this time without changes. The technical and legal framework required to use HDRSD as a stand-alone method to "verify" gross emitters for enforcement purposes would need to be developed before this tool could be fully deployed.

In the interim HDRSD could potentially be used as a screening tool as part of an existing I/M program, with vehicles identified as high emitters inspected for tampering. Delays for such inspections might provide some incentive for vehicle operators to perform repairs, even without the potential for a fine.

Section I. Introduction

This pilot project report presents estimates and comparisons of in-use emissions from cross border trucks using three distinct technologies. The results characterize average in-use truck emissions at the US-Mexico border crossing at Nogales, Arizona during the peak trade season at that crossing. Emissions estimates from emerging technologies are compared with those from EPA-recognized technologies. The report discusses and quantifies potential benefits of using emissions screening tools to identify gross emitting heavy duty vehicles along the border.

The pilot project included input from the Arizona Department of Environmental Quality (AZDEQ), Environmental Systems Products (ESP), the United States Environmental Protection Agency (EPA) and Michael Bradley & Associates. It was funded through a cost share agreement between EPA, ESP, and AZDEQ.

I.A Pilot Project Overview

The project team designed the pilot project to simultaneously explore the dual issues of measuring in-use emissions from individual heavy duty trucks and quantifying the total emissions inventory from cross border truck traffic along the US-Mexico border. The objectives of the project were to examine the use of existing and new technologies capable of measuring in-use truck emissions and to begin quantifying average in-use emissions levels of the cross border truck fleet for key pollutants. Three technologies were used including portable emissions monitors (PEMs), opacimeters, and heavy duty remote sensing (HDRSD). PEMs and opacimeters are well known technologies used to measure truck emissions. PEMs are installed in the truck and measure emissions of hydrocarbons (HC), oxides of nitrogen (NOx), carbon monoxide (CO), and carbon dioxide (CO2) as well as exhaust flow, fuel consumption, and other engine data, while trucks are operated in actual or simulated service. After trucks were pulled over, opacimeters were used to measure the truck's exhaust opacity. These devices are currently employed at border sites in California to evaluate incoming trucks. HDRSD is an emerging technology that measures instantaneous emissions of HC, NO, CO and fine particles from trucks as they pass a stationary sensor. More details of these technologies are offered in Section III, Pilot Project Description. The pilot project used all three of these technologies in estimating emissions from the cross border truck fleet at the Nogales border crossing.

The goals of the pilot project were multi-fold; including:

- to demonstrate and evaluate the application of HDRSD technology as an emissions screening tool for commercial trucks
- to compare HDRSD emissions measurements with results from other recognized emission measurement methods, i.e., PEMs and opacimeters
- to provide information on the average in-use emissions levels of the commercial truck fleets crossing the US-Mexico border during the study period
- to identify possible emissions levels for "gross emitter" cut points, and
- to investigate the feasibility and estimate emission reduction benefits of a gross-emitter identification program for heavy duty vehicles using HDRSD

On March 11, officials from the EPA, Mexico's Environment Ministry (SEMARNAT), the Arizona Department of Environmental Quality, and ESP launched the pilot project with a half-day demonstration of heavy duty remote sensing, portable emissions monitors, and opacimeters at the Nogales test site. The attendees included: environmental and non-profit groups, business groups, and State air quality officials from the US and Mexico. The participants viewed each of the technologies in action and had the opportunity to ask questions.

I.B Project Advisory Panel

A small group of professionals with relevant experience were asked to serve as an Advisory Panel for this pilot project. The Advisory Panel, composed of the following members, reviewed and commented on the analyses and draft report:

- Nancy Wrona is the Director of the Air Quality Division for the Arizona Department of Environmental Quality. In additional to setting direction for this project, Ms. Wrona also participates in the Advisory Panel.
- Mario Molina is a Nobel Lauriat in atmospheric chemistry. Dr. Molina participates in many air pollution studies in and around Mexico and is currently at the University of California in San Diego.
- Mike Walsh is an international expert in transportation and air quality. He was the director of EPA's OTAQ office and currently advises many developing countries on their efforts to reduce transportation sector emissions.
- Darryl Gaslan works on border emissions testing with the California Air Resources Board (CARB).
- Merrylin Zaw-Mon is the Director of the Transportation and Regional Programs Division in EPA's Office of Transportation and Air Quality.
- Enrique Rebolledo of SEMARNAT (the environment ministry in Mexico) and Leonora Rojas Bracho of Mexico's National Ecology Institute.

I.C Why Explore In-Use Emissions from Heavy Duty Engines?

Light duty vehicles have made many technological advances over the last 30 years, leaving diesel engines responsible for a growing portion of mobile source emissions. For example, in California heavy duty vehicles represent only 2 percent of the vehicle fleet but contribute about 30 percent of the nitrogen oxides and 65 percent of the particulate emissions from motor vehicles.[8] Diesel exhaust emissions contribute to ground-level ozone (smog), fine particulate pollution, and air toxics inventories, which are believed to be carcinogenic. Strategies to clean up diesel exhaust are well underway, with EPA's more stringent emission standards for new diesel engines and requirements for low sulfur diesel fuel set to phase-in in late 2006 and 2007. Existing diesel engines will last for several decades and many may be retrofit to reduce emissions. With all of these strategies falling into place the need to monitor emissions from in-use diesel engines is growing, to ensure that emission reduction strategies are performing as expected and to allow additional mitigation measures to be put in place in a timely manner.

For a conventional diesel engine without emission control after treatment - engines built prior to implementation of the 2007 standards - excess emissions related to engine malfunctions can be

[8] California Air Resources Board, 2004 (http://www.arb.ca.gov/msprog/hdvip/hdvip.htm see pampl1-4.pdf)

substantial. HDRSD data collected during this deployment suggests the existence of a limited number of trucks with emissions levels 2-3 times those from the majority of trucks in the fleet.

In 2007 and 2010 US emission standards for diesel engines will require that engines be fitted with exhaust after treatment technologies for PM and NOx respectively, in order to reduce emissions of each pollutant by about 90 percent. For these future vehicles malfunctions of either the engine or the emission control technology could potentially result in an order of magnitude increase in emissions (i.e. >10x, 1000%). At that time the need to identify and repair gross emitting diesel vehicles will be even greater.

I.D Cross Border Truck Emissions and Border Air Quality Challenges

Air quality along the 2,000 mile US-Mexico border is poor in many locations, potentially affecting the more than 10 million US and Mexican border residents. Recent studies of air quality at congested US-Mexico border crossings indicate that cross-border vehicle emissions have contributed to severe air pollution problems.[9] Over four million trucks enter the United States each year from Mexico, and cross border trucking volumes are projected to rise significantly over the coming years.[10] As the US prepares to fully implement the NAFTA trade agreement by processing applications from Mexican carriers to operate on US highways, there is an expectation that Mexico will begin allowing US trucks on Mexican highways as well. As a result, both the volume and nature of cross border commercial truck traffic are expected to change. Air quality will potentially be impacted by emissions from the increased truck traffic in both countries, and could place additional demands on the resources border states allocate towards meeting air quality standards. Technology capable of capturing in-use emissions data from commercial trucks will be a helpful tool for quantifying the emissions impacts of cross-border commercial truck traffic on the southern border States. Officials from the United States and Mexico are turning more attention to the question of how to better quantify the impact of car and truck emissions on local air quality and the identification of measures to reduce those emissions.

The remainder of this report provides background on air quality and truck traffic along the US-Mexico border and describes the pilot project design and data collection process. The analytical and statistical results of the project are presented in Sections IV through VII From the data that were collected and analyzed, several policy-related observations were made. These are offered in Sections VIII and IX. Acknowledgements of the many of people who helped make this project possible are offered in the last section.

[9] Council on Environmental Cooperation, 2004 (http://www.cec.org/pubs_docs/documents/index.cfm?varlan=english&ID=1403, see report on air quality at congested border crossings)
[10] Sierra Research, 2001

Section II. Border Air Quality and Cross Border Truck Traffic

II.A Air Quality along the US-Mexico Border

Air quality issues vary along the 2,000 mile stretch of the US-Mexico border. The border region has many bi-national air basins where pollution mixes and stagnates from sources on both sides of the border. We will look at the US air quality as a proxy for the border area. This section examines the status of border counties in terms of EPA's National Ambient Air Quality Standards (NAAQS) which have been set for the following six criteria pollutants: ozone, particulates, carbon monoxide, nitrogen dioxide, sulfur dioxide and lead.

Ozone is a secondary pollutant, formed in the atmosphere when adequate levels of volatile organic compounds, oxides of nitrogen and sunlight are present. There are many sources of NO_x that contribute to ozone formation. Emissions from diesel engines are among the most significant sources – particularly in California. In the case of ozone air pollution, border air quality appears to be most impaired along the California border. The largest California border crossing, Otay Mesa is in San Diego County, which has been classified as "basic" nonattainment for EPA's revised 8-hour ozone standard[11]. California's other major border crossing, at Calexico in Imperial County, is in marginal nonattainment for ozone. Texas and Arizona also have nonattainment areas for ozone; however, these areas are not located along the US-Mexico border. El Paso, which is on the Texas-Mexico border was considered in nonattainment for EPA's previous 1-hour ozone standard.

Particulate concentrations have two ambient standards. EPA's original PM_{10} standard, which is a measure of coarse particles, and EPA's newly revised $PM_{2.5}$ standard, which is a measure of fine particles. $PM_{2.5}$ particles are thought to penetrate deeper in lung tissue. Both size ranges of particulate can be harmful to the respiratory system. Emissions from diesel engines are known to contribute significantly to elevated $PM_{2.5}$ concentrations. Since by definition PM_{10} includes all particles smaller than 10 microns, diesel PM contributes to both $PM_{2.5}$ and PM_{10}, with most diesel particulate smaller that 1 micron. All major border crossing cities, including San Diego CA, Calexico CA, Laredo TX, El Paso TX and Nogales AZ are in attainment for fine particles[12]. However, many nonattainment areas for PM_{10} exist along the border – including the border of the State of New Mexico, El Paso, TX, and Nogales, AZ[13]. Elevated PM_{10} concentrations in the border area are commonly linked to unpaved roads and agricultural sources. The El Paso area in Texas also fails to meet the NAAQS for carbon monoxide (CO) as well. According to EPA, 77 percent of the nationwide CO emissions are from transportation sources, the largest emissions contribution comes from highway motor vehicles[14]. Other major CO sources are wood-burning stoves, incinerators and industrial sources.

Data obtained in the mid-1990's in San Diego County, CA gives some indication of the impact of emissions from heavy duty diesel engines on air quality around the Otay Mesa border crossing in that County. This data shows that diesel burning trucks accounted for only 4 percent of the total VMT and 0.8 percent of the total vehicles in San Diego County, yet they accounted for 80 percent

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[11] Information obtained from EPA's website: http://www.epa.gov/ozonedesignations/regions/region9desig.htm
[12] Information obtained from EPA's website: http://www.epa.gov/air/oaqps/greenbk/qnay.html
[13] Information obtained from EPA's website: http://www.epa.gov/air/oaqps/greenbk/mappm10.html
[14] Information obtained from EPA's website: http://www.epa.gov/oar/oaqps/greenbk/o3co.html#Carbon%20Monoxide

of the PM_{10} and 25 percent of the NO_x emissions[15]. Such a significant contribution is of great interest to policy makers tasked with attaining and maintaining air quality standards.

II.B Air Quality in Nogales

Nogales, Arizona is in attainment with all of EPA's national ambient air quality standards, with the exception of PM_{10}. Despite the moderate nonattainment status with PM_{10}, Nogales is in attainment with EPA's new $PM_{2.5}$ standards. The Arizona Department of Environmental Quality (ADEQ) and Mexico's then Secretaria de Medio Ambiente, Recursos Naturales y Pesca (SEMARNAP) conducted a study from 1994 to 1998 to address air quality concerns in Nogales, Arizona and its sister city south of the border, Nogales, Sonora. This study addressed hazardous air pollutants (HAPs) and PM_{10}. The study found that the air quality on the southern side of the border was generally more degraded than on the northern side with respect to HAPs and particulates. HAPs emissions in Nogales, Sonora were higher than in Nogales, Arizona due to the many industrial sources, higher motor vehicle traffic density, and larger population. Most of the HAPs emissions were from areas sources, except for HAPs originating from solvent use and soldering operations at the maquiladoras in Nogales, Sonora[16].

PM_{10} emissions were also higher in Nogales, Sonora than in Nogales, Arizona, due mainly to emissions from entrained paved and unpaved road dust. The PM_{10} emissions in Nogales, Sonora were six times greater than in Nogales, Arizona. Although, Nogales, Sonora has 66 percent of the vehicle miles traveled compared to Nogales, Arizona, its PM_{10} emissions are higher due to a higher percentage of vehicle traffic that occurs on unpaved roads, and, to a lesser extent, a higher percentage of vehicle traffic on dustier paved roads[1]. Throughout Arizona, PM_{10} concentrations have declined since 1985. Road paving and better industrial dust controls are responsible for most of the improvement.

II.C Trends in US-Mexico Truck Crossing Volumes

Through the year 2000, the volume of trucks entering the United States from Mexico steadily increased after passage of the North American Free Trade Agreement (NAFTA) in 1994. The total annual incoming truck volume on the US side of the border in 1994 was just over 2.5 million. The volume increased to over 4.5 million by the year 2000. The year 2001 marked the first year annual incoming truck volumes declined slightly since the signing of NAFTA. This trend is illustrated in Figure 2.1 which presents total annual incoming truck crossing volumes on the US side of the US-Mexico border.

Trends at the Nogales border crossing have largely mirrored those across the entire border region – with peak volumes recorded in the years 1999 and 2000 and a slight decline in 2001 and 2002.

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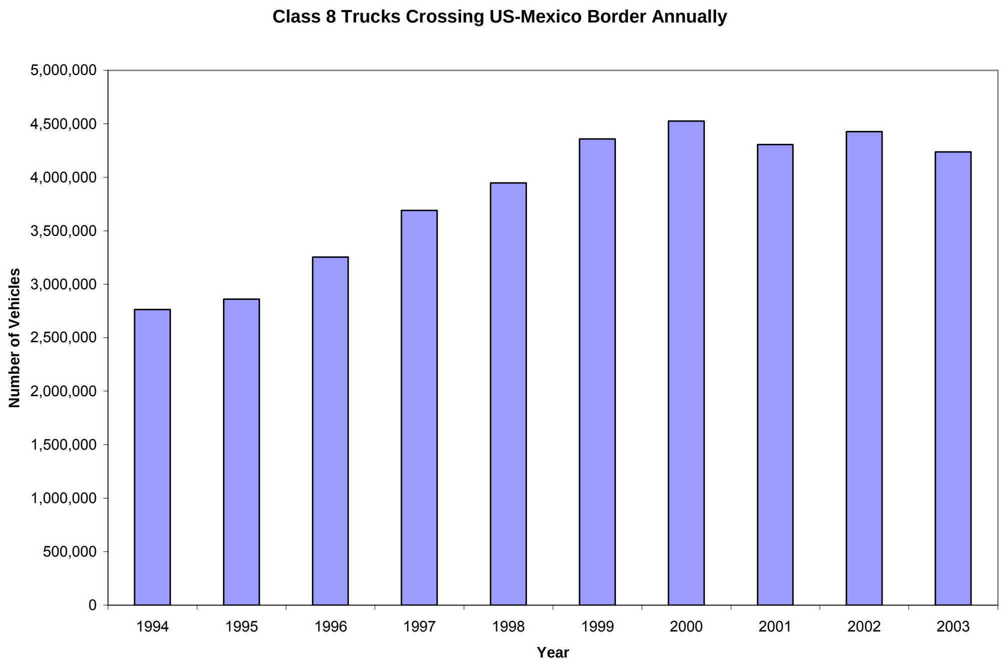
[15] Emissions from Heavy-Duty Trucks at the San Diego Tijuana Border Crossing, Camilla Kazimi et. al., Department of Economics, San Diego State University. 1998. Available at: http://www-rohan.sdsu.edu/dept/physics/CES_Res_3/truck4.html

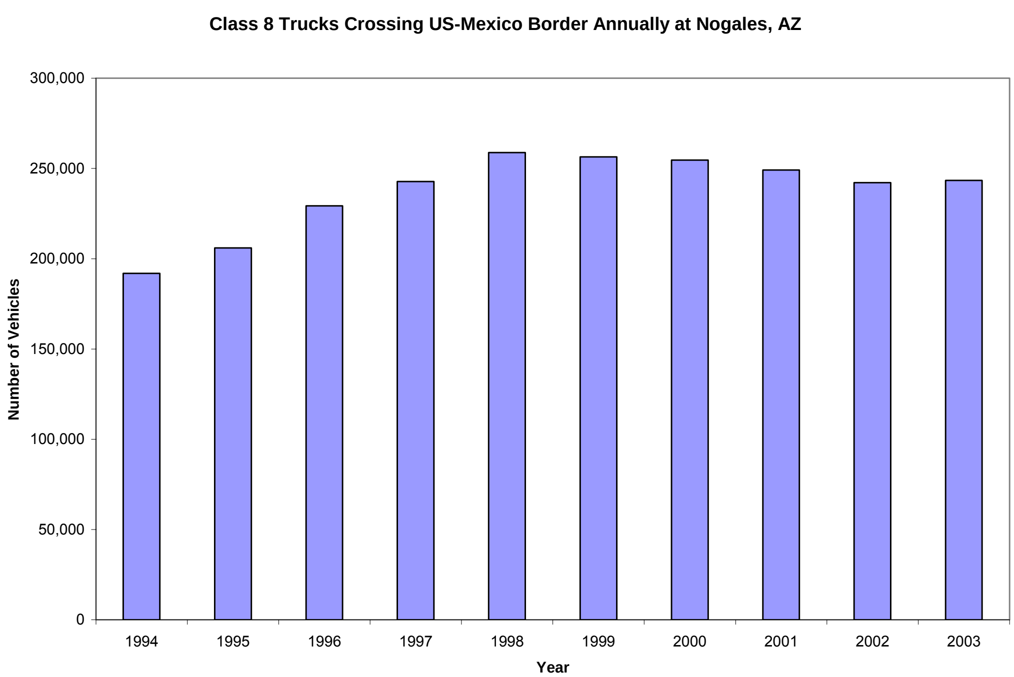
[16] *Ambos Nogales Hazardous Air Pollution And Particulate Matter Study Executive Summary.* Prepared for ADEQ by Steven L. Heisler, Lisa Bradley, Howard Balentine, and Marcus Garcia, ENSR. June 1999.

Annual traffic volume for the Nogales Port is presented in Figure 2.2. Unlike the broader border pattern, traffic volumes in 2003 were up slightly from 2002.



Source: Bureau of Transportation Statistics

Figure 2.1 Truck Crossing Volume Trends at the US-Mexico Border

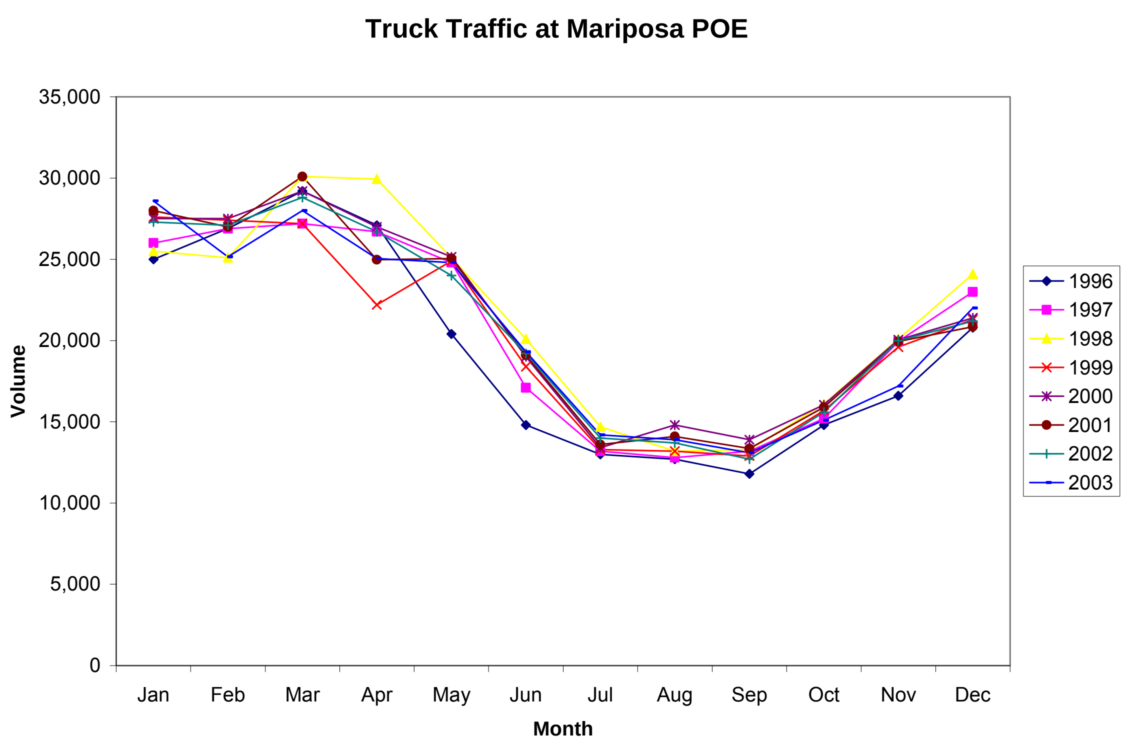


Source: Bureau of Transportation Statistics

Figure 2.2 Truck Crossing Volume Trends at the Nogales Border Crossing

Figure 2.3 shows a monthly break down of truck crossing traffic through the Mariposa Port of Entry at Nogales. Annually, about 250,000 trucks enter through the Nogales port. Commercial cargo crossing the Nogales port-of-entry is composed mainly of fresh produce and maquiladora products. Agricultural trade passing through the Nogales border surges in the winter months from January through April (see Figure 2.3). Peak traffic typically occurs in February and March. According to border officials, commercial truck volumes of as high as 1,400 incoming trucks per day are common during February and March. The March timeframe was selected as the ideal timeframe to conduct the pilot project – to capitalize on the increased truck traffic volumes.

Note that the data shown in Figures 2.1 – 2.3 are the number of truck crossings. At Nogales, and likely at other crossing points, some individual trucks make more than one crossing per month or per year. Within any given time period the number of unique trucks crossing the border is therefore less than the number of total crossings.



Source: Mariposa Port of Entry, Nogales Arizona

Figure 2.3 Seasonal Truck Traffic Trends at Nogales, Arizona

Mexico is the second largest single-country trading partner with the United States and has been among the fastest growing major export markets for goods. Most projections of future cross border truck traffic anticipate significant increases over the next decade. Some projections were buoyed by the NAFTA provision to lift the restrictions on Mexican domiciled trucks traveling throughout the US highway system. While major legal barriers for Mexican carriers to access US highways have been cleared, some issues remain under discussion between the US and Mexico. Many States and environmental groups have voiced concern over emissions and safety of heavy

duty diesel vehicles, and the likelihood that cross border commercial truck traffic will rise considerably over the next decade.

II.D Need for Tools to Quantify Emissions from Heavy Duty Engines

Strategies to clean up diesel exhaust are well underway with EPA's emission standards for new diesel engines in place and set to begin phase-in starting with the 2007 model year, and reduced diesel fuel sulfur levels which will begin phase-in in late 2006. Mexico has recently signaled that it will follow suit with commensurate controls on heavy duty diesel engines.

Existing diesels will last for several decades and may have to be retrofitted with oxidation catalysts and particle filters to reduce emissions. Diesel particulate filters (DPFs) are particularly effective and capable of eliminating up to 90 percent of $PM_{2.5}$ emissions. However, this technology is quite sensitive to fuel sulfur levels and engine exhaust temperatures. Using fuel with higher sulfur content can result in excess PM emissions, as well as masking and damaging the catalytic functions of the filter, eventually leading to filter plugging with accumulated carbon (since sulfur-based molecules provide a good base for particulate growth). Similarly, slow vehicle speeds, which are characterized by a lightly-loaded engine, typically result in low exhaust temperatures. This can also cause the filter to become plugged. Increased diesel truck traffic combined with a new age of sensitive control equipment has led State officials along the border to investigate technologies capable of measuring in-use truck emissions. This pilot project helps to illuminate the existing and new technologies capable of estimating in-use truck emissions at border crossings.

Section III. Pilot Project Description

The pilot project used three different emissions measurement technologies, a PEMs, an opacity meter, and HDRSD, to evaluate the exhaust emissions from commercial trucks crossing the US-Mexican border at the Mariposa port of entry in Nogales, Arizona. These technologies were deployed over a four-week period from March 14 to April 8, 2005. Over 15,000 gas measurements were made by HDRSD from 1,753 unique trucks. PEMS and opacity data were collected from fourty-two trucks, yielding twenty-seven useful PEMS data files.

III.A The Nogales Border Crossing

Data collection for this project took place at the Nogales port-of-entry, which includes three border crossing locations. Commercial cross border truck traffic flows through the Mariposa Road crossing, which is shown in Figure 1. Annually, about 250,000 trucks enter the United States through this Nogales port. Commercial cargo crossing the Nogales port-of-entry north-bound is composed mainly of fresh produce and maquiladora products. Agricultural trade passing through the Nogales border surges in the winter months, with the peak typically occurring in February and March. All north-bound trucks enter through the initial check points, after which about 30 percent veer off Mariposa Road (path 8, as shown in Figure 1) to have an inspection or complete necessary paperwork (area 9). All north-bound commercial truck traffic converges again into one lane to exit the border compound (marked with an “x”). After passing over a weigh-in-motion station the trucks accelerate to merge with other traffic heading north on Rte 19 (not shown in Figure 3.1; approximate location is at end of arrow extending from the “x”).

Figure 3.1 Mariposa Road Crossing for Commercial Trucks, Nogales, AZ

During this study, the HDRSD units were located just after the weigh-in-motion station, beside the highway on ramp. This is a good location for heavy-duty HDRSD testing because of the single-lane operation. In addition, the slight upward slope of the roadway and the fact that trucks are accelerating to merge with highway traffic means that many trucks passed the HDRSD sensors with their engines under moderate load. For this study, four HDRSD units were set up in series at this location.

Opacity testing and installation of the PEMS device took place in the motor vehicle inspection area (shown on the extreme left of the photo in Figure 3.1.). Trucks with the PEMS device installed passed through the final weigh-in-motion station and passed the HDRSD sensors before

merging onto the highway at the border exit. Data were collected with the PEMS device as the truck traveled through the border compound, over the highway, and on local roads until it reached its final destination. The PEMs data files ranged from 0.7 to 10.5 miles (average of 5.6) and from 8.6 to 34.5 minutes (average of 19.4).

III.B Emissions Measurement Technologies

Each of the technologies used to collect emissions data under this project is described briefly below.

III.B.1 Portable Emissions Monitoring System

For this project a SEMTECH D™ portable emissions monitoring system manufactured by Sensors, Inc. was used to measure the exhaust emissions from a sub-set of trucks crossing the border. A PEMS device uses the same or similar technologies typically used in bench exhaust gas analyzers to measure and record continuous instantaneous time-series emissions data. However, the device is small enough to be installed on a truck, and to collect data while the vehicle is operated in actual or simulated service, rather than being operated on a chassis dynamometer.

The SEMTECH D pulls a continuous exhaust sample into the unit and uses non-dispersive infrared spectroscopy to measure concentrations of CO and CO_2, dispersive ultraviolet spectroscopy to measure concentrations of NO and NO_2, and a flame ionization detector to measure concentrations of HC in the sample, in units of parts per million. For this project an exhaust flow meter manufactured by Sensors, Inc. was used to measure the total flow of exhaust from each vehicle. By integrating measured concentration and flow the instantaneous mass emissions rates (g/second) of each measured exhaust constituent can be calculated. Using carbon balance calculations fuel specific emissions rates (g/gallon of fuel input) can also be calculated. By assuming an average engine efficiency, the fuel specific emission rates can also be converted to approximate power specific emissions rates (g/bhp-hr engine power output). The instantaneous values can also be integrated over the entire drive cycle, to calculate cycle average emissions rates.

III.B.2 Opacity Meter

For this project a green light opacity meter, in conjunction with the snap-acceleration procedure outlined in SAE J1667, was used to measure the density of smoke in the exhaust of a sub-set of vehicles crossing the border. An opacity meter (or opacimeter) is a device that measures the density of the smoke in a vehicle's exhaust by shining a green light with a wavelength of 0.55 µm through the exhaust plume and measuring what percentage of the light energy is blocked by the smoke particles. The more smoke, the more light is blocked, and the higher the opacity (%).

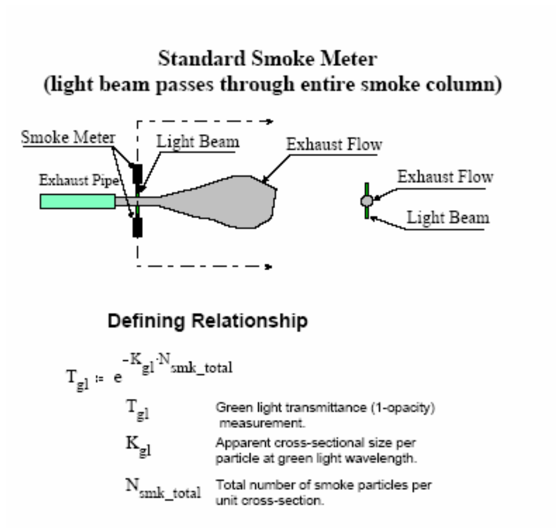


Figure 3.2 Opacity Meter Defining Relationship

The J1667 snap-acceleration procedure requires measurement of the maximum opacity registered while the engine of a stationary vehicle in park (or neutral) is quickly ramped up from idle to maximum governed engine RPM. After several practice cycles this procedure is repeated three times, and the results averaged to give a single value of percent opacity.

Opacity testing is currently used by sixteen US states to monitor smoke emissions from heavy-duty vehicles in the context of a state emissions inspection and maintenance program. See Figure 3.2 for the defining relationship for opacity measurement.

Smoke opacity is generally considered to be a proxy for particulate (PM) emissions from diesel vehicles. However, the correlation between opacity measurements and PM mass emission rates as measured by other instruments has not been demonstrated. This is at least partially due to limitations of the J1667 snap-acceleration procedure. Most PM mass is emitted by diesel vehicles while the engine is under moderate to heavy load, particularly during engine transients. The J1667 procedure is essentially an unloaded test, and can therefore not duplicate conditions under which most PM mass is created in a diesel engine.

<u>III.B.3 Remote Sensing Devices</u>

For this project ACCUSCAN 4000™ remote sensing devices manufactured by ESP were used. HDRSD uses principles of spectroscopy to take an approximately 0.5 second measurement of the exhaust emission concentrations from vehicles as they drive by a fixed sensor. The sensor passes a beam of infrared and ultraviolet light through the exhaust plume of the passing vehicle. This light is reflected off a mirror on the other side of the roadway back to the sensing unit, which determines how much of the light energy was absorbed by the plume. Based on the relative absorption at different frequencies, the concentrations of different gaseous substances in the plume can be measured.

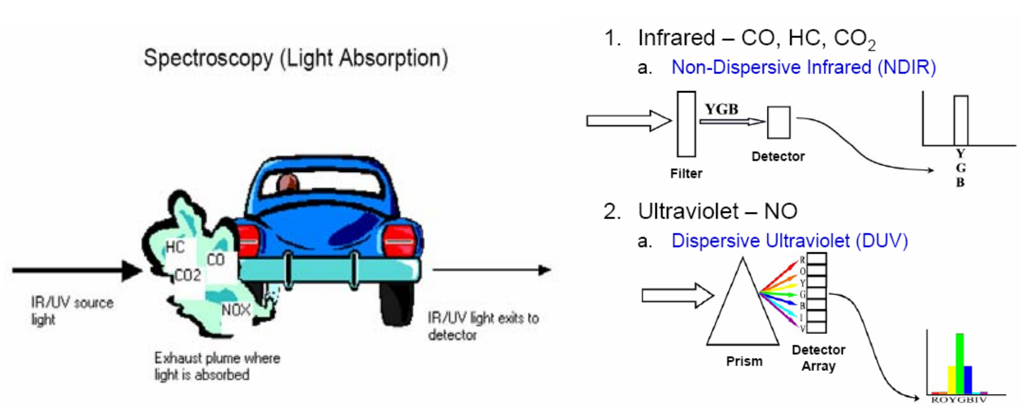


Figure 3.3 HDRSD Measurement Principles

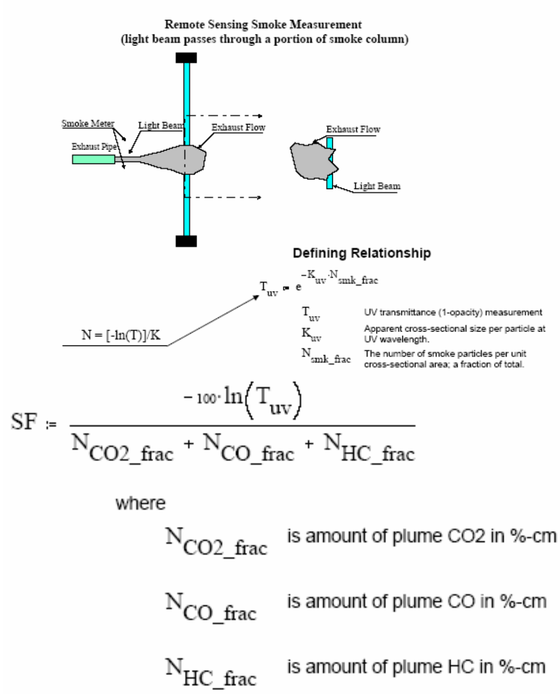


Figure 3.4 Smoke Factor Defining Relationship

The ACCUSCAN unit uses non-dispersive infrared spectroscopy to measure CO, CO_2, and HC concentrations and it uses dispersive ultraviolet spectroscopy to measure NO concentrations as illustrated in Figure 3.3. The HDRSD unit measures and records the ratio of the concentration of each pollutant to the concentration of CO_2 (NO:CO_2, CO:CO_2, and HC:CO_2). These ratios to CO_2 concentration are proportional to fuel specific NO, CO, and HC emissions rates (g/gal of fuel input). By assuming an average engine efficiency the fuel-specific emission rates can also be converted to approximate power-specific emissions rates (g/bhp-hr engine power output)[17].

In addition to the gaseous pollutants, the HDRSD unit calculates a "smoke factor" based on the measured opacity of the exhaust plume. This measurement of opacity is based on the same principles used by a green light opacimeter. However, the HDRSD unit uses light with a shorter wavelength (0.23 µm). This shorter wavelength is blocked by smaller particles, in the PM fine range. In addition, in order to calculate smoke factor the measured opacity is divided by the measured amounts of the other carbon containing gases in the exhaust plume. The HDRSD smoke factor value is therefore theoretically proportional to PM mass emitted per unit of fuel input, outlined in Figure 3.4. See Appendix G for a more detailed explantion of the derivation of HDRSD Smoke Factor values.

In addition to recording gaseous emissions concentrations and smoke factor, the ACCUSCAN units used in this project were integrated with a laser device which measured the speed and acceleration of each passing truck, and a camera which took a picture of the front license plate so that each truck could be uniquely identified.

III.C Project Design and Equipment Set-up

Four HDRSD units were used to collect data for this project. They were installed beside an on-ramp at the exit of the border compound, where all trucks heading north from the border formed a single lane to merge onto the highway. Multiple units were used to maximize the amount of data that could be collected during the three week project period, as well as to evaluate the consistency of HDRSD measurements of the same vehicles from different devices.

[17] These power-specific emissions estimates are reasonably accurate at moderate to high engine power levels seen while vehicles are cruising at high speed or accelerating at moderate speed. They are less accurate when accelerating from very low speed (before the turbo charger has spooled up), when decelerating, and during transmission shifts when the engine is momentarily unloaded.

Figure 3.5 HDRSD Set-Up at Mariposa Crossing

HDRSD is a line-of-sight device, so it must be set up to allow a beam of light to pass through the rising exhaust plume of passing vehicles. Prior experience has shown that the best results are achieved if the HDRSD device is located within two feet above the exhaust outlet from the vehicle. Since the heated exhaust generally rises after exiting the vehicle, an HDRSD unit located below the exhaust outlet will miss the plume entirely. As the plume rises, it mixes with ambient air. Dilute plumes more than a few feet above the exhaust outlet have pollutant concentrations that are too low to measure accurately and consistently, so the HDRSD device is set just above the stack outlet.

Most large commercial trucks have exhaust stacks that exit at or slightly above the top of the vehicle cab. Beta testing for this project at the Mariposa crossing determined that approximately 9% of the border fleet trucks actually have low exhaust that exits below the vehicle near ground level. Therefore, for the three-week data collection period one HDRSD unit was set up low, with the beam crossing the roadway approximately twelve inches off of the road surface. The other three HDRSD units were set up on towers, with the beam crossing 13 feet above the roadway. This height was determined to be optimal during beta testing. With this combination of high and low sensors, valid HDRSD gas measurements were recorded from over 84 percent of the trucks that passed the HDRSD location. The term "valid" simply means that sufficient plume gas was sampled to permit calculations to be performed. The 84% rate compares well with light duty remote sensing programs which typically vary from 60 to 90%.

Each of the HDRSD units was connected to its own host computer, which recorded a test record for each passing vehicle. Each test record included the pollutant concentrations, recorded speed and acceleration, and a license plate photo. These computers were housed in a trailer located next to the HDRSD towers. Figure 3.5 shows the HDRSD site set-up.

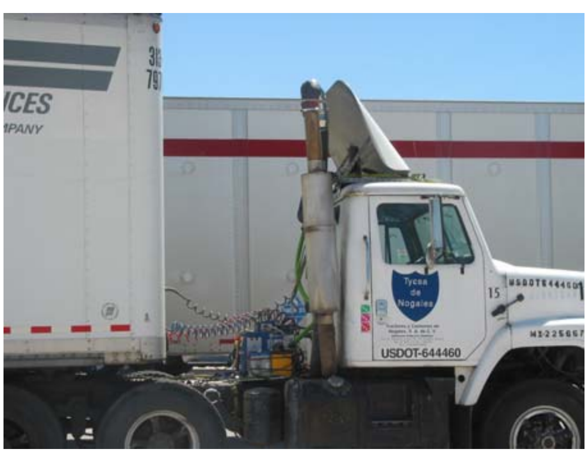


Figure 3.6 Typical PEMS installation

Unlike HDRSD, which is set up remotely at the roadside, PEMs testing requires that equipment be installed on the vehicle to be tested. After the PEMs equipment is installed, emissions data are collected while the vehicle is operated in actual service. For this project, data were collected as the vehicle traveled from the border compound to its final destination in the border zone, a trip of 0.7 to 10.5 miles and 8.6 to 34.5 minutes. At the truck's destination, the PEMs equipment was removed and returned to the border compound for installation in another vehicle.

During this project, PEMs testing generally took 3 – 4 hours per vehicle. Two or three trucks were tested each day. There was a learning curve for installation of the PEMS equipment, and testing generally took less time as operators gained familiarity. Trucks were recruited for PEMs testing from among those that were sent by border officials to a separate facility within the border compound for safety inspections. Figure 3.6 shows PEMs being installed on a typical truck.

Opacity testing can be conducted virtually anywhere, and does not require any special set-up or equipment other than an opacity meter. For this project, every truck that was tested with PEMs was also tested with an opacity meter. The testing took place in conjunction with the installation of the PEMS device.

III.D Supplemental Data Collection

To create a dataset for an HDRSD-PEMs correlation analysis, a supplemental experiment was conducted at the border crossing facility with four trucks of varying ages and weight class. This experiment was conducted in a different part of the border compound, separate from the main flow. The four trucks were equipped with PEMs and routed around the border facility. They passed through an HDRSD array twenty times over the course of several minutes. The repetitive nature of the route of the vehicle allowed for better time alignment between the HDRSD readings and the PEMs. Emissions of HC, NO, NO2 , CO_2 and CO were measured with PEMs while emissions of HC, NO, CO, and $PM_{2.5}$ were measured using the HDRSD equipment.

Section IV. Fleet Emissions Results

The data collected during this project was used to characterize the in-use emissions of the current cross-border truck fleet. HDRSD and PEMs were used to develop estimates of CO, NO (and NOx) and HC emissions. HDRSD and the opacity meter were used to characterize PM emissions. When analyzing collected data, all tested vehicles were classified into groups based on four characteristics: country of primary registration (US, Mexico, or dual plates), model year, weight class, and tested weight (loaded or unloaded). Only loaded trucks were tested with PEMS.

The primary metric used to evaluate emissions rates was grams per gallon of fuel, and little difference was seen between loaded and unloaded trucks in the HDRSD data. In addition, the vast majority of trucks which crossed the border during the study period were the largest, Class 8 vehicles. In the discussion below, therefore, data is generally only segregated by model year ranges and country of registration. Separate results are not provided for trucks of different weight classes.

The details of vehicle classification and binning, and HDRSD and PEMS data post-processing, are described in this section and related Appendices.

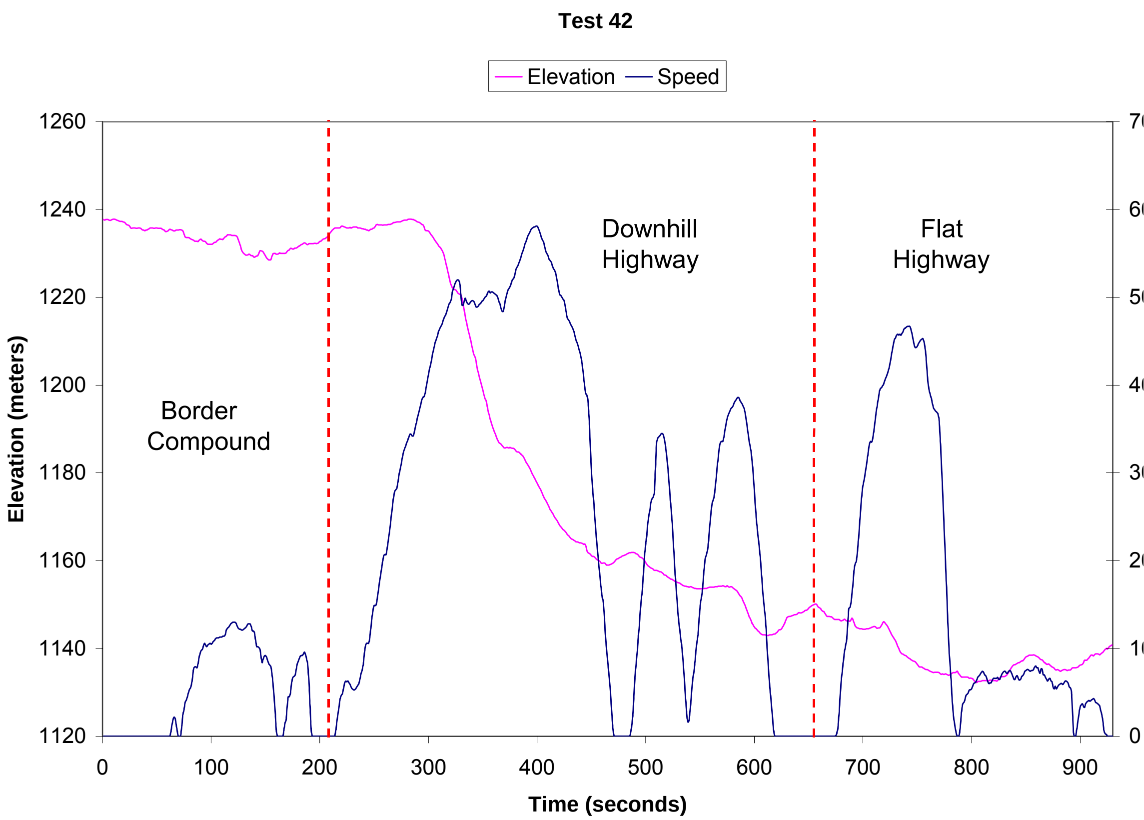
IV.A PEMs Data Collection and Analysis

PEMs data collection was attempted on 42 trucks, and valid data files were obtained for 27 of these trucks. The majority of invalid files resulted from bad flow data. There were also several instances of data file corruption, and four runs were aborted due to PEMS equipment problems.

This section presents aggregate emissions profiles for the subset of 27 trucks successfully tested by PEMs. Emission rates by vintage and country of origin are also presented.

A PEMs unit reports average pollutant concentrations (parts per million) measured over each one second time interval. By multiplying measured concentration by measured exhaust flow over the same interval, the unit calculates and reports the measured emission rate in grams per second for each interval. Using carbon balance, the amount of fuel consumed during each interval can also be calculated, which can be used to calculate fuel-specific emission rates for each interval (g/gallon). Assuming an average diesel engine efficiency of 33 percent, approximate power-specific emission rates for each interval (g/bhp-hr) can be calculated. By summing the total grams of emissions over the entire measured drive cycle and dividing by total miles, total fuel and total power output, cycle average emissions rates can be calculated.

For each tested truck, cycle average pollutant emissions rates were calculated in each of these units (g/mi, g/gal, g/bhp-hr). A description of this conversion can be found in Appendix A. Examination of the preliminary data indicated high average pollution rates as well as unreasonably high fuel economies, even for unloaded trucks, for many of the tests. Investigation of this issue determined that it was likely the result of the significant change in elevation (i.e. downhill) in the duty-cycle over which testing occurred. Each truck was fitted with the PEMs unit at the border crossing. The vehicles then traveled to their destination, where the PEMs were removed. Since no trucks were tested on their return trip, each test cycle contained a significant drop in elevation as indicated by the GPS – typically 100-200 meters depending on the length of the cycle. Therefore, the manner in which the results were analyzed was modified in order to account for the fact that each truck was traveling downhill for the majority of the test.



In order to better interpret the results, each drive cycle was divided into sections. A typical cycle is shown in Figure 4.1, with its divisions labeled. Although this particular vehicle has a cycle-average fuel economy of about 6.4 mpg (somewhat high for a loaded class 8 truck), the average fuel economy during the border compound portion was about 3.4 mpg, and during the flat highway portion, about 4.8 mpg, A results table for this truck is shown in Figure 4.2. Similar tables of results for each tested truck are included at Appendix B. Analysis of these results is discussed below. Note that not all cycles included a flat highway portion.

1996 Freightliner AZ

		Distance Traveled (mi)	Change in elv. (meters)	Avg Speed (mph)	Fuel Cons. (gal)	Avg FE (mpg)		Avg NOx (g/mi)	Avg CO (g/mi)	Avg HC (g/mi)		hp-hr out	Avg NOx (g/bhp-hr)	Avg CO (g/bhp-hr)	Avg HC (g/bhp-hr)		Avg (g
Total		4.92	-97	18.95	0.77	6.41		14.79	5.10	4.38		11.87	6.12	2.11	1.81		
Border Compound		0.28	-4	4.94	0.08	3.42		38.33	7.94	13.22		1.28	8.48	1.76	2.92		[illegible]
Downhill Highway		2.64	-73	34.66	0.27	9.67		8.79	2.67	3.32		4.23	5.49	1.67	2.07		
Flat Highway		1.99	-20	15.78	0.41	4.85		19.37	7.90	4.53		6.37	6.07	2.48	1.42		

Test 42

IV.B PEMs Test Results

Forty two different trucks were tested with PEMS, yielding a total of 27 useful test files; some tests were discarded or aborted due to operational and/or equipment issues. Since over 1,700 unique trucks crossed the border during the data collection period, this sample size of 27 is not statistically representative of the fleet. Additional details of the PEMs and HDRSD samples are included in Section IV.D.

IV.B.1 NO Emissions Results

Charts depicting PEMs NO emission results by vehicle vintage and nationality are shown in Figures 4.3 and 4.4. While PEMs measures both NO and NO_x (NO plus NO_2), the NO results are shown for direct comparison to the HDRSD results discussed later. For all of the tested trucks, NO represented 80 -85 percent of total NO_x.

Figure 4.3 shows total cycle average NO emissions rates for the tested trucks. In this chart each point represents the results of one tested truck. In Figure 4.4, separate data points are included for total cycle average, border compound, downhill highway, and flat highway portions of the test cycle for each vehicle. Please note that these charts depict fuel specific emission rates (g/gal). Each chart also includes a line showing the approximate expected NO_x emissions rate based on EPA emissions standards in effect at the time of engine manufacture.

As shown, the NO emission rates are generally consistent with engine certification standards. Several of the newest trucks appear to have slightly elevated NO emissions compared to the standards, however, given the small number of tests it is not possible to draw conclusions about general trends.

As can be seen from the total cycle averages in Figure 4.3, there is very little differentiation by vehicle nationality. However, the amount of data collected in this pilot project is too small to draw any definite and concrete conclusions. For NO, there do not appear to be any gross emitters in the 27 vehicle sample.

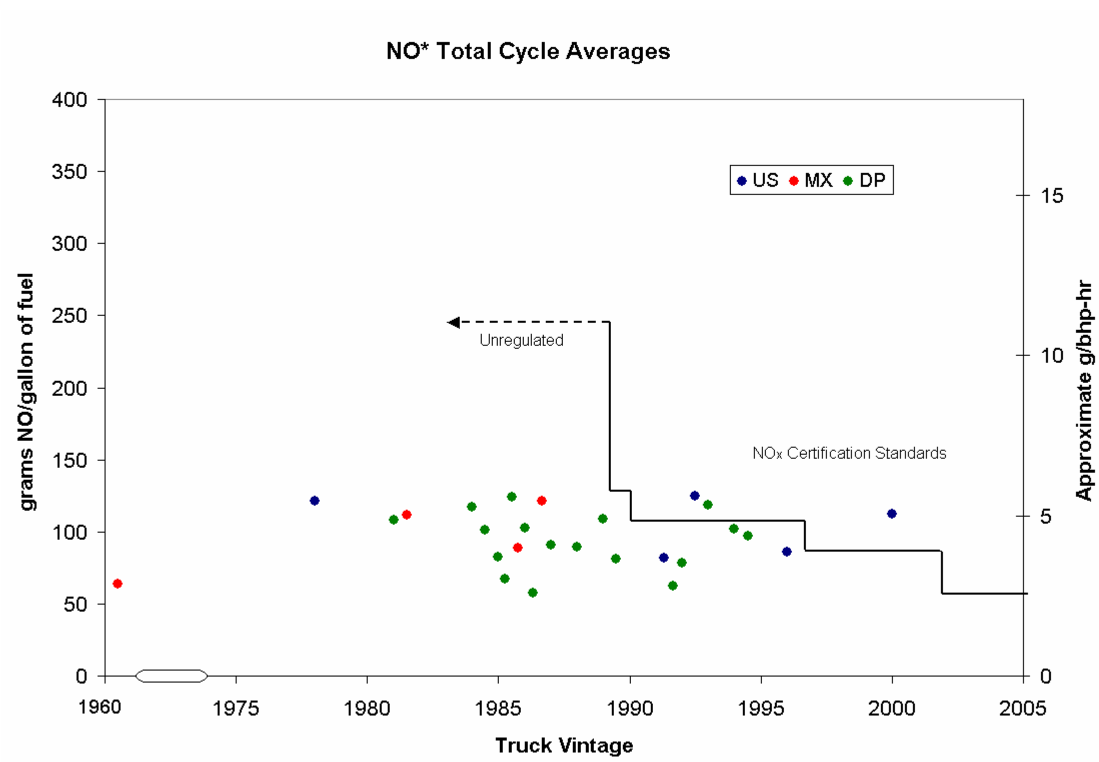


Figure 4.3 Average PEMs NO Emission Rates

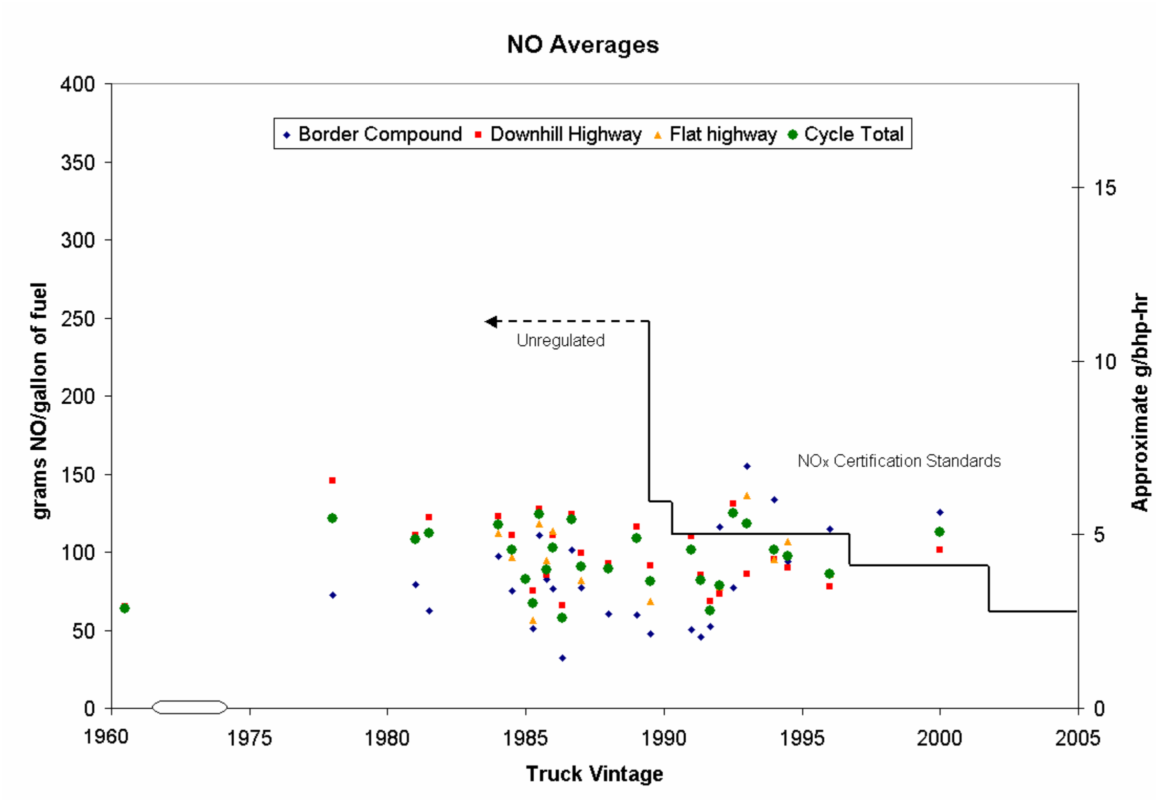


Figure 4.4 Average PEMs NO Emission Rates by Cycle Section

One unexpected phenomenon can be seen in Figure 4.4. As shown, for older vehicles the fuel specific emissions rate of NO is consistently lower during the border compound section of the duty cycle than in the highway sections. Starting with 1990 vehicles this changes - later vehicles appear to have higher fuel specific emissions rates during the border compound portion of the duty cycle than during the highway sections. Presumably this is related to idle emissions, and perhaps to the change to electronic fuel control in later model year engines. However, since fuel use is relatively low at idle, higher fuel-specific emissions rates at idle would not result in significant additional mass of NO emissions.

IV.B.2 CO Emissions Results

PEMs CO emissions by vehicle vintage and nationality are shown in Figures 4.5 and 4.6. On a relative scale the border-fleet CO emissions were higher than the NO emissions, but still well below current emissions certification standards. There is no clear relation between CO emissions and truck vintage or nationality seen in these charts. It does appear that a few of the dual-plated vehicles had higher CO emission rates in this sample, but these rates were not high enough that the trucks would be considered gross emitters.

As shown in Figure 4.6, fuel specific CO emission rates were consistently higher during highway portions of the drive cycle for all vehicles than they were during the border compound section of the cycle.

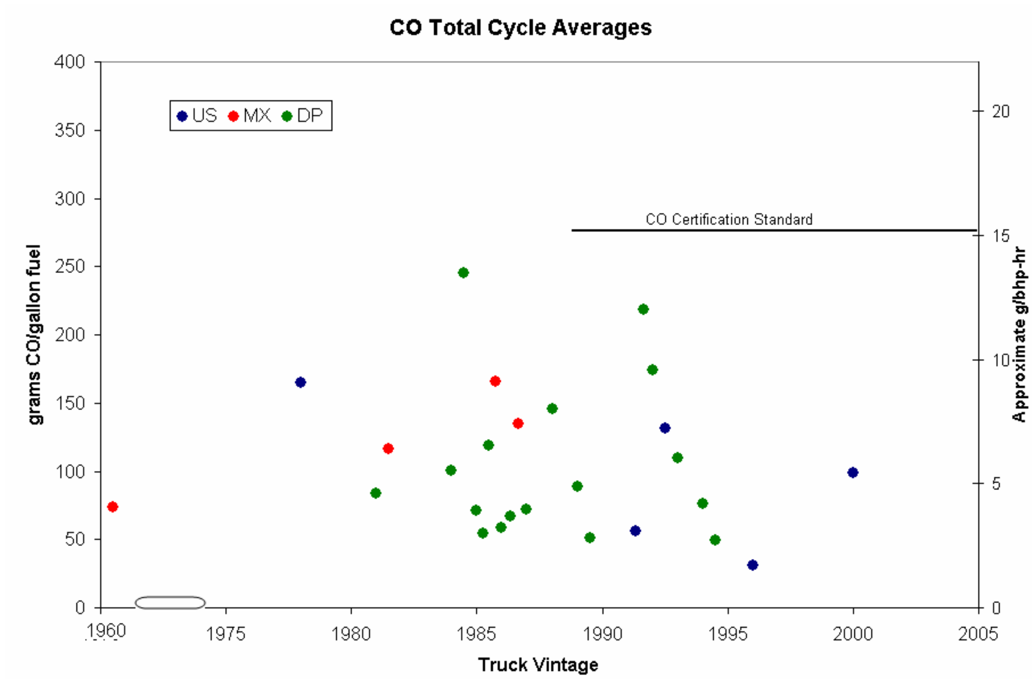


Figure 4.5 Average PEMs CO Emission rates

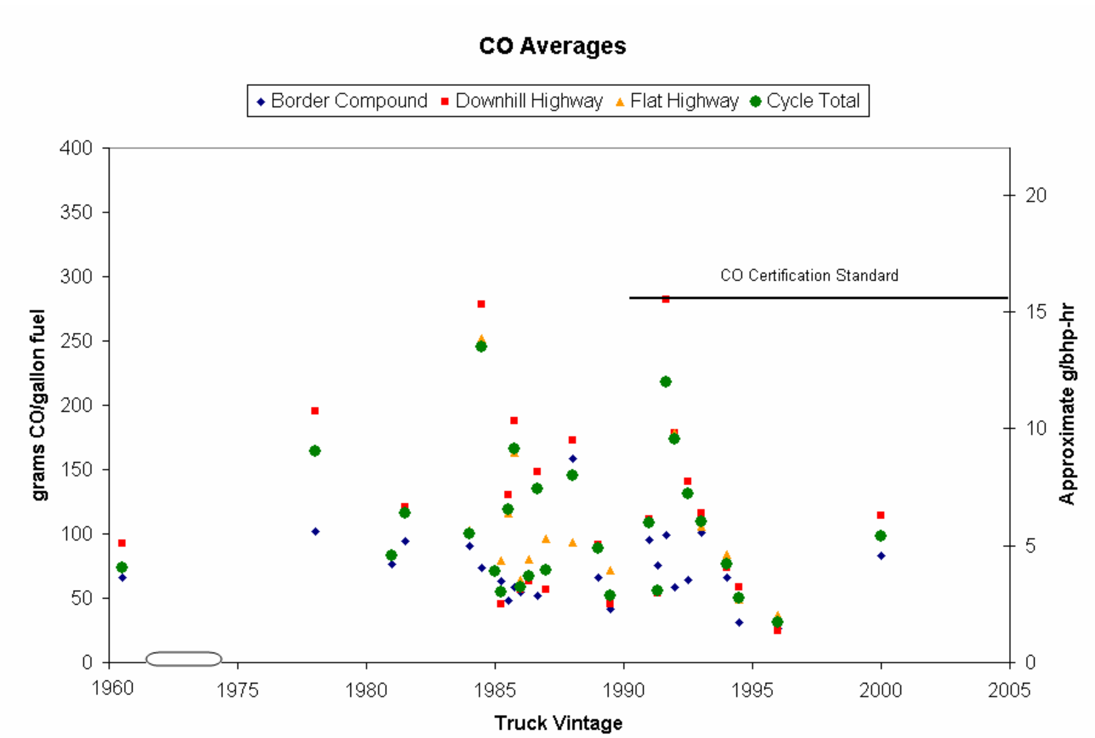


Figure 4.6 Average PEMs CO Emission Rates by Cycle Section

IV.B.3 HC Emissions Results

Unlike the NO and CO results discussed above, the PEMs results for HC shown in Figures 4.7 and 4.8 indicate a clear trend by vintage. The newest vehicles clearly have lower HC emissions than older vehicles. While many of these older vehicles built prior to 1990 have high HC emissions relative to the other tested vehicles, labeling them as "gross emitters" is complicated by the fact that there were no HC emissions standards in place when these engines were built. Some of these vehicles may have mechanical problems that, when fixed, would reduce HC emissions, while others may not. Evaluating the engine condition of these trucks was beyond the scope of this project, so definitive statements as to the cause of these high HC emissions can not be made. Most of the trucks with high HC emissions were dual-plated as opposed to US- or Mexican-plated trucks.

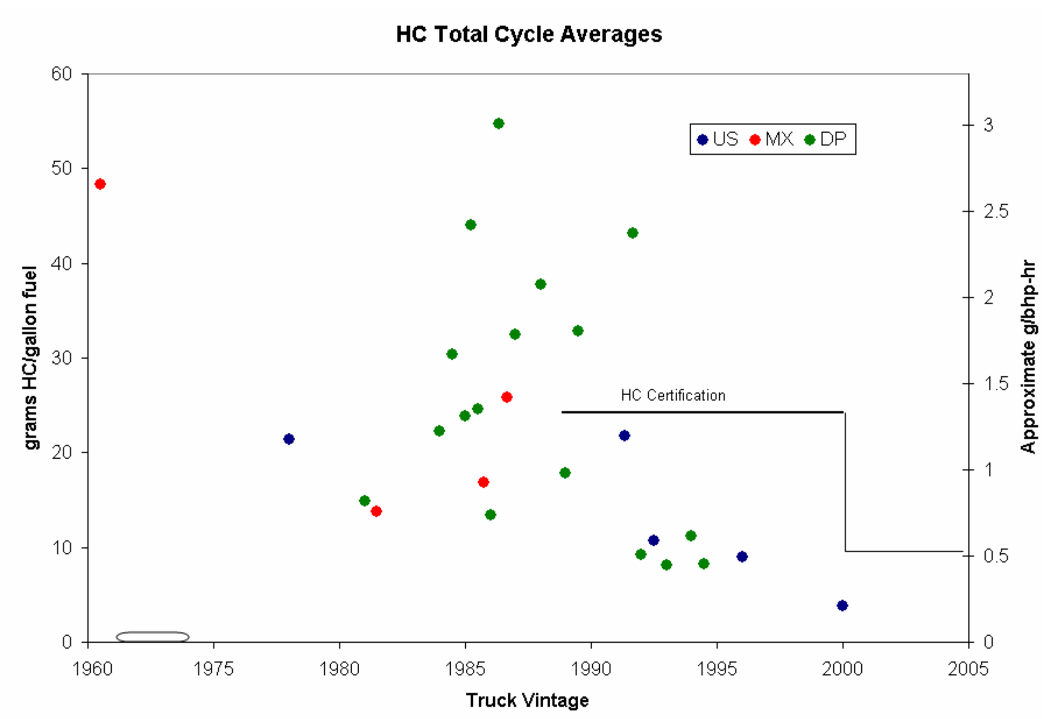


Figure 4.7 Average PEMs HC Emission Rates

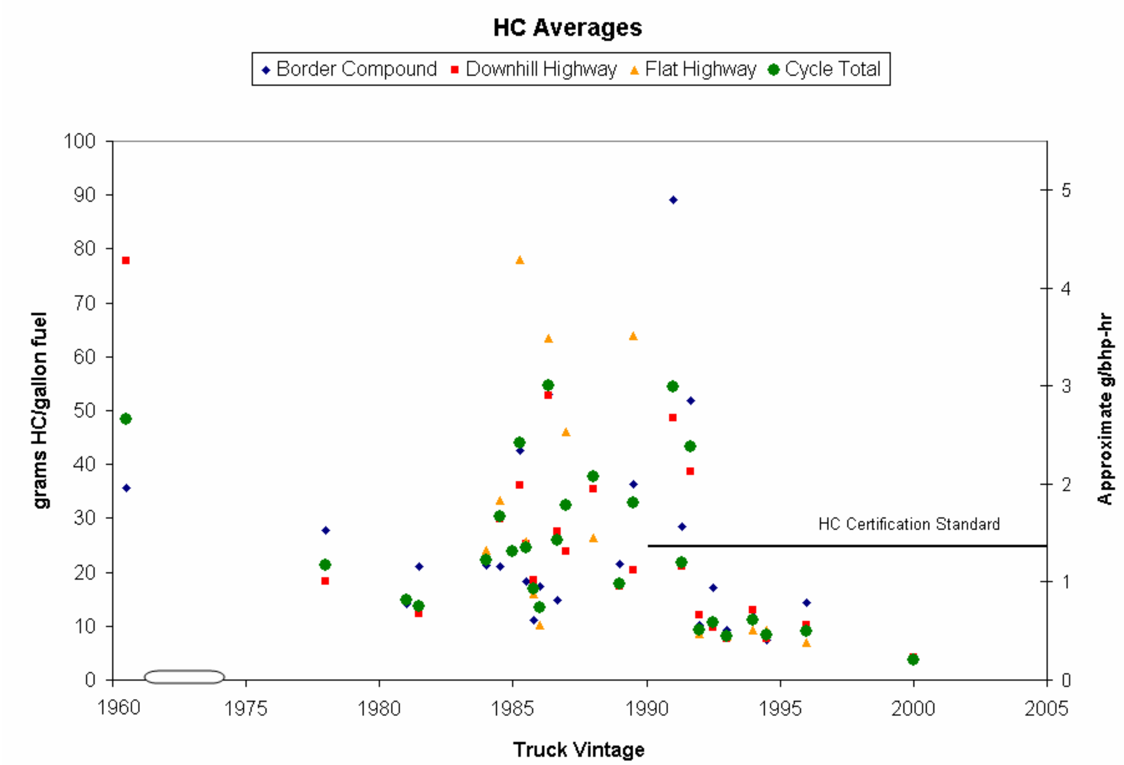


Figure 4.8 Average PEMs HC Emission Rates by Cycle Section

IV.C Opacity Test Results

Opacity tests were conducted on 40 of the 42 trucks that were PEMs tested. In accordance with the SAEJ1667 procedure, opacity was measured during three repeats of a snap idle test. The results of each individual snap and the average of the three were reported. These data are shown in Figures 4.9 and 4.10. In figure 4.9, measured opacity from each of the three snaps, and the average for each truck, is plotted by truck model year. In Figure 4.10 the average opacity result for each truck is plotted by model year, with the truck nationality (United States, Mexican, dual-plated) also shown. In each figure, a line showing "typical" cut points to designate a gross emitter is included for reference; the cut points shown are consistent with the sixteen current US opacity-based state heavy-duty diesel inspection and maintenance programs[18]. These cut points are 70 percent opacity for pre-1974 trucks[19], 55 percent opacity for 1974-1991 trucks, and 40 percent opacity for post-1991 trucks.

[18] Energy & Environmental Analysis, Inc, *Scoping Study- State Diesel Emission Inspection Programs: Trends and Outcomes*, March 2004

[19] A separate cut point for pre-1974 trucks is not always used. Some state programs use only the 55 percent opacity limit for all trucks built prior to 1991.

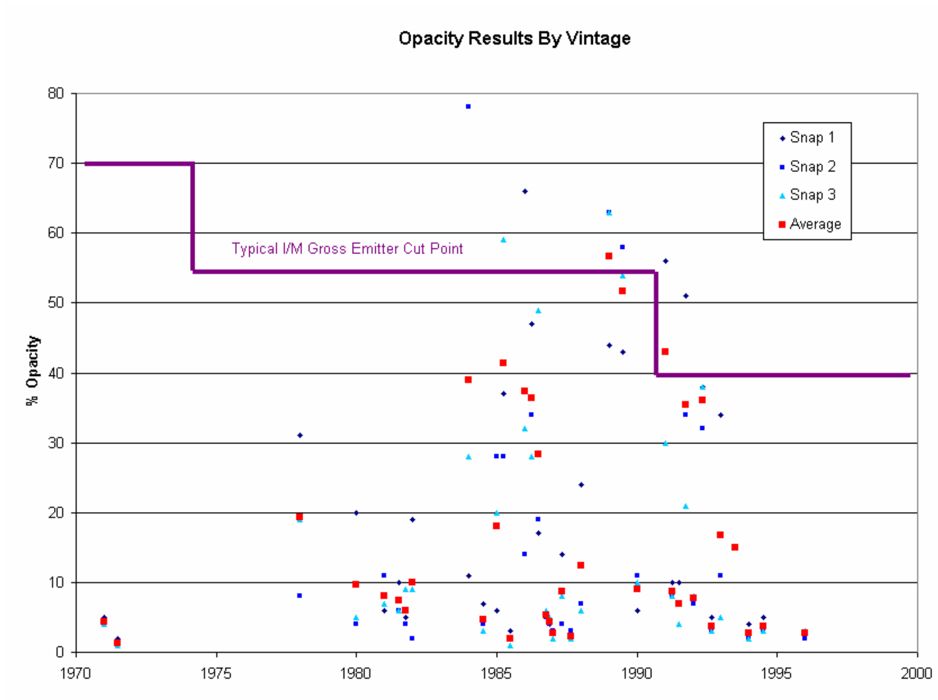


Figure 4.9 Opacity Test Results by Vintage

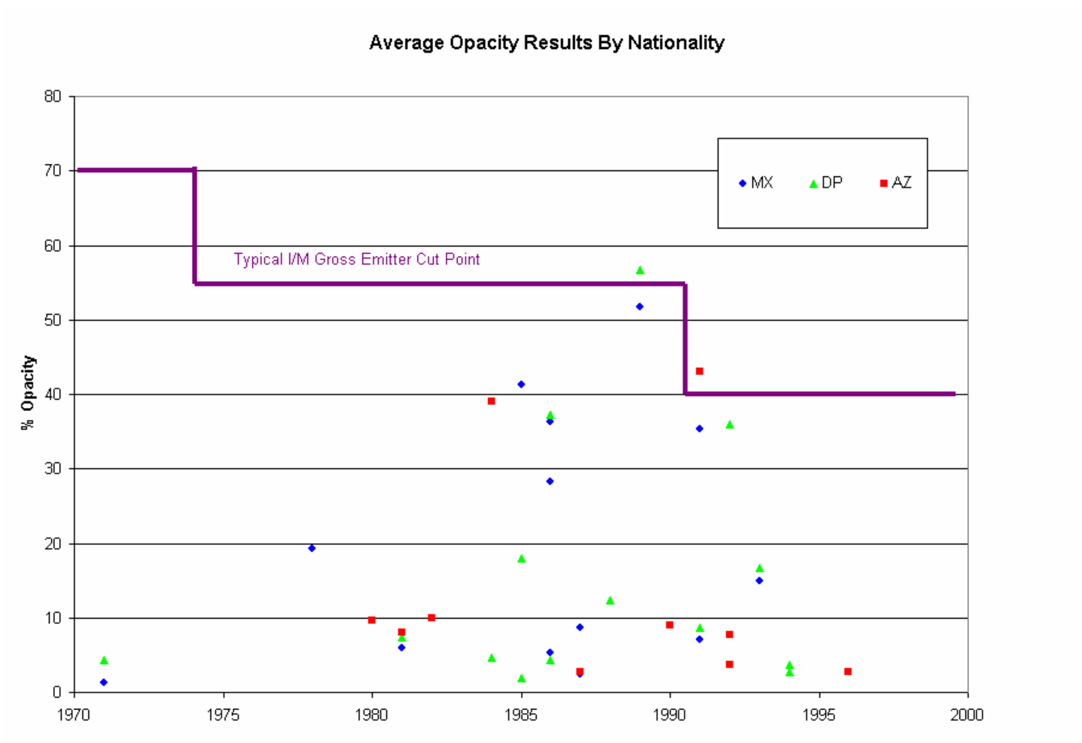


Figure 4.10 Opacity Test results by Vintage and Nationality

As shown, there is no clear pattern of measured opacity either by vintage or by nationality. Also note that for some vehicles there was a significant variation in the values of the three snap tests – in one case ranging from 11 percent to 78 percent. In other cases, the variation in opacity from test to test was much lower.

Only two of the tested vehicles would have “failed” the test in accordance with most current I/M programs, and as such have been labeled as gross emitters. In both cases they were early 1990’s vintage trucks; one was registered in the United States and the other was dual-plated.

IV.D HDRSD Data Sample Size and Composition

The HDRSD technology collected full data sets (valid emissions measurements with valid speed and acceleration data and visible license plate photos) for over 11,000 truck trips across the border by 1,753 unique trucks. This sample size is several orders of magnitude larger than the PEMs sample size. Some discussion of the differences between the samples will clarify the comparison results. Figure 4.11 shows the vintage of trucks that were PEMs tested, alongside the vintages of all of the unique vehicles that were measured by the HDRSD.

Since the HDRSD collected a full data set on over 60 percent of all trucks passing through the border over a three week period (measurements with valid emissions, speed and acceleration, and visible license plates) the HDRSD data are believed to be representative of the border fleet crossing at Nogales during the peak-trade winter months.

The process of selection of PEMs trucks yielded a sample set of vehicles that does not match the characteristics of the the border fleet as represented by the HDRSD data. As seen in Figure 4.11, the selection process favored trucks of 1980s vintage slightly, while resulting in a significant under representation of the newest trucks in the fleet (1999 and newer). No trucks newer than 2002 were PEMS tested while HDRSD data was collected on over 100 post-2002 trucks.

HDRSD emissions results and discussion are presented by pollutant type in Section IV.E through IV.G. A comparison of average emission rates as estimated by the PEMs and HDRSD technologies is presented in Section V.

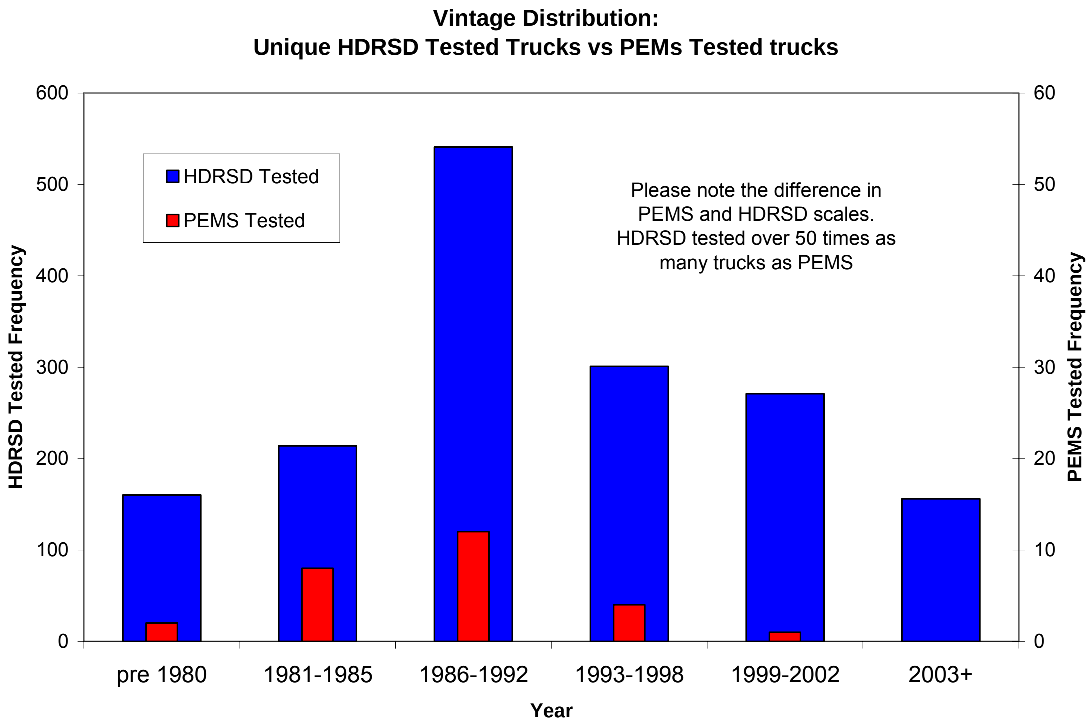


Figure 4.11 PEMS Tested Vintage Distribution vs. HDRSD Tested Vintage Distribution

IV.E HDRSD Test Results: Fleet Characterization

As describer earlier, three HDRSD systems were elevated at thirteen feet and set ten feet apart to measure emissions from vertical exhaust stacks; one system was deployed at road level. The thirty-inch long speed and acceleration measurement sub-systems were deployed with the trailing edge six feet in advance of each HDRSD system. During the on-road collection phase, the four HDRSD systems attempted 18,272 measurements as presented in Table 4.1

For the combination of all four HDRSD units, the emissions plume capture was valid in 84 percent of passing vehicles. For the valid gas measurements 86% had valid speed and acceleration measurements, and for the valid combinations of the above 87% of the set had readable license plates. The net number of measurements with valid emissions, speed, and license plate data was therefore 63 percent of the total attempted. Speed and acceleration are required to judge whether or not the engine was under load while the HDRSD emissions measurement was taken. The license plate number is require to identify unique vehicles. Many trucks made multiple border crossings during the data collection period.

The overall data capture rates are consistent with many current light-duty RSD testing programs. In addition, the individual station capture rates did not differ significantly from the overall capture rates. Since individual high stack station heights were varied ~+/-1 foot, this indicates that measurement height is not a critical capture rate variable, and strongly implies that a single low stack measurement station combined with a single high stack measurement station deployment configuration can provide measurement coverage consistent with typical light-duty RSD fleet measurement configurations.

Further refinement of the HDRSD set up may also provide opportunities to increase the data capture rate in future deployments. In particular, enhancement of the speed/acceleration measurement system should increase the speed/acceleration data capture rate to 95 percent or more, and the use of secondary cameras could also increase the data capture rate of license plate numbers. For deployments at locations less subject to truck gear shifting in the vicinity of the HDRSD equipment the emissions plume data capture rate should also rise. See Section VIII.C for additional discussion of HDRSD site selection and set up.

For vehicles registered in both Mexico and the United States, both plates were not always visible, or, possibly, not displayed on the truck. The data was carefully reviewed to identify individual dual-plated trucks regardless of which plate or plates were observed. In this process the number of unique vehicles was reduced to 1,753.

To determine vehicle model year, license plate numbers were used to access databases of truck registrations. For Mexican vehicles the TransPort database maintained by the Arizona Department of Transportation was used. For US trucks, only records kept by the Arizona Department of Motor Vehicles were used to match plates, as records from other states were not readily available to the project team. Therefore, the model year could not be determined for any trucks registered in states other than Arizona. Arizona trucks accounted for 94 percent of total US-plated truck crossings during the study period.

Table 4.1Breakdown of Measurements Collected

	Unique Vehicles	Measurements	Incremental %	% of Total Measurements
Measurements Attempted with Equipment Operational	N/A	18,272		
Successful Gas Measurement	N/A	15,323	84%	84%
Gas Measurement with Vehicle Speed and Acceleration	N/A	13,230	86%	72%
With Visible Plates	1,753	11,490	87%	63%

Table 4.2 Number of Observations, Vehicles and Trips

Vehicle Stack	Vehicles	Trips	Observations	Observations Per Trip
High	1,518	8,306	15,566	1.87
Low	129	547	602	1.10
Emissions High & Low	106	329	595	1.81
Total	1,753	9,182	16,763	

Table 4.3 Vehicles and Trips by Weight Class

Weight Class	Unique Vehicles	% of Vehicles	Trips*	% of Trips	Trips Per Vehicle
2	4	0%	12	0%	3.0
2.5	3	0%	7	0%	2.3
3	18	1%	84	1%	4.7
4	7	0%	45	0%	6.4
5	16	1%	80	1%	5.0
6	38	2%	146	2%	3.8
7	4	0%	13	0%	3.3
8	1,663	95%	8,795	96%	5.3
Total	**1,753**	**100%**	**9,182**	**100%**	**5.2**

Table 4.4 Vehicles and Trips by Plate Nationality

Plate(s)	Unique Vehicles	% of Vehicles	Trips*	% of Trips	Trips Per Vehicle
Dual Plates	282	16%	3,754	41%	13.3
Mexican Plate	1,302	74%	4,183	46%	3.2
US Plate	169	10%	1,245	14%	7.4
Total	**1,753**	**100%**	**9,182**	**100%**	**5.2**

With the cooperation of State authorities it was relatively easy for the project team to gather model year and other data that would be required to flag a truck as a high emitter, on most of the trucks which crossed the border at Nogales. However, this data was not available in real time at the testing location. Availability of equivalent data at other border crossings was not evaluated by the project team.

Including some periods when the HDRSD systems were not actively measuring emissions, a total of 16,763 readable plate images were recorded by the HDRSD camera systems. License plate images from vehicles with high exhausts were typically captured by two out of the three HDRSD units on each trip. Table 4.2 shows the breakdown of unique vehicles, trips and observations.

The vast majority of trucks were Class 8, as shown in Table 4.3. Fourteen percent of trucks had both US and Mexican plates and accounted for 41 percent of trips, an average of almost one trip per day during the data collection period. Ten percent of trucks had US plates and accounted for 14 percent of trips, making a trip on average every two to three days. Seventy-four percent had Mexican plates and made an average of three trips each during the three to four week collection period in March 2005. It is unknown whether these patterns are consistent throughout the year, or are seasonal.

The fleet of Mexican plated trucks was newer than the US and dual plated fleets and the dual plated fleet was oldest. Dual-plated trucks are assumed to be part of the drayage fleet captive to the border region and used mostly for the short haul trips back and forth across the border. Dual registration allows easier movement back and forth across the border, without the need for a special permit. The observed pattern of movements supports this assumption, as dual plated

trucks made significantly more frequent crossings than US or Mexican plated trucks, as discussed above and shown in Tables 4.4 and 4.5[20].

Within each fleet, the number of trips was roughly consistent with the number of trucks in each age group as shown in Table 4.6.

Table 4.5 Vehicle Model Year Distribution

Model Year	DP	MX	US
1980 & Older	5%	11%	2%
1981-1985	18%	12%	5%
1986-1992	40%	30%	19%
1993-1998	16%	16%	25%
1999-2002	2%	19%	12%
2003 & newer	1%	12%	2%
Unknown	18%	0%	34%
Total	**100%**	**100%**	**100%**

Table 4.6 Percent of Trips by Model Year

Age	DP	MX	US
1980 & Older	4%	12%	2%
1981-1985	18%	13%	8%
1986-1992	45%	27%	35%
1993-1998	19%	21%	31%
1999-2002	1%	16%	10%
2003 & newer	0%	10%	1%
Unknown	12%	0%	13%
Total	**100%**	**100%**	**100%**

Please note that this study examined a border crossing with significant seasonal variation in total truck traffic, with data collected during the peak traffic season. The type and distribution of vehicles seen in this study may not be representative of year round traffic at Nogales, and may not be representative of truck traffic at other border crossings.

IV.F HDRSD Test Results: Emissions Distribution

Before determining emission distribution results for the cross border truck fleet as measured by the HDRSD technology several important steps needed to be taken. First, the instantaneous measurements were calculated in units of grams per gallon. Details of this calculation are presented in Appendix C. Second, several significant data screening procedures were conducted to ensure that only valid and useful data points were used in the analysis. A discussion of the data screening process can be found in Appendix D.

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[20] Of the US-plated vehicles with "unknown" model year as shown in Table 4.5, 16% had Arizona plates but no VIN number was available in Arizona DMV's database. The remainder were registered in states other than Arizona and no attempt was made to identify their model year because relevant databases were not available to the project team. Of all of the Arizona license plate numbers checked, the DMV database contained VIN numbers for approximately 92% of them

Emissions distributions for CO, HC, NO and smoke factor were computed using the average emissions for each unique identified vehicle that had at least four measurements during the data collection period. These are shown from dirtiest to cleanest as the lower colored lines in Figures 4.12 through 4.15. Lines showing the approximate expected fuel-specific emissions rates based on 1991-1993 EPA diesel engine emissions standards are included for reference. The upper curves show the cumulative contribution of emissions assuming that truck diesel engines all operate at approximately the same efficiency. These curves illustrate that based on the HDRSD results, for the Nogales fleet:

- 50 percent of CO emissions are produced by less than 20 percent of vehicles;
- 40 percent of HC emissions are produced by less than 20 percent of vehicles;
- 40 percent of NO emissions are produced by less than 25 percent of vehicles, and
- 50 percent of smoke emissions are produced by 20 percent of vehicles.

Therefore, there is evidence that significant emissions reductions could be achieved by identifying high-emitting vehicles and ensuring that they are repaired – especially for particulates (smoke). As shown in Figure 4.15, a much larger percentage of total vehicles may be exceeding the relevant standard for smoke emissions than for the other pollutants, and the highest emitting vehicles are potentially emitting at a much higher level relative to the standard than for the other pollutants[21].

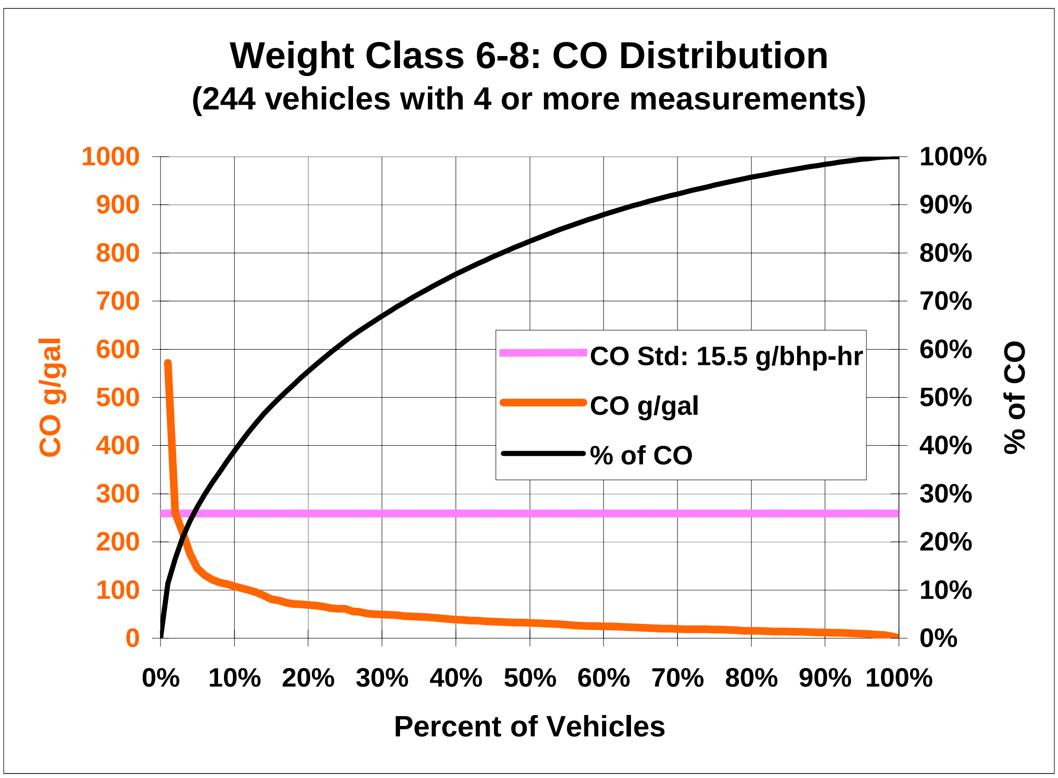


Figure 4.12 CO Emissions Distribution

[21] For smoke, this data is illustrative only. The exact relationship between HDRSD smoke factor and PM mass as measured on the certification test cycle must still be determined.

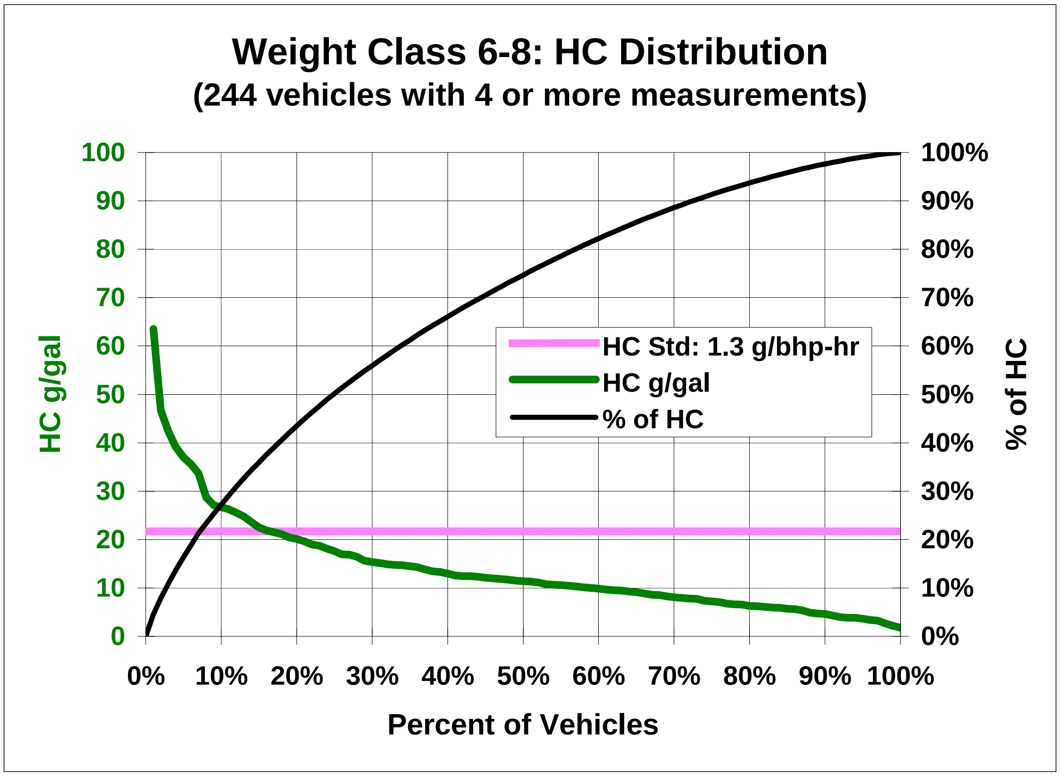


Figure 4.13 HC Emissions Distribution

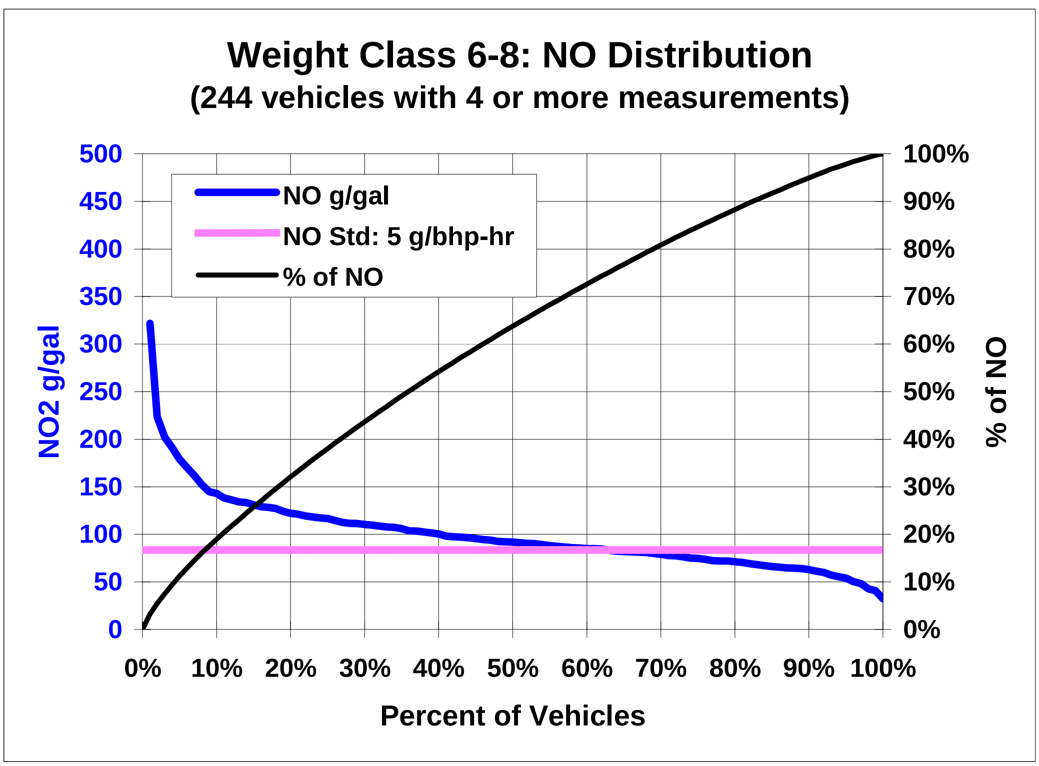


Figure 4.14 NO Emissions Distribution

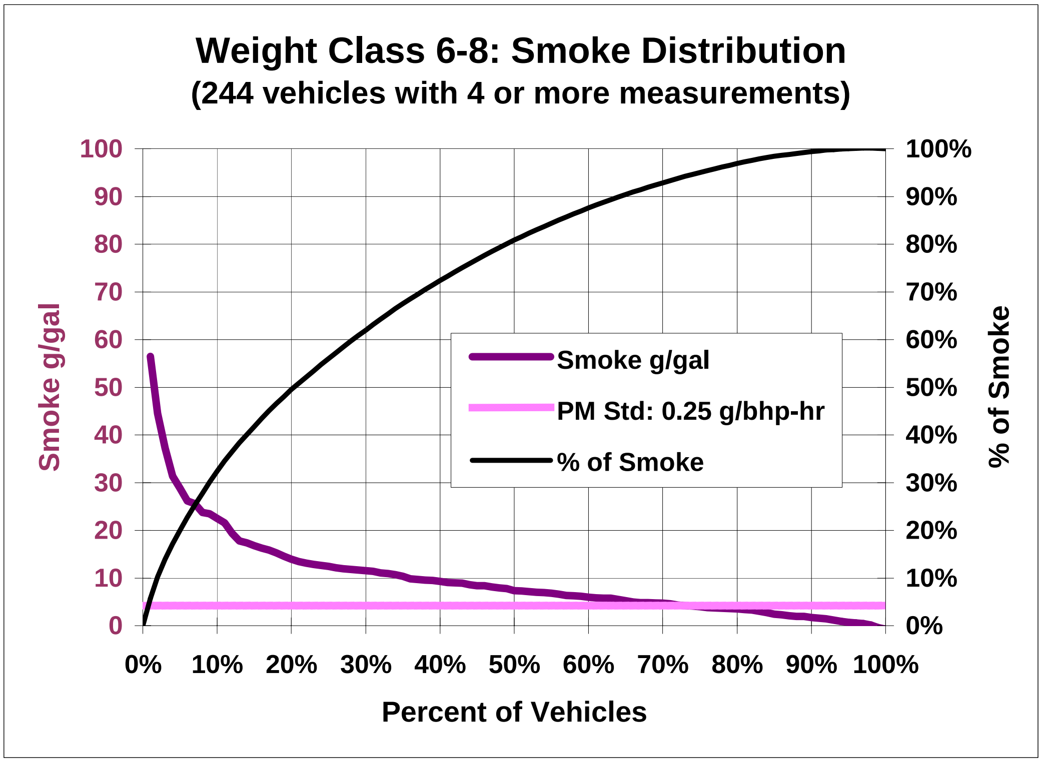


Figure 4.15 UV-Smoke Emissions Distribution

IV.G HDRSD Test Results: Fleet Average Emissions Estimates

HDRSD measured emissions levels for identified Class 6 and higher vehicles were binned by nationality and vehicle age. The mean emissions with 95 percent confidence intervals are illustrated in Figures 4.16 through Figure 4.19[22].

As shown in Figures 4.16 and 4.17, smoke factor and HC emissions were significantly lower for 1993 and newer trucks than for older vehicles. CO results were mixed. Figure 4.18 shows that CO emissions from post-1992 trucks were lower than from older, pre-1993 vintage vehicles for Mexican and dual-plated trucks. NO emissions were not significantly different among the different age groups. Refinement of the age bins shown in Figures 4.16 through 4.19 did not reveal additional significant trends in smoke factor or NO, as illustrated in Figures 4.20 and 4.21.

Review of the data also shows that there were no significant differences between the fleets based on nationality, except that 1993 and newer US plated vehicles appear to have lower HC and higher CO emissions than other vehicles.

[22] In these charts, only data from vehicles for which a model year could be determined are included. For US-plated vehicles they were all registered in Arizona, as no attmpt was made by the project team to determine vehicle model year for US trucks registered in other states. The Arizona trucks included in these figures accounted for 94 percent of total US-plated truck crossings during the study period.

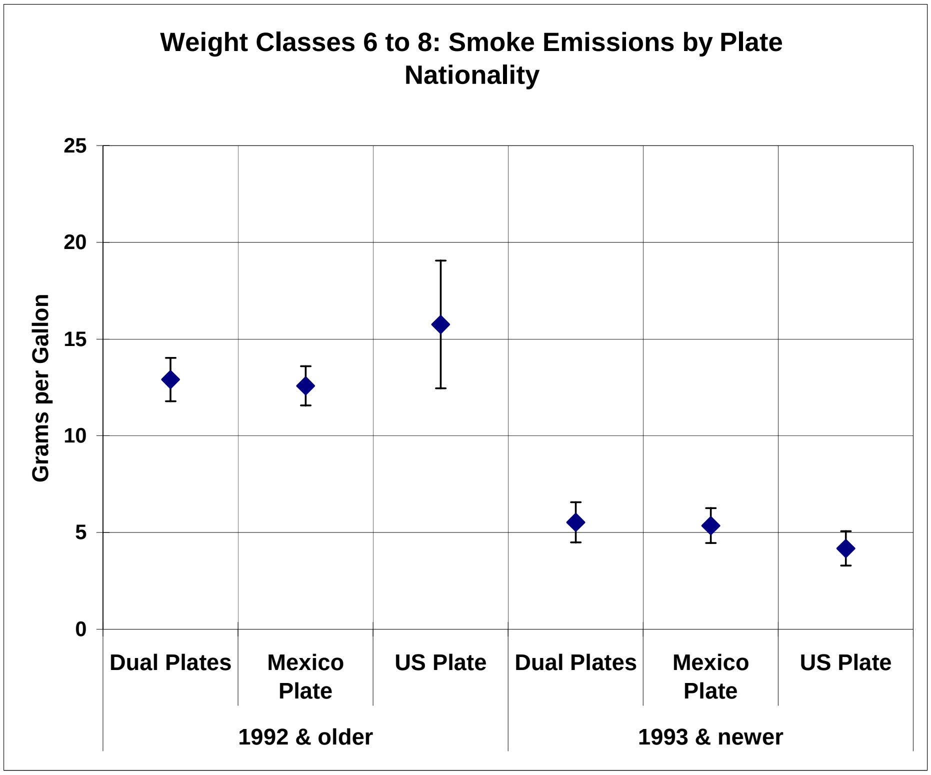


Figure 4.16 Average UV-Smoke Emissions

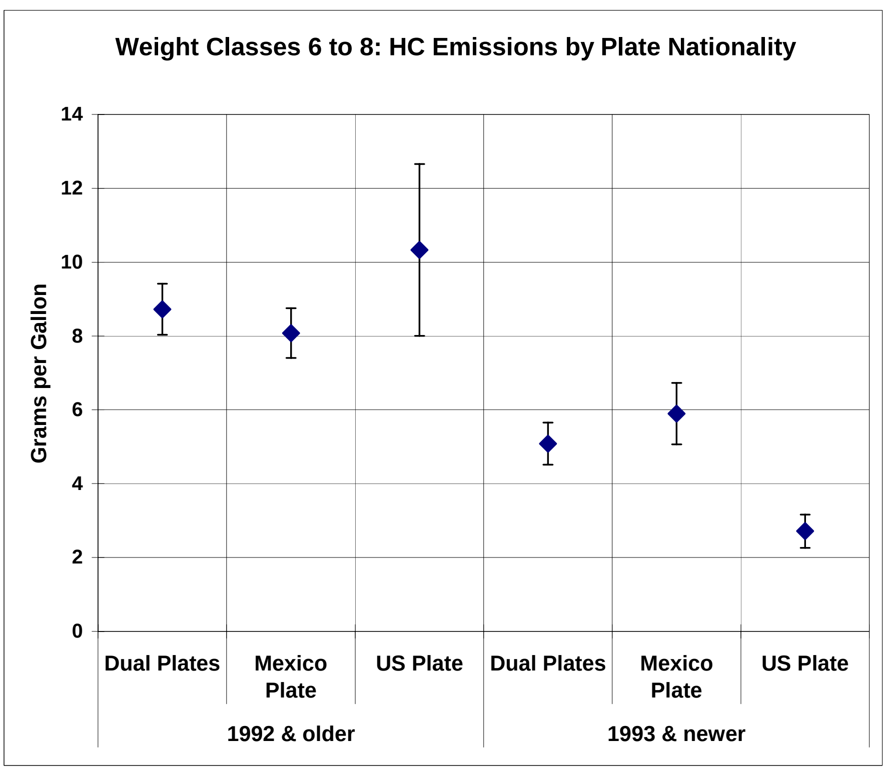


Figure 4.17 Average HC Emissions

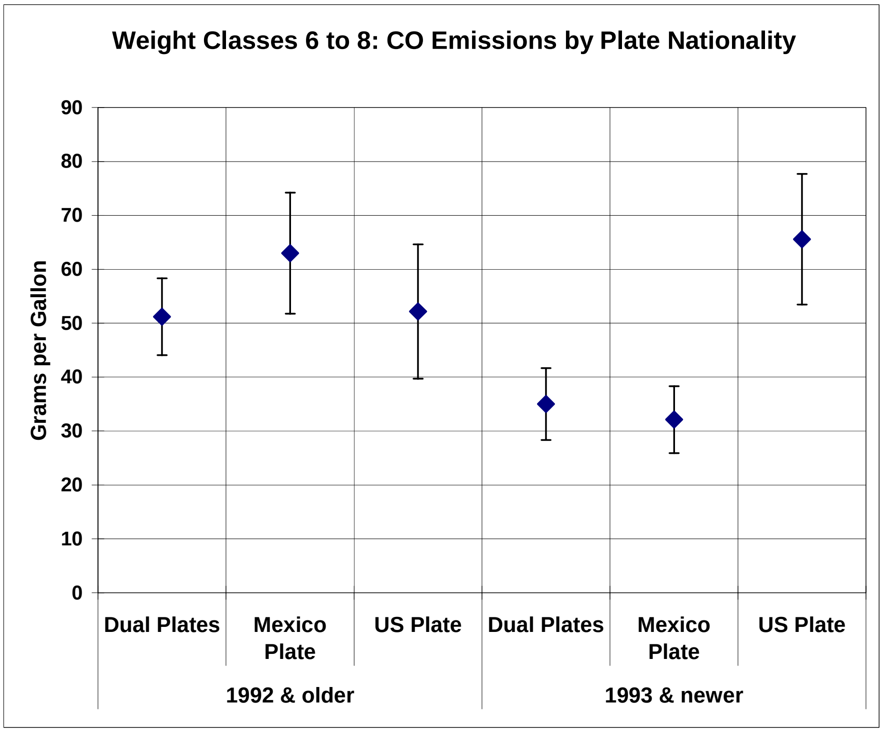


Figure 4.18 Average CO Emissions

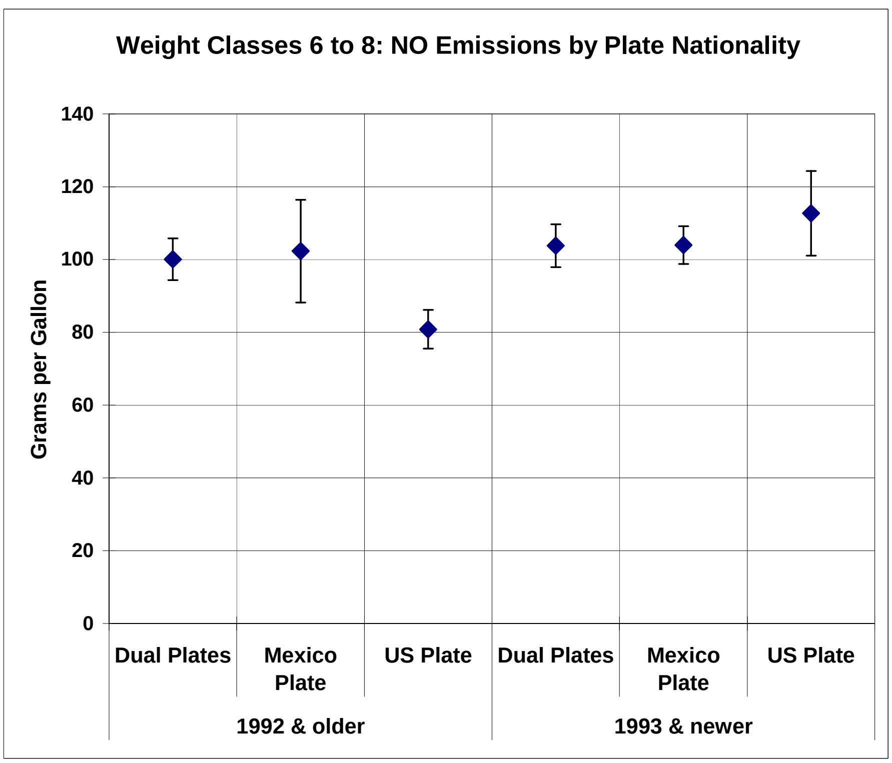


Figure 4.19 Average NO Emissions

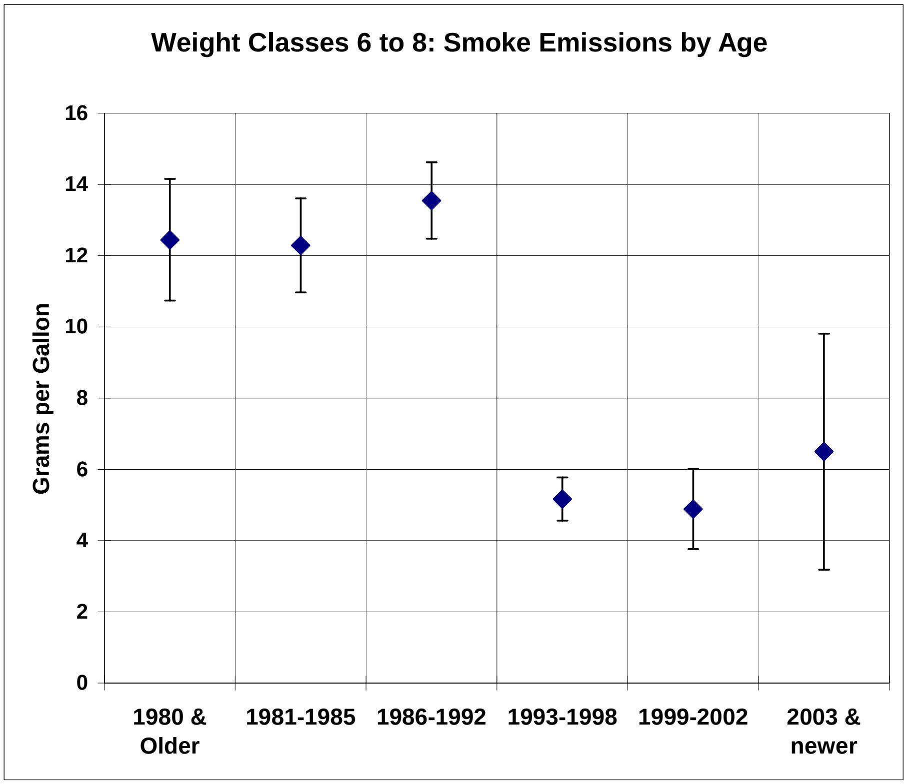


Figure 4.20 Average Smoke Emissions by Age

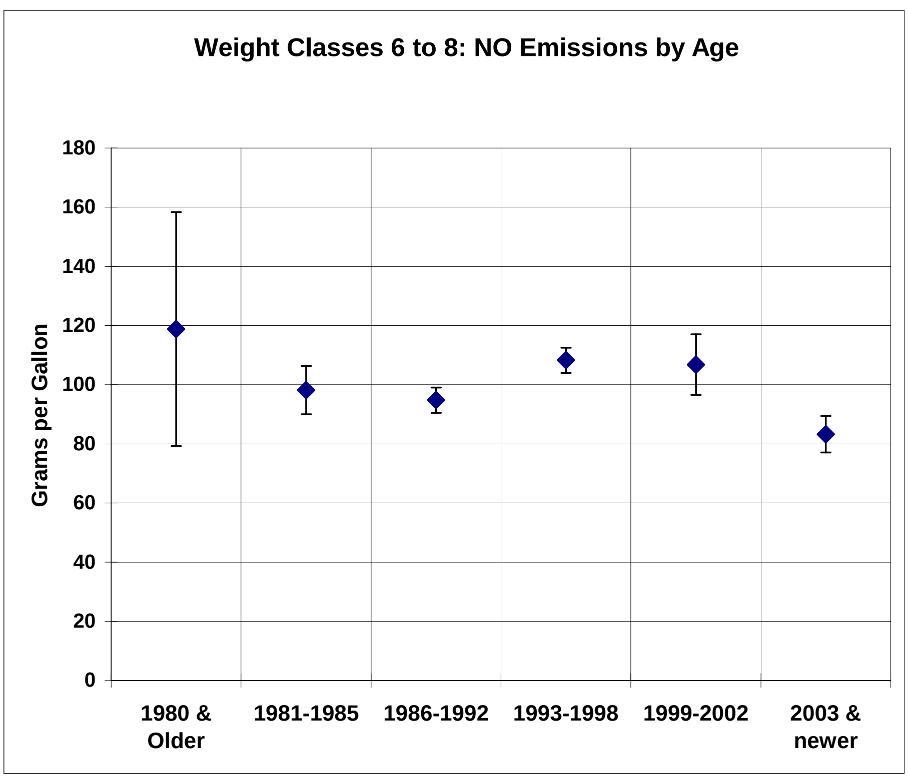


Figure 4.21 Average NO Emissions by Age

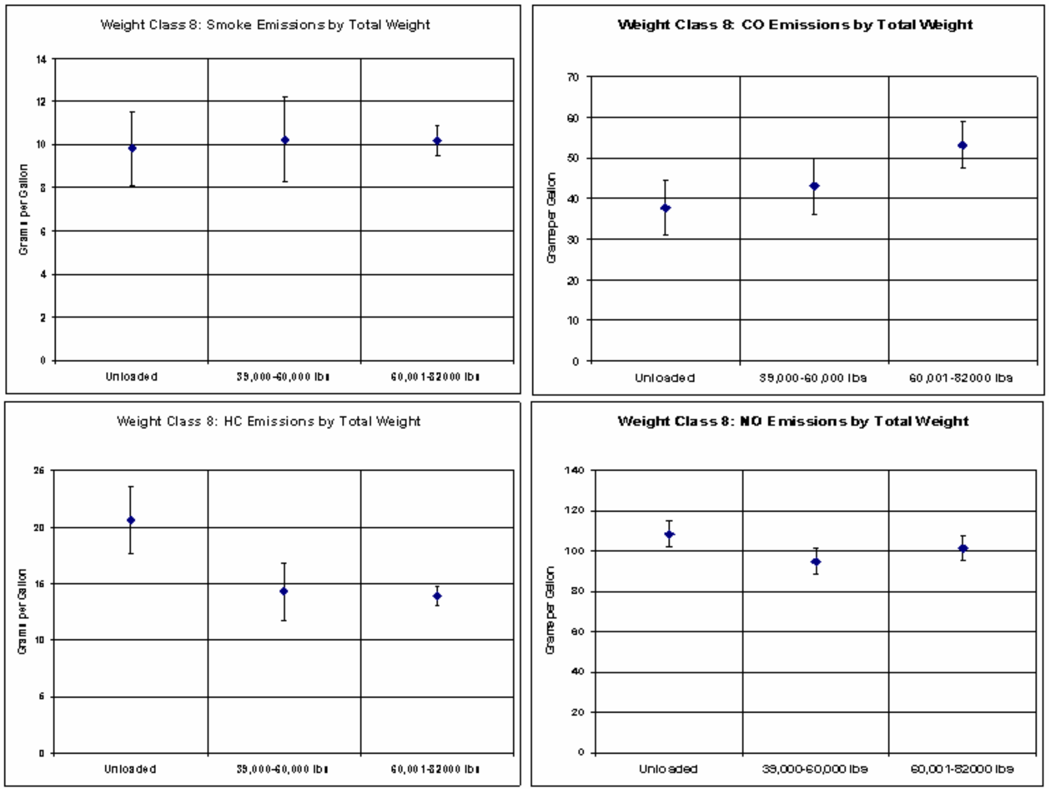


Figure 4.22 Average Emissions by Truck Weight

As shown in Figure 4.22, the loaded weight of the truck also had no material effect on fuel specific emissions rates of NO and Smoke, though unloaded trucks produced higher HC mass per gallon of fuel and more heavily loaded trucks produced higher CO mass per gallon of fuel. Obviously, for all four pollutants total fuel usage and total mass of emissions per trip would be expected to be greater for more heavily loaded trucks even if their fuel specific emissions rates were similar to those for more lightly loaded vehicles.

Section V Measurement Technology Comparison

In this section the data on emissions of the trucks crossing the border at Nogales as measured by each of the three technologies used in this project are directly compared.

V.A Comparison of HDRSD & PEMS Fleet Average Results

In this section, the average emissions of the Nogales fleet, as measured by HDRSD and PEMs, are compared. This comparison is qualitative at best, and must be evaluated with caution. The sample size of HDRSD measurements is several orders of magnitude larger than the sample size of PEMs results. In addition, as discussed above, the limited PEMS data set is not fully representative of the border fleet since there are very few measurements for the newest vehicles.

The comparisons by vintage for each of the pollutants as measured by both technologies (NO, CO, HC) are shown in Figures 5.1 – 5.3.   Comparisons for all three pollutants by truck nationality are shown in Figure 5.4.

As one can see in Figures 5.1 the fleet averages for NO emissions as measured by HDRSD are very similar to those measured by PEMs for all vintages of truck. As shown in Figure 5.2, HC emissions are also comparable for pre-1998 trucks. While the HDRSD may appear to measure higher HC emissions than PEMs from 1999-2002 trucks there is insufficient PEMs data from this vintage of vehicle to draw realistic inferences from the comparison.

As shown in Figure 5.3, HDRSD consistently measured only about half of the CO emissions as measured by PEMS, for all vintages. This may be due to the fact that the HDRSD measurements used to create these charts included only results taken while the vehicles were accelerating. The elevated average CO emissions as measured by PEMS may be influenced by other portions of the test cycles, as discussed below under Section V.B.

As shown in Figure 5.4, both PEMs and HDRSD provide very similar estimates of the average emissions of the US, Mexican, and dual-plated fleets, which are consistent with the estimates of average emissions by vintage. Again, no clear distinction is evident among the truck nationalities.

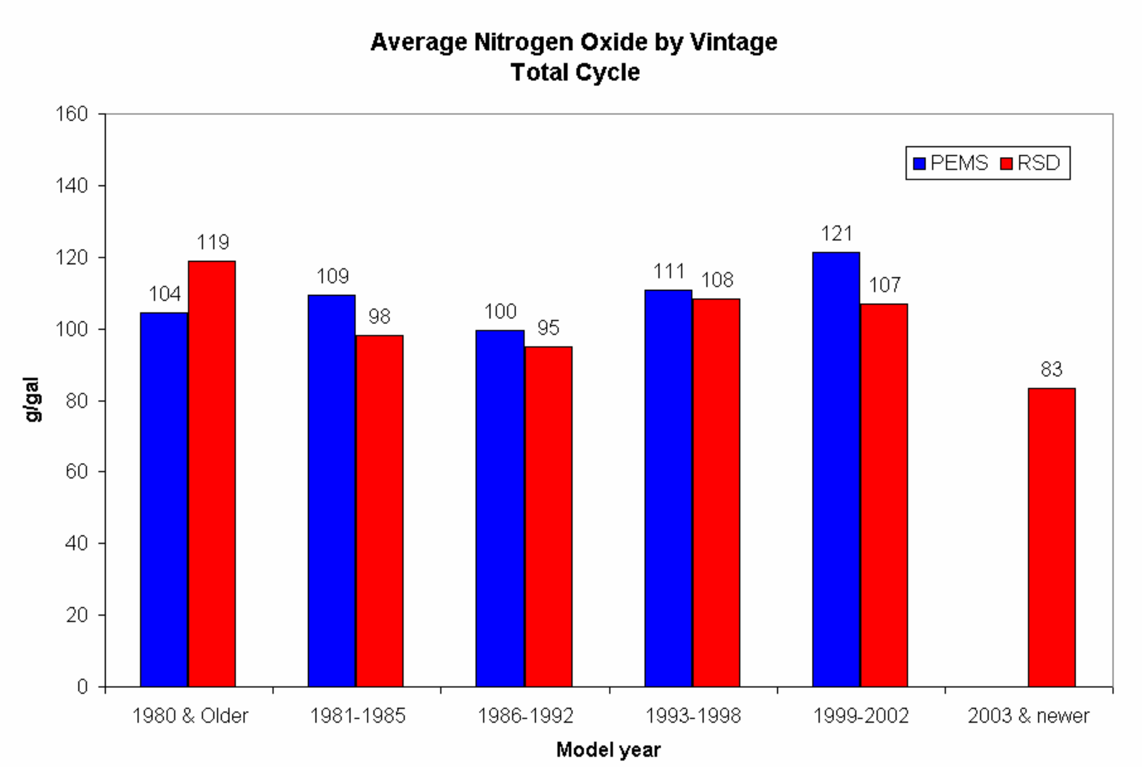


Figure 5.1 HDRSD –PEMs Comparison, NO by Vintage

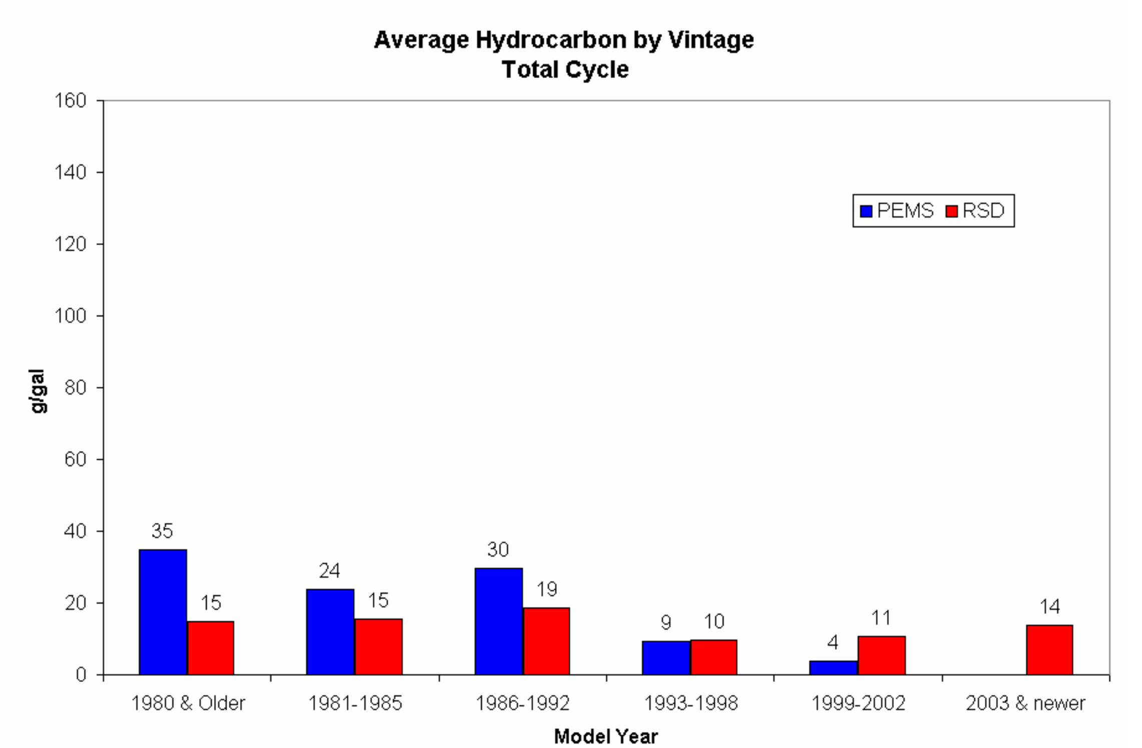


Figure 5.2 HDRSD-PEMs Comparison, HC by Vintage

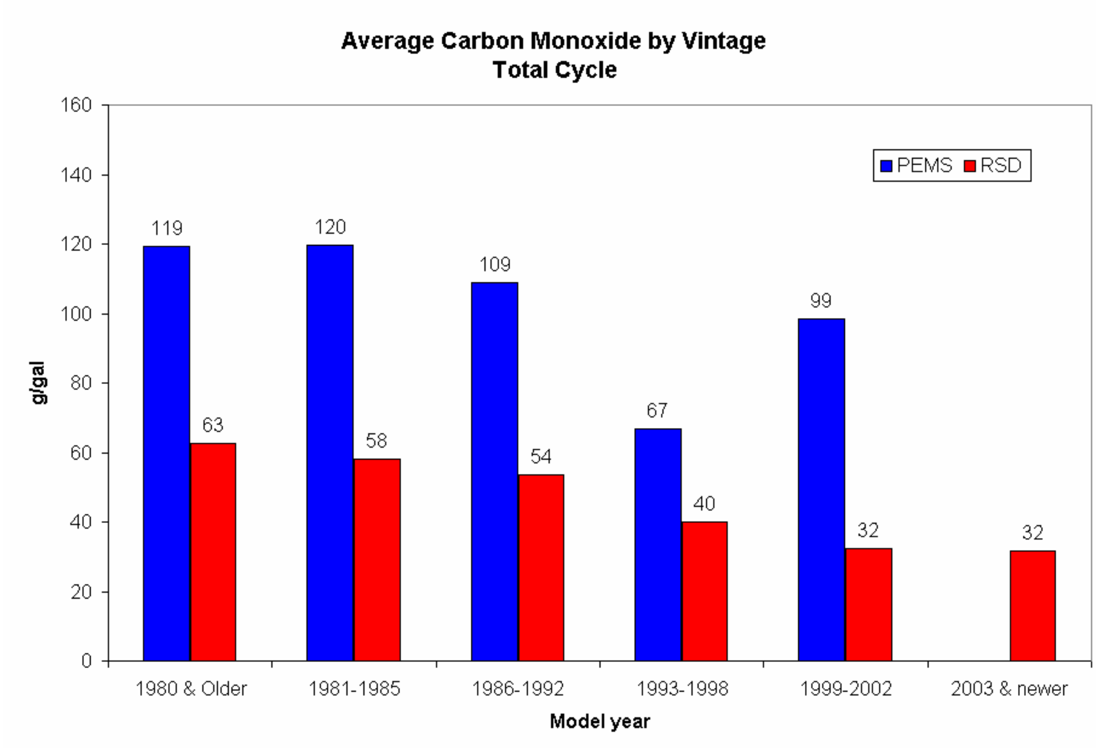


Figure 5.3 HDRSD-PEMs Comparison, CO by Vintage

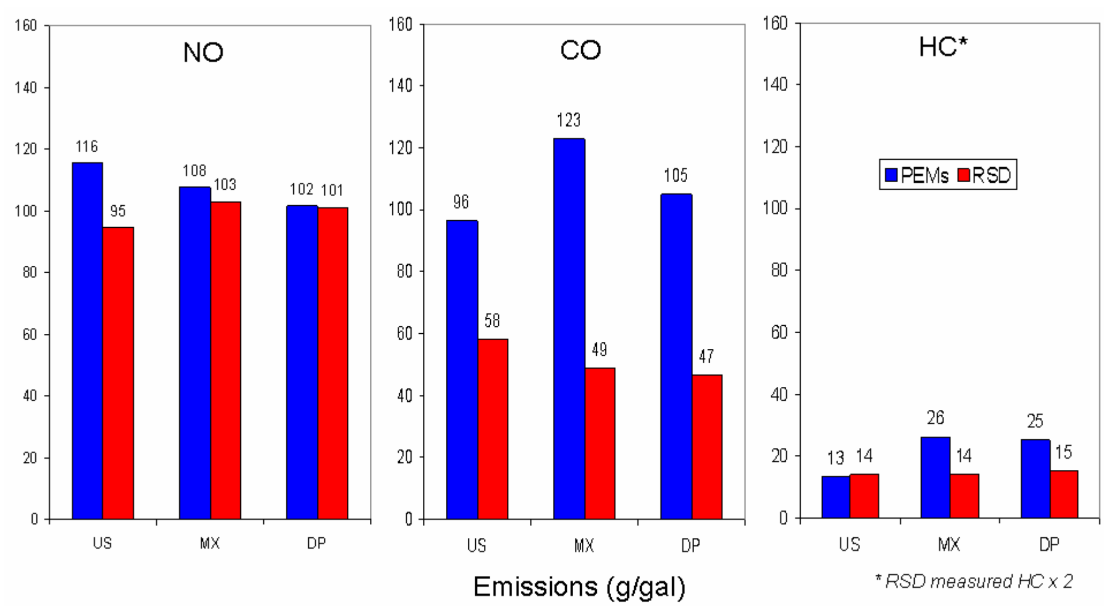


Figure 5.4 HDRSD-PEMs Comparison, NO, CO, HC by Truck Nationality

V.B Comparison of PEMS to HDRSD Measurements for Individual Trucks

In this section the emissions of individual trucks as measured by HDRSD and PEMS are directly compared. The original project plan envisioned time-matching PEMS and HDRSD results from all PEMS trucks, since these trucks passed the HDRSD sensors on their way out of the border compound. This proved to be impossible, primarily because the flow meter used with the PEMS testing re-directed the exhaust flow and valid HDRSD gas readings could not be recorded for most of the trucks when they passed HDRSD with PEMS installed.

However, as with many of the other trucks at Nogales, some of the PEMS-tested trucks crossed the border multiple times during the three-week HDRSD deployment, and valid HDRSD readings were recorded from some of these trucks either before or after they were PEMS tested. Of the 27 trucks with valid PEMS data, twelve also had at least one valid HDRSD reading collected over the three-week HDRSD deployment, and taken while the truck was accelerating. The actual number of valid HDRSD readings from these twelve PEMS trucks varied from one to 18.

For each truck these HDRSD readings were compared to the PEMS data recorded from the same truck. Please note that this comparison is not a "correlation" because the data compared was not collected at the same time by both technologies. A necessary assumption in comparing these data sets is that fuel-specific emissions rates from any single truck are relatively stable over time for similar engine operating states. Given the limited duration of the HDRSD testing this is a reasonable assumption, but its specific applicability for the trucks measured in this study can not be judged accurately.

Two examples of the results of this comparison are shown in Figures 5.5 and 5.6.

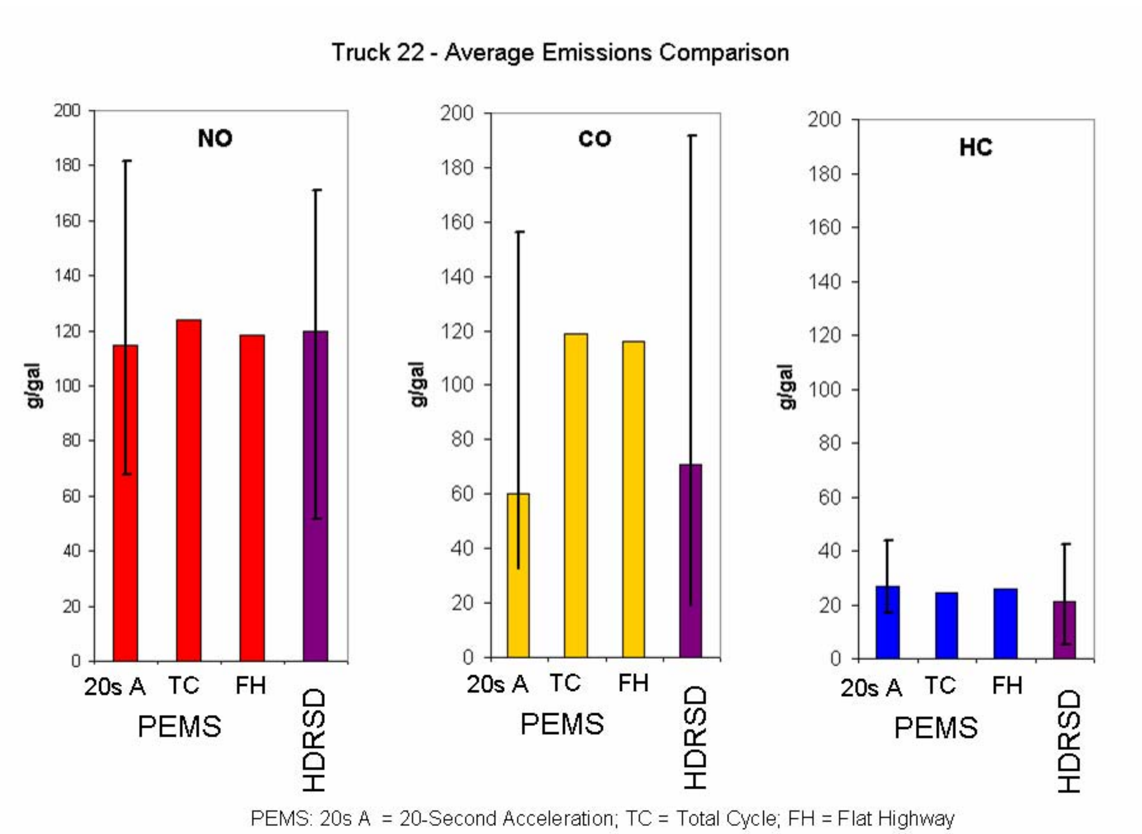


Figure 5.5 Truck 22 Comparison of Average PEMS to Average HDRSD Results

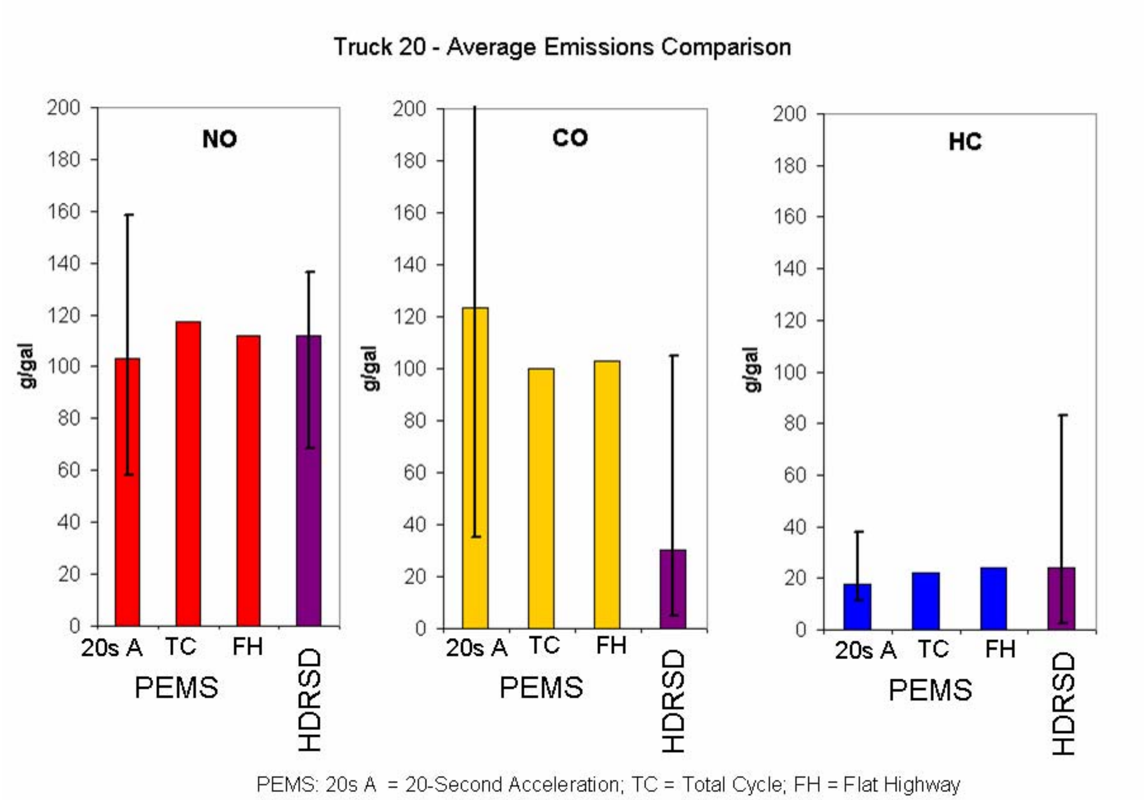


Figure 5.6 Truck 20 Comparison of Average PEMS to Average HDRSD Results

In these figures the average HDRSD result (g/gal) is shown along with the average PEMS result from three different "drive profiles", including Total Cycle, Flat Highway, and 20-Second Acceleration. "Total Cycle" is the average over the entire PEMS file that was collected; this is the same data used for the analysis in Section IV.H. "Flat Highway" is the average over only the section of the PEMS file where the truck was traveling at relatively high speed and was not losing significant elevation; this is as close to representative of "typical" highway driving as we can achieve with the available data. "20-Second Acceleration" is the average over 20 seconds in the PEMS file during which vehicle speed was increasing. These accelerations were taken from the PEMS file in the vicinity of where the HDRSD was set up (per GPS), and in most cases probably represent acceleration of the vehicle past the HDRSD sensors as the vehicle merged onto the highway. In each case the data for the PEMS 20-Second Acceleration case starts when the truck was going 4 mph.

In the figures the heavy bars represent the average and the black lines that extend above and below the average for the HDRSD and PEMS 20-Second Acceleration cases represent the range of instantaneous (one second) values in that data set.

As shown, for NO and HC the "average" HDRSD result for these trucks is well representative of the average PEMS result – regardless of PEMS drive cycle. In addition, the range of values seen in a set of multiple HDRSD readings taken over time is generally consistent with the range of instantaneous one second PEMS values seen during a typical acceleration event – when the vehicle was passing the HDRSD array in this project.

Note that the 20-second Acceleration data set for each truck virtually always contains shift points when the engine is momentarily unloaded. During these shifts the instantaneous fuel-specific emissions rates would be expected to be higher than when the engine was loaded; the highest values in the 20-second Acceleration data set for each truck are almost certainly these shift points. While the HDRSD data was specifically screened to try to remove shift points (using measured vehicle acceleration) the accuracy of actual acceleration measurements made by HDRSD in this project was not sufficient to ensure that all HDRSD data corresponding to shift points was removed. Therefore, at least some of the high data points contained in the HDRSD data set for each truck may also correspond to shift points. Improved measurement of vehicle acceleration is an area that requires further refinement for future HDRSD deployments (see section VIII.C).

The comparison of HDRSD to PEMS 20-Second Acceleration for all twelve trucks is shown in Figures 5.7 and 5.8, for NO and HC respectively. As in Figures 5.5 and 5.6 both the average and the range of instantaneous values in each data set is shown. As one can see, most of the other ten trucks were consistent with the two trucks shown in Figures 5.5 and 5.6.

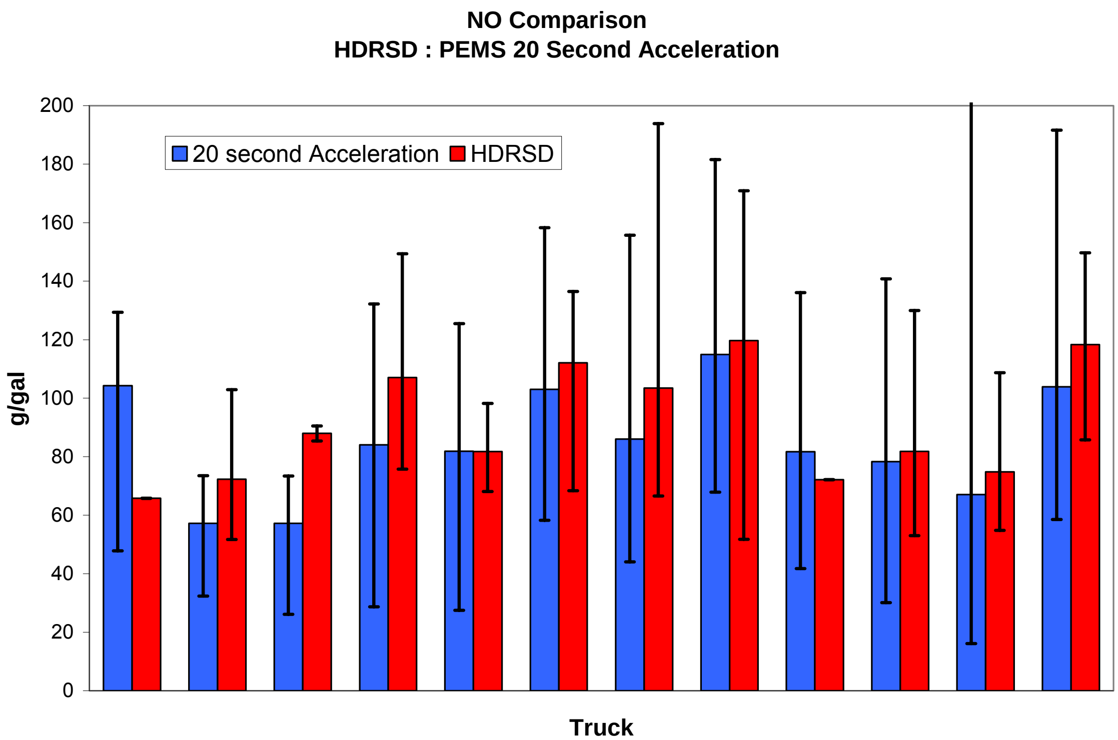


Figure 5.7 Comparison of Average PEMS NO to Average HDRSD NO, 12 Trucks

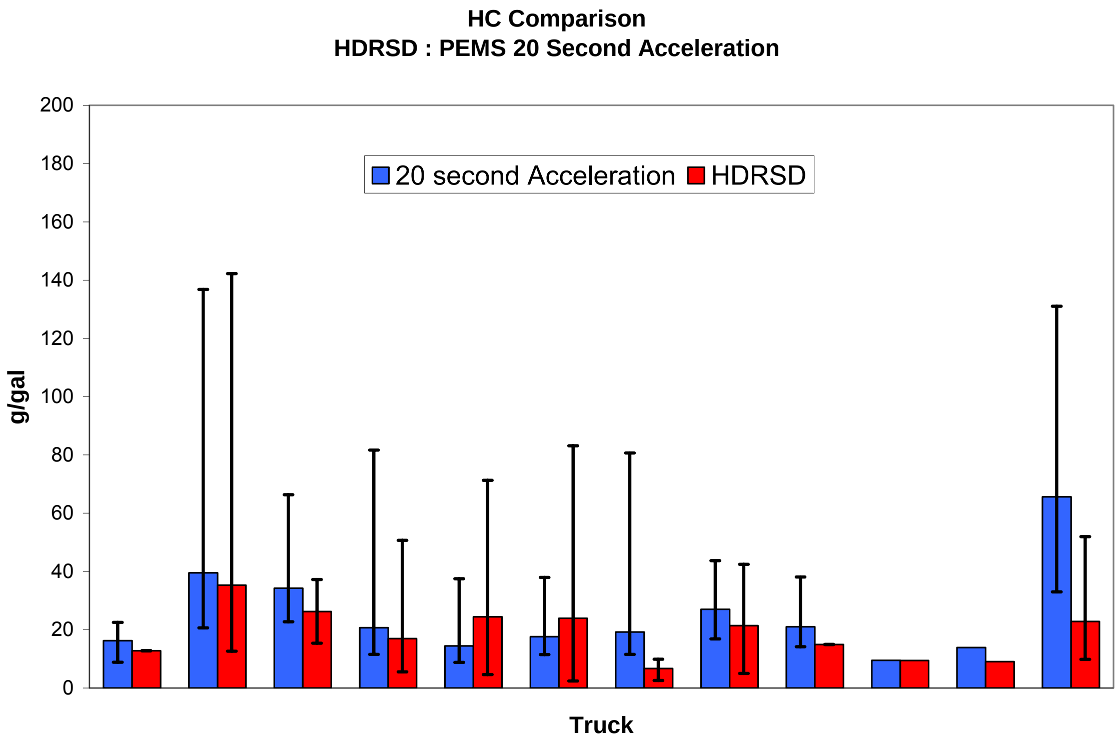


Figure 5.8 Comparison of Average PEMS HC to Average HDRSD HC, 12 Trucks

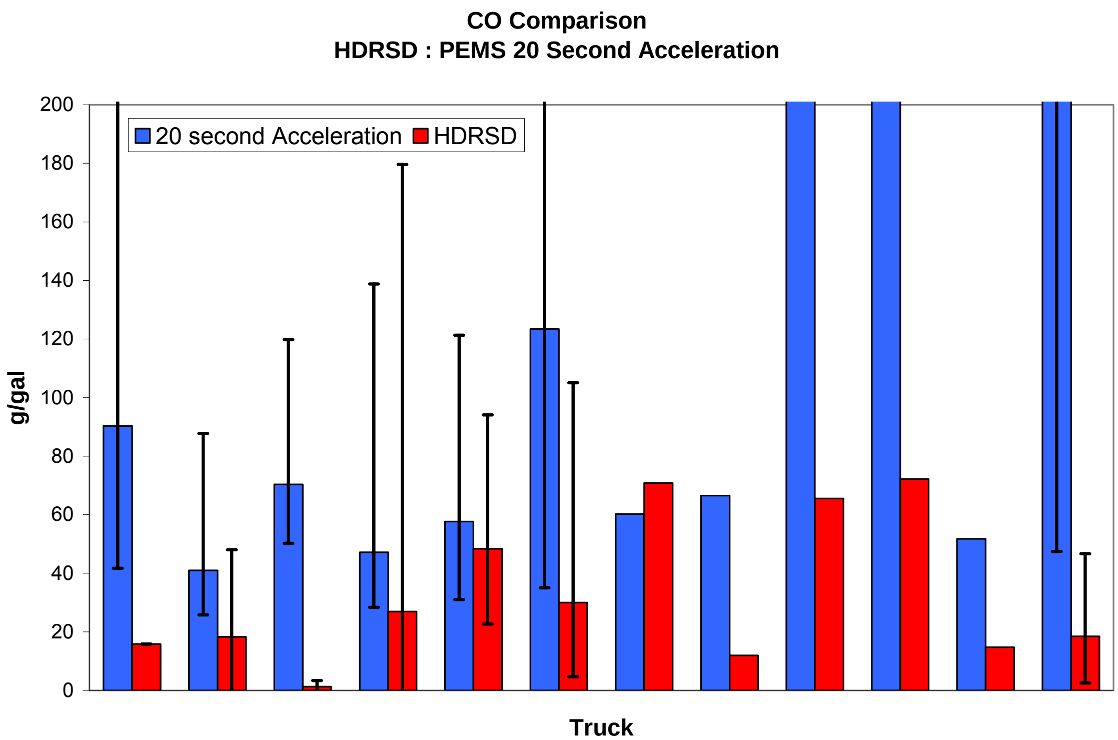


Figure 5.9 Comparison of Average PEMS CO to Average HDRSD CO, 12 Trucks

The results for CO were not as consistent from truck to truck as the results for NO and HC. As shown in Figure 5.5, for Truck 22 the average and range of HDRSD results were well representative of the PEMS 20-Second Acceleration data, but the HDRSD average was significantly below the PEMS Total Cycle and Flat Highway averages. As shown in Figure 5.6, for Truck 20 the HDRSD data was not well representative of PEMS results for any drive cycle. Figure 5.9 shows the CO data for all twelve trucks.

Further review of the PEMS data collected in this project points toward an explanation for the lack of concurrence between HDRSD and PEMS average CO results, both when aggregated by vehicle age bin (Section V.A) and when compared for the same truck.

As shown in Figure 5.7, instantaneous NO emission rates as measured by PEMS varied between 30 and 120 g/gal for most trucks while they were accelerating. For most trucks the high value was only 3 - 4 times the low value. As shown in Figure 5.8, instantaneous HC emission rates as measured by PEMS varied between 5 and 50 g/gal for most trucks while they were accelerating. While the high value reached 140 g/gal for some trucks, even for these trucks the high value was generally less than seven times the low value.

As shown in Figure 5.9, for a number of trucks the range of instantaneous PEMS values were much greater for CO. In fact, while accelerating a single truck could record instantaneous CO values between 20 and 3,600 g/gal. For the most part these “spikes” in CO are of short duration – lasting only a few seconds or less. These CO spikes occur throughout the recorded drive cycle for various trucks – during acceleration from low speed, as well as at various times while the vehicle is operating at high speed on the highway. In many, though not all, cases they appear to be associated with transmission shifting. During the highway portions of the drive cycle they may also be associated with operation of the vehicle’s exhaust brake.

This can be seen is Figure 5.10, which plots CO emissions (g/gal) versus CO_2 emissions (g/s) for Truck 21. Because instantaneous CO_2 output is proportional to instantaneous fuel input it is also roughly proportional to instantaneous engine load.

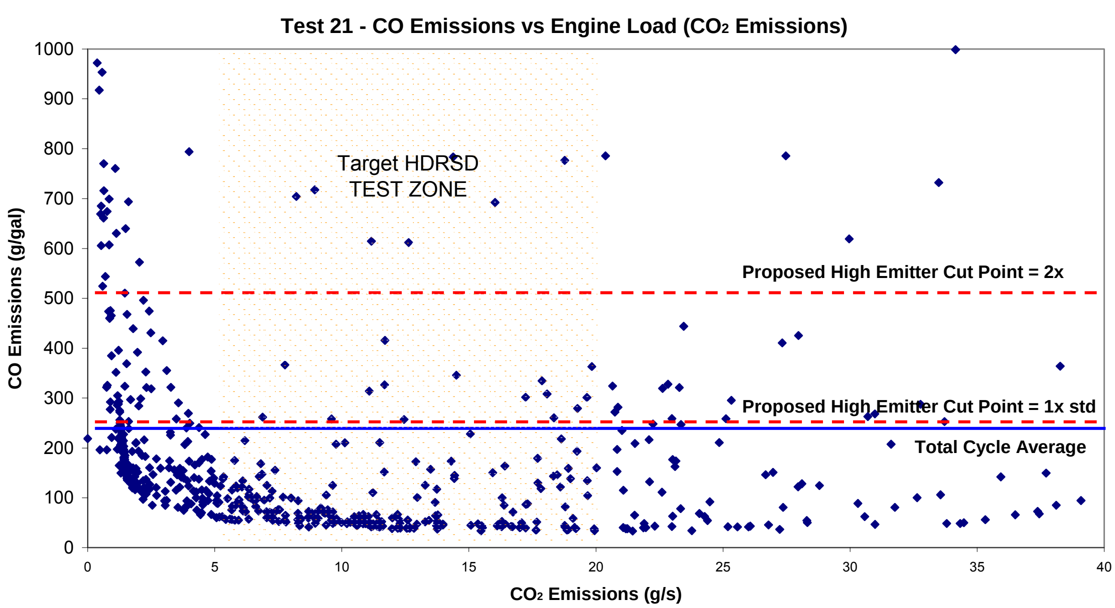


Figure 5.10 CO Emissions vs Engine Load for Truck 21

CO emissions from this truck were much more variable while the engine was under load than NO and HC emissions. While the CO emissions rate was generally below 100 g/gal it periodically jumped to 800 g/gal or more.

Despite being short in duration these spikes in CO while the engine is under load can account for a significant portion of total CO emissions in many cases. The entire PEMS file for the 27 PEMS-tested trucks was analyzed to determine what percentage of total CO mass was emitted while the engine was emitting at a level above several different "cut-points" representing the general average CO emissions rate in most of the PEMS files. The cut points chosen were 100 g/gal and 200 g/gal. The results are shown in Figure 5.11. As shown, in many cases 50% or more of total CO mass was emitted in 10% or less of the total drive time.

Truck	When CO emissions rate is above:			
	100 g/gal		200 g/gal	
	% CO mass	% Time	% CO mass	% Time
00	63%	26%	48%	11%
06	84%	45%	78%	38%
09	96%	69%	83%	19%
11	89%	44%	74%	15%
13	79%	45%	55%	14%
14	89%	62%	57%	13%
15	97%	51%	92%	31%
16	92%	64%	75%	31%
18	91%	50%	81%	27%
20	95%	62%	84%	25%
21	98%	74%	93%	39%
22	77%	32%	69%	24%
24	98%	49%	97%	42%
25	70%	32%	54%	15%
26	97%	69%	85%	15%
27	91%	46%	82%	22%
28	53%	21%	31%	6%
30	91%	55%	81%	34%
31	94%	28%	92%	20%
32	94%	66%	80%	33%
33	77%	31%	62%	9%
34	92%	47%	84%	21%
35	89%	35%	75%	14%
36	72%	17%	67%	10%
39	63%	15%	57%	10%
41	87%	71%	32%	10%
42	77%	15%	75%	13%

Figure 5.11 CO Emissions above CO Emissions Rate Cut points

These CO spikes count disproportionally toward the PEMS averages, but because they are infrequent they are not always "caught" by the short-duration HDRSD measurement. In fact, it appears that while short-duration HDRSD measurements are a good proxy for longer-duration

cycle average emissions measurements when evaluating NO and HC, they are less accurate for CO, based on typical engine operation of the trucks tested at Nogales. It is possible that extension of the HDRSD measurement window to 2-3 seconds could improve the usefulness of HDRSD measurements in evaluating CO emissions, but this has not been evaluated in practice.

Please note that, in general, this comparison of PEMS to HDRSD results on a truck by truck basis is consistent with the analysis of results grouped by vehicle age bin in Section V.A, for all three measured gaseous pollutants, CO, HC, and NO.

V.C Comparison of Opacity Measurements to HDRSD Smoke Factor

In this section the emissions of individual trucks as measured by HDRSD smoke factor and traditional J1667 snap-idle opacity testing are directly compared. Of the 42 trucks with opacity test data 18 also had at least one valid HDRSD reading collected over the three-week HDRSD deployment and taken while the truck was accelerating. The actual number of valid HDRSD readings from these opacity tested trucks varied from one to 18.

For each truck the set of HDRSD smoke factor values were compared to the J1667 opacity values recorded from the same truck. These data, for all 18 trucks, are shown in Figure 5.12. In the figure, both the average and the range of values are shown for each truck. For opacity three individual “snaps” were taken for each truck. As shown, both opacity and Smoke Factor values vary considerably for the same truck. There is no clear, consistent relationship between opacity and HDRSD Smoke Factor, but in fact no correlation was expected. Opacity testing with the J1667 procedure and HDRSD Smoke Factor results have significant technical differences which include:

- Loaded engine (HDRSD) vs unloaded engine (J1667) test
- Accelerating snapshot (HDRSD) vs peak (J1667) result
- Includes estimate of fuel burned based on CO_2 measurement (HDRSD) vs measurement of plume with unknown dilution (J1667)
- Short wavelength (HDRSD) vs long wavelength (J1667) measurement

“Correlation” charts comparing average and maximum recorded opacity to average and maximum recorded smoke factor for the 18 trucks are included below in Figures 5.13 and 5.14. As shown these provide further evidence that there is no clear, consistent relationship between opacity and HDRSD smoke factor.

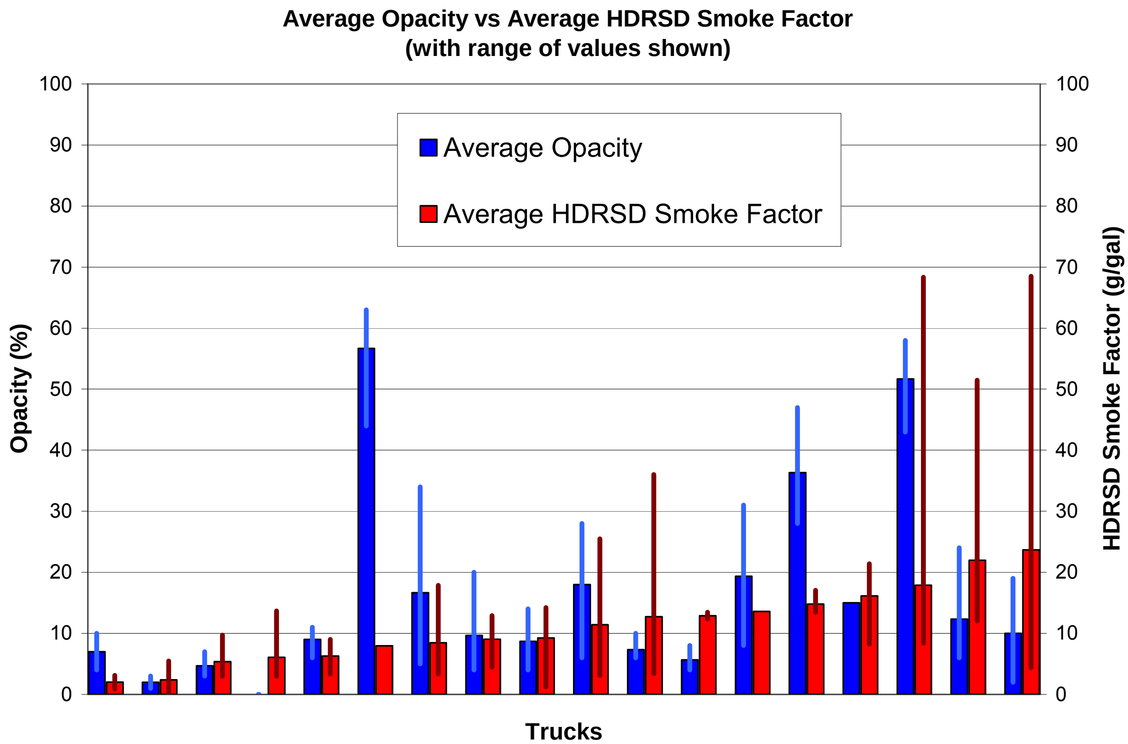


Figure 5.12 Comparison of Average Opacity to Average HDRSD Smoke factor, 18 Trucks

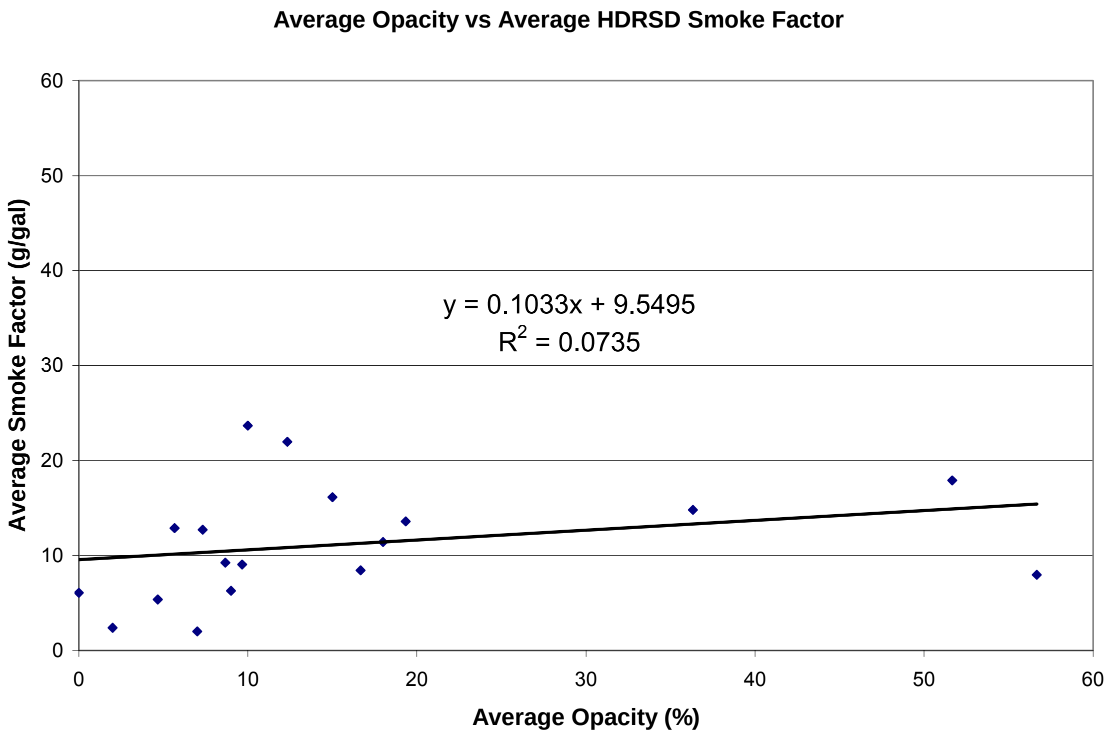


Figure 5.13 Comparison of Average Opacity to Average HDRSD Smoke factor, 18 Trucks

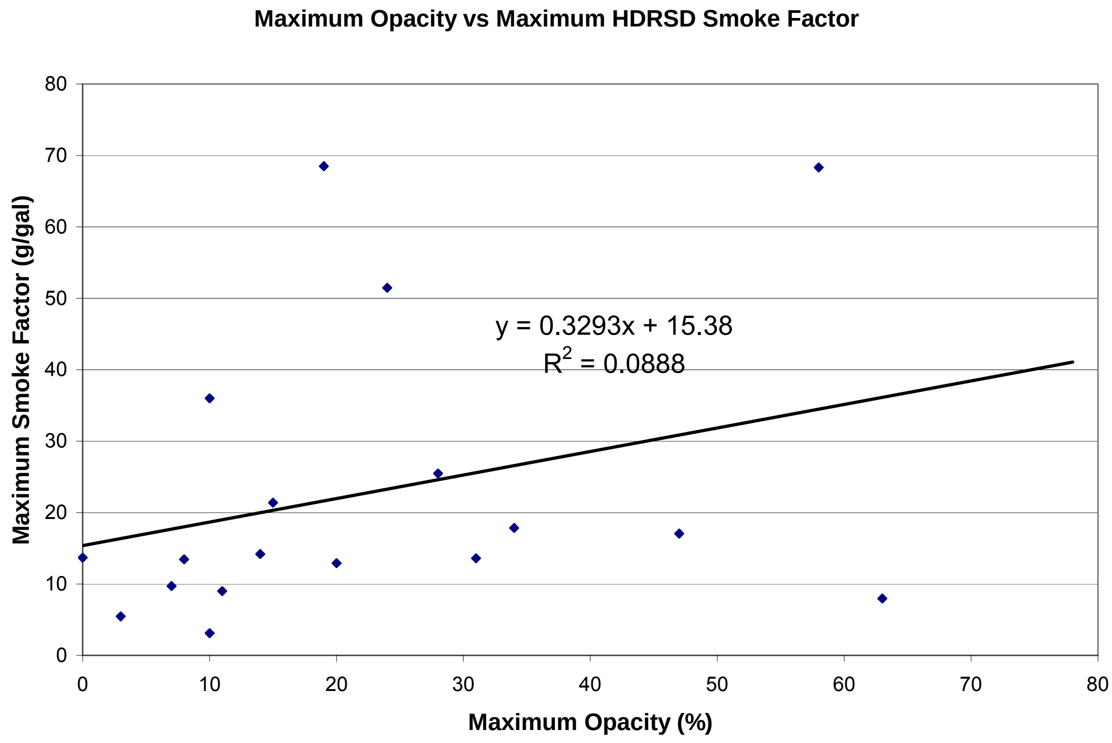


Figure 5.14 Comparison of Maximum Opacity to Maximum HDRSD Smoke factor, 18 Trucks

Section VI Identification of Potential Gross Emitting Vehicles

VI.A Gross Emitter Identification Using HDRSD

One chief goal of this pilot project was to demonstrate the capability of HDRSD technology to identify gross emitting trucks. Identification of potential gross emitters by the HDRSD equipment was determined by plotting the emissions for each unique vehicle on each trip that it made, along with the average for all of its trips. To add greater certainty to HDRSD identification of gross emitters, only trucks that had crossed the border multiple times with multiple valid HDRSD measurements were analyzed. Figures 6.1 - 6.4 show these average emissions per trip plotted for all vehicles that made at least four trips during the study period where the emissions measurement for each trip met the screening conditions described in Appendix D. In these charts, unique vehicles are arranged along the horizontal axis, shown from high to low within each nationality group. Results from each trip for each vehicle are plotted vertically above each truck identifier. The average for each truck for all of the trips that it made is shown in red.

Figures 6.1 - 6.4 demonstrate that the HDRSD technology has the capability to identify trucks with an HDRSD signature significantly different than the majority of trucks in the fleet. These trucks are readily identified as trucks with points elevated along the Y axis – indicating that their average emissions as measured by HDRSD were higher than the other tested vehicles. Figure 6.5 highlights the smoke emissions of vehicles with Mexican plates, as an example. As shown, three vehicles have consistently high smoke emissions, which are approximately three times the fleet average. Similarly, Figure 6.6 shows the NO emissions of vehicles with US plates. As shown, two vehicles have NO emissions that are consistently two to three times the fleet average.

This project did not include follow-up testing of the potential gross emitting trucks highlighted in Figures 6.5 and 6.6 (or any others) using PEMS or other test methods to confirm their status. Confirmation that the trucks flagged by HDRSD are in fact gross emitters would require such testing, which was beyond the scope of this project.

Also note that there was significant variability in the HDRSD readings from some individual trucks. Some of this variability may be due to the HDRSD equipment, some may be due to variability in engine emissions levels, and some may be due to variability in engine operating state during the different HDRSD measurements. As discussed in Section VIII.C, of particular concern are potential HDRSD readings taken during a transmission shift as the truck passed the HDRSD equipment, which would not be relevant to designation of a high emitter.

The use of multiple HDRSD readings enhances the confidence for any high emitter designation. During this pilot project we were able to easily collect multiple HDRSD readings from many crossing trucks, but not all deployment locations will necessarily allow for this. As discussed in Sections VII.V and IX, additional work is required to evaluate the best HDRSD set-up and deployment strategies in different situations, and to determine the minimum number of HDRSD measurements required to confidently flag high emitting vehicles.

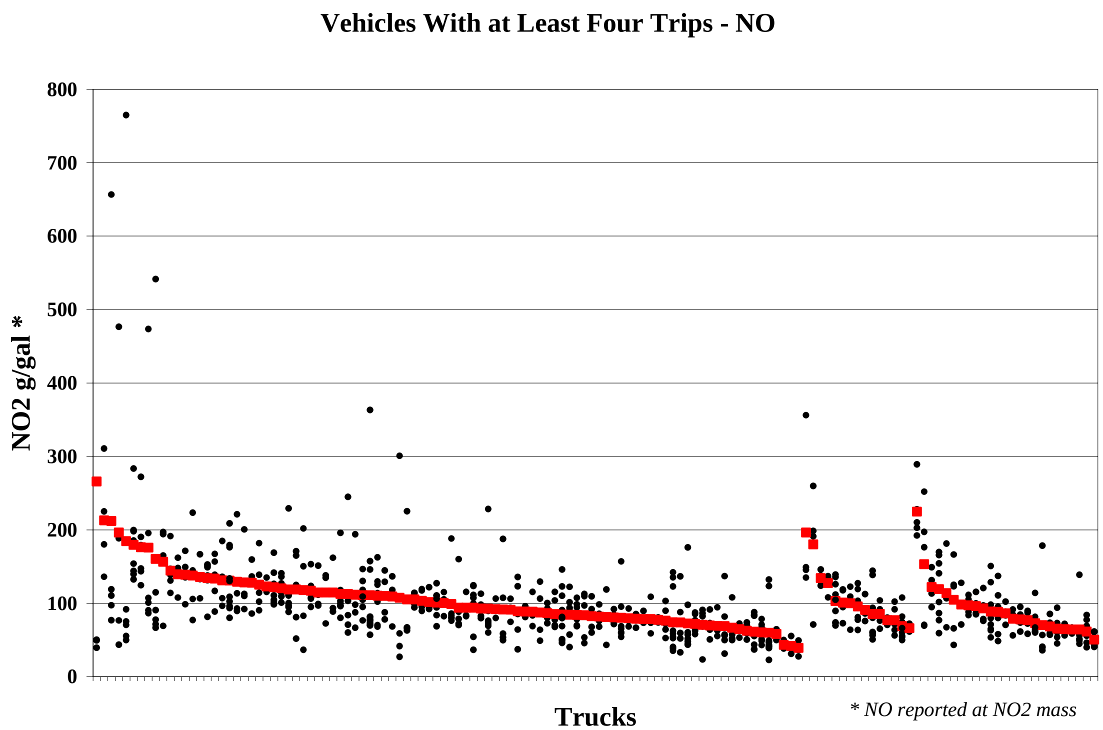


Figure 6.1 Vehicle Trip Emissions - NO

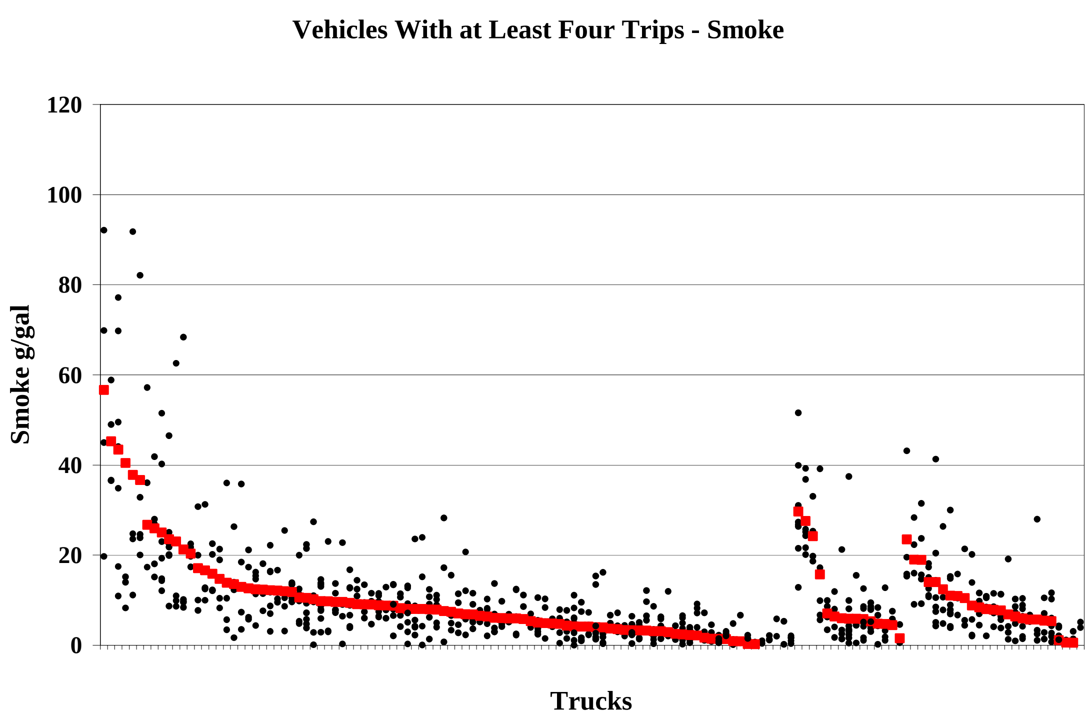


Figure 6.2 Vehicle Trip Emissions - Smoke

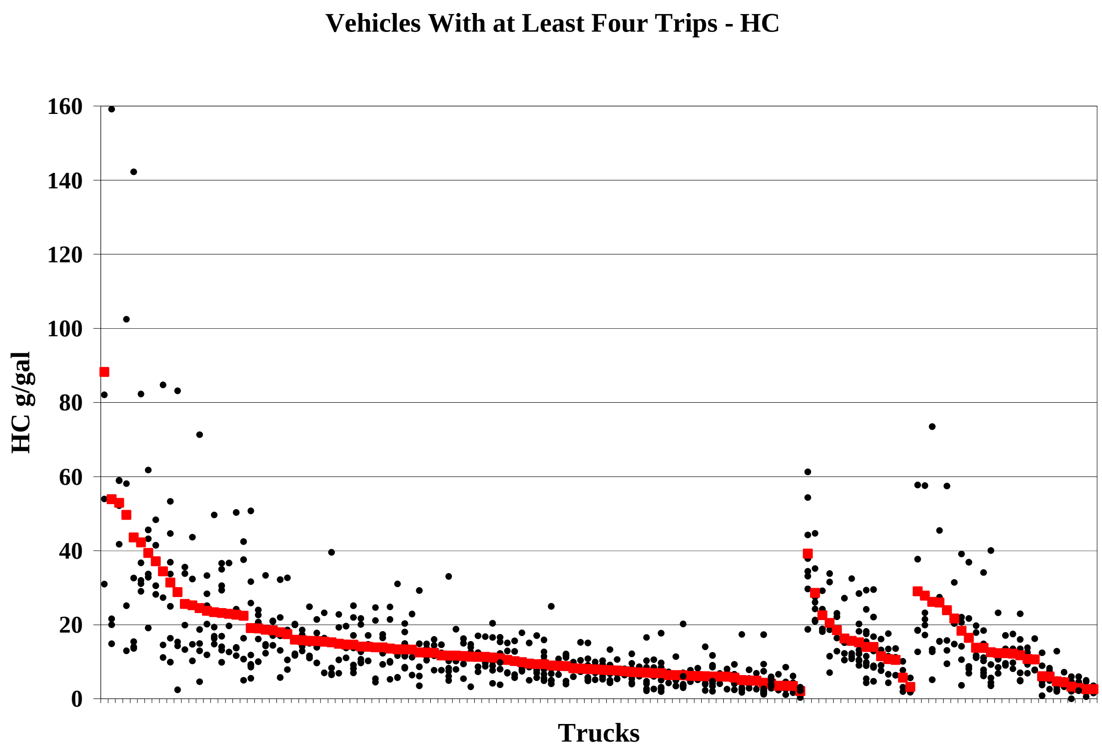


Figure 6.3 Vehicle Trip Emissions - HC

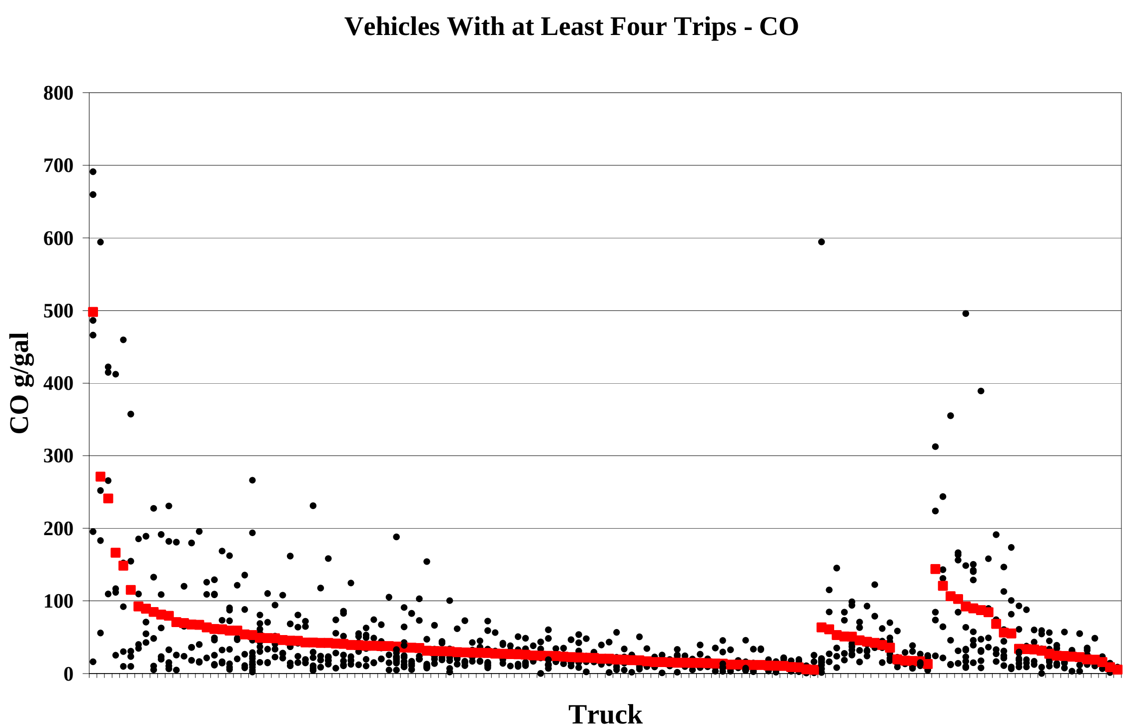


Figure 6.4 Vehicle Trip Emissions - CO

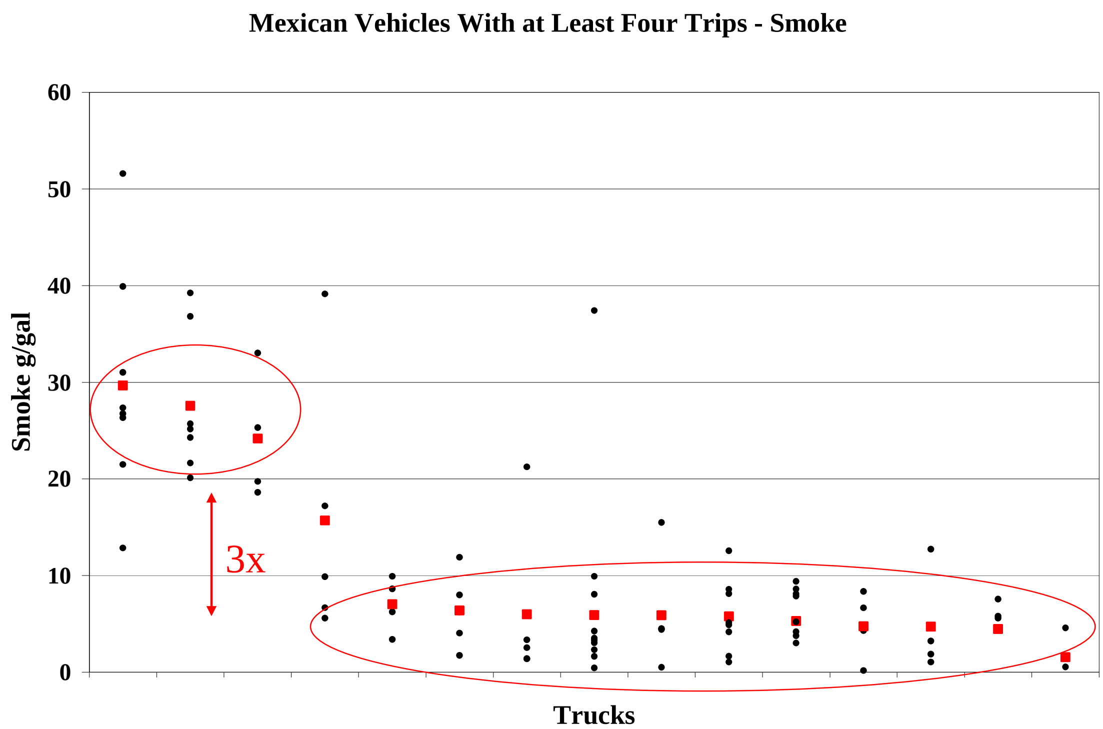


Figure 6.5 Mexican Plated Vehicle Trip Emissions - Smoke

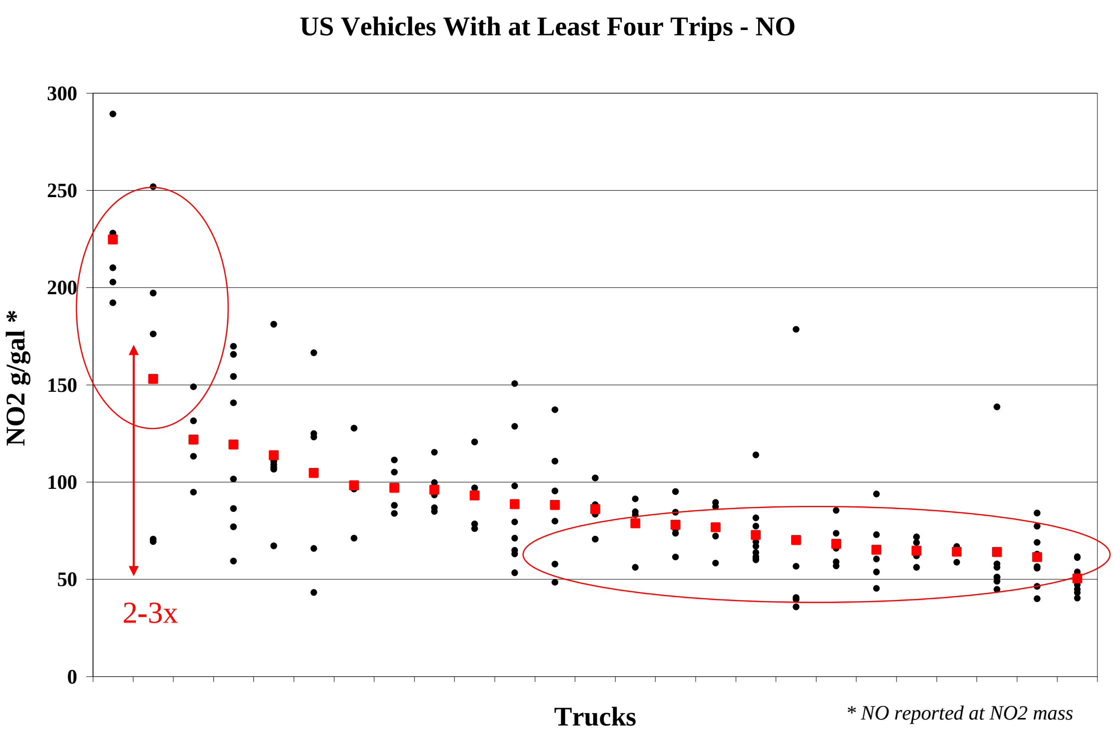


Figure 6.6 US Plated Vehicle Trip Emissions - NO

VI.B Determining Appropriate Cut Points for Pilot Project Dataset

By reviewing Figures 6.1 through 6.6, preliminary assumptions can be made about where a reasonable threshold would be placed, above which vehicles flagged by HDRSD would be considered gross emitters in need of maintenance and repair. For discussion purposes, a truck was considered a potential 'gross emitter' if its fuel specific emissions rates as measured by HDRSD were consistently greater than the majority of tested trucks. The cut points were selected by examining the point in the distribution curve where emissions clearly increased. For example, in Figure 6.5, most of the trucks had emissions of smoke below 10 g/gallon, but there are three trucks whose smoke emissions were between 20 and 30 g/gallon. These three trucks might be considered potential gross emitters.

Review of the collected HDRSD smoke factor data suggested that a cut point of 20 g/gal Smoke would be appropriate. The EPA engine standard for PM was 0.25 g/bhp-hr, or approximately 4 g/gallon PM, from 1991 – 1993, after which it dropped to 0.1 g/bhp-hr (approximately 1.6 g/gallon). Direct comparison between these values may not be appropriate since the correlation between HDRSD smoke factor and PM mass as measured by other methods has not yet been demonstrated.

In Figure 6.6, it can be seen that NO emissions for the majority of trucks are consistently below 100 g/gallon, but that two trucks had NO emissions between 150 and 250 g/gallon. In this case, approximately 150 g/gallon seems a reasonable cut point. For NO_x, the certification standard in the late 1980's was 10.7 g/bhp-hr or 144 g/gallon, which subsequently was reduced to 5 g/bhp-hr **(**67 g/gallon) in 1991. For a diesel vehicle, NO generally comprises about 75% - 90% of NO_x, so that trucks meeting the certification standard for NO_x would be expected to emit between 50 and 130 g/gallon NO, depending on vintage and operating conditions. For the pilot project, an NO gross emitter cut point of 150 g/gallon therefore represents NO emissions of 1.5 to 3 times the latest certification standard.

HC and CO standards for virtually all of the trucks tested in this project were 1.3 g/bhp-hr (22 g/gallon) and 15.5 g/bhp-hr (258 g/gallon) respectively. The potential HC cut point chosen for this pilot project was twice the the certification standard (44 g/gallon) while for CO it was exactly at the standard of 258 g/gallon. Using only the standard for CO is appropriate since most experts agree that the standard isn't very strict. Most trucks emit only one fifth of the standard, so anything that even approaches the standard is likely a gross emitter.

Much more data need to be collected and analyzed to determine if HDRSD accurately flags gross emitting trucks, and to establish the appropriate cut points. Nonetheless, the cut points chosen for this pilot project suggest the following results for the tested Nogales border fleet:

- With a cut point of 20 grams/gallon (~ 1.2 g/bhp hr) for PM, HDRSD would flag 13 percent of trucks as potential gross emitters, which were responsible for 40 percent of particulate emissions.

- With a cut point of 144 grams/gallon of NO (~ 10.7 g NO/bhp hr – equivalent to approximately 13.4 g/NO_x/bhp hr since NO_x from a diesel engine is generally about 80% NO) for NO, HDRSD would flag 10 percent of the trucks as potential gross emitters, which were responsible for 19 percent of the NO emissions.

- With a cut point of 44 grams/gallon (~ 2.6 g/bhp hr) for HC, HDRSD would flag 3 percent of the trucks as potential gross emitters, which were responsible for 12 percent of the total HC emissions.

- With a cut point of 258 grams/gallon (~15.5 g/bhp hr) for CO, HDRSD would flag 1.5 percent of the cross border fleet as potential gross emitters, which contributed 12 percent of the total CO emissions. While this is equivalent to the current certification standard, this standard is very lenient and well functioning diesel engines never approach this level of CO emissions. With a cut point twice the standard (516 g/gal) none of the border trucks would be flagged as potential gross emitters.

Section VII. PEMS vs HDRSD Correlation

Another central goal of the pilot project was to directly correlate HDRSD emissions measurements against PEMS measurements for the same truck taken at the same time. The original project plan envisioned such a correlation for every truck tested with PEMS, since these trucks passed the HDRSD sensors with PEMS installed on their way out of the border compound. For many of the PEMS trucks valid HDRSD gas readings could not be collected with PEMS installed, due to redirection of the exhaust flow by the installed PEMS flow meter. For the remainder of the PEMS trucks time alignment of the data proved to be quite challenging and the PEMs and HDRSD data could not be aligned with enough accuracy to run a correlation analysis.

Given these difficulties, the original plan for HDRSD-PEMS correlation was replaced by a specific supplemental correlation experiment which was conducted on four trucks recruited at the border. Details of time alignment and data analysis for the data collected from these four trucks are included in Appendix E. Given the limitations of each testing technology, individual PEMs and HDRSD data points could only be aligned within +/- 2 seconds. The correlation charts shown below are based on comparison of HDRSD data points to the nearest PEMs reading within this +/- 2 second window. All plots contain only values measured during vehicle acceleration as noted by the data collection log sheets. Note, however, that vehicle acceleration does not necessarily indicate increasing engine activity, as data could have been taken during shift points.

Pollutant:CO_2 Volume Ratio	Approximate Pollutant ppm
0.001	150
0.005	750
0.010	1500
0.020	3000

Table 7.1 Volume Ratio to ppm Conversions

The units of all charts are volume ratios of the pollutant of interest to CO_2. This ratio is generally proportional to the fuel-specific emissions rate (g/gal). Table 7.1 provides information on how HDRSD measured HC, CO, and NO ppm concentrations can be estimated from these values[23]. While the time alignment issues at +/- 2 seconds appear to be correctly adjusted, scatter plots for correlations at ±1 second are included for each pollutant in Appendix F.

VII.A NO Correlation Results

The NO to CO_2 correlation is presented in Figure 7.1. The results show good correlation between HDRSD and PEMS measurement of NO. The slope of the best fit line is very close to one with a small y-intercept value, and the R-squared value of the best fit line (indicating the amount of diversion from the trend line) is high. Furthermore, the scatter seen for individual vehicles is limited.

These results indicate that the PEMs and HDRSD devices generally measured the same value for NO emissions rate (relative to CO_2) on each pass of each truck. Please note, however, that the variation in fuel-specific NO emissions rates from the four trucks included in this correlation exercise was limited. Additional correlation work is merited, to include trucks with a wider range

[23] These values are approximate only as the HDRSD measured CO_2 values range from about 14.7%-15.1%, and therefore any particular point may vary by approximately ±3%. For simplicity, a universal CO_2 concentration of 15% was applied to all calculations.

of NO emissions, including new post-2002 vehicles with lower NO emissions levels as well as NO high emitters, to determine the exact range over which HDRSD results are accurate, and how this would effect high emitter identification

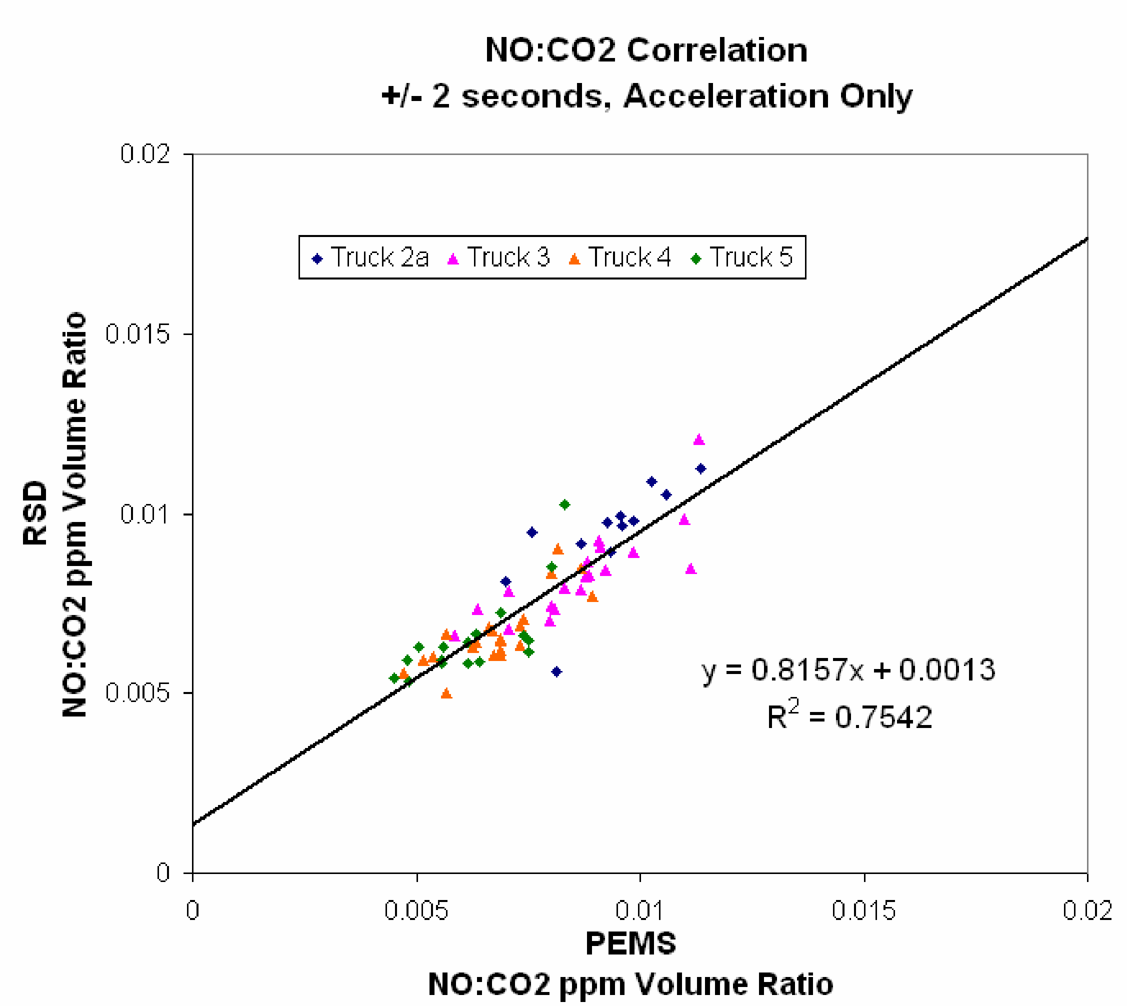


Figure 7.1 NO:CO_2 Correlation (±2 seconds)

VII.B CO Correlation Results

The CO to CO_2 correlation is presented in Figure 7.2. As with NO, the results show potential correlation between HDRSD and PEMS measurement of CO. The slope of the best fit line is very close to one with a small y-intercept value, and the R-squared value of the best fit line (indicating the amount of diversion from the trend line) is high.

The scatter seen for individual trucks is higher than that seen for NO (Section VII.A). In particular, many of the individual points for truck 5 showed relatively poor correlation, while for truck 4 points with high ratio values showed good correlation and those with low values did not. These data suggest that the instrumentation (HDRSD, PEMS, or both) are less accurate toward the lower end of the measurement range. This is likely of little concern, however, as the amount of CO being emitted within this range is negligible. CO high emitters would have CO emissions at the higher end of the range where correlation is stronger.

Additional correlation work is merited, using a set of vehicles that can provide a wider range of CO emissions.

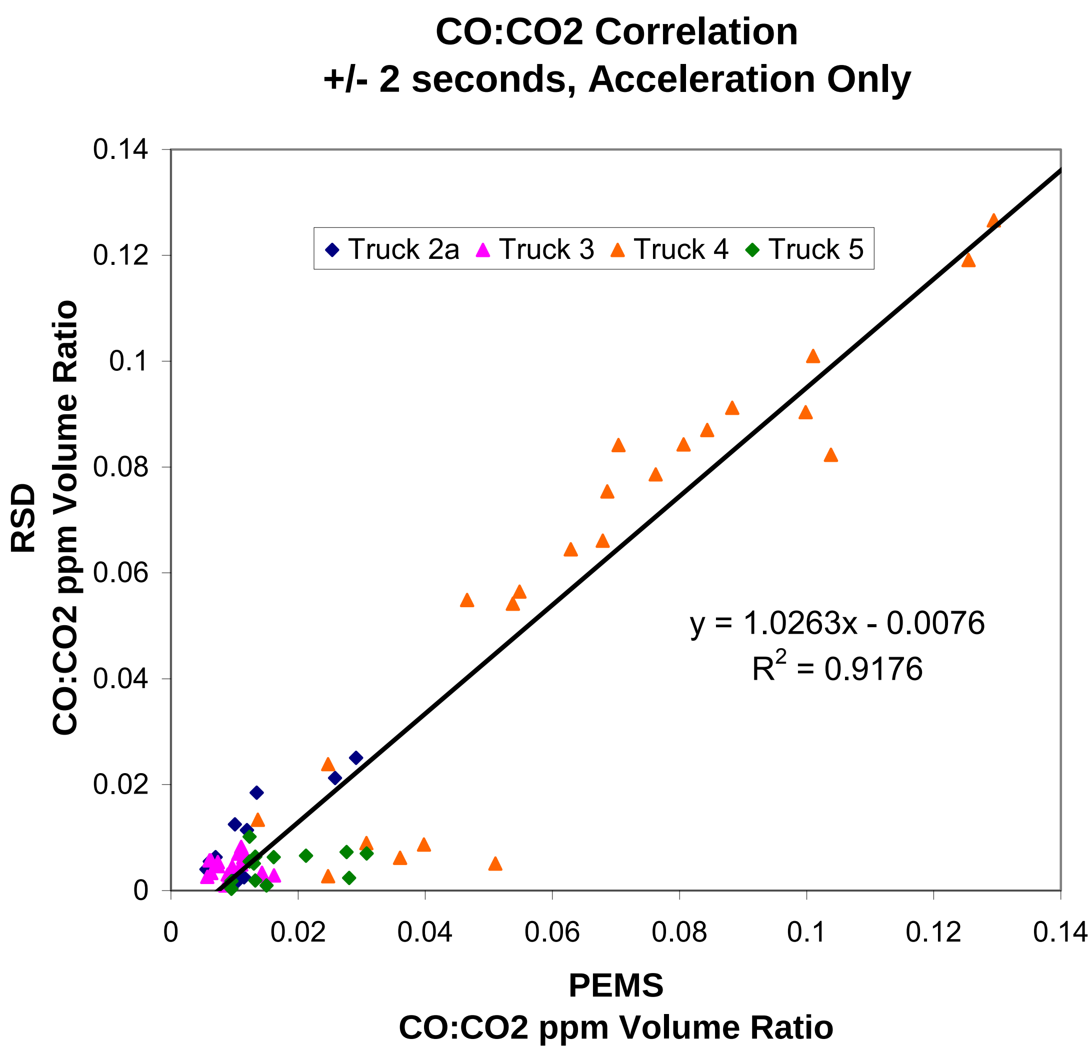


Figure 7.2 CO:CO_2 Correlation (±2 seconds)

VII.C HC Correlation Results

The HC to CO_2 correlation is presented in Figure 7.3. Unlike the NO and CO results, these data show very little correlation for these trucks.

Please note, however, that the absolute value of HC concentrations as measured by both devices was extremely low for virtually all of the data points. It is possible that the values were too low to be accurately measured by one device or the other (or both). The amount of HC being emitted by trucks measured within this range is negligible; HC high emitters would have higher HC emissions.

As with CO and NO, additional correlation work is merited, using a set of vehicles that provide a wider range of HC emissions.

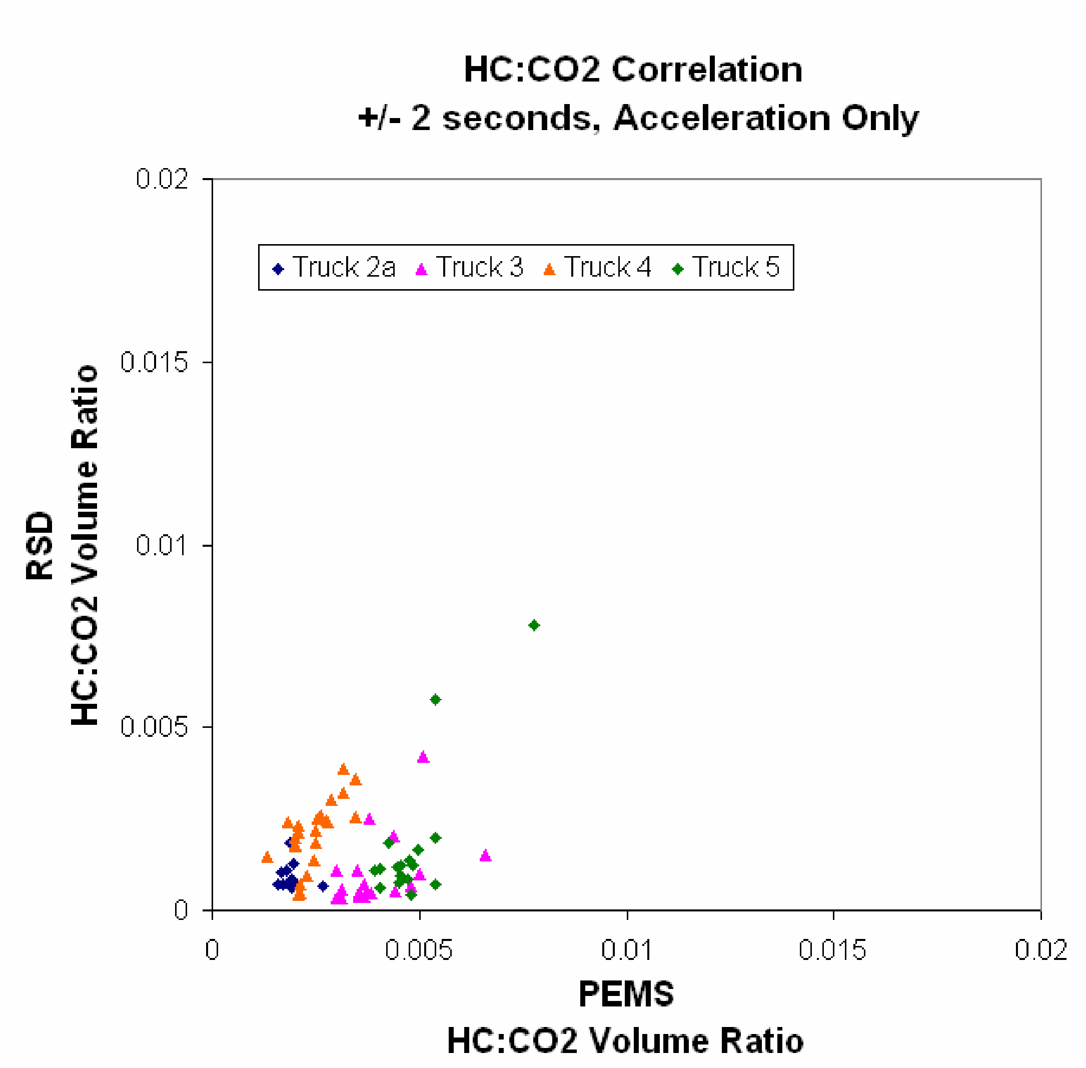


Figure 7.3 HC:CO_2 Correlation (±2 seconds)

Section VIII Policy Implications

This section presents the main policy implications derived from the pilot project. The capability of HDRSD technology and its application as a screening tool will be discussed, along with the potential benefits of an emissions screening program for cross border commercial trucks. In addition, lessons learned during this pilot project about requirements for HDRSD set-up and site selection are also discussed.

VIII.A HDRSD Screening for Gross Emitters

The use of remote sensing as a screening tool for light duty vehicles (cars) is well accepted, and the border states have consistently been at the forefront in deploying remote sensing technologies. In the mid-1990's two border states, California and Arizona, launched pilot projects using remote sensing for light duty vehicles. By 1996 EPA had released guidance on how to use and claim emission reduction credits for high-emitter identification programs. Another border state, Texas, began its high emitter identification program in 1998. Soon thereafter, EPA released guidance on using remote sensing for a clean screening program (like a pre-screen to an inspection and maintenance program). The utility of screening programs for cars has been well demonstrated by several states, and the following States incorporate remote sensing screening into their inspection and maintenance programs: Colorado, Missouri, Texas and Virginia.

This pilot project was the first step in demonstrating the utility of remote sensing emissions screening for heavy duty trucks, and the results were encouraging. The deployment strategy allowed HDRSD data to be collected from over 15,000 truck crossings by 1,753 unique trucks, representing over 80 percent of the total truck trips across the border during the data collection period.

While more work needs to be done to correlate HDRSD results to emissions measurements using other testing technologies, the preliminary and limited comparison to PEMS data collected during the project was also encouraging. For NO and potentially for CO, HDRSD measurements over the range experienced were shown to correlate well to PEMS measurements collected from the same truck at the same time. In addition, for NO and HC the short-duration HDRSD measurements compared well to cycle average results over longer PEMS drive cycles, indicating that for these pollutants HDRSD results may well be a good indicator of general emissions levels from driving. Finally, HDRSD was shown to be able to identify a sub-set of trucks with significantly higher fuel-specific emissions rates than the rest of the fleet, for all four pollutants measured: NO, CO, HC, and Smoke Factor. These trucks may be potential high emitters in need of maintenance. The study design did not allow for verification (with other test methods) that trucks flagged by HDRSD were in fact high emitters. This type of verification project is one of the necessary follow-ups to this study.

HDRSD presents the possibility of screening nearly all trucks as they pass through a border crossing. The ability to quantify cross border truck emissions could help US and Mexican states as they tackle the difficult task of compiling an emissions inventory of and eventually reducing diesel-related emissions. Emissions data for cross border trucks could also be useful for metropolitan non-attainment areas located along the major highways extending away from the border crossings. These locations often experience more serious, and therefore more costly, pollution problems; e.g., Tucson, AZ; San Antonio, TX; Dallas, TX; and San Diego, CA.

Monitoring of cross border truck emissions could also help ease the concerns over potential air quality impacts from increased cross border truck traffic once NAFTA is fully implemented[24].

VIII.B Potential Benefits of a Border Wide Emissions Screening Program

Based on HDRSD data collected during this poject, a gross emitter screening program might well be an effective emission control strategy at the Nogales border crossing. HDRSD showed that for all pollutants, there were a small number of trucks contributing a large percentage of the emissions. Specifically;

- 50 percent of CO emissions are produced by less than 20 percent of vehicles;
- 40 percent of HC emissions are produced by less than 20 percent of vehicles;
- 40 percent of NO emissions are produced by less than 25 percent of vehicles, and
- 50 percent of smoke emissions are produced by 20 percent of vehicles.

While these HDRSD results must be verified with other follow-on studies, it appears that at the Nogales port of entry identifying and repairing the few vehicles that create a large percentage of truck emissions would lead to significant emissions reductions and improve air quality for the US and Mexican citizens living in the border area. Approximately 5 percent of the total incoming truck traffic from Mexico enters the United States at Nogales. Approximately 85 percent of all incoming trucks enter through the six border crossings indicated in Table 8.1. Deploying screening programs at all or a portion of these border crossings may produce substantial air quality benefits.

Table 8.1 Incoming Truck Volumes at Select US-Mexico Border Crossings

Border Crossing	Cumulative Percent of Total Incoming Trucks
Laredo, TX	33%
Otay Mesa, CA	49%
El Paso, TX	65%
Hidalgo, TX	74%
Brownville, TX	79%
Nogales, AZ	85%

An additional, longer term study using HDRSD could further identify which border crossings would reap the greatest benefits from a gross emitter screening program for heavy duty vehicles.

VIII.C HDRSD Site Selection and Set Up

To date, most applications of remote sensing emissions measurement have been applied to light-duty vehicles (cars, light trucks). This study has demonstrated that remote measurement of exhaust emissions from heavy-duty trucks, while possible, is more challenging for a number of reasons:

[24] The moratorium on Mexican domiciled trucks traveling on US highways was lifted by President Bush in November of 2002, legal obstacles have been cleared. However, some bilateral issues remain between the US and Mexico.

- There is greater variabilty in the position of the exhaust outlet on large trucks than on cars. While a majority of trucks have exhaust that exits above the cab roof level there is a range of exhaust stack heights, and a non-trivial proportion of trucks have exhaust that exits below the truck frame near the street surface.
- Given the ubiquity of high-mounted exhaust pipes, HDRSD units are most effective if mounted 12-14 feet above the road surface. This requires more infrastructure than ground-mounted equipment and also presents a much larger visible signature that may effect driving behavior of passing vehicles.
- During acceleration from low speeds most trucks shift much more frequently than cars. Fuel-specific emissions rates while the engine is momentarily unloaded during the shift are not representative of cycle-average emissions rates. This can complicate the task of identifying "gross emitters" unless HDRSD can be set up where passing trucks will not be shifting, or unless these shift points can be identified such that HDRSD data taken during a shift can be screened out of the data set.
- The laser-based speed/acceleration measurement system developed for light-duty RSD applications which was used during this project proved to be incapable of accurately and consistently measuring the speed and acceleration of passing trucks. Improved methods of speed and acceleration measurement must be developed in order to properly screen collected HDRSD data to remove HDRSD measurements which correspond to transmission shift points.

Given the challenges of measuring heavy-duty truck emissions, the site selection and set-up of HDRSD must be carefully planned to maximize data collection efficiency, and in many cases it will almost certainly be necessary to collect multiple HDRSD readings from the same truck to identify gross emitters.

The Nogales border site proved to be ideal to collect multiple HDRSD readings, as many of the trucks made repeat trips across the border in the same week. Not all truck corridors will have the same characteristics, but multiple readings could also be collected consistently by deploying multiple HDRSD units sequentially along the same corridor within a limited area.

The deployment site used for this study at Nogales proved to be less ideal with respect to consistently measuring trucks that were accelerating, and avoiding transmission shift points during data collection. Remote sensing emissions measurements must be taken across a single travel lane. For that reason, highway on-ramps have proven to be a good location for light-duty RSD deployments, and that is the approach taken for this project as well. Unfortunately, the available location at Nogales was on a relatively short ramp, and the need for large platforms to elevate the HDRSD equipment meant that it could not be located close to the highway end of the ramp where trucks would be moving at relatively high speeds. Permanent or semi-permament installations could be constructed with much smaller tower/equipment platforms located closer to the highway entrance. Alternatively, one could explore installation of HDRSD on a highway overpass, with the optical line-of-sight downward at an angle to a mirror located on the side of the road. Such a location, especially if located in the middle of an uphill grade, would potentially be ideal for HDRSD data collection.

Another approach to heavy-duty truck emissions testing might be to implement HDRSD screening in conjunction with existing weight testing at road side weigh-in-motion stations. At some sites it might be possible to set up a "test lane" either before or after the scale. Collecting HDRSD data in this manner would allow for much better control of truck/engine operation during the test, resulting in more consistent results. In such a situation it might be practical to base gross emitter identification on a single HDRSD reading. Alternately, multiple HDRSD units could be

set up sequentially along the test lane to collect multiple readings from each truck. Obviously, some existing weigh-in-motion sites might be too constricted to accommodate a test lane, and the actual practicality of such a concept must be further reviewed.

Section IX Study Limitations and Potential Follow-on Projects

This study has demonstrated that HDRSD has promise as an emissions screening tool for heavy-duty diesel vehicles. However, the study findings are limited, and more work must be done to establish a technical and regulatory basis for using HDRSD to identify gross emitting vehicles within the general population. The following limitations apply to the study results:

- Correlation of HDRSD and PEMS measurements was not definitive, as the range of fuel-specific emissions rates from the tested trucks was limited. In particular very few new trucks with very low NOx and PM levels were tested.
- No correlation of HDRSD-measured smoke factor with other PM measurement methods could be made.
- The in-use truck fleet at Nogales included very few post-2002 trucks meeting EPA's 2.5 g/bhp-hr or lower NOx emissions limits, and no newer trucks certified to produce less than 0.25 g/bhp-hr PM. As such, the accuracy and repeatability of HDRSD to measure emissions from newer, relatively low-emitting trucks was not demonstrated in this project.
- Trucks flagged by HDRSD as potential high emitters were not tested with other technologies to confirm their emissions levels.
- The characteristics of truck traffic at the Nogales crossing was conducive to collecting multiple HDRSD readings from many of the crossing trucks. Other truck traffic corridors may have significantly different characteristics

A number of follow-up activities are suggested by the results of this study, including:

- Additional controlled correlation testing, particularly for NOx and PM. This testing should include vehicles with a wider range of fuel-specifc emissions rates, including new lower-emitting vehicles and known high emitters, to evaluate the range, accuracy, and repeatability of HDRSD results from the entire in-use fleet.
- Pull-over studies to evaluate vehicles flagged by HDRSD as high emitters, using PEMS or other emissions testing technologies.
- Tests with a controlled set of trucks whose engines can be de-tuned to generate various emissions conditions.
- Additional HDRSD deployments at other border crossings and/or along high-volume truck corridors to refine siting and set-up strategies. Issues to explore include siting strategies to maximize the percentage of HDRSD readings taken with the engine under moderate to high load; strategies to avoid HDRSD readings during transmissions shifts; and methods to more accurately measure vehicle speed and acceleration and to identify transmission shifting to improve data screening.

Section X. Acknowledgements

The success of this pilot project, funded by a public-private partnership, depended upon team work and coordination among a diverse group of experts and officials across the country. Given the number of people involved the authors cannot name each contributor, though we appreciate and acknowledge everyone's outstanding efforts.

The authors would like to thank the EPA for assisting with the design and funding of this pilot project. The EPA team represented many distinct offices within the organization, including: the Office of Transportation and Air Quality, in particular Merrylin Zaw-Mon and her expert staff, Jim Blubaugh, Dennis Johnson and Lori Stewart; John Beale in the Office of Air and Radiation and his policy advisor Sarah Sowell; Andrew Steckel and Gary Wolinsky from EPA-Region 9; Barry Feldman from EPA-Region 6; and Peter Tsirigotis and Robin Segall from the Office of Air Quality Planning and Standards.

We would also like to thank Nancy Wrona of the AZDEQ for her efforts and attention to project management throughout the life of this project. She and her staff, especially Placido Dos Santos, and Jose Rodriguez also made enormous contributions to the March, 2005 kick-off event held at the Nogales border crossing.

We would not have been able to gather any data on commercial trucks at the Nogales border crossing without the support and help of a team of officials at the Border, including: James Tong, the Port Director at the Nogales Port of Entry; and Alejandro S. Perez, Teen Klump, Scott Williams, and Jesus Cruz from the US Dept of Homeland Security, Customs & Border Protection. Lt. Doug Holler, the Area Manager for the Arizona Department of Transportation, also provided invaluable assistance accessing data on the cross border truck fleet.

Numerous members of the staffs of M.J. Bradley & Associates and ESP contributed to the success of this project. The authors would like to thank them for their hard work.

Lastly, we thank the members of the Advisory Panel for taking time out of their busy schedules to review this report and offer their expert advice. Members of the Advisory Panel included: Darryl Gaslan (CARB); Mario Molina (University of California-San Diego); Nancy Wrona (AZDEQ); Merrylin Zaw-Mon (EPA); Mike Walsh (Michael T. Walsh); Enrique Rebolledo (SEMARNAT) and Leonora Rojas Bracho (INE).

Appendix A. PEMs Unit Conversion (ppm to g/bhp-hr)

In order to provide a complete picture of vehicle operation, it was desired that emission rates be displayed as cycle-averages in three separate units: grams per mile (g/mi), grams per brake-horsepower-hour (g/bhp-hr), and grams per gallon of fuel consumed (g/gal). In addition, total cycle fuel economy was of particular interest. In order to obtain these numbers, the following manipulations to the original PEMs data occurred.

First, pollutant ppm values were converted to grams per second (g/s) by utilizing the measured instantaneous exhaust flow rates, via the following equation:

$$\frac{g(xx)}{s} = \frac{(xx)\,ppm}{10^6} \times MW(xx)\left(\frac{g}{gmol}\right) \times Flow\left(\frac{ft^3}{s}\right) \times 1.1778\left(\frac{gmol}{ft^3}\right)$$

Where: **(xx) = Pollutant of interest**

MW = Molecular Weight

(Equation A-1)

These numbers report the mass of each pollutant that is emitted during each second of operation. By summing gram per second values for each second of the cycle and dividing by the total distance traveled (reported by the GPS), cycle-weighted gram per mile values can be reported. Likewise, gram per gallon values can be reported by summing total grams and dividing by total fuel consumption over the cycle (reported by the PEMs).

The remaining step was therefore to calculate g/bhp-hr values. Horsepower-out can be calculated based on pollutant values, as long as the energy content of the fuel is known. The following equation was used to calculate total-cycle horsepower, assuming that all of the carbon present in the fuel was combusted and converted to exhaust CO_2, and assuming an overall engine efficiency of 33%, typical of non-throttled four-stroke diesel engines:

$$bhp - hr_{out} = \frac{\sum CO_2\left(\frac{g}{s}\right) \times 33\%}{0.000160\,\frac{lbCO_2}{Btu} \times 453.59\left(\frac{g}{lb}\right) \times 2542\left(\frac{Btu}{hp - hr}\right)}$$

(Equation A-2)

Using calculated horspower over the PEMS cycle, power-specific emissions rates (g/bhp-hr) were calculated. These power-specific values are approximate only, as actual engine efficiency may not have been 33% throughout the drive cycle.

Appendix B PEMs Truck Test Results

Test 14	MX		1NKDL29X4HS339153														
No Data		**Distance Traveled (mi)**	**Change in elv. (meters)**	**Avg Speed (mph)**	**Fuel Cons. (gal)**	**Avg FE (mpg)**	**Avg NOx (g/mi)**	**Avg CO (g/mi)**	**Avg HC (g/mi)**	**hp-hr out**	**Avg NOx (g/bhp-hr)**	**Avg CO (g/bhp-hr)**	**Avg HC (g/bhp-hr)**	**Avg NOx (g/gal)**	**Avg CO (g/gal)**	**Avg HC (g/gal)**	**Avg HC (g/gal)**
Total		4.36	-96.80	9.80	0.83	5.26	18.60	13.71	6.18	14.99	5.40	3.98	1.79	97.87	72.14	32.52	30.40
Border Compound		0.24	-1.60	4.30	0.11	2.22	38.36	33.18	14.58	1.98	4.71	4.07	1.79	85.23	73.72	32.39	21.01
Downhill Highway		3.44	-94.60	25.53	0.44	7.88	13.23	7.16	3.02	7.94	5.73	3.10	1.31	104.18	56.37	23.82	29.96
Flat Highway		0.67	-0.60	2.66	0.28	2.39	38.93	40.19	19.28	5.08	5.16	5.33	2.56	93.11	96.12	46.12	33.35
1987 Kenworth																	

Test 15	AZ		1HTE23272BGA12033														
73,000 lbs		**Distance Traveled (mi)**	**Change in elv. (meters)**	**Avg Speed (mph)**	**Fuel Cons. (gal)**	**Avg FE (mpg)**	**Avg NOx (g/mi)**	**Avg CO (g/mi)**	**Avg HC (g/mi)**	**hp-hr out**	**Avg NOx (g/bhp-hr)**	**Avg CO (g/bhp-hr)**	**Avg HC (g/bhp-hr)**	**Avg NOx (g/gal)**	**Avg CO (g/gal)**	**Avg HC (g/gal)**	**Avg HC (g/gal)**
Total		8.67	-174.40	24.40	1.16	7.46	15.17	11.17	1.99	21.07	6.24	4.60	0.82	113.13	83.32	14.85	24.59
Border Compound		0.24	-3.50	2.78	0.09	2.73	32.42	28.06	5.16	1.56	4.89	4.23	0.78	88.66	76.74	14.10	18.32
Downhill Highway		8.44	-170.90	31.12	1.08	7.84	14.69	10.70	1.90	19.51	6.35	4.63	0.82	115.10	83.87	14.92	25.25
Flat Highway		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	25.73
1981 International																	

Test 16	MX		2HSFHGUROMC044414														
No Data		**Distance Traveled (mi)**	**Change in elv. (meters)**	**Avg Speed (mph)**	**Fuel Cons. (gal)**	**Avg FE (mpg)**	**Avg NOx (g/mi)**	**Avg CO (g/mi)**	**Avg HC (g/mi)**	**hp-hr out**	**Avg NOx (g/bhp-hr)**	**Avg CO (g/bhp-hr)**	**Avg HC (g/bhp-hr)**	**Avg NOx (g/gal)**	**Avg CO (g/gal)**	**Avg HC (g/gal)**	**Avg HC (g/gal)**
Total		4.88	-92.60	17.28	0.28	17.49	6.07	6.22	3.11	5.01	5.91	6.06	3.03	106.25	108.87	54.46	21.72
Border Compound		0.24	6.60	4.77	0.04	5.96	9.76	16.04	14.95	0.72	3.24	5.32	4.96	58.13	95.56	89.09	28.44
Downhill Highway		4.64	-99.20	19.96	0.24	19.44	5.88	5.72	2.51	4.29	6.36	6.18	2.71	114.37	111.16	48.72	21.08
Flat Highway		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1991 International 940																	

Test 18	MX		AV. 4# 1296 RLV														
77,000 lbs		**Distance Traveled (mi)**	**Change in elv. (meters)**	**Avg Speed (mph)**	**Fuel Cons. (gal)**	**Avg FE (mpg)**	**Avg NOx (g/mi)**	**Avg CO (g/mi)**	**Avg HC (g/mi)**	**hp-hr out**	**Avg NOx (g/bhp-hr)**	**Avg CO (g/bhp-hr)**	**Avg HC (g/bhp-hr)**	**Avg NOx (g/gal)**	**Avg CO (g/gal)**	**Avg HC (g/gal)**	**Avg HC (g/gal)**
Total		5.37	-119.30	20.86	0.82	6.54	19.16	20.63	3.96	14.74	6.98	7.52	1.44	125.32	134.95	25.88	10.64
Border Compound		0.29	-3.30	4.17	0.11	2.66	41.73	19.45	5.57	2.00	6.09	2.84	0.81	110.84	51.68	14.79	17.06
Downhill Highway		5.08	-116.00	27.06	0.71	7.14	17.87	20.70	3.87	12.75	7.12	8.25	1.54	127.58	147.82	27.60	9.82
Flat Highway		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1986 Freightliner Tracto C																	

Test 20	AZ		1FUEYBYBXBP194426														
55,000 lbs		**Distance Traveled (mi)**	**Change in elv. (meters)**	**Avg Speed (mph)**	**Fuel Cons. (gal)**	**Avg FE (mpg)**	**Avg NOx (g/mi)**	**Avg CO (g/mi)**	**Avg HC (g/mi)**	**hp-hr out**	**Avg NOx (g/bhp-hr)**	**Avg CO (g/bhp-hr)**	**Avg HC (g/bhp-hr)**	**Avg NOx (g/gal)**	**Avg CO (g/gal)**	**Avg HC (g/gal)**	**Avg HC (g/gal)**
Total		4.22	-92.70	16.24	0.49	8.68	14.33	11.55	2.57	8.77	6.88	5.55	1.23	124.29	100.19	22.28	13.72
Border Compound		0.24	-2.20	3.72	0.06	3.84	28.43	23.61	5.56	1.14	6.04	5.01	1.18	109.14	90.66	21.34	21.16
Downhill Highway		3.51	-87.50	27.32	0.32	11.06	11.65	9.16	1.98	5.74	7.14	5.61	1.21	128.86	101.34	21.92	12.24
Flat Highway		0.46	-3.00	6.94	0.11	4.38	27.35	23.45	5.49	1.90	6.63	5.69	1.33	119.83	102.75	24.06	NA
1984 International																	

Test 27	A/M		1HSRDGUR6KH697831														
No Data		**Distance**	**Change**	**Avg**	**Fuel**	**Avg FE**	**Avg NOx**	**Avg CO**	**Avg HC**	**hp-hr**	**Avg NOx**	**Avg CO**	**Avg HC**	**Avg NOx**	**Avg CO**	**Avg HC**
		Traveled	**in elv.**	**Speed**	**Cons.**					**out**						
		(mi)	**(meters)**	**(mph)**	**(gal)**	**(mpg)**	**(g/mi)**	**(g/mi)**	**(g/mi)**		**(g/bhp-hr)**	**(g/bhp-hr)**	**(g/bhp-hr)**	**(g/gal)**	**(g/gal)**	**(g/gal)**
Total		3.49	-77.60	15.69	0.45	7.83	15.34	11.32	2.28	8.07	6.64	4.90	0.99	120.10	88.62	17.87
Border Compound		0.23	6.50	3.09	0.06	4.08	17.41	16.30	5.28	1.04	3.91	3.66	1.19	70.94	66.43	21.54
Downhill Highway		3.26	-84.10	22.08	0.39	8.38	15.19	10.97	2.07	7.03	7.04	5.08	0.96	127.34	91.92	17.35
Flat Highway		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1989 International																

Test 28	A/M		1FUYDCYBZRH810297													
44,000 lbs		**Distance**	**Change**	**Avg**	**Fuel**	**Avg FE**	**Avg NOx**	**Avg CO**	**Avg HC**	**hp-hr**	**Avg NOx**	**Avg CO**	**Avg HC**	**Avg NOx**	**Avg CO**	**Avg HC**
		Traveled	**in elv.**	**Speed**	**Cons.**					**out**						
		(mi)	**(meters)**	**(mph)**	**(gal)**	**(mpg)**	**(g/mi)**	**(g/mi)**	**(g/mi)**		**(g/bhp-hr)**	**(g/bhp-hr)**	**(g/bhp-hr)**	**(g/gal)**	**(g/gal)**	**(g/gal)**
Total		4.20	-140.00	16.10	0.37	11.34	10.78	6.75	0.99	6.72	6.74	4.22	0.62	122.25	76.52	11.22
Border Compound		0.31	-49.80	5.61	0.06	4.96	32.48	13.41	2.39	1.12	8.86	3.66	0.65	161.03	66.48	11.83
Downhill Highway		2.63	-74.80	28.57	0.15	17.85	6.53	4.10	0.73	2.67	6.41	4.03	0.72	116.47	73.15	13.03
Flat Highway		1.26	-15.40	11.02	0.16	7.84	14.41	10.65	1.19	2.93	6.23	4.61	0.52	112.95	83.53	9.37
1994 Freightliner			*modified speed data												0	0

Test 30	A/M		1FUEYCYBXJP326590													
No Data		**Distance**	**Change**	**Avg**	**Fuel**	**Avg FE**	**Avg NOx**	**Avg CO**	**Avg HC**	**hp-hr**	**Avg NOx**	**Avg CO**	**Avg HC**	**Avg NOx**	**Avg CO**	**Avg HC**
		Traveled	**in elv.**	**Speed**	**Cons.**					**out**						
		(mi)	**(meters)**	**(mph)**	**(gal)**	**(mpg)**	**(g/mi)**	**(g/mi)**	**(g/mi)**		**(g/bhp-hr)**	**(g/bhp-hr)**	**(g/bhp-hr)**	**(g/gal)**	**(g/gal)**	**(g/gal)**
Total		9.85	-142.70	23.83	0.99	9.99	10.34	14.58	3.77	17.64	5.78	8.14	2.11	103.37	145.68	37.72
Border Compound		0.24	-0.30	3.28	0.08	3.01	25.96	52.61	34.20	1.39	4.40	8.92	5.80	78.09	158.27	102.88
Downhill Highway		7.60	-146.30	37.04	0.59	12.96	8.21	13.31	2.73	10.46	5.97	9.67	1.98	106.47	172.52	35.33
Flat Highway		2.01	3.90	14.71	0.32	6.27	16.58	14.95	4.19	5.80	5.75	5.18	1.45	103.94	93.70	26.30
1988 Freightliner																

Test 31	A/M		1HSRDA7RXPH483215													
66,000 lbs		**Distance**	**Change**	**Avg**	**Fuel**	**Avg FE**	**Avg NOx**	**Avg CO**	**Avg HC**	**hp-hr**	**Avg NOx**	**Avg CO**	**Avg HC**	**Avg NOx**	**Avg CO**	**Avg HC**
		Traveled	**in elv.**	**Speed**	**Cons.**					**out**						
		(mi)	**(meters)**	**(mph)**	**(gal)**	**(mpg)**	**(g/mi)**	**(g/mi)**	**(g/mi)**		**(g/bhp-hr)**	**(g/bhp-hr)**	**(g/bhp-hr)**	**(g/gal)**	**(g/gal)**	**(g/gal)**
Total		4.23	-96.60	13.89	0.34	12.52	10.03	8.73	0.65	6.11	6.96	6.05	0.45	125.60	109.26	8.13
Border Compound		0.28	-9.60	3.69	0.07	4.25	38.62	23.78	2.16	1.18	9.08	5.59	0.51	164.17	101.09	9.16
Downhill Highway		2.65	-78.50	27.77	0.14	18.35	4.99	6.33	0.42	2.60	5.07	6.44	0.42	91.51	116.15	7.62
Flat Highway		1.31	-8.50	9.72	0.13	10.18	14.20	10.40	0.81	2.33	8.00	5.85	0.45	144.54	105.78	8.21
1993 International																

Test 32	MX		1HSRDJWROHHB12261													
76,000 lbs		**Distance**	**Change**	**Avg**	**Fuel**	**Avg FE**	**Avg NOx**	**Avg CO**	**Avg HC**	**hp-hr**	**Avg NOx**	**Avg CO**	**Avg HC**	**Avg NOx**	**Avg CO**	**Avg HC**
		Traveled	**in elv.**	**Speed**	**Cons.**					**out**						
		(mi)	**(meters)**	**(mph)**	**(gal)**	**(mpg)**	**(g/mi)**	**(g/mi)**	**(g/mi)**		**(g/bhp-hr)**	**(g/bhp-hr)**	**(g/bhp-hr)**	**(g/gal)**	**(g/gal)**	**(g/gal)**
Total		5.69	-125.90	18.67	0.80	7.07	14.90	23.47	2.38	14.38	5.89	9.28	0.94	105.36	165.95	16.83
Border Compound		0.24	-7.30	6.87	0.07	3.20	28.02	18.12	3.45	1.35	4.93	3.19	0.61	89.79	58.08	11.06
Downhill Highway		3.51	-94.90	20.18	0.42	8.37	12.03	22.42	2.22	7.48	5.64	10.52	1.04	100.61	187.54	18.54
Flat Highway		1.94	-23.70	20.08	0.31	6.25	18.49	26.03	2.55	5.56	6.46	9.09	0.89	115.59	162.74	15.95
1985 International																

Test 33	A/M	1FUEYBYB4GP273694														
32,000 lbs		**Distance Traveled**	**Change in elv.**	**Avg Speed**	**Fuel Cons.**	**Avg FE**	**Avg NOx**	**Avg CO**	**Avg HC**	**hp-hr out**	**Avg NOx**	**Avg CO**	**Avg HC**	**Avg NOx**	**Avg CO**	**Avg HC**
		(mi)	**(meters)**	**(mph)**	**(gal)**	**(mpg)**	**(g/mi)**	**(g/mi)**	**(g/mi)**		**(g/bhp-hr)**	**(g/bhp-hr)**	**(g/bhp-hr)**	**(g/gal)**	**(g/gal)**	**(g/gal)**
Total		0.70	4.10	4.98	0.15	4.72	19.82	15.02	5.05	2.69	5.18	3.93	1.32	93.58	70.95	23.84
Border Compound		0.70	4.10	4.98	0.15	4.72	19.82	15.02	5.05	2.69	5.18	3.93	1.32	93.58	70.95	23.84
Downhill Highway		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Flat Highway		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1985 Freightliner																

Test 34	A/M	1FUPACYB1NP527006														
42,000 lbs		**Distance Traveled**	**Change in elv.**	**Avg Speed**	**Fuel Cons.**	**Avg FE**	**Avg NOx**	**Avg CO**	**Avg HC**	**hp-hr out**	**Avg NOx**	**Avg CO**	**Avg HC**	**Avg NOx**	**Avg CO**	**Avg HC**
		(mi)	**(meters)**	**(mph)**	**(gal)**	**(mpg)**	**(g/mi)**	**(g/mi)**	**(g/mi)**		**(g/bhp-hr)**	**(g/bhp-hr)**	**(g/bhp-hr)**	**(g/gal)**	**(g/gal)**	**(g/gal)**
Total		6.52	-34.40	11.33	1.04	6.28	13.93	27.67	1.46	18.58	4.89	9.72	0.51	87.45	173.69	9.19
Border Compound		0.24	12.10	5.64	0.04	5.73	21.94	10.22	1.76	0.77	6.91	3.22	0.56	125.73	58.57	10.11
Downhill Highway		1.66	-48.30	16.49	0.19	8.83	8.90	20.15	1.35	3.36	4.40	9.96	0.67	78.60	177.93	11.95
Flat Highway		4.62	1.80	10.68	0.81	5.71	15.33	31.30	1.49	14.45	4.90	10.01	0.48	87.56	178.77	8.50
1992 Freightliner																

Test 35	A/M	1GTT9K4C3GU540703														
65,000 lbs		**Distance Traveled**	**Change in elv.**	**Avg Speed**	**Fuel Cons.**	**Avg FE**	**Avg NOx**	**Avg CO**	**Avg HC**	**hp-hr out**	**Avg NOx**	**Avg CO**	**Avg HC**	**Avg NOx**	**Avg CO**	**Avg HC**
		(mi)	**(meters)**	**(mph)**	**(gal)**	**(mpg)**	**(g/mi)**	**(g/mi)**	**(g/mi)**		**(g/bhp-hr)**	**(g/bhp-hr)**	**(g/bhp-hr)**	**(g/gal)**	**(g/gal)**	**(g/gal)**
Total		4.17	-98.00	15.69	0.61	6.85	9.14	9.75	7.99	11.00	3.46	3.69	3.02	62.60	66.78	54.71
Border Compound		0.32	1.50	2.86	0.12	2.69	14.98	24.78	19.69	2.17	2.23	3.69	2.93	40.34	66.74	53.05
Downhill Highway		3.40	-91.20	30.87	0.38	8.95	7.79	7.04	5.90	6.89	3.85	3.48	2.92	69.78	63.06	52.83
Flat Highway		0.44	-8.30	10.20	0.11	4.06	15.31	19.77	15.63	1.96	3.44	4.44	3.51	62.11	80.18	63.40
1986 GMC																

Test 36	A/M	1HSZBJSR76GHA31061														
No Data		**Distance Traveled**	**Change in elv.**	**Avg Speed**	**Fuel Cons.**	**Avg FE**	**Avg NOx**	**Avg CO**	**Avg HC**	**hp-hr out**	**Avg NOx**	**Avg CO**	**Avg HC**	**Avg NOx**	**Avg CO**	**Avg HC**
		(mi)	**(meters)**	**(mph)**	**(gal)**	**(mpg)**	**(g/mi)**	**(g/mi)**	**(g/mi)**		**(g/bhp-hr)**	**(g/bhp-hr)**	**(g/bhp-hr)**	**(g/gal)**	**(g/gal)**	**(g/gal)**
Total		2.25	-39.80	10.64	0.29	7.87	13.73	7.46	1.70	5.21	5.94	3.23	0.74	108.06	58.69	13.41
Border Compound		0.27	9.20	2.61	0.07	3.72	22.80	14.79	4.64	1.34	4.67	3.03	0.95	84.88	55.05	17.28
Downhill Highway		1.44	-53.20	25.74	0.12	12.15	9.47	4.69	1.12	2.15	6.32	3.13	0.75	115.10	57.02	13.59
Flat Highway		0.54	4.20	10.50	0.09	5.74	20.46	11.11	1.78	1.72	6.45	3.50	0.56	117.43	63.77	10.22
1986 International																

Test 39	A/M	1FUYDCYB2RH810Z97														
No Data		**Distance Traveled**	**Change in elv.**	**Avg Speed**	**Fuel Cons.**	**Avg FE**	**Avg NOx**	**Avg CO**	**Avg HC**	**hp-hr out**	**Avg NOx**	**Avg CO**	**Avg HC**	**Avg NOx**	**Avg CO**	**Avg HC**
		(mi)	**(meters)**	**(mph)**	**(gal)**	**(mpg)**	**(g/mi)**	**(g/mi)**	**(g/mi)**		**(g/bhp-hr)**	**(g/bhp-hr)**	**(g/bhp-hr)**	**(g/gal)**	**(g/gal)**	**(g/gal)**
Total		4.34	-87.50	14.63	0.46	9.34	11.18	5.32	0.89	8.46	5.73	2.73	0.45	104.44	49.72	8.29
Border Compound		0.24	4.20	6.50	0.08	2.85	35.31	10.97	2.63	1.54	5.50	1.71	0.41	100.60	31.27	7.49
Downhill Highway		2.69	-78.60	29.01	0.19	14.18	6.76	4.12	0.54	3.45	5.27	3.21	0.42	95.87	58.42	7.66
Flat Highway		1.41	-13.10	8.41	0.19	7.39	15.55	6.67	1.26	3.47	6.30	2.70	0.51	114.90	49.26	9.29
1994 Freightliner																

Test 41	A/M															
No Data		**Distance**	**Change**	**Avg**	**Fuel**	**Avg FE**	**Avg NOx**	**Avg CO**	**Avg HC**	**hp-hr**	**Avg NOx**	**Avg CO**	**Avg HC**	**Avg NOx**	**Avg CO**	**Avg HC**
		Traveled	**in elv.**	**Speed**	**Cons.**					**out**						
		(mi)	**(meters)**	**(mph)**	**(gal)**	**(mpg)**	**(g/mi)**	**(g/mi)**	**(g/mi)**		**(g/bhp-hr)**	**(g/bhp-hr)**	**(g/bhp-hr)**	**(g/gal)**	**(g/gal)**	**(g/gal)**
Total		2.15	-31.50	11.94	0.32	6.77	10.28	32.26	6.38	5.61	3.93	12.34	2.44	69.55	218.25	43.19
Border Compound		0.30	7.20	3.08	0.11	2.75	23.33	35.86	18.85	1.99	3.56	5.48	2.88	64.14	98.61	51.83
Downhill Highway		1.84	-38.70	22.64	0.21	8.91	8.13	31.68	4.33	3.62	4.14	16.11	2.20	72.48	282.26	38.62
Flat Highway		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1991 Eagle/International																

Test 42	AZ		1FUTSDB6WP705596													
No Data		**Distance**	**Change**	**Avg**	**Fuel**	**Avg FE**	**Avg NOx**	**Avg CO**	**Avg HC**	**hp-hr**	**Avg NOx**	**Avg CO**	**Avg HC**	**Avg NOx**	**Avg CO**	**Avg HC**
		Traveled	**in elv.**	**Speed**	**Cons.**					**out**						
		(mi)	**(meters)**	**(mph)**	**(gal)**	**(mpg)**	**(g/mi)**	**(g/mi)**	**(g/mi)**		**(g/bhp-hr)**	**(g/bhp-hr)**	**(g/bhp-hr)**	**(g/gal)**	**(g/gal)**	**(g/gal)**
Total		4.92	-96.70	18.95	0.80	6.13	14.79	5.10	1.46	14.66	4.96	1.71	0.49	90.63	31.24	8.95
Border Compound		0.28	-3.90	4.94	0.09	3.28	38.33	7.94	4.41	1.59	6.87	1.42	0.79	125.56	26.01	14.43
Downhill Highway		2.64	-72.60	34.66	0.29	9.25	8.79	2.67	1.11	5.22	4.45	1.35	0.56	81.36	24.72	10.23
Flat Highway		1.99	-20.20	15.78	0.43	4.64	19.37	7.90	1.51	7.86	4.92	2.01	0.38	89.81	36.64	7.00
1996 Freightliner																

Appendix C Calculation of HDRSD Grams Per Gallon Values

HDRSD measures pollutant to CO_2 ratios and the results are normally expressed as CO %, HC ppm, NO ppm and smoke-factor. To convert from concentrations to grams per gallon, the following general formula is used:

Pollutant grams.per gallon = (Pollutant concentration / total carbon concentration) * pollutant molecular weight * fuel moles per gallon.

Thus:

CO g/gal = (CO% / [CO2% + CO% + 3*HC ppm propane*10^-4]) * 28 * (3198/13.9)

HC g/gal = (HCppm*(10^-4) / [CO2% + CO% + 3*HC ppm propane*10^-4]) * 44 * (3198/13.9)

NO g/gal = (NOppm*(10^-4) / [CO2% + CO% + 3*HC ppm propane*10^-4]) * 46 * (3198/13.9)

Where 3,198 are the grams per gallon of diesel fuel and 13.9 is the molecular weight of the assumed fuel.
The HDRSD smoke-factor measurement is grams of diesel smoke per 100 grams of fuel (assuming black smoke). Thus to convert to grams per gallon it is necessary only to multiply the HDRSD reported smoke-factor by the fuel grams per gallon divided by one hundred (3198/100).

Note that while HDRSD measures NO, which constitutes a majority of the nitrogen oxides exiting the exhaust system, it is conventional when reporting measured nitrogen oxide emissions from vehicles to report NOx as equivalent NO_2 mass (as if all of the nitrogen in the exhaust had been oxidized to NO_2, even though much of it exits as NO). Therefore, for comparability with other mass measurements (including those reported by PEMS) and engine standards, the NO concentration has been converted into grams per gallon of the equivalent concentration of NO_2.

HDRSD does not measure the NO_2 that is emitted in exhaust along with NO. In this report, comparisons to PEMS results have been made using PEMS reported NO mass (PEMS measures and reports NO, NO_2, and NOx). To use the HDRSD NO grams per gallon values for inventory purposes or to compare to engine standards, the results should be multiplied by a factor of 1.2, where 0.2 is the typical ratio of NO_2 to NO mass for diesel exhaust. The resulting value for total NOx will be approximate only.

Like all infrared analyzers, HDRSD also does not measure all species of hydrocarbons. To compare to HC values measured by flame ionised detectors (FIDs) and for emissions inventory calculations, Singer and Harley[i] determined that a factor of 2.0 must be applied.

To convert truck standards from g/bhp-hr to g/gal, the standards are multiplied by 128,000 btu/gal times a 33% engine efficiency factor and divided by 2,545 btu/bhp-hr. This yields conversion multiplier of 16.6.

Appendix D Data Screening and Consistency of HDRSD Measurements

Remote sensing systems are sophisticated data acquisition systems that acquire much information, not all of which is useful for a given analysis. This section describes the approach taken to include or exclude remote sensing data used in the analyses discussed in this report.

The total data set for this study consists of roadside data and pictures acquired by the remote sensing equipment (4 separate measurement systems), tag edit (picture interpretation) license plate entries to the database, and manually recorded data logs of weight station information. The subsections that follow describe, in turn, basic data screens that are common to almost any remote sensing study, special raw data screens to remove records where there were known operational issues, and screens that focus the dataset to the particular engine operating modes of interest.

<u>Basic Data Screens</u>

Basic data screens utilize either special flags that are built into the HDRSD database or the presence of a particular data column having an entry (e.g. license plate number that is filled in if the picture can be interpreted). The data flags and status indications represent designed-in quality indicators that have evolved over more than a decade of remote sensing studies. These screens apply to all data analyses of this report.

The following are the records selected for inclusion:

Normal records:	excludes calibration or audit gas measurement records.
Gas Valid records:	a gas record is marked valid if at least 5 exhaust plume data points are measured where the sum of carbon-based gases exceed a threshold of 10 %-cm.
S/A Valid record:	the speed/acceleration subsystem provides a flag that indicates valid or invalid measurement readings.
CVA "GO" status:	The CVA (computer verified audit) status marks data records according to whether or not calibrations have been performed followed by a series passing verification gas audits. Only records that follow verified gas audits are used.
License Number:	Only records that have valid license plate number are included.

<u>Special operational screens</u>

In reviewing the data, several small data segments were discovered that appeared anomalous. Operating and other development personnel were interviewed to better understand what kind of scenarios could have lead to the problem, and screening techniques were developed to eliminate these segments from the data considered for analyses of this report. Three separate classes of problems are described below. The identification of these problems will lead to improved HDRSD software for measuring heavy-duty vehicles.

<u>*Improper CO channel Gain Setting*</u>

The high stack tower configurations resulted in longer than normal path lengths from the gas analyzer to the cross-road reflector and back. This resulted in marginally weaker signal strengths for the CO channel than are recognized in the operating guidelines for the equipment. Some operators attempted to resolve this situation by increasing the channel gain using special

engineering access to these settings but the change was not always implemented properly. Under certain operating conditions the gain could revert back to its normal value after calibration. This type of problem does not occur during normal remote sensing operations, and is associated with operating in an "engineering access" mode. A screening technique was developed that recognized large magnitude values of "ambient CO" as the signature of the problem. This screening resulted in the elimination of 897 records.

Lack of Beam Block prior to measuring (some NO readings)

The HDRSD spectrometer calculation algorithms require the voltage reading for used CCD pixels when there is no light present. This is obtained by blocking the UV light beam path. During normal ground level deployment of HDRSD the body of the vehicle being measured blocks the beam to satisfy the requirement. However, with the tower deployment to measure the diesel high stack exhaust, no part of the vehicle actual blocks the beam path. A 'quick-fix' to this problem for the cross-border study, although not the best solution, was to require the operator to manually block the beam every time the system was transferred into its normal measurement mode. Failure to perform this block results in a large default value being used for the zero beam values in the spectrometer algorithm and very large NO readings. There were several lapses in the following of the protocol. A screening technique was developed to review daily sessions by sorting the NO data from largest to smallest. When the largest NO readings occurred in a contiguous time sequence, the time sequence was eliminated. This screening resulted in the elimination of 169 records.

Spectrometer Off

During some portions of the study a version of the SDM flash code was used that could erroneously identify the operational status of the spectrometer as being offline. When this condition was detected, a default fixed data set was supplied for the spectrometer that resulted in hard zero measurement results for both NO and Smoke Factor calculations. The data sets were screened to exclude gas records where both NO and Smoke Factor readings were identically 0.0000. This screening resulted in the elimination of another two records that would otherwise have been considered valid.

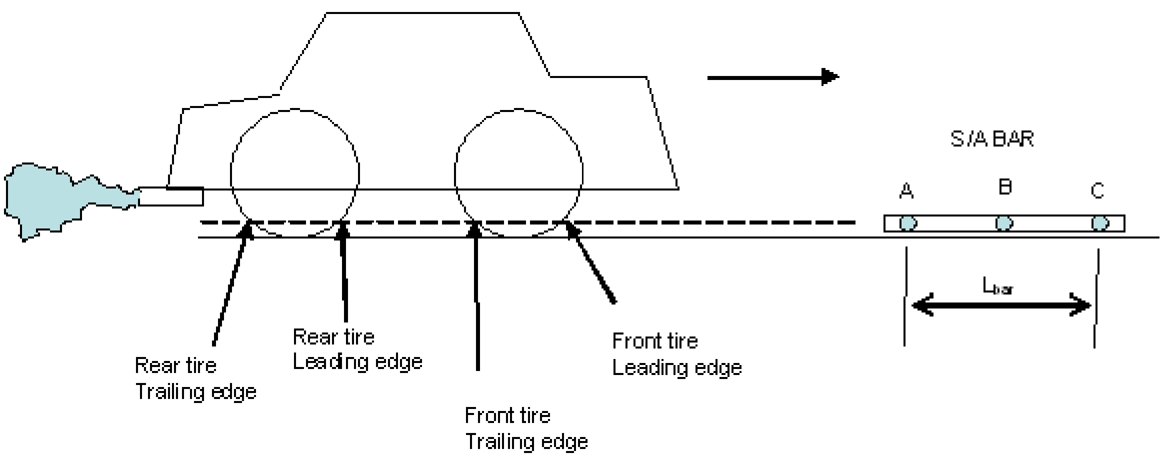
Engine Operating Condition Screens:

It is generally well understood that fuel-specific NOx emissions from a diesel engine without after treatment is essentially constant for engine loads greater than about 20-30%. For lighter loaded conditions the fuel specific NOx concentrations are significantly higher.
Since HDRSD readings are essentially fuel specific readings (e.g. NO/CO_2), it is important to recognize the difference between a lightly loaded engine condition and a moderate to heavy loaded engine condition when assessing the measurements. Failure to address this issue results in significant data variability.

The remote sensing method of determining basic engine operation utilizes its measurement of vehicle speed and acceleration, and knowledge of the road grade and vehicle weight, to determine vehicle power at the wheels, which can then be extrapolated to represent engine power via an estimate of power train efficiency. If one further assumes that the vehicle is operated in such a way (proper gear) as to maintain engine speed within a narrow range of operation, then wheel power can be loosely interpreted as engine load, i.e. high engine power implies moderate to high engine loads; low engine power implies light load.

The above scenario holds for both dynamic and steady operating conditions of the engine. However, the dynamics of the speed and acceleration measurements become extremely important when considering dynamic engine operation. These measurements must be "instantaneous enough" to track significant changes in engine power. Large, rapid changes in engine operation such as occur during a transmission shift may be transparent from speed and acceleration measurements that are derived from measurements of motion made at the start and end of a time interval that is longer than the time of a transmission shift. Such was the case for the speed/acceleration measurement subsystem used to measure the heavy-duty trucks for this study. The speed/accelerations measurement overview is presented below.

PRESENT SPEED/ACCELERATION MEASUREMENTS:



Velocity:

The ESP reported velocity is the average of trailing edge measurements of the front and rear tires as they cross the 30-inch measurement bar from bar position "A" to bar position "C", i.e.:

$$\text{Velocity} = \frac{V_{front} + V_{rear}}{2}$$

Where

$$v_{front} = \frac{L_{bar}}{t_{Cfront} - t_{Afront}}$$

$$v_{rear} = \frac{L_{bar}}{t_{Crear} - t_{Arear}}$$

t_{Cfront} is time that front tire unblocks beam C.

This is an approximate representation of the average speed for the vehicle traveling a distance from its front axle to its rear axle plus 30-inch bar length. It is not rigorously the true average, but is a reasonable approximation. The difference becomes significant only when the rate of change in acceleration (jerk) is large.

Acceleration:

The reported acceleration is the average acceleration for the vehicle as it travels from front to rear axle plus the bar length of 30-inches. Trailing edge tire events are used for the above speed calculations.

$$a_{front\_rear} = \frac{v_{rear} - v_{front}}{\left(\frac{t_{Crear} + t_{Arear}}{2}\right) - \left(\frac{t_{Cfront} + t_{Afront}}{2}\right)}$$

Assuming a typical velocity of a truck passing by the cross-border remote sensing station is 12-MPH (17.6 ft/sec) and further assuming that a typical first to second axle distance is ~16-ft, yields a total measurement distance of (16ft plus 2.7ft for the bar) 18.7 ft corresponding to a measurement time of 1.1 seconds. This is a long time period when compared to the amount of time it takes for an operator to unload the engine or to heavily load the engine during shifting operations. A more dynamic measurement is required to differentiate between loaded and unloaded engine conditions. Note that remote sensing measurements for cars are much more dynamic. This is because the axle to axle distances are shorter (~8ft) and because cars are usually traveling at ~25 MPH. This represents a typical measurement average of 0.25-second.

At the HDRSD site, the trucks being measured were gathering speed after starting from a virtual stop a few hundred yards before the HDRSD stations. The road at the measurement stations had an incline of 1.1 degrees. Trucks were observed to be quite often shifting gears as they approached or passed the HDRSD units. Since the individual speed/acceleration measurements (typically representing ~18 to 20 feet of vehicle travel or about 1-second time averages) were deemed to be too heavily averaged for predicting actual engine load or power state, an alternative scheme was chosen to select only measurements made when the engine was highly likely to be in a moderate to high load condition.

The approach chosen was to select paired sets of data measurements from adjacent stations (either station 1 and station 2, or station 2 and station 3) with additional constraints imposed that the first station must have a measured positive acceleration and the second station must have a measured velocity greater than the first station.

The analyses of subsequent sections of this report are restricted to the pairing constraints described above. In addition, the gross emitter analysis described later in this section used an additional filter requiring selected vehicles to have met the above constraints at least 4 times during the course of the study.

Despite some residual potential for gear changes to have been occurring at the time of an HDRSD measurement, the correlation of measurements made at successive HDRSD stations is good. Table D-1 shows the R2 correlations for speed, acceleration and pollutants for pairs of measurements made on vehicle trips past the array of three HDRSD stations. For simplicity, regression lines were forced through the origin, which slightly reduces the R2 correlations. Table D-2 shows the regression slopes. The values measured at the second HDRSD station were compared to those measured at the first station and values measured at the third HDRSD station were compared to those measured at the second. From Table D-2it is apparent that speed increased slightly as these vehicles passed through the stations but acceleration and emissions grams per gallon tended to decline slightly at successive stations.

Table D-1: HDRSD Pairs R^2 Correlation

	RSD 2 vs. RSD 1 (N=639)	RSD 3 vs. RSD 2 (N=309)
Speed	0.95	0.99
Accel	0.26	0.18
Smoke	0.75	0.71
HC	0.66	0.57
CO	0.62	0.49
NO	0.48	0.49

Table D-2: Regression Slopes

	RSD 2 vs. RSD 1 (N=639)	RSD 3 vs. RSD 2 (N=309)
Speed	1.03	1.02
Accel	0.80	0.73
Smoke	0.85	0.95
HC	0.77	0.89
CO	1.06	0.79
NO	0.96	1.00

Figures D-1 through D-4 compares the values from the first two stations for speed, acceleration, NO and smoke. It is possible that on the NO chart trucks with HDRSD 1 emissions of ~100ppm and HDRSD 2 emissions from 150 to 350 ppm were shifting gear passing HDRSD 2. Similarly, trucks with HDRSD 2 NO emissions of ~100ppm and HDRSD 1 emissions of 15 to 350ppm may have been shifting gear as they passed HDRSD 1.

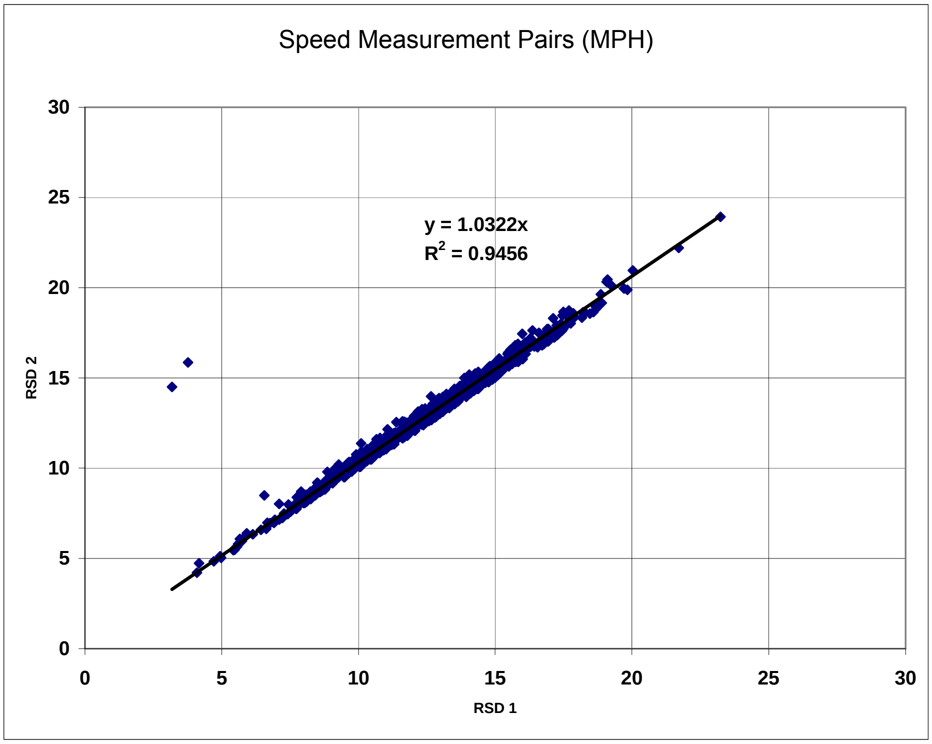


Figure D-1 Speed Measurement Pairs

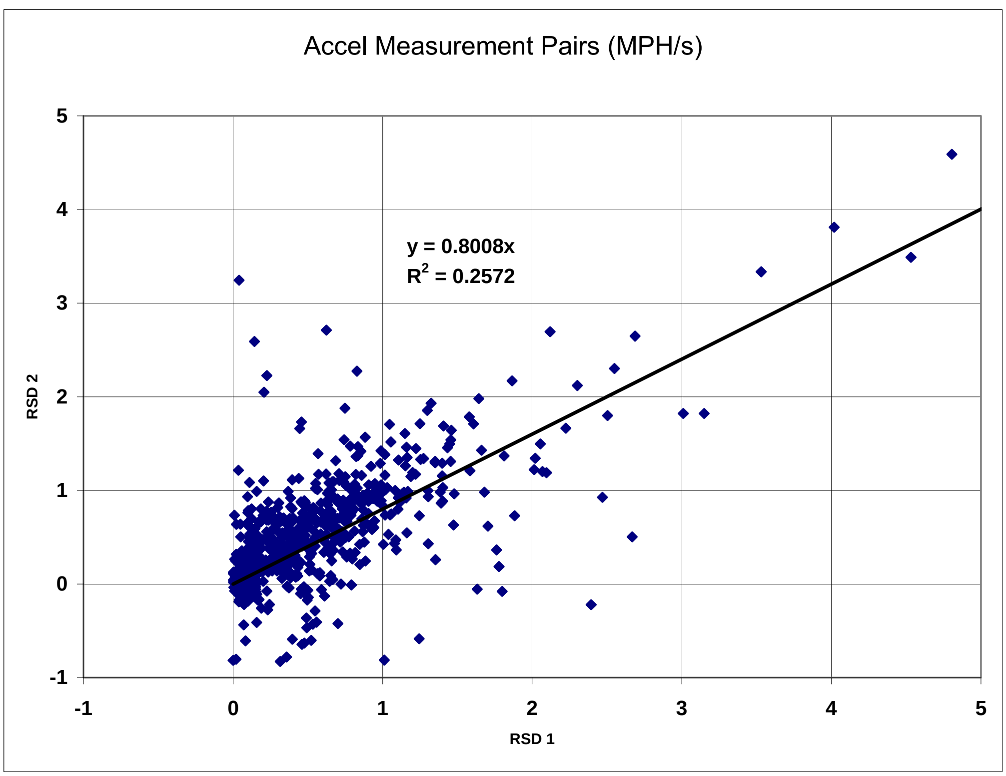


Figure D-2 Acceleration Measurement Pairs

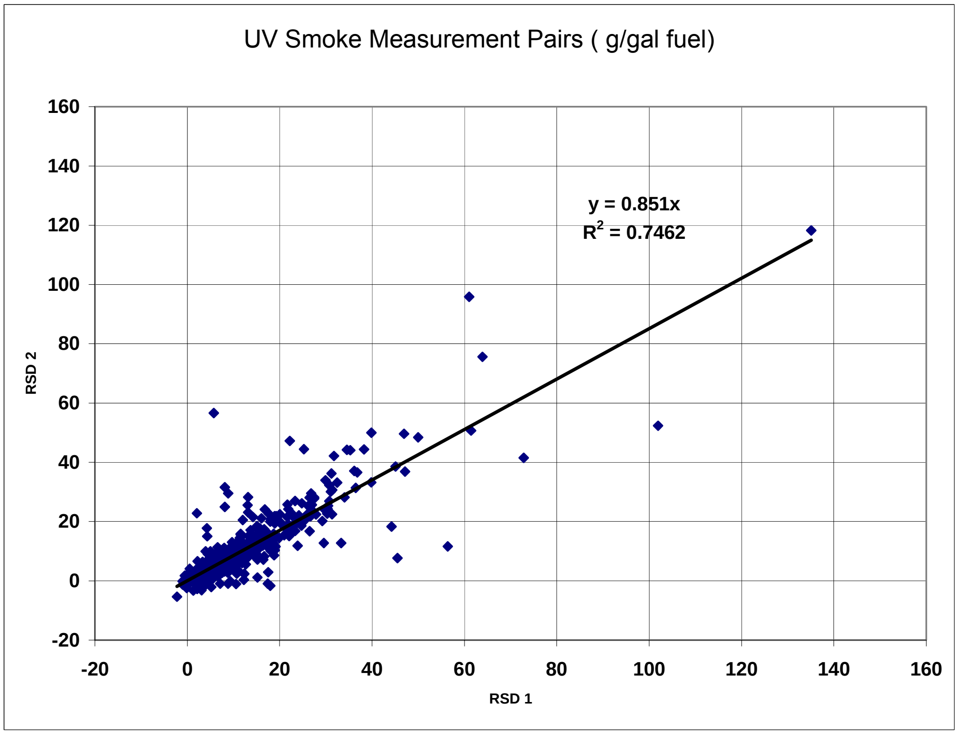
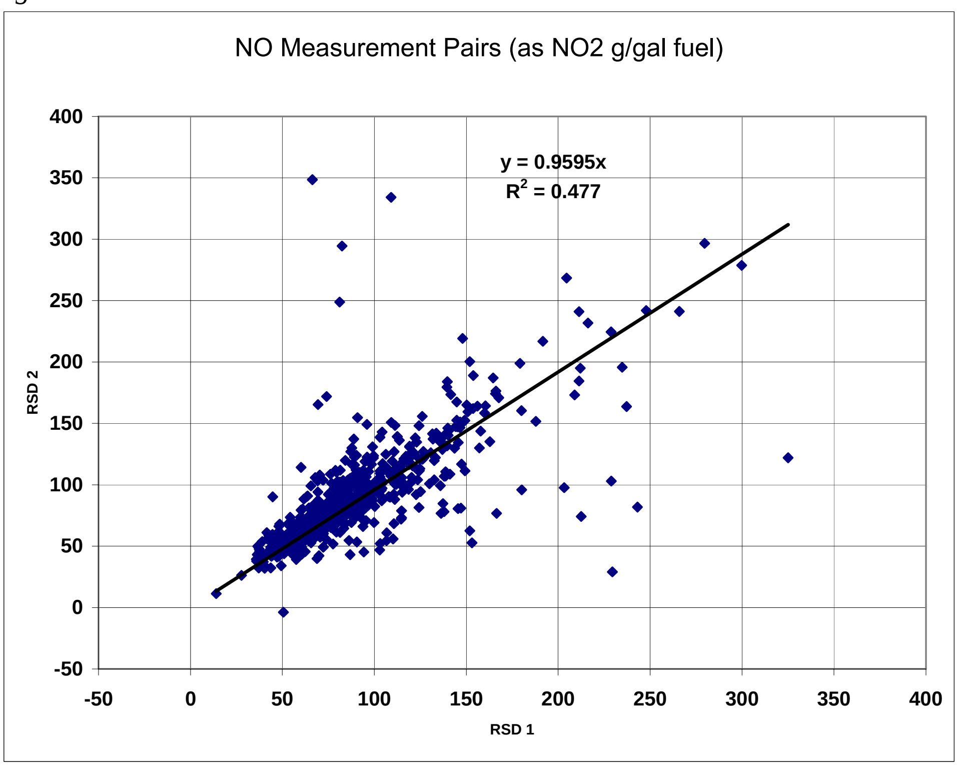


Figure D-3 UV-Smoke Measurement Pairs

Figure D-4 NO Measurement Pairs



Appendix E PEMs-HDRSD Correlation: Time Alignment and Data Analysis

The first step in the procedure to analyze the correlation between instantaneous PEMS and HDRSD readings was to find a means to determine at what point in the PEMs data set the vehicle passed the HDRSD sensor. Once the PEMs data was time-aligned, the HDRSD data had to be compared to the PEMs data that was taken simultaneously. Attempts to synchronize clocks during the data collection process did not prove to be useful; both the PEMs and the HDRSD gather time data based on their own internal clocks, rather than from the clocks internal to the PCs that the devices were connected to, as initially expected. Therefore, data had to be aligned by some other means.

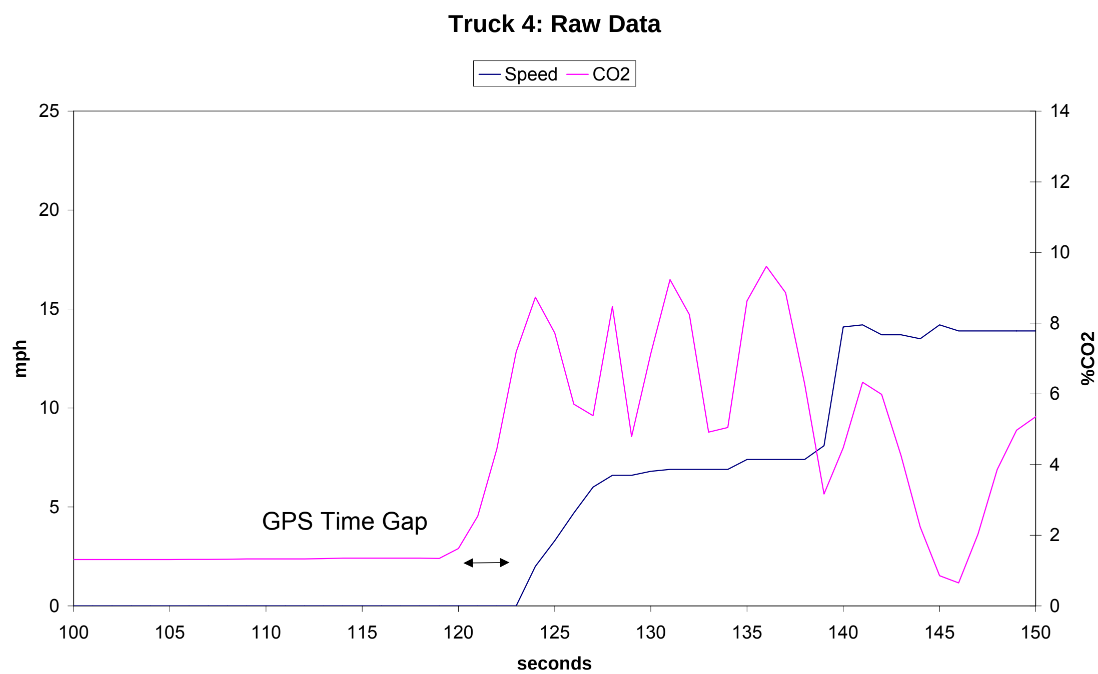


Figure E-1 GPS Time Lag, Relative to PEMS CO_2.

Fortunately, both systems include an integrated GPS sensor that records latitude, longitude and elevation of each measurement taken. It should be noted that GPS data is also used by the PEMs device to calculate vehicle speed for applications such as this one, where no ECU data is available. It was reasoned that since the GPS coordinates of each of the two HDRSD sensors was known, this data could be used in conjunction with the PEMs GPS data to determine at which points in the PEMs file the trucks passed the HDRSD sensors. Then, once these points were determined, the time stamps reported by each of the devices could be compared to provide a time difference between the two that was universal for the entire test.

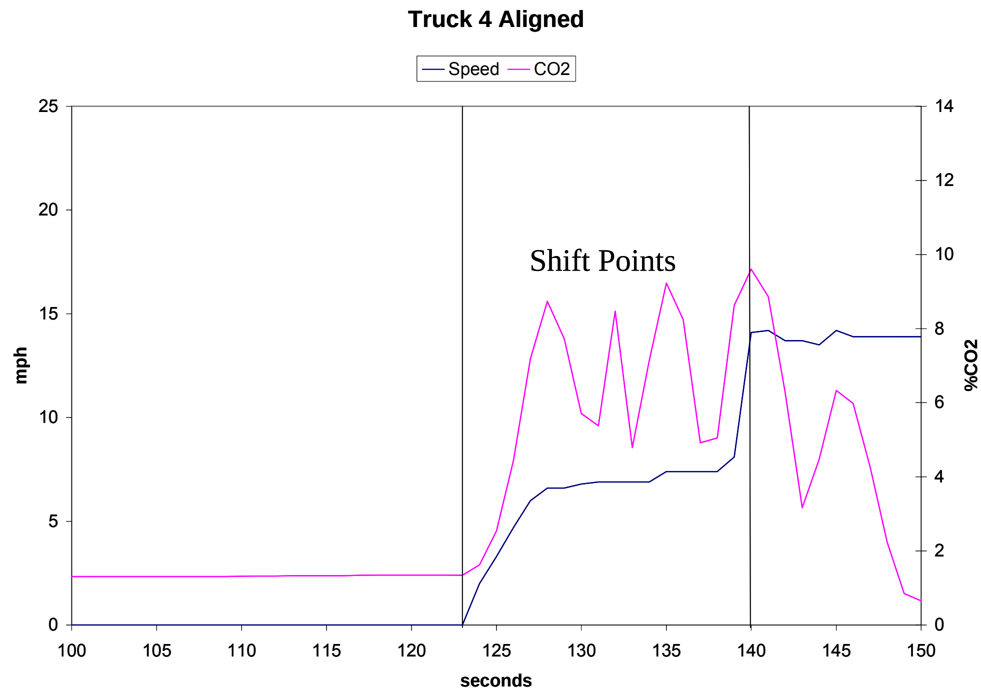


Figure E2 Aligned GPS Data

The first step in this process was to align the GPS data to the PEMs pollutant channels. Although both the pollutant channels and the GPS location are measured from the same clock (internal to the PEMs device), the GPS data does not account for the time that it takes for the signal to be measured and reported by the GPS satellite. Therefore the GPS locations and vehicle speed calculations lag the PEMs pollution channels by a few seconds in each file. Figure E1 illustrates this time lag, as time-aligned data would show a rise in CO_2 simultaneous with a rise in speed. The time difference in this particular file is four seconds. All files required a GPS time adjustment of either three or four seconds relative to the PEMs CO_2 measurement. A properly aligned trace of GPS speed and PEMs CO_2 is shown in Figure E2.

With the GPS time alignment values applied to the data, the next step was to search the PEMs data for latitude/longitude values that matched the latitude/longitude values of the HDRSD sensors. It was hoped that once these points in the PEMs file were identified that the same time lag would be visible between the time stamp reported by the PEMs and that reported by the HDRSD, for each point that the truck passed the HDRSD sensors. Unfortunately, this was not found to be the case as there were three sources of error with this method:

- The GPS locations of the two devices were not expected to match exactly, as the trucks pass close to the HDRSD sensors, rather than directly over them. (± 5’)
- GPS measurements are reported by an array of orbiting satellites, which is subject to inaccuracies caused by variations in their orbit. (± 30’)
- The PEMs device, and accompanying GPS, report measurements once per second, and therefore do not necessarily coincide with the exact instant that the trucks pass through the sensors (± 22’ at 15 mph)

Combining the error associated with these three inaccuracies indicates that the GPS measurements reported by the two devices will only be accurate within approximately ± 50' of each other, or approximately the fourth decimal place of GPS latitude/longitude readings. Therefore, rather than searching the PEMs file for exact coordinate matches, they were searched for the closest match within the amount of time that it takes the truck to complete a loop around the test site. GPS data analysis revealed this time to be approximately 1½ - 2 minutes, depending on the driver.

The PEMs file was searched for the GPS coordinates that most closely matched the HDRSD coordinates. In order to ensure that the measurements were reasonably accurate, the truck route, HDRSD locations, and PEMs GPS values used were plotted in a chart. An example of one such chart is shown in Figure E3. The figure also illustrates the variation in the GPS measurements, as the path that the truck follows as measured by the GPS is approximately 50 feet wide, whereas the trucks actually drove in a single lane, and therefore could not have varied by more than a foot or two each time around. Measurement points that were particularly distant from the GPS sensors were re-examined to ensure that their coordinates were in fact those that most closely matched the HDRSD coordinates for that particular pass through the sensors.

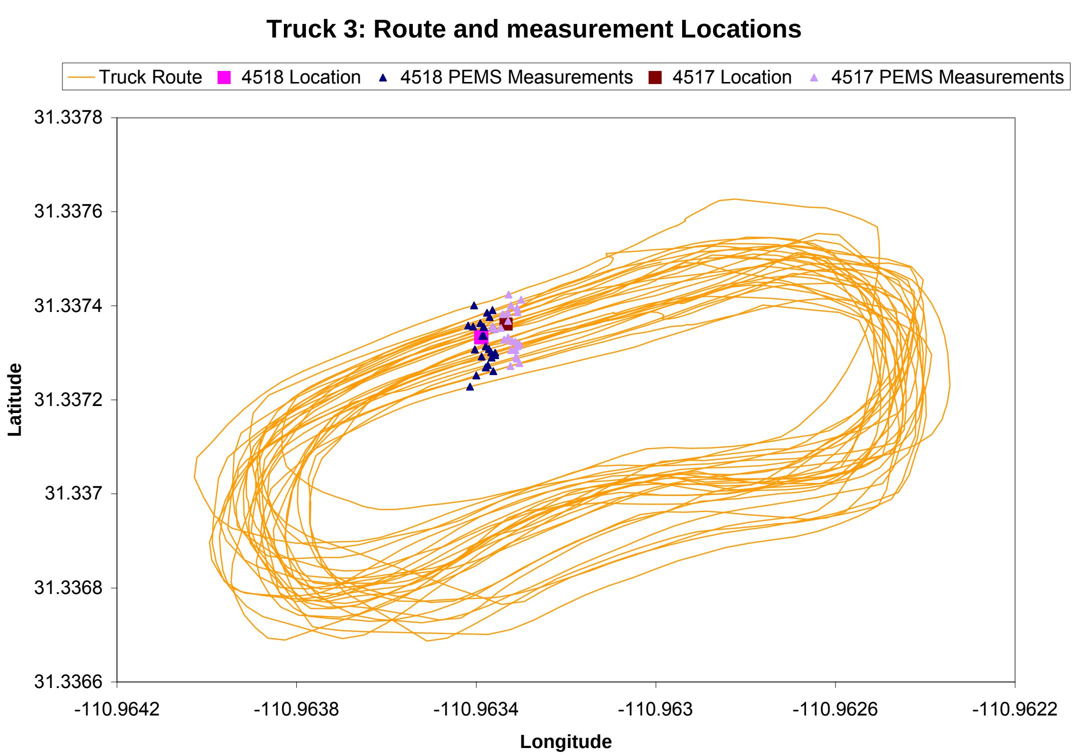


Figure E3 Truck Route, HDRSD Estimated Locations, and Coordinates of PEMS Measurement Locations Used for Time Alignment analysis

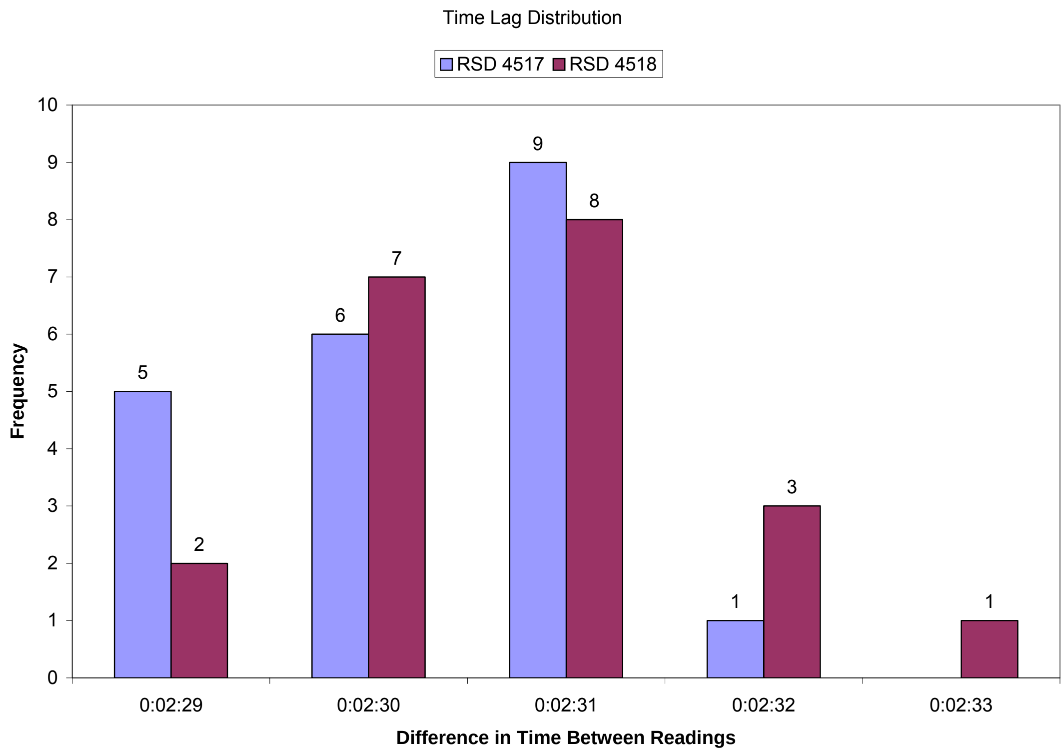


Figure E4 Truck 4 Time Lag Distribution

Once the closest matching values were determined, these points along with their respective timestamps were recorded in a table. Corresponding HDRSD time stamps were also recorded, and the difference between the two were calculated. It was initially hoped that the time difference would be the same for each pass through the sensors, but due to the various inaccuracies mentioned above, this was not found to be the case. Assuming that both clocks keep accurate time, it stands to reason that the time lag between the HDRSD and the PEMs should be constant for each test. Therefore, based on the results of the table, a single time difference for the purpose of time alignment had to be chosen to be applied to each measurement, regardless of how close the PEMs GPS readings were to the HDRSD GPS coordinates. This method is validated by the fact that there is significant error in the relative GPS measurements, but essentially no error in either device's method of time recording. Analysis of the time differences revealed that for each truck, the measured differences between the HDRSD and GPS clocks formed a bell-shaped curve, with extremes varying from the average by only 2-3 seconds in every case. Therefore, a statistically sound estimation of the time difference between the two could be made for each file. Figure E4 displays these results for one particular test. For this truck a time difference of 2 minutes 31 seconds was applied to all calculations, as this time is the most common time difference, as well as the median difference. Time lag distribution charts looked similar for each of the four trucks tested. Final time lags varied from 2:28 to 2:31 based upon the distribution for any particular test.

At this point, the correlation between the HDRSD and PEMs data could be examined. However, because of multiple sources of error in the time estimation procedures, it was estimated that the data was only accurate within ±2 seconds; recall that each of the following is a source for error, each of which add several tenths of a second of uncertainty to the final data.

- The PEMs pollutant channels are aligned only within the constraints of the measurement frequency (1Hz)
- GPS measurements are accurate only within 50 feet, or approximately 2 seconds at 15 mph
- GPS speed and PEMs channels are aligned only within the constraints of the measurement frequency
- HDRSD readings are averaged over ½ second snapshot, rather than instantaneous

Unfortunately, these possible causes of time discrepancy cannot be ignored, for pollution and CO_2 concentrations can vary by a significant amount within a single second. Furthermore, many calculations involve dividing pollution concentrations by CO_2 concentrations, which if slightly misaligned will cause even greater variation in the results. Instantaneous HDRSD correlation results could potentially be greatly affected by a slight time misalignment. This point is illustrated in figures E5 and E6. Figure E5 shows the direct comparison of PEMs NO:CO_2 readings to HDRSD NO:CO_2 readings for a large part of the cycle for a particular truck.

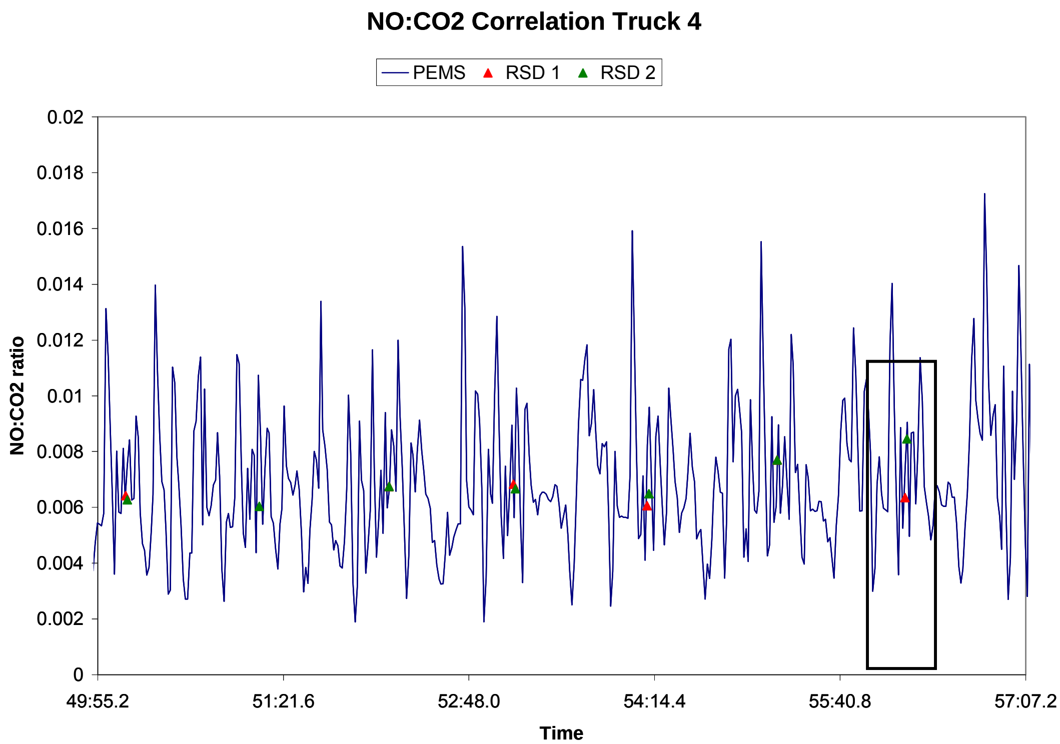


Figure E5 NO:CO_2 PEMS trace with corresponding HDRSD points

It is clear from the figure that the PEMs and the HDRSD measure NO emission rates similar to one another, as all of the HDRSD readings fall within the bulk of the PEMs readings. In fact, by looking at this figure, it appears as though the two devices coincide well. Also seen in this figure is the degree of variation in pollution concentration levels that occur over short periods of time as the driver shifts while accelerating. Figure E6 shows an expanded view of the boxed off section

of Figure E5. This figure shows the variations in PEMs pollutant concentrations levels even more clearly. In Figure E6, each point along the PEMs trace represents one second.

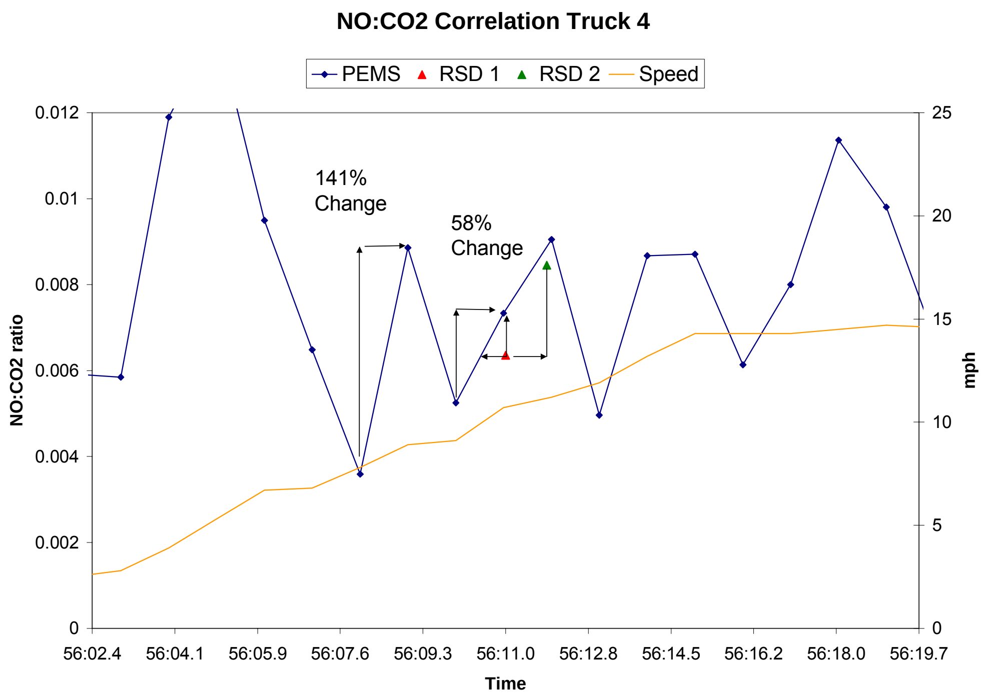


Figure E6 An expanded view of the NO:CO_2 comparison shown in Figure 5.5

The figure illustrates that variations of 100% or more from one second to another are not uncommon. Furthermore, it shows how slight time alignment inaccuracies can adversely affect the HDRSD correlation results, as a two-tenth of a second shift would place the HDRSD points exactly on the PEMs trace. The magnitude of variation visible in the PEMs trace is statistically significant, as the time alignment analysis discussed above is accurate only within ±2 seconds. Finally, note in the figure that the HDRSD points are nine tenths of a second apart, as opposed to a whole second. The time difference between HDRSD measurements varied depending on how fast the vehicle was moving as it passed the sensors, but it is important to note that this time difference was rarely, if ever, exactly one second. Therefore, since the PEMs records data at a rate of 1 Hz, no matter how well the data is time-aligned, the HDRSD points will never be able to be exactly matched up with PEMs measurements, as PEMs measurements simply do not occur frequently enough.

The next challenge faced in the data analysis process was to find a way to compare the two devices given this time-alignment discrepancy, with the various points of error accounted for to the extent possible. The most practical means of displaying the results for a correlation study such as this one is to chart each point as measured by one device against the value measured by the other device, simultaneously. Figure E7 shows such a chart for all NO:CO_2 data gathered throughout the study. In the case of a perfect correlation, all of the points would form a straight line protruding from a y-axis zero intercept at a 45 degree angle, indicating that each point as measured by one device was measured exactly the same by the other. Changes in the slope of the line indicate that a particular device (either HDRSD or PEMs) measures consistently higher or lower than the other. Points that deviate from the line indicate a disagreement between the two devices, and are quantified by the R^2 value displayed on the chart. Of course, given the various

time alignment issues and other sources for error in this experiment as catalogued in previous sections, such a clean correlation was never expected in this case.

Because it is impossible to align the PEMs data and the HDRSD data exactly, Figure E7 shows each HDRSD point charted against the PEMs measurement that was closest to it within a 2-second (±1 second) range. The results are certainly promising, as a positive-slope trend is clearly visible. Since it was theorized that much of the scatter seen in this data was due to time alignment inaccuracies, further means of examining the data were explored.

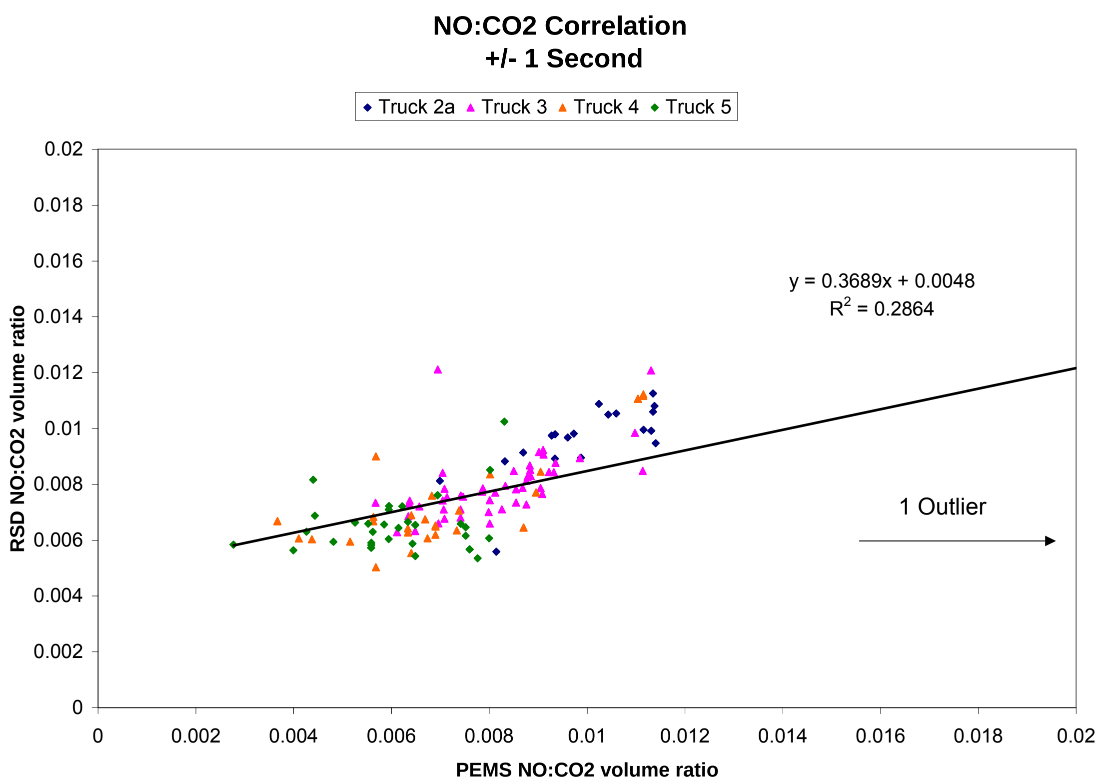


Figure E7 Initial NO:CO_2 Correlation Results

It is clear from the initial correlation that both the PEMs and HDRSD agree on which vehicles are clean and which are dirty. For example, truck 5 shows lower average readings from both devices than truck 2a. Based on this observation, it was concluded that a chart displaying averages might provide a cleaner correlation. Unfortunately, displaying HDRSD averages is statistically irrelevant, as HDRSD readings are expected to vary greatly depending on engine activity (i.e. acceleration, deceleration or idling) at the time of the HDRSD snapshot. PEMs data however, is not a snapshot, and since it is representative of all engine activity rather than just various instants of activity, PEMs averages over an entire cycle do hold merit. Therefore, PEMs averages were calculated and plotted against the entire group of HDRSD readings for that truck. The PEMs averaged NO:CO_2 plot is shown in Figure E8. Again, the results are positive, showing trucks with a lower total cycle PEMs average to have a lower overall grouping of HDRSD readings. However, the problem with this form of analysis is that it is unclear as to whether the scatter in the data is the result of inaccuracies in the measurement devices, or simply in variation in engine

activity as the trucks pass the HDRSD sensors. For this reason, further means of data analysis were explored.

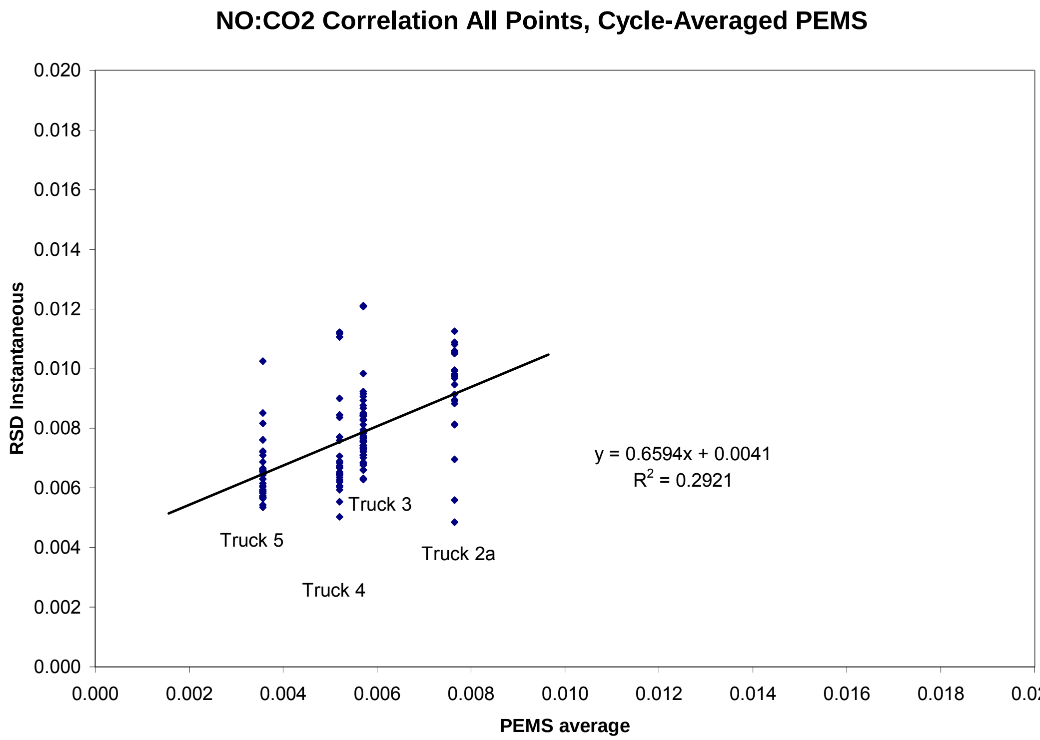


Figure E8 PEMS Total Cycle Averaged NO:CO_2 vs. HDRSD Instantaneous NO:CO_2

Under the assumption that much of the scatter in these charts are the result of varying engine activity, the next phase in the data analysis was to attempt to isolate the engine activity by only displaying the most useful HDRSD readings. HDRSD readings that are taken during periods of deceleration are not useful for identifying high emitting vehicle. The reason for this is that all pollution readings are reported as ratios to exhaust CO_2 concentration. During engine deceleration, both the CO_2 concentration and the various pollutant concentrations drop significantly, but if CO_2 readings become too low, the ratio of pollutant to CO_2 becomes very high. This is more of a mathematical anomaly than a vehicle operational issue, and therefore vehicle decelerations are commonly ignored during HDRSD data analysis. Keep in mind that vehicles do not emit at high rates during deceleration either. In this case, vehicle decelerations were filtered out based on information provided on the on-site log sheets. As seen in Figure E9, doing so eliminated some of the HDRSD outliers, but did not vastly change the results.

At this point, a new approach was taken to minimize variation caused by time alignment issues. Since it was determined that the time alignment was only accurate within ±2 seconds, HDRSD readings could be charted against the closest respective PEMs readings within this time range in order to account for the error. Although such an approach may give the appearance of a neater correlation than the data initially suggests, it is countered by the fact that the possibilities of a clean correlation are hindered from the onset due to the mis-match between PEMs measurement frequency (1 hz) and HDRSD measurement duration (less than one second), coupled with the

extreme 1-second variations in the pollutant concentration data. A chart of the NO: CO_2 correlation using this 2-second span is displayed in Figure E10.

The results seen here are very positive. Not only are data points all within the same range as measured by each device, for each vehicle, but the majority of the points also fall on or very close to the trend line. Furthermore, the slope of the trend line is very close to 1, and there does not appear to be any deviation at the extremes caused by a limit in the NO detection range. These results are well corroborated by PEMs-HDRSD correlation studies done on a bus fleet where time alignment issues were much less significant due to the project design. The remainder of the analysis, shown below, is carried out in this fashion.

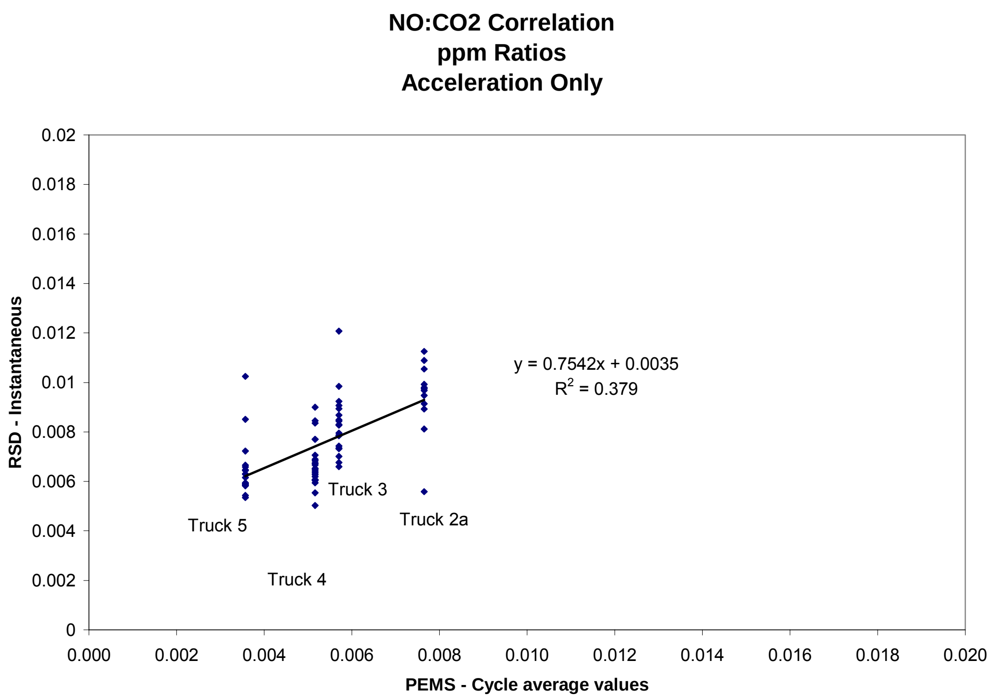


Figure E9 PEMS Total Cycle Averaged NO:CO_2 vs. HDRSD Instantaneous NO:CO_2 for Acceleration Only

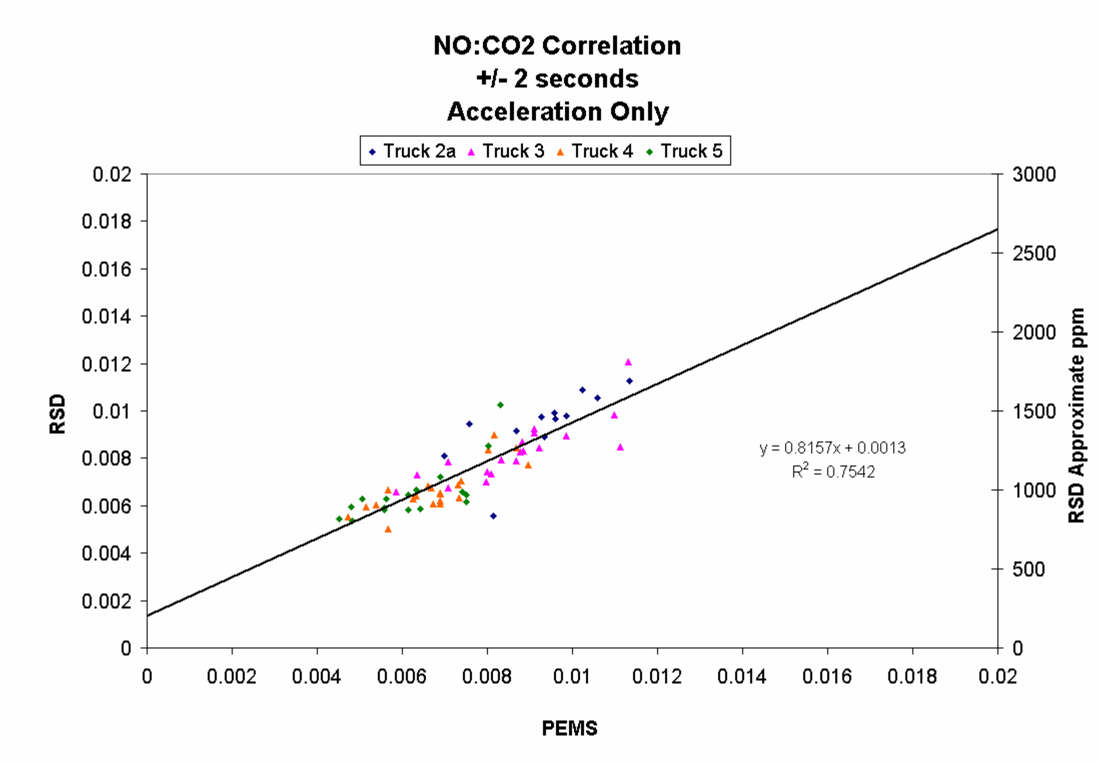


Figure E10 PEMS-HDRSD Instantaneous NO: CO_2 Correlation Using PEMS Value Closest To HDRSD Value within the Margin of Error of the Experiment

Appendix F: PEMs-HDRSD Scatter Plots at Readings of +/- 1 Second

The scatter plots shown in Figures F-1 through F-3 present correlations of instantaneous PEMS and HDRSD readings from the four trucks used to collect supplementary correlation data. These plots show each HDRSD reading taken from the four trucks plotted against the closest PEMS reading recorded within +/- 1 second of the HDRSD reading. Only points for which the vehicle was accelerating in accordance with the data collection log sheets are plotted.

These scatter plots are analogous to the plots shown in the results section of the report, except that those plots correlated HDRSD data to the closest PEMS data recorded within +/- 2 seconds, in accordance with the assumed accuracy of time alignment. Given the accuracy of time alignment, the project team believes that the charts shown in the body of the report are most relevant for evaluating correlation of instantaneous PEMs and HDRSD measurements. These charts are provided in the interests of full disclosure.

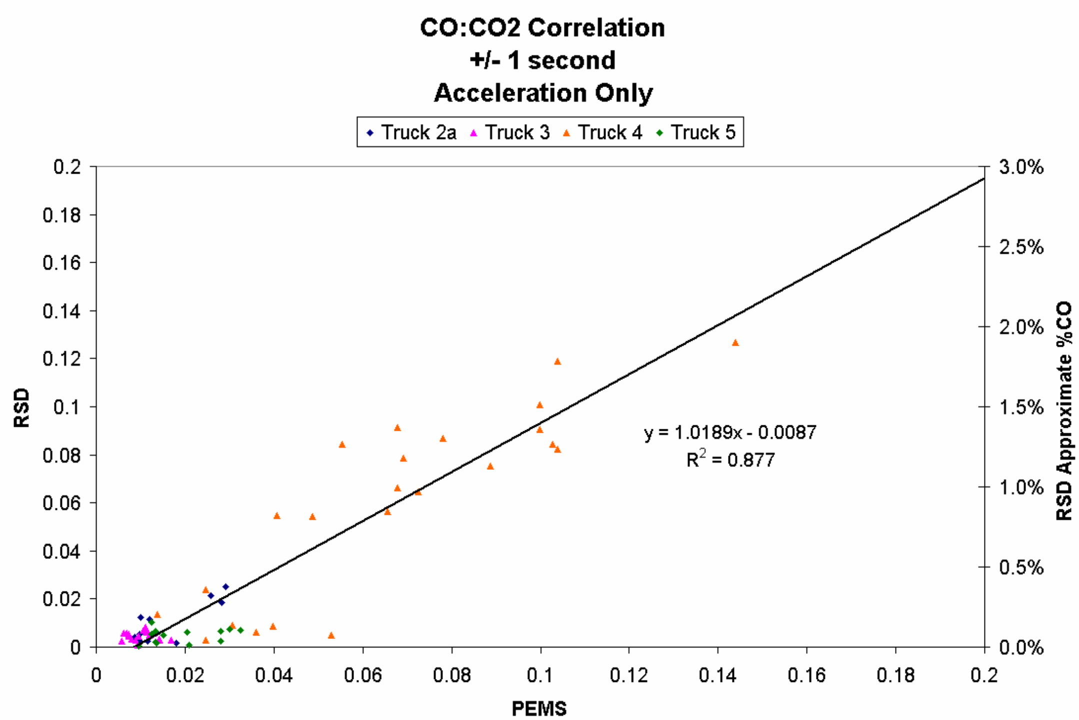


Figure F1 CO:CO2 Correlation

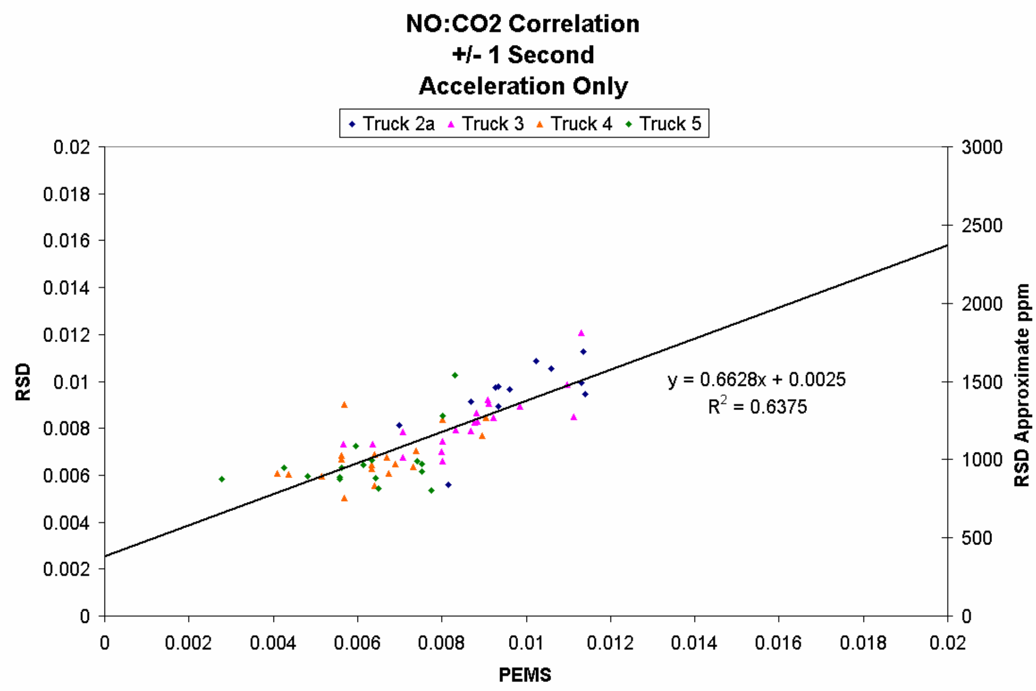


Figure F2 NO:CO_2 Correlation

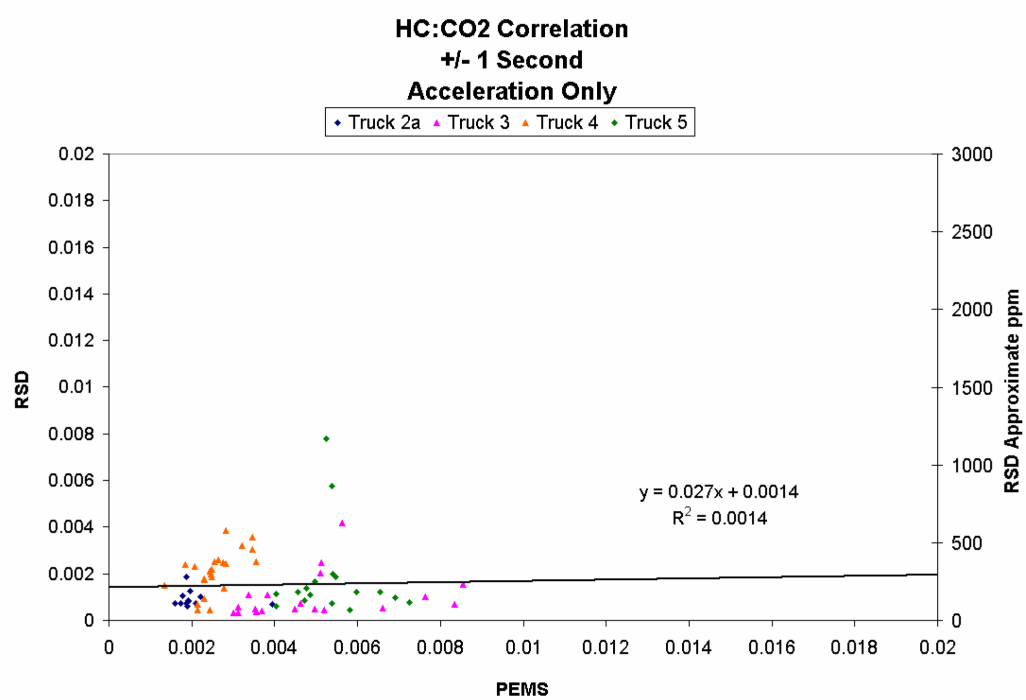


Figure F3 HC:CO_2 Correlation

Appendix G: HDRSD Smoke Factor Theory and Derivation

SMOKE FACTOR THEORY

The ESP Smoke Factor, SF, is included in the latest generation of RSD measurement products. The smoke factor is fuel specific measurement that is isimilar in concept to other remote sensing measurements. It is the theoretical ratio of soot mass to fuel mass at the instant of measurement.

THE ACTUAL CALCULATION:

$$SF = \frac{-\ln(T) \cdot 100}{n_{CO2} + n_{CO} + n_{HC}}$$

where SF is the smoke factor in grams soot per 100 grams fuel.

T is measured plume transmittance at 230 nm.

n_{CO2} is amount of measured plume CO_2 in %-cm.

n_{CO} is amount of measured plume CO in %-cm.

n_{HC} is amount of measured plume hydrocarbons in %-cm.

THE THEORETICAL EQUATION BASIS:

$$sf = \frac{N_P \cdot \left(\frac{grams_{part}}{cm^2}\right)}{N_F \cdot \left(\frac{grams_{fuel}}{cm^2}\right)}$$

where sf is the fuel specific measurement in grams of particulate per grams of fuel

N_P is the measured particulate (soot) mass per unit optical beam cross-section

N_F is the measured fuel mass per unit beam cross-section.

THEORYand DERIVATION:

The numerator is derived from the Beer-Lambert Law:

$T = e^{-k_{UV} \cdot N_P}$ where T is measured plume transmittance at 230 nm.

k_{UV} is the optical extinction factor (cross-section) for soot at 230 nm expressed as cm^2/gram soot.

$$k_{UV} = 18 \cdot 10^4 \cdot \left(\frac{cm^2}{gram_{soot}} \right)$$ **(This is the key assumption documented from literature sources)**.

From above:

N_P is the particle mass per beam cross-section (particles soot per cm^2).

$$N_P = \frac{-\ln(T)}{k_{UV}} = \frac{-\ln(T)}{18 \cdot 10^4 \cdot \left(\frac{cm^2}{gram_{soot}} \right)}$$

The denominator is derived from conventional RSD gas measurements and combustion chemical balance considerations:

1 mole of fuel = 1 mole of combustion carbon gases

1 mole of fuel in mass is 14 grams

divide by unit cross-sectional area of the measurement beam

$$\frac{N_F \cdot (\text{moles}) \cdot \left(\frac{14 \cdot \text{gram}_{\text{fuel}}}{\text{mole}}\right)}{\text{cm}^2} = \frac{(n_{CO2} + n_{CO} + n_{HC}) \cdot (\text{moles}) \cdot \left(\frac{14 \cdot \text{gram}_{\text{fuel}}}{\text{mole}}\right)}{\text{cm}^2}$$

Actual measurement values for RSD gases are in units of %-cm; therefore, Avorgadro's Number and Loschmidt's Numbers are used to convert to appropriate units.

$$= \left[\left[(n_{CO2} + n_{CO} + n_{HC}) \cdot (\% - \text{cm}) \right] \cdot \left(\frac{0.01}{\%}\right) \cdot \frac{2.479 \cdot 10^{19} \cdot \left(\frac{\text{molecules}}{\text{cm}^3}\right)}{6.023 \cdot 10^{23} \cdot \left(\frac{\text{molecules}}{\text{mole}}\right)} \right] \cdot \left(\frac{14 \cdot \text{gram}_{\text{fuel}}}{\text{mole}}\right)$$

where N_L is Loschmidt's Number 2.479x10^19 molecules per cm^3

N_{AV} is Avorgadro's Number 6.023x10^23 molecules per mole

$$= (n_{CO2} + n_{CO} + n_{HC}) \cdot 5.762 \cdot 10^{-6} \cdot \left(\frac{\text{gram}_{\text{fuel}}}{\text{cm}^2}\right)$$

$$sf = \frac{N_P \cdot \left(\frac{grams_{part}}{cm^2}\right)}{N_F \cdot \left(\frac{grams_{fuel}}{cm^2}\right)} = \frac{\left[\frac{-\ln(T)}{18 \cdot 10^4 \cdot \left(\frac{cm^2}{gram_{soot}}\right)}\right]}{\left[\left(n_{CO2} + n_{CO} + n_{HC}\right) \cdot 5.762 \cdot 10^{-6} \cdot \left(\frac{gram_{fuel}}{cm^2}\right)\right]} = \left[\frac{-\ln(T)}{\left(n_{CO2} + n_{CO} + n_{HC}\right)}\right] \cdot (0.964) \cdot \left(\frac{gram_{soot}}{gram_{fuel}}\right)$$

where n_{CO2}, n_{CO}, and n_{HC} are in (%-cm)

NOTE: the constant 0.96 is considered 1 for all practical purposes.

$$SF \cdot \left(\frac{gram_{soot}}{100 \cdot gram_{fuel}}\right) = sf \cdot \left(\frac{gram_{soot}}{gram_{fuel}}\right) \cdot 100$$

This is the reported smoke factor.

NOTES:

(1) Density effects are ignored in both numerator and denominator calculations since they cancel. This is a key feature of the measurement since the result is independent of air dilution effects. Conventional smoke meters are subject to such dilution effects. A smoke meter measurement would be reduced by additional air injected by a turbocharger.

(2) The optical extinction factor use above is only for diesel soot particulate (black smoke). It is not accurate for other forms of particulate such as oil-based "blue smoke" or "white smoke" containing water or raw fuel.

(3) The RSD gas amount measurement units are in (%-cm). An example of the meaning of these units is as follows. At standard pressure and temperature fill a 5-cm deep measurement cell with 10% concentration of CO and 90% N2. Insert the cell into an optical measurement beam path. The result is a 50 %-cm amount (the product of concentration time path length). The same measurement would result if the cell were 10-cm in depth and the concentration of CO were 5%.