Remote Sensing of In-Use Heavy-Duty Diesel Trucks

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On-road measurements in 2005 of carbon monoxide (CO), hydrocarbons, nitric oxide, nitrogen dioxide, and sulfur dioxide from 1641 individually identified heavy-duty diesel trucks at two locations in Colorado are reported. Carbon monoxide and nitric oxide show increasing emissions with increased altitude. Oxides of nitrogen (NO_x) emissions have decreased with more recent model years over the last 10 years but are the same as vehicles that are 20 years old. At the Golden, CO site, there was a statistically significant decrease in fleet emissions of CO and NO_x since a similar study in 1999. There was no emission trend for CO or NO_x with gross vehicle weight or odometer in units of grams of pollutant per kilogram of fuel consumed. Data from this study suggest that on-road remote sensing can detect illegal, high sulfur fuel use from individual heavy-duty diesel trucks. Ammonia emissions from this study were below the detection limit of the instrument but will be useful as a baseline value for future comparison.

Introduction

It is well-known that diesel vehicles produce significant quantities of nitric oxide (NO) and, to a lesser extent, nitrogen dioxide (NO_2) (*1*, *2*). These two gases are together referred to as NO_x and contribute to a number of environmental problems including urban smog, acid deposition, and secondary aerosols in the form of nitrates. Heavy-duty diesel (HDD) vehicles are becoming the dominant source of mobile NO_x emissions and account for 30−60% of the on-road NO_x even though they comprise only 2% of the fleet by number (*3*, *4*). As such, HDD vehicles emissions have received growing attention in a variety of studies such as chassis dynamometers (*5*, *6*), in a tunnel (*7*), and remote sensing (*8*−*10*) as well as one critical review (*4*). These studies generally agree that there has been little reduction in NO_x over the last 20 measured years. Although NO is the major component of NO_x, previous remote sensing studies have underestimated NO_x since they have not measured NO_2. Jimenez et al. measured NO and NO_2 remotely using tunable diode laser absorption spectroscopy (TDLAS) but did not measure carbon monoxide (CO) or hydrocarbons (HC) (*10*). They reported on 73 unidentified HDD trucks without make, model year, and odometer reading. This paper reports the first NO_x on-road measurements that can be correlated to fuel consumption for individually identified vehicles.

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The United States Environmental Protection Agency (U.S. EPA) and the California Air Resources Board (CARB) have passed stringent HDD vehicle NO_x and particulate matter (PM) reduction regulations that begin to take effect with 2007 model year engines and become 100% effective in 2010 (*11*, *12*). Reduction of PM can be achieved with the use either of oxidation catalysts or regenerative diesel particulate filters (DPF), but DPFs have been found to be much more effective (*13*). DPFs for regeneration rely on exhaust temperature and the intentional catalytic oxidation of NO to NO_2 to oxidize particles; however, any new NO_2 emissions are a concern because of accelerated ozone formation (*14*−*17*). To this end CARB proposed a complimentary regulatory limit for vehicular NO_2 emissions that will limit postcontrol NO_2 emissions to less than 20% of precontrol NO_x (*18*). This protocol was later suspended and rewritten to be a bit more relaxed by limiting postcontrol NO_2 emissions to be no more than an incremental increase of 30% over precontrol NO_2 with a further reduction to 20% in 2009 (*19*). On-road measurements made with a chase vehicle have found that the NO_2/NO_x ratio from DPF equipped transit buses was 33%, whereas non-DPF equipped buses emitted less than 10% of the NO_x as NO_2 (*15*). Thus, in an attempt to reduce PM, DPF technology may actually increase ozone formation. The ability to measure and monitor on-road NO_2 release from DPF equipped vehicles will be important in evaluating this technology's overall success.

Further NO_x reductions may require the use of catalytic techniques such as selective catalytic reduction (SCR) as it is used to reduce NO_x from stationary sources (*20*). The downside of this technology is that excess hydrolyzed urea, not used to catalyze NO_x, can be released in an "ammonia slip". This would be especially true during transient driving modes. CARB has looked into proposing limits for ammonia (NH_3) emissions arising from this technology (*21*). NH_3 emissions from a number of SCR equipped vehicles have been investigated in a dynamometer study (*22*). Two tunnel studies have measured on-road HDD NH_3 emissions, but the results differed significantly (*23*, *24*). The study in 1981 reports the HDD NH_3 emission factor to be 16 ± 4 mg/mile, whereas a study in 1999 reported 8.3 ± 2.4 mg/mile. This paper reports the first NH_3 emissions from individual on-road HDD vehicles which will help to determine pre-SCR on-road ammonia baseline measurements.

After-treatment technologies such as SCR and DPF require low sulfur diesel fuel, and as a result, sulfur in on-road diesel fuel across the country is currently in the process of being lowered to 15 ppmw. Off-road fuels that contain significantly more sulfur can be burned in diesel engines. These fuels are not taxed for highway use and therefore provide a financial incentive for on-road use. Combustion of sulfur compounds leads to the production of SO_2 and to a lesser extent SO_3 (*2*). On-road SO_2 emissions from a small number of transit buses have been measured by a chase vehicle, but fleet on-road HDD vehicle SO_2 emissions have never been reported (*25*). This paper reports HDD vehicle fleet SO_2 emissions and suggests that these data can be used to identify individual vehicles using high sulfur fuel.

In addition to providing emissions information on previously unmeasured gaseous species from HDD vehicles, this paper also obtained the largest set of CO, HC, and NO emissions from individually identified HDD vehicles.

Experimental Section

In this study the emissions from in-use HDD trucks were measured by remote sensing at two different locations in

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TABLE 1. Measurement Site Statistics, Characteristics, and Environmental Data

site collection dates	number of valid NO measurements	estimated speeds (km/h)	altitude (m), grade	mean temp (°C)/relative humidity (%)
		Golden, CO		
Aug 17, 2005	85	5−25	1695	29/22
Aug 18, 2005	88		+0.2°	31/20
Aug 19, 2005	101			29/24
Aug 22, 2005	99			29/30
Aug 23, 2005	90			28/33
Aug 24, 2005	14			27/31
		Dumont, CO		
Aug 29, 2005	179	20−40	2530	26/15
Aug 30, 2005	243		+1.4°	25/18
Aug 31, 2005	326			17/33
Sept 1, 2005	223			20/18
Sept 2, 2005	193			21/18

Colorado during the summer of 2005. These locations included an exit from a distribution facility in Golden, CO and a State Port of Entry on eastbound I-70 at Dumont, CO. Three site factors facilitated that the emission measurements were dominated by >33 000 lbs gross vehicle weight rated (GVWR) trucks. The Golden site measured vehicles that were capable of hauling full semitrailers of goods, the Dumont site only required commercial vehicles to be at the site, and at both sites only vehicles with elevated exhaust stacks were measured. A variety of environmental conditions and engine operating parameters existed during measurements and site specifics are noted in Table 1. We determined make and model year at both measurement sites as well as odometer readings from the Golden site and gross vehicle weight (GVW) from Dumont.

The remote sensing instrumentation and measurement technique (FEAT, fuel efficiency automobile test) has been discussed previously for both light-duty (*26*−*28*) and heavy-duty vehicles (*9*). Recently, FEAT capabilities have been expanded with the addition of three new species, NO_2, SO_2, and NH_3 (*29*). The reported detection limits are 1.18 g/kg, 0.78 g/kg, and 0.72 g/kg, respectively, for individual readings. Due to the spectral range of the FEAT spectrometers, NO, SO_2, and NH_3 can be measured together, while NO_2 must be measured by a separate spectrometer. There are no known interferences at the wavelengths used for detection (*29*). The vast majority of HDD trucks in the U.S. have elevated exhaust stacks, and therefore the sensing beam was elevated approximately 4−4.5 m off the ground. This is achieved by placing the two remote sensors and light sources on the top of two sections of 2 m walk-up scaffolding. The sensors were arranged in an "X" pattern to optimize the two sensing beams such that they measured the same area of the plume. The scaffolding was secured with guy wires to limit vibrations. Researchers were only on the scaffolding during setup, removal, and alignment and not during measurements. As in all remote sensing measurements, only the ratios of the pollutants to the CO_2 above background levels are measured. These are independent of wind and turbulent dilution.

With HDD trucks an external retroreflective infrared position sensor (Maxi-Beam RSBLV, Banner Engineering Corp. Minneapolis, MN) positioned approximately 1.5 m above the road was used to sense the end of the tractor cab to begin the measurement. At both sites, calibrations were preformed 2−3 times a day depending on ambient conditions. Calibrations were performed using four certified gas mixtures (Scott Specialty Gases, Longmont, CO) containing 6% CO, 0.6% propane, 6% CO_2, and 0.3% NO in N_2; 1000 ppm SO_2 and 15% CO_2 in N_2; 1000 ppm NH_3 and 6000 ppm propane in N_2; and 500 ppm NO_2 and 15% CO_2 in N_2.

Truck drivers had to stop their vehicle and file paper work with the gate office at the site in Golden, CO. This allowed the researchers to ask the drivers for the odometer reading from the tractor. The last eight digits of the vehicle's 17 digit vehicle identification number (VIN) is located on the passenger side of the cab, and these numbers were recorded. These identifier numbers were cross referenced with the State of Colorado Department of Revenue's database to obtain the entire 17 digit VIN.

The HDD trucks at Dumont, CO were first weighed on the scales of the Port of Entry before being measured by the remote sensor. The vehicles with low reported weights were dominated by vehicles with either no trailer or empty trailers/beds. We recorded GVW as reported by the scales and typed the 8 digit VIN identifier directly into the state's computer to obtain the 17 digit VIN. These VINs and those from Golden were then decoded for engine manufacturer, chassis manufacturer, and model year (*30*). The VIN was also used to confirm that over 90% of the measurements came from vehicles rated >33 000 lbs.

Results and Discussion

The FEAT remote sensor measures ratios of pollutants to CO_2, from which grams of pollutant per kilogram of fuel burned can be calculated (*31*). Hydrocarbon emissions are reported as propane equivalents and multiplied by two to compensate for the known difference between NDIR and FID based measurements (*32*). Unlike previous FEAT remote sensing reports, NO_x is reported as NO + NO_2 in grams of NO_2 (*28*). Although Table 1 lists mean temperature and humidity data for each measurement day, the NO, NO_2, and NO_x data have not been adjusted for humidity (*33*).

Table 2 provides the mean emissions for each of the six pollutants measured, the NO_2/NO_x ratio, and average model year from the two measurement sites. The bold values show statistically significant differences at the 95% confidence limit between the two sites in 2005, whereas the italicized values show a statistically significant difference between measurement years 1999 and 2005 at the same site. The difference in CO and NO has been shown previously (*9*) and was thought to be a result of the difference in altitude of the two sites. This could not be confirmed because the previous study could not report vehicle model year, and thus the emissions difference could have been a result of fleet age differences. As is seen in Table 2 from this study, the emissions differences remain, and the fleet age at the two sites is not significantly different. Although NO and thus total NO_x emissions are effected by elevation, the NO_2 emissions are the same for the two sites. The current NH_3 emissions from HDD trucks are expected to be approximately 0.015 g/kg (*24*). Current individual vehicle NH_3 emissions are below the detection limit of the remote sensor of 0.72 g/kg fuel and also below the 0.019 g/kg detection limit for this fleet, but these data provide an important baseline value for future measurements (*29*). The emissions and vehicle data for this paper are available at our Web site, www.feat.biochem.du.edu.

Figure 1 plots CO and NO_x emissions versus GVW as reported by the scales at Dumont and versus tractor odometer reading as reported by the drivers at Golden. Neither CO nor NO_x emissions in g/kg of fuel burned show a trend with vehicle weight. Although a trend has been shown in previous studies between increasing emissions and increasing weight, these emissions were reported in g/mi or g/km (*4*, *34*). Our results do not disagree since fuel economy decreases with increasing load. Figure 1 also shows no dependence on odometer reading with NO_x or CO emissions once corrected to remove the model year dependence shown in Figure 2 since 1997.

Figure 2 shows, for the first time, remote sensing of total NO_x and NO_2 from on-road diesel vehicles by model year.

TABLE 2. Comparison of Data from 1999 and 2005 from the Same Locations[a]

pollutant	2005 Golden, CO avg g/kg fuel (n)	2005 Dumont, CO avg g/kg fuel (n)	1999 Golden, CO avg g/kg fuel[b] (n)	1999 Dumont, CO avg g/kg fuel[b] (n)
CO	***26.0*** ± 2.1 (477)	**37.9** ± 1.6 (1164)	*44.5* ± 6.1 (206)	51.5 ± 6.2 (194)
HC	1.8 ± 0.6 (477)	3.3 ± 0.4 (1163)	12.9 ± 2.7 (196)	5.5 ± 1.6 (194)
NO	***20.8*** ± 0.7 (477)	**30.6** ± 0.5 (1164)	*24.0* ± 0.9 (205)	31.0 ± 1.0 (194)
SO_2	0.83 ± 0.02 (397)	0.85 ± 0.01 (1011)	N/A	N/A
NH_3	−0.01 ± 0.0 (397)	−0.02 ± 0.00 (1011)	N/A	N/A
NO_2	2.6 ± 0.1 (446)	2.8 ± 0.1 (1055)	N/A	N/A
NO_2/NO_x ratio	0.091 ± 0.005 (446)	0.061 ± 0.001 (1036)	N/A	N/A
model year	2001.4	2000.7	N/A	N/A

[a] The uncertainties are the standard errors of the mean. Bold values indicate a statistically significant difference of the means at the 95% confidence limit (twice the standard error) between these two locations in 2005. Italicized values indicate a statistically significant difference of the means at the 95% confidence limit between the two measurement years at the same site. [b] These data were obtained from ref *9*.

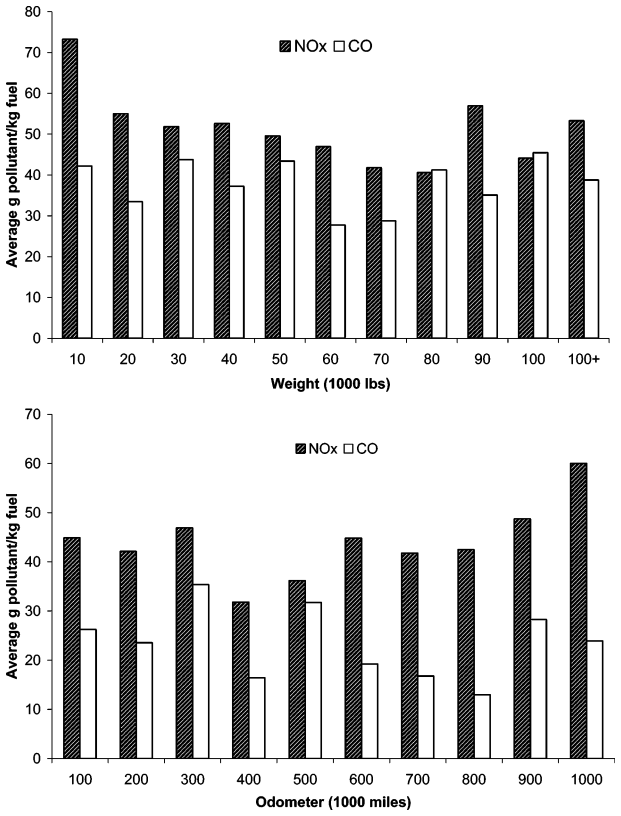

FIGURE 1. Plot of NO_x and CO emissions versus GVW as measured by the weigh station scales (top) and odometer mileage as reported by the truck driver (bottom).

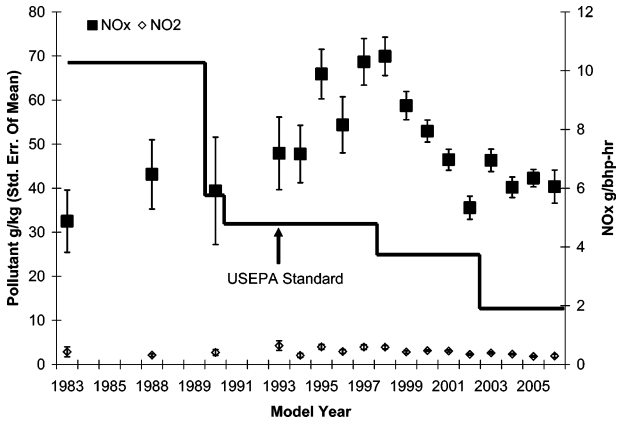

FIGURE 2. Mean NO_x and NO_2 emissions plotted versus VIN model year. The solid line represents the new engine certification standards in g/bhp-h. The two *y*-axes have been plotted together assuming 0.15 kg of fuel consumed per bhp-h for all model years. The uncertainties are the standard errors of the mean.

This plot illustrates the increased NO_x emissions from the late 1990s model years that had computer controlled engines and defeat device technology. In the 1990s, it was found that seven of the largest HDD engine manufacturers violated certification regulations by turning off, or defeating, emission control devices during in-use highway driving. Consequently, the Department of Justice, U.S. EPA, and CARB signed consent decrees with seven engine manufacturers (*35*, *36*). These vehicles had electronic engine control systems that would lean out engine operation to improve fuel economy resulting in more NO_x. Since the implementation of the 1998 consent decrees, on-road NO_x emissions have decreased. Also displayed in Figure 2 are the engine dynamometer certification standards for new engines. Because engine standards are measured in grams of pollutant per work done by the engine or grams/brake horsepower hour (g/bhp-h), these units must be converted in order to be plotted along with the pollutant per fuel burned unit. This was done by assuming a constant fuel use of 0.15 kg/bhp-h. As can be seen in Figure 2, although the consent decrees did have an effect in reducing on-road NO_x emissions, they are above their new engine emission standards at the two sites measured. Figure 2 also illustrates that 1990 and 2006 model year vehicles have the same emissions even though the certification standards have decreased 3-fold. Newer engines may produce more power per fuel burned and thus bring the NO_x g/kg of fuel closer to the emission standards. Note that HDD certification standards shown here are for comparison only. Certification tests are performed on an engine dynamometer under specific conditions which do not include operation above 1676 m (5500 ft).

The decoded VINs provided the engine manufacturer for each vehicle, and this information allowed for different emission control strategies to be discerned by the manufacturer. The differences are most apparent during the 4-year period, 1995−1998; when most of the engines were computer controlled but before the consent decrees had taken affect. Figure 3 shows that Detroit Diesel had the most aggressive NO_x emissions of the three, well represented, engine manufacturers in this study. This difference among manufacturers is not apparent after the 2000 model year.

As mentioned in the Introduction, a gallon of on-road diesel fuel is taxed at a higher rate than off-road diesel. This difference is a federal tax of $0.183 and a state tax typically near $0.20 ($0.205 in CO and $0.18 in CA) per gallon. To mark untaxed fuel, a red dye is added and can be visibly seen if a sample is removed from a fuel tank. The use of untaxed fuel, if detected, carries a hefty fine but is an invasive test. Starting in 2006, the off-road diesel is allowed to contain 33

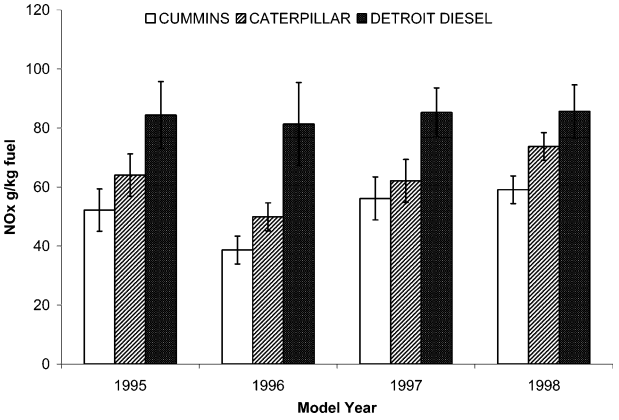

FIGURE 3. NO_x emissions for the three most represented engine manufacturers from this study during the model years preceding the 1998 consent decrees. Uncertainties are the standard errors of the mean.

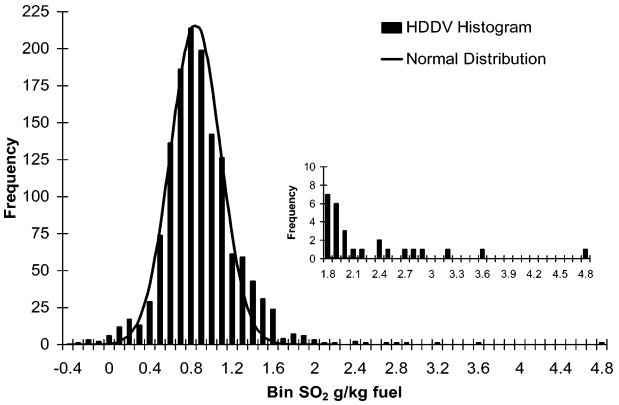

FIGURE 4. The histogram of combined SO_2 emissions from the two measured sites. The solid line represents the least-squares fit normal distribution associated with a mean of 0.84 g/kg SO_2. The insert contains the 27 measurements with SO_2 values greater than the 99.9% confidence interval.

times more sulfur in the fuel until 2010 when off-road diesel is mandated to contain the same 15 ppmw as the on-road fuel. Figure 4 shows a normal distribution for SO_2 emissions from diesel vehicles overlaid upon the total distribution from the two sites measured. The mean SO_2 emission of 0.84 g/kg is consistent with about 450 ppmw sulfur in the fuel which was a typical amount in 2005. Twenty-seven of the 1409 measurements fall outside the 99.9% confidence limit of the distribution. These vehicles are most likely using high sulfur fuel and are detected by remote sensing. On Wednesday August 31st, 2006, the U.S. EPA in consultation with the Department of Energy and representatives of various states decided to help minimize or prevent supply disruptions of diesel fuel based on the Hurricane Katrina disaster by allowing the sale and use of fuel with a sulfur content greater than 500 ppmw and/or visible evidence of the red dye (*37*). Thus there is a possibility that nearly half, 13, of these vehicles may be legally using off-road, red dyed fuel as they were measured on September 2nd. Anecdotally, when researchers responded to a question concerning the purpose of the scaffolding used at the Golden site, the questioning truck driver then refused to give any odometer mileage and became uncooperative. This vehicle was measured as having the greatest SO_2 emissions of the entire study.

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