Remote Sensing of NO and NO$_2$
Emissions from Heavy-Duty Diesel Trucks Using Tunable Diode Lasers

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On-road remote sensors can measure the emissions of motor vehicles under real-world conditions. The most sensitive remote sensing technique reported to date is tunable infrared laser differential absorption spectroscopy (TILDAS). A TILDAS remote sensor was used in this study to measure the NO$_x$ emissions of heavy-duty diesel trucks (HDDTs). The remote sensor could operate with an optical path length of 88 m or more than five times that of NDIR-UV instruments. Good agreement was obtained when comparing the TILDAS measurements with the on-board measurements of an instrumented HDDT. The distribution of NO emissions from HDDTs was found to be close to normal. Remote sensing of NO$_2$ emissions was demonstrated for the first time. The NO$_x$ emission factor determined in this study is consistent with other recent measurements. These emissions are underestimated in the EPA inventory, although part of the discrepancy can be explained by the effect of a “defeat device” that increases NO$_x$ emissions.

Introduction

Emissions of oxides of nitrogen (NO and NO$_x$, collectively referred to as NO$_x$) contribute to a variety of environmental problems, including photochemical smog, acid deposition, and visibility impairment through particulate nitrates (1). As the NO$_x$ emissions of passenger cars and light-duty trucks (LDTs) have become more tightly controlled, the relative importance of heavy-duty diesel trucks (HDDTs) as a NO$_x$ source has increased. EPA estimates that HDDTs emitted 8% of the NO$_x$ emissions in the U.S. in 1997 vs 20% for cars and LDTs. In contrast, a recent assessment of on-road emissions estimated that HDDTs contribute as much NO$_x$ as cars and LDTs; it also indicated that large uncertainties remain about the magnitude and distribution of these emissions (2). A recent study found that California’s emission inventory model may underestimate NO$_x$ emissions from heavy-duty diesel trucks (HDDTs) by up to a factor of 2.3 (3).

Recent developments highlight the increasing attention being given to HDDT NO$_x$ emissions. The composition of U.S. on-road diesel fuel was changed to reduce emissions in 1993 (4). More stringent U.S. emission standards for heavy-duty diesel engines, which seek to reduce NO$_x$ emissions by about 50% (from 4 to 2 grams per brake horsepower hour or g/bhp-h) were enacted in 1997 (5). In addition, in 1998 EPA accused seven major diesel engine manufacturers of using a “defeat device” in order to improve fuel economy. The use of this device resulted in large increases in NO$_x$ emissions (6). This claim was settled with a total cost for the manufacturers in excess of $1 billion, including a faster introduction of the new emission standards, a rebuild program for in-use engines, and the largest civil penalty ever for violation of environmental law ($83 million) (6). Standards requiring further reductions to about 0.5 g/bhp-h starting in 2007 are now being planned (7).

Achieving low-NO$_x$ emissions from heavy-duty diesel engines is a significant challenge. Two fundamental approaches can be taken: lowering in-cylinder NO$_x$ formation or removing NO$_x$ from the exhaust gases. The latter is problematic for on-road diesel engines. The three-way catalysts used for highly efficient NO$_x$ reduction to N$_2$ in light-duty vehicles perform very poorly when the exhaust O$_2$ concentration is high (8). Other postcombustion NO$_x$ removal concepts, such as lean-NO$_x$ catalysts, NO$_x$-trap catalysts, selective catalytic reduction systems, and plasma treatment technologies, are under very active research but still face significant issues for commercial application in heavy-duty vehicles (9, 10). EPA sees the 2007 standards now under planning as forcing exhaust gas aftertreatment and ultralow sulfur diesel fuel (7). Until now, lowering in-cylinder NO$_x$ formation has been the main strategy used to reduce emissions. This approach is difficult due to the nature of the diesel combustion process. In diesel engines NO$_x$ formation is due mainly to the thermal (Zeldovich) mechanism (11). NO appears first; smaller amounts of NO$_2$ may result from NO oxidation reactions (see below). NO production by the thermal mechanism increases exponentially with temperature. The other important variable is oxygen concentration, with NO formation peaking at slightly lean of stoichiometric and decreasing rapidly for rich and lean conditions. In diesel engines the average cylinder composition is always fuel-lean. Fuel injection into the air-containing cylinder begins toward the end of the compression stroke just before the start of combustion and continues after combustion initiation. Combustion starts with spontaneous ignition of a small part of the fuel which has vaporized and mixed with the hot air in the combustion chamber and continues in a mixing-limited, near stoichiometric regime as additional fuel is injected. The flame region and post-flame gases are inevitably at high-temperature and near stoichiometric conditions, which produces high NO levels (11). An observed tradeoff between reducing in-cylinder NO$_x$ formation and increasing undesirable particulate emissions further complicates NO$_x$ reduction (12). However, substantial NO$_x$ reductions have been and continue to be achieved by fine-tuning the mixing and combustion processes, mainly through electronic engine control, followed by changes in diesel fuel injection systems, air intake improvements, combustion chamber modifications, and exhaust gas recirculation. Some of these strategies may cause a fuel economy penalty.

The “defeat device” that EPA claims that manufacturers have used since 1988 was a series of engine electronic control...
Experimental Section

In this study a TILDAS remote sensor was used to measure the emissions of heavy-duty diesel trucks. The details of this technique have been described elsewhere (32). Briefly, a TILDAS instrument measures pollutant emissions from vehicles by sending beams of infrared laser light across the road and back while measuring the transmitted light with an infrared detector. The column density of a given species is determined by fitting the spectral dependence of the transmitted light to a Lorentzian line shape. In this study, two spatially overlapped, temporally multiplexed lead-salt mid-infrared lasers were used to determine the column density of NO and CO\(_2\) (or NO and NO\(_2\)) in the exhaust plume of a given vehicle. The NO emission index of a vehicle is determined from the ratio of the column density of NO to that of CO\(_2\). A correction is necessary if the amounts of CO and hydrocarbons in the exhaust are significant, which is generally not the case for HDDTs (11, 23, 25).

Some modifications of the optical setup used for automobiles were necessary in order to adapt the TILDAS technique to the remote sensing of emissions from heavy-duty diesel trucks. The exhaust pipe of most heavy-duty trucks in the U.S. terminates as a vertical stack located immediately behind the tractor cab discharging exhaust gas to the atmosphere at a height of about 3.3–3.6 m above the roadway. The trailer height may exceed the exhaust discharge height and can be as high as 4.3 m. The TILDAS laser beam was therefore elevated to a height of about 4.4 m in order to traverse the exhaust gases while avoiding blockage by the truck’s trailer. Another difference between the experimental configurations used with HDDTs and light duty vehicles is that the light duty vehicle emissions measurements are automatically triggered by the signal interruption associated with the passing of the vehicle. A spectrum acquired before the interruption is used as a reference spectrum to reduce noise and to account for background absorption. Since the HDDTs do not block the laser beam, triggering was accomplished manually. This approach worked well, and background corrections were accomplished in the usual manner. The alignment of the optical system is facilitated by a visible HeNe laser which is co-aligned with the infrared laser beam. The experimental setup is shown in Figure 1.

We carried out a measurement campaign in the Raleigh–Durham area of North Carolina on June 16–19, 1997. This work was carried out in collaboration with the heavy-duty...
6.5 gr/bhp-h NO displacement of 12.7 L). This engine was certified at about equipped with a 60 Series Detroit Diesel Engine (with a displacement of 12.7 L). This engine was certified at about 6.5 gr/bhp-h NO or about 0.010 NO/CO₂ (using the conversion factor in ref 15 and the fuel properties and fuel economy in ref 4).

Four experiments were performed in four consecutive days and are described in the next section. This comprised measurements (1) across a four-lane highway to demonstrate the long optical path length of the TILDAS remote sensor; (2) of the EPA instrumented heavy-duty truck exhaust to verify the accuracy of the remote sensor; (3) across a two-lane interstate highway to obtain a distribution of the emissions from random trucks at high-speed cruise; and (4) of the EPA instrumented HDDT to demonstrate the capability of measuring the NO/NO₂ emission ratio.

Results and Discussion

Demonstration of Long Optical Path Length. NDIR-based instruments can operate with very limited cross-road path lengths due to the angular dispersion of their nonlaser light, and because the absorption due to relatively large background CO₂ levels decreases the signal-to-noise ratio of their CO₂ measurement (34). The longest path lengths reported with this type of instrument are 12–15 m (34, 35). Bishop and Stedman (26) report in a recent description of their NDIR-NDUV instrument that “the system is designed to operate on a single lane road... Multiple lane operation has been reported but is not recommended”. Near-infrared TILDAS systems specify total path lengths of up to 36 m; however, they are about 50 times less sensitive for NO₂ than the mid-infrared TILDAS system used here (28, 32).

A long path length is of interest since it allows greater flexibility in the placement of the sensors. One example is sampling across multilane highways, although for heavy traffic conditions this introduces the need to detect and discard the measurements for which several vehicles are driving by the sensor simultaneously in different lanes. Some studies also suggest that drivers change their behavior while driving in front of a remote sensor. Walsh and Gertler (36) found that for those light-duty vehicles with one high and one low remote sensing measurement, the first measurement was the high one in 60% of the cases. They suggest that motorists may have become aware of the remote sensing device after the first pass and may have altered their driving in response. A longer path length could avoid this problem since the instrument could be moved farther off the road and made less visible. It would also diminish associated concerns of motorist and operator safety, which greatly limit the selection of remote sensing sites (36), and of vandalism of unmanned remote sensors.

To demonstrate the long path capabilities of the TILDAS technique, measurements were made across a four-lane highway (NC-54) with a total optical path length of 88 m. Figure 2 shows the NO and CO₂ column densities vs time and (right) NO vs CO₂ regression. This measurement was made across a four-lane highway (NC-54) with a total optical path length of 88 m. Figure 2 shows the NO and CO₂ column densities vs time and a regression plot from such a measurement. The NO and CO₂ signals are highly correlated. Only a minor degradation in signal-to-noise is observed compared to shorter path lengths. This is the longest path length which has been demonstrated with any on-road remote sensor.

During this experimental campaign we observed systematic deviations in the first one or two data points of some measurements. We believe that this deviation was caused by the measurement of unmixed relatively hot plumes very near the exhaust outlet. The deviation was always in the same direction and consistent with the relative variation of the line strengths of NO and CO₂ with source gas temperature. High gas temperature also induces small variations in the widths of the absorption lines, which were also observed in these cases, providing additional evidence for this explanation. A more sophisticated analysis than we used in this work is required to account for these temperature effects and will be implemented in future measurements. In this case we simply rejected those data points at the beginning of the plume which were clear outliers. Such effects could also complicate the interpretation of the results of other remote sensing techniques. This effect was rare in our previous measurements of light duty vehicle emissions (30).

Comparison with On-Board Instrumentation. A series of emissions measurements were performed in the parking lot of the EPA facility with the intention of comparing the results from the NO remote sensor and the on-board instrumentation of the EPA heavy-duty diesel truck under low speed (20 mph) conditions. The parameter chosen for the comparison is the NO/NO₂ ratio. Expressing the emission index in this way avoids the problem of determining the air-to-fuel ratio in the diesel engine which, unlike gasoline engines, can vary by more than a factor of 2 (11). The TILDAS remote sensor measures NO/CO₂ directly, but the EPA instrumented truck measured NO/CO₂ during this intercomparison. The NO/CO₂ ratio produced by the TILDAS instrument was converted to NO/NO₂ using the average of the NO/NO₂ ratios measured with the TILDAS instrument for this same truck (described below).

The comparison of both sets of measurements is shown in Figure 3. Although a wider range of emission ratios would have been desirable for this test, the available HDDT
produced a very constant emission level. Seven out of 8 measurements are within the 95% confidence interval of the 1:1 line (which would represent perfect agreement between both instruments). The one anomalous measurement is probably due to delays in the EPA truck’s sampling system and analyzers during transients in speed and acceleration at the remote sensing site, which were observed in the record of the on-board analyzers. Most of the measurements are close to the certification level estimated for this vehicle of 0.010 NO\textsubscript{X}/CO\textsubscript{2}. Note that the uncertainty of each TILDAS measurement is different, varying with the overlap between the exhaust plume and the laser beams during a given pass, as described previously (32).

**Distribution of Emissions from Random Diesel Trucks.**

Measurements of NO/CO\textsubscript{2} for 73 HDDTs were obtained at this location. The distribution of NO/CO\textsubscript{2} emissions for these measurements is presented graphically in Figure 4, together with the distribution measured for cars and light-duty trucks (LDTs) in California in 1996 using the same TILDAS instrument (30). Some statistics of both distributions are presented in Table 1. The distribution of NO emissions from HDDTs resembles a normal distribution, while the car and LDT distribution is very skewed, with most of the readings clustered at very low NO/CO\textsubscript{2} values. Differences between individual HDDTs are small as indicated by a ratio of maximum to minimum emission of 6.5, as compared to about 750 for cars and LDTs. The HDDT distribution has a much larger average value; however, the maximum values of both sets of measurements are very similar. The dirtiest 16% of cars and LDTs contributed 50% of the NO emissions for these vehicles, while the dirtiest 10% of the HDDTs only contributed 17% of the total HDDT emissions. From the other side, the cleanest 50% of cars and LDTs were responsible for only 4% of the NO emissions, while the cleanest 50% of HDDTs contributed 32% of the total emissions. These differences are very important since they imply that the concepts of “super-emitters” and “clean vehicles” that are applicable for catalyst-equipped vehicle emissions are not appropriate for heavy-duty diesel truck NO\textsubscript{X} emissions. This is in qualitative agreement with the results of chassis dynamometer studies (18, 20). A consequence of this result is that inspection and maintenance programs for HDDTs cannot be designed to exclude a large fraction of the fleet (“clean-screening”) or to repair broken “super-emitters”, as is often done for light-duty vehicles. Strategies that deal with the whole fleet such as stricter emission standards and reformed diesel fuel are necessary for reducing these emissions.

Figure 4 also shows the distribution of NO/CO\textsubscript{2} emissions from HDDTs measured in another 1997 study in California using an NDIR-NDUV remote sensor by Countess et al. (23). The distribution measured by the TILDAS remote sensor has a larger average and is less skewed than the one from the California HDDT study. However, the two distributions have a similar shape, span the same range of values, and are very different from the automobile distribution in the ways described above. The difference between the two HDDT remote sensing distributions may be partially due to differences in driving conditions. The nearest entrance into the highway in our HDDT study was about 6 miles before the measurement location or about 5–7 min of high speed steady state driving. It is likely that most vehicles had been driving considerably longer. Under these conditions the “defeat device” described above would have been activated in those vehicles that had it, resulting in higher emissions. The HDDTs in the California study were leaving a weighing station after a low speed transient, and the enabling of the “defeat device” is highly unlikely to have occurred there. Another possible reason is differences in the HDDT fleets. For example, Countess et al. report that trucks with in-state registration and dump trucks had higher NO\textsubscript{X} emissions than out-of-state trucks, indicating an effect of fleet composition, age, and/or maintenance on emissions.

The differences between the automobile and the HDDT distributions in Figure 4 are traceable to the differences in NO\textsubscript{X} production and control between light-duty gasoline vehicles and heavy-duty diesel trucks. The flame region in diesel engines inherently combines near-stoichiometric and high-temperature conditions, which result in significant NO\textsubscript{X} formation. This, together with a lack of a catalyst explains why there are no measurements near zero and the relatively large emissions of all vehicles. The chemical mechanism of NO formation for gasoline (or “spark ignition”) engines is the same as for diesel engines described above. However, the combustion process in a traditional gasoline engine is
TABLE 1: Summary of Statistics for the Distributions of NO/CO₂ Ratios Measured for Heavy-Duty Trucks and Automobiles and Light-Duty Trucks

<table>
<thead>
<tr>
<th></th>
<th>heavy-duty diesel trucks</th>
<th>automobiles and light-duty trucks</th>
<th>HDĐT/autos</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of vehicles</td>
<td>73</td>
<td>1473</td>
<td>5.2</td>
</tr>
<tr>
<td>average</td>
<td>12.5 × 10⁻³</td>
<td>2.4 × 10⁻³</td>
<td>5.2</td>
</tr>
<tr>
<td>standard deviation</td>
<td>4.9 × 10⁻³</td>
<td>4.0 × 10⁻³</td>
<td>1.2</td>
</tr>
<tr>
<td>median</td>
<td>12.4 × 10⁻³</td>
<td>0.7 × 10⁻³</td>
<td>18</td>
</tr>
<tr>
<td>maximum</td>
<td>27.2 × 10⁻³</td>
<td>28.6 × 10⁻³</td>
<td>0.95</td>
</tr>
<tr>
<td>minimum</td>
<td>4.2 × 10⁻³</td>
<td>0.037 × 10⁻³ b</td>
<td>113</td>
</tr>
<tr>
<td>max/min</td>
<td>6.5</td>
<td>751c</td>
<td>0.009</td>
</tr>
<tr>
<td>skewness</td>
<td>0.33</td>
<td>2.80</td>
<td>0.1</td>
</tr>
<tr>
<td>% of emissions due to the 10% dirtiest vehicles</td>
<td>17%</td>
<td>50%</td>
<td>0.34</td>
</tr>
<tr>
<td>% of emissions due to the 50% cleanest vehicles</td>
<td>32%</td>
<td>4%</td>
<td>8.0</td>
</tr>
</tbody>
</table>

*For both gasoline and diesel vehicles the exhaust concentration of NO in the exhaust gases (including water vapor) can be approximated as NO (ppmv) = NO/CO₂ × 135 000 (multiply by 154 000 for concentration in the dry gases). These concentrations have been corrected to the amount of air present at stoichiometric conditions; actual concentrations will be significantly lower for diesel vehicles. TILDAS precision of ~5 ppm NO, which is of the order of the emissions of the cleanest light-duty vehicles (27, 30, 32). Estimated as (maximum value)/TILDAS detection limit.*

very different than that of a diesel engine (11). In a gasoline engine, air and fuel are premixed and combustion is started by a spark. The composition is close to stoichiometric and homogeneous across different locations in the cylinder. NO forms in the high-temperature burned gases during combustion and is “frozen” by the cooling brought about by the expansion of the cylinder. This type of engine can generate from very low to about 3000 ppm NO (22.4 × 10⁻³ NO/CO₂) depending mainly on power demand, since flame temperature scales with this parameter (11). The main control technology for gasoline engine NO emissions is the three-way catalyst (8, 10, 11, 37), which when warmed-up reduces engine-out emissions by about 90%, to levels below about 300 ppm (2.2 × 10⁻³ NO/CO₂). For this reason the emission distribution for cars and light-duty trucks is clustered at low emission values. Higher emission levels, unlikely but possible in properly functioning vehicles (38) and common for the small fraction of vehicles with malfunctioning emission control systems, result in the long tail of higher emissions and a very skewed distribution. Additional support for this explanation comes from remote sensing data showing that the emission distributions of catalyst cars were much more skewed than those of noncatalyst cars (39) and from dynamometer data that show the same difference between the distributions of catalyzed and engine-out emissions (38).

Remote Sensing of the NO₂/NO Ratio. Although most of the NO emitted by heavy-duty diesel trucks is in the form of NO, a nonnegligible fraction may be present as NO₂ (11, 40). The NO₂ fraction is much smaller for gasoline engines (11). NO₂ is primarily formed in hot gases by the reaction of NO with the HO₂ radical and is subsequently converted back to NO very quickly via reactions with the O or H radicals (11, 41). NO₂ can persist if the decomposition reactions are quenched by mixing with cooler gases. This situation is expected to occur in diesel engines due to the large amount of excess air present in the cylinder but not in spark-ignition engines (11), consistent with observations. During this project the TILDAS instrument was adapted to the simultaneous measurement of NO and NO₂ emissions from HDDTs. A diode laser was used to detect NO₂ by scanning across a group of 24 transitions at a frequency of 1605 cm⁻¹ (6.2 μm). NO was measured by scanning the same group of transitions used for the NO/CO₂ measurements at a frequency of 1900 cm⁻¹ (5.3 μm). Figure 5 shows both absorption features as detected in a HDDT plume. The shape of the absorption features detected for NO and NO₂ was the same for a reference cell containing both gases and for HDDT exhaust, indicating that no detectable interfering species were present.

The time-domain and NO₂ vs NO regression plot of a remote sensing measurement of the EPA instrumented truck are presented in Figure 6. The close correlation of the two signals is a demonstration of the capacity of the TILDAS technique to measure the NO₂/NO ratio in heavy-duty truck exhaust. To our knowledge, this is the first time that on-road remote sensing of NO₂ has been accomplished. Note that in the time domain plot, the signal-to-noise ratio (SNR) is worse for NO₂ than for NO. This is due to the lower column density of NO₂. Since to a first approximation the absolute noise level is similar for both species (of the order of 0.5 ppm-m for this particular measurement) and the signal is about 10 times stronger for NO, the SNR is also about 10 times larger for this species. Temperature effects such as those observed for some NO/CO₂ measurements are of minor importance in the NO/NO₂ measurement since the NO and NO₂ absorption transitions used have very similar temperature dependence. No deviation was observed in any of the time domain or regression plots.

The measured NO₂/NO ratio (molar) ratios range from 5.6% to 10.9 vol %. The average ratio for the five measurements performed for the EPA instrumented truck was 7.8% ± 2.2%. No comparison can be made with the on-board instrumentation of the EPA truck in this case since the on-board system is not appropriate for NO₂ quantification (42). Hilliard and Wheeler (40) reported NO₂/NO ratio (molar) ratios...
of 2–30% for diesel engine exhaust. Higher NO2 fractions were measured at low engine loads and speeds, which can be explained by the higher likelihood of NO2 quenching due to the larger fraction of air in the cylinder (11). Harris et al. (43) measured NO2 concentrations in the range of 0.4–33 ppmv of diesel exhaust with a low-pressure sampling TILDAS system but did not report NO2/NO ratios. They do report higher NO2 concentrations at low loads, in agreement with the results of Hilliard and Wheeler. Clark et al. (17) operated several diesel engines in steady-state conditions on an engine dynamometer and found NO2/NO mass ratios which correspond to volume ratios of 1.5%–12.5%. The same authors also reported some results from testing diesel buses on a chassis dynamometer on the Central Business District cycle and found NO2/NO volume ratios of up to 2.7%. The trends with speed and load were consistent with those of Hilliard and Wheeler. The 5.6–10.9% range that we measured with the TILDAS instrument while the EPA instrumented truck was operated at about 20 mph under mild acceleration is consistent with these literature studies.

**Estimation of the NOx Emission Factor for Heavy-Duty Diesel Trucks.** The on-highway NO and NOx emission factors for heavy-duty diesel trucks can be estimated from the average of the measurements taken on interstate highway I–40. Although this study has a small sample size of 73 vehicles and a single operating condition, a reasonable emission factor can still be determined since heavy-duty truck NOx emissions (per unit fuel) have been shown to be relatively insensitive to vehicle power demand under high-speed cruise conditions (21), and the normality of the distribution allows the determination of an approximate average from a smaller sample than with a skewed distribution. The quantity determined directly from our measurements is the NO emission factor. To estimate the NOx emission factor we assumed that the average NO2/NO ratio of the fleet was equal to the average of the EPA instrumented truck that we measured by remote sensing. Since there could be some variability in the NO2/NO ratio for different trucks this assumption introduces some additional uncertainty. The average NO2/CO2 ratio was found to be 0.0136 ± 0.008, while the emission factor is estimated at 45 ± 2 g of NOx (as NO2) per kg of diesel fuel.

This value has been compared in Table 2 to the values obtained in other studies in North America. There is no clear trend of emissions with the year, location of the study, or speed and/or roadway grade of the measurements. The average of all the studies is 39.3 ± 2.4 g NOx/kg of fuel (40.6 ± 3.6 if only studies since 1995 are included in the average). The value reported in this study is 15% higher than the average of all studies. As explained above the location of our study is likely to have selected for higher NOx emissions due to the operation of the “defeat devices”. The other three remote sensing experiments reported the two lowest and the one highest emission factors of all 12 studies. Those studies were conducted at two HDDT highway weigh stations (23, 25) and at the exit of an industrial distribution center (24) respectively. At these locations vehicles were operated under relatively low speed transient driving conditions, and the “defeat devices” were most likely disabled. This should have resulted in lower emissions consistent with two of the studies. The

**TABLE 2: Comparison of the Heavy-Duty Diesel Truck NOx Emission Factor Obtained in This Study with Those of Other Studies**

<table>
<thead>
<tr>
<th>Location/Reference</th>
<th>Year</th>
<th>Method</th>
<th>NOx Emission Factor (g of NOx as NO2/kg of diesel fuel)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>dynamometer data</td>
<td></td>
</tr>
<tr>
<td>West Virginia (20)</td>
<td>1995</td>
<td>chassis dynamometer</td>
<td>46</td>
</tr>
<tr>
<td>Colorado (19)</td>
<td>1999</td>
<td>chassis dynamometer</td>
<td>39 ± 2</td>
</tr>
<tr>
<td>Pennsylvania (21)</td>
<td>1992</td>
<td>tunnel study</td>
<td>39 ± 3</td>
</tr>
<tr>
<td>Maryland (22)</td>
<td>1992</td>
<td>tunnel study</td>
<td>37 ± 4 (uphill)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>34 ± 2 (downhill)</td>
</tr>
<tr>
<td>Canada (22)</td>
<td>1995</td>
<td>tunnel study</td>
<td>48 ± 17</td>
</tr>
<tr>
<td>California (4)</td>
<td>1997</td>
<td>tunnel study</td>
<td>42 ± 5</td>
</tr>
<tr>
<td>North Carolina (this study)</td>
<td>1997</td>
<td>remote sensing</td>
<td>45 ± 2</td>
</tr>
<tr>
<td>California (23)</td>
<td>1997</td>
<td>remote sensing</td>
<td>31 ± 0.2</td>
</tr>
<tr>
<td>Colorado (24)</td>
<td>1998</td>
<td>remote sensing</td>
<td>53</td>
</tr>
<tr>
<td>Texas (25)</td>
<td>1998</td>
<td>remote sensing</td>
<td>21 ± 2</td>
</tr>
</tbody>
</table>

*a The diesel fuel properties and HDDT fuel economy reported in ref 4 were used to convert the emission rates reported in the different studies into g/kg fuel.
reason for the very high emissions in the remote sensing study performed in Golden, CO (24) is not clear. Some possible reasons include the high altitude of the site (1800 m), differences in engine load and speed with respect to the other sites, and the particular vehicle fleet. Further research is needed to clarify the origin of the differences between the recent studies.

**Contribution to the NO\textsubscript{x} Inventory in the U.S.** Figure 7 shows the EPA HDDT NO\textsubscript{x} inventory for the U.S. between 1990 and 1997 (44) and the total inventory including the increase estimated by EPA due to the effects of the “defeat device” (15). Also shown are the inventories derived from the emission factors in Table 2 using the recent U.S. fuel consumption for diesel trucks (45), the fraction of heavy-duty trucks among diesel trucks (44), and the fuel properties (4). The figure shows a consistent underestimation of these emissions by EPA, which is only partially explained by the “defeat device” correction. It also highlights the variation in the most recent measurements.

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**Literature Cited**


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