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On-Road Remote Sensing of Heavy-duty Diesel Truck Emissions in the Austin- San Marcos Area: August 1998

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Executive Summary

In the summer of 1998, the University of Denver conducted a remote sensing study in the Austin-San Marcos, Texas area. The focus of the study was to measure the ratios of CO, HC, and NO to CO_2 and to get percent opacity readings for heavy-duty diesel trucks with elevated exhaust. We calculated the grams of CO, HC, and NO per kilogram of fuel combusted from the ratios as would be observed by probing the exhaust. In the process of measuring the ratios, the remote sensing unit results are independent of water and excess oxygen in the tailpipe not involved in combustion. The remote sensing unit also reports percent opacity from the amount of transmitted light at a wavelength of 3.9 μm from the source. The data show, on average, a correlation between high CO emissions and reported opacity.

For the measurements of CO, HC, and NO there were 389 valid readings for each. The mean concentrations in grams of pollutant/kilogram fuel were 21.2, 1.1, and 14.0 and the medians were 9.7, 0.77, and 12.5 respectively. The fleet of these heavy-duty diesel trucks exhibits a distribution that is close to normal where the top 20% of the polluters account for approximately 35% of the total emissions. This observation contrasts with data from automobiles with gasoline combustion engines, their distribution is gamma where the top 10% of the fleet is generally responsible for approximately 50% of the total emissions.

Percent opacities were measured with 314 valid measurements. The mean percent opacity was 0.9 and the median was 0.7. Compared to the ratios, there are fewer valid measurements for opacities than for the ratios, this is because many of the smoke plumes where very heavy which did not allow for a significant amount of transmission of light so the opacity measurement is rendered by the software as “invalid”. The real mean and median my be slightly higher, but with comparison to other data from opacities taken with this instrument the numbers will be appropriate.

We compared our data from Texas to other data from Switzerland, Hong Kong, Pennsylvania, and California where previous fieldwork was done with diesel powered vehicles and found that the values that were calculated for CO, HC, NO and opacities are extremely similar.

Introduction

Remote sensing has became a very effective and efficient way to directly measure the concentrations of CO, HC, NO, and CO_2 in automobile and truck emissions while in route to their destination. Of the various cities in the United States, many are in violation of the air quality standard of these pollutants that is established by the Environmental Protection Agency (EPA), so measurement of these compounds is important.

Opacities were also measured as part of our fieldwork to compare to other work done previously on this same matter. Opacity is important because it gives an indication of the concentration of pollutants leaving a smokestack. The more particles that are passed through a stack, the more light will be blocked, and, as a result, a higher opacity percentage is measured. Particulate and CO are formed under the same conditions in diesel burning engines so they should correlate. This was mainly done as a preliminary to see if we could actually see heavy-duty diesel opacities with our instrument and how well they correlate to CO.

In diesel vehicles the air/fuel mixture is lean of stoichiometric and is usually at high temperatures which causes two relevant events to take place: (1) causes NO emissions to be maximized and (2) CO and HC emissions to be minimized.[1] Heavy-duty trucks also lack a catalytic converter so there is no mean of converting engine-out $NO \rightarrow N_2$. Due to these facts on diesel vehicles, the focus on our fieldwork will be on NO emission

The justification of emphasizing NO emissions in the Austin-San Marcos area is a need to reduce urban ground-level ozone. NO emissions directly effect the production of ozone (O_3), which the EPA regulates in the lower atmosphere by the new 8 hour standard introduced in 1997.[2] Ambient ozone in the lower troposphere can be harmful at elevated concentrations and can cause shortness of breath, coughing, eye and throat irritation and lung damage.[3] Individuals suffering from lung diseases like bronchitis, pneumonia, emphysema, asthma and colds have even more trouble breathing at elevated ozone levels. Inhalation of ozone can possibly cause fatal pulmonary edema and chromosomal damage has also been observed in subjects exposed to ozone.[4]

High concentrations of ozone are related to emissions of NO because atmospheric oxidation of volatile organic compounds (VOCs) produces ozone in the presence of NO and sunlight (*hv*):[5]

$$RH + OH + O_2 \rightarrow RO_2 + H_2O$$

$$RO_2 + NO + O_2 \rightarrow NO_2 + HO_2 + R'CHO$$

$$HO_2 + NO \rightarrow NO_2 + OH$$

$$NO_2 + h\nu \rightarrow NO + O(^3P)$$

$$O(^3P) + O_2 + M \rightarrow O_3 + M$$

Sources of volatile organic compounds and nitric oxide include diesel fuel, gasoline, natural gas and oil and kerosene combustion. Ozone levels are strongly influenced by weather conditions, when temperatures are high and sunshine is strong.

The fieldwork in Texas was conducted two and one-half miles north of San Marcos on northbound Interstate Highway 35. This site was a weigh station with an approximate uphill gradient of 2.6%. The field studies took place diring the first week of August when the average daytime high was 104°. Of all the parameters that were measured at this site, the main emphasis was on NO emissions because of the large role NO plays in formation of ozone. This data will provide Texas with a measurement of NO emissions from diesel trucks in their area and to compare the data with previous data for on-road emission of heavy-duty trucks.

The EPA has set federal emission standards for NO_x of heavy-duty diesel-cycle engines. The limit is 4.0 g NO_x/brake horsepower-hour with the availability of averaging, banking, and trading with nonconformance penalties. Using a average of 3.5 bhphr/mile and 6 miles/gallon, 4.0 g NO_x/bhphr is equivalent to 22.51 g NO_x/kg fuel

Instrumentation and Setup

The remote sensing instrumentation is fully and previously described by the University of Denver in the published literature.[6] The setup was the same as performed by Countess and Cohen in past remote sensing of heavy-duty trucks except for a new NO system.[7] The new NO system, recent technology of the University of Denver, is also described in the published literature.[8]

Experimental Data Analysis and Statistics

For the purpose of reporting, the ratios of NO/CO_2, CO/CO_2, and HC/CO_2 are all converted to grams of NO, CO, or HC/kg fuel, where the percent carbon in diesel fuel is 82 by weight.

Figure 1 shows a histogram of g NO/kg fuel of the 389 trucks that were successfully measured. The average and standard deviation was 13.93 and 6.48 respectively with the largest bin from 13-14. With 99% confidence level, the average g NO/kg fuel was 13.93 ± 0.98 or 12.95 to 14.91.

In figure 2 the histogram shows the error of the feat unit as it measures NO emissions. 90% of the errors are ≤ 1, which implies that our data is extremely precise since literally all of our NO emission measurements are > 4.   The mean error is 0.47 and is compares to the old NO system that Countess and Cohen used in California quite significantly because the mean NO error they measured was 1.01. The technology of the new NO system is the best it has ever been, which it is now allowing us minimal error.

For other statistical purposes, five random sets of data were compiled and averages were calculated for each set. The five averages were 12.97, 13.73, 13.86, 14.44, and 14.64

which all were in the range of the 99% confidence level of the entire data set. With 99% confidence level, the g NO/kg fuel of these five averages was 13.9 ± 0.76 or 13.17 to 14.69. These statistics show that the smaller groups of data have a slightly better confidence level and that the averages are the same. The implication of this analysis is that further sampling of a larger sample of trucks would not significantly change the outcome.

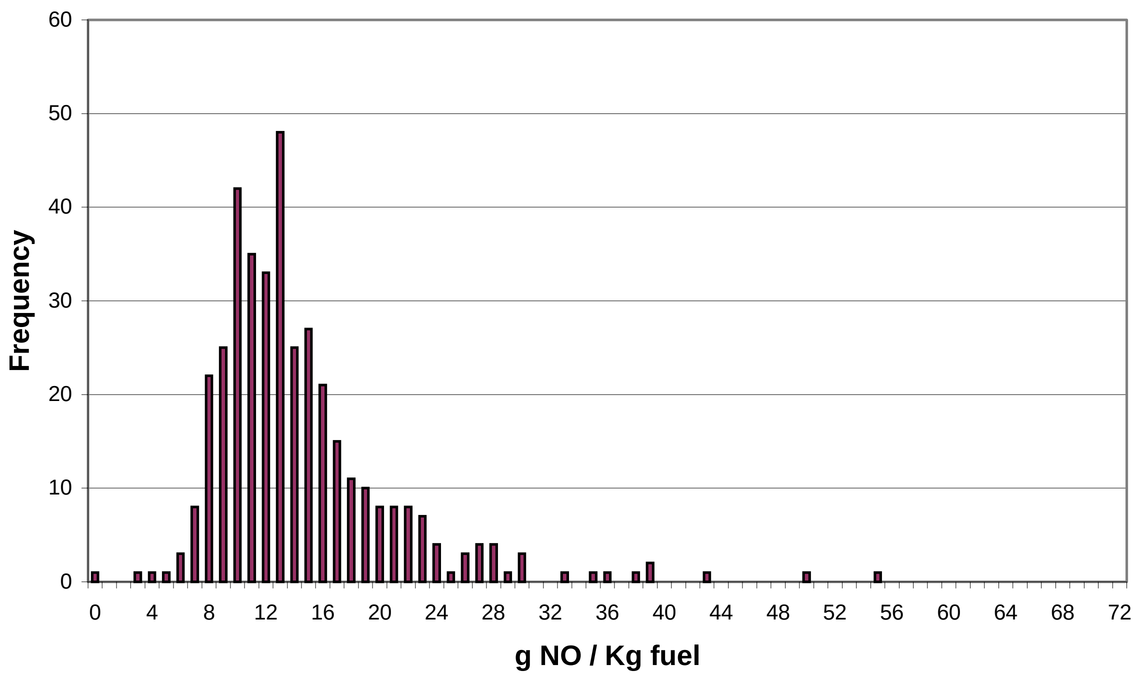

Figure 1. Results from remote sensing data where the average measurement was 13.9 g/kg and the most populated bin was between 13-14.

The concentrations of CO and HC as propane was also measured and recorded in g/kg fuel. The mean and median for CO was 22.1 and 10.0 respectively and for HC it was 1.1

and 0.88. A comparison between the car fleet and heavy-duty diesels in Austin-San Marcos area is presented in Table 1. From that table are the results we expected. CO and HC emission from cars represent anywhere from four to seven times the emission than trucks and as far as NO is concerned, trucks represent a little over three times the emissions than automobiles.

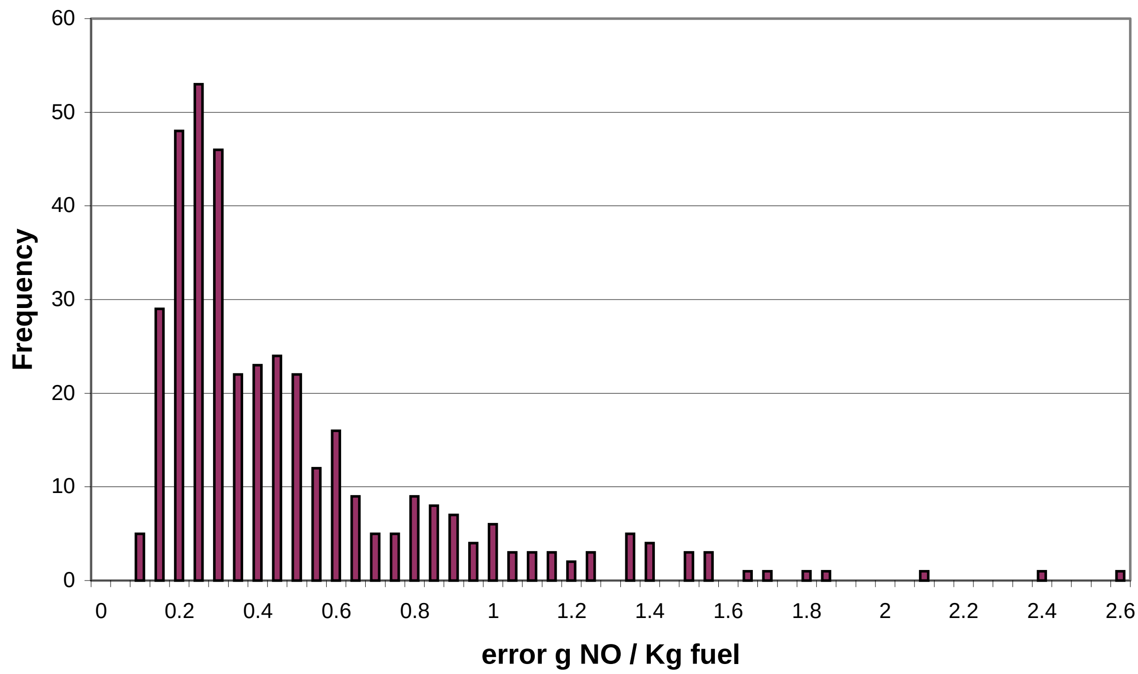

Figure 2. The reported error of the FEAT instrument at which the average was 0.467 and the largest bin was between 0.3-0.35.

	HC	CO	NO
Automobiles	8.1	102.3	4.1
Diesel trucks	1.1	21.2	14.0

Table 1. Mean values for hydrocarbons as propane, carbon monoxide, and nitric oxide for automobiles and heavy-duty trucks in the Austin-San Marcos region. The numbers represent a gram of pollutant per kg of fuel combusted.

Remote sensing of heavy-duty diesel trucks has been done around the world and a comparison of their emissions and testing sites were compiled. California was one of the first places to collect information on emissions of trucks in 1996. Their testing site was at a weigh station in Orange County where there was an uphill gradient of 4% and the average speed was 16mph. The average NO emission was 18.6. In the Canton Uri of Switzerland measurements were made for NO emissions also, but the trucks were in destination on a highway. The testing site was also an uphill gradient of 4% but the average speed here was 50mph. The average NO emission was 17.8. In table 2 a comparison of emissions were made for the sites in California, Switzerland, and Texas data. The gradient of the road was included because it is relevant to the amount of load on the engine, which causes more or less emissions. Overall the means are all similar and do not vary substantiality from one area of the world to another.

	NO emissions	**Uphill gradient**
Austin-San Marcos, TX	14.0	2.6 %
Switzerland, Canton Uri	17.8	4.0%
Orange County, CA	18.6	4.0%

Table 2. Mean NO emissions in g NO/kg fuel of heavy-duty diesel trucks in three different places in the world.

Another part of the data collected was percent opacity. Opacity is the most abundant under heavy load because the efficiency of combustion is lowest. We correlated the data of % opacity vs. CO concentrations and found that they correlated very well. The opacities were sorted from lowest to highest and sectioned into 18 equal groups from lowest to highest also and averaged. This was done so a better correlation could be seen. In figure 3 we show this correlation and the expected happened. On the whole, as the CO emissions increased, so did the % opacities. We think this should be the case in diesel trucks since the formation of CO and particulate matter happen under the same conditions.

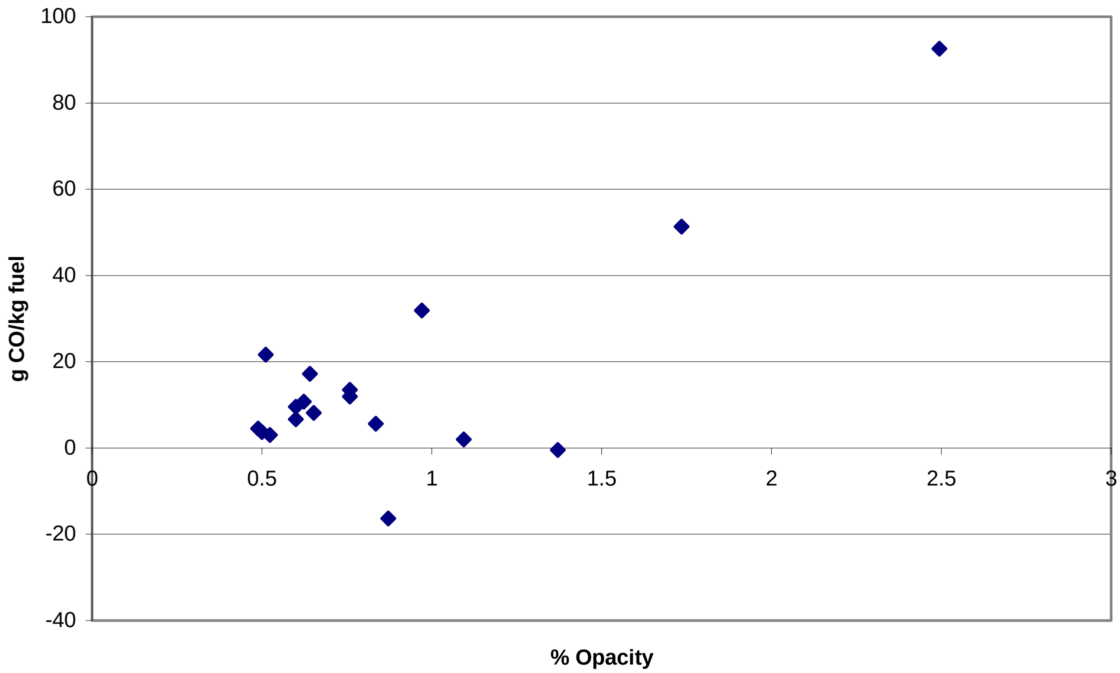

Figure 3. A correlation of the concentration of CO in g CO/kg fuel vs. the % opacity of heavy-duty diesel trucks in the Austin-San Marcos area.

Summary and Conclusions

The University of Denver was successful in measuring the concentration of nitric oxides (NO) in heavy-duty truck emissions with elevated exhaust. The important results of the field study were the following: (1) Average NO emissions ranged from 12.95 to 14.91 g NO/kg fuel with 99% confidence for all the data as unique measurements. Average NO emissions ranged from 13.17 to 14.69 with 99% confidence when data were randomly compiled into five equal groups. This leads us to believe that no matter how many trucks we observe at this site that the average and distribution would be analogous. (2) Comparison of Texas data to that of Switzerland and California was very similar, but the small differences could be due to testing conditions such as the gradient of the road, weight of load, and gear that the truck was using at the time of the measurements. The gradient of the road during both the Switzerland and California studies was 4% and during our study in Texas the gradient was only 2.3%. Gradients are a factor in the case of NO emissions because the air/fuel mixture tends to be more stoichiometric as the gradient increases. The richer the fuel mixture becomes the higher the temperature, thus higher NO emissions.

Along with the NO emissions, data for CO and HC were also reported. CO and HC do not differ much in diesel combustion engines with respect to the load or speed, but with a comparison to the automobile fleet there is substantial difference in emission. Automobiles emit several times more emissions per kg fuel than diesels even though a catalytic converter is present. The higher the air/fuel ratio the less the emissions of CO and HC, which we hope we proved.

The opacity data was very encouraging because it correlated well with CO emissions. In the comparison to our previous data of opacities from Hong Kong, the correlation of opacities to CO is extremely similar.

It seems to us, at the University of Denver, that heavy-duty trucks with diesel emissions were all relatively similar. We compared diesel emission from different areas of the world to the measurements we made in Texas and the emission from NO, CO, and HC compare very well. Opacities also seem to be the same for diesel combustion engines. On the whole, diesel emissions are all similar and we think it would be safe to calculate the percentage of NO, CO, or HC contributed by heavy-duty trucks in an area using the numbers provided.

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