Measurement of Carbon Monoxide in Auto Exhaust Using a Fast and Inexpensive Sensor

by

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Abstract

Carbon monoxide is an important pollutant because of its severe health effects at high concentrations. In urban areas, the primary source of CO is vehicle emissions from incomplete combustion. Previous studies have shown that a small number of high emitting vehicles are responsible for the majority of the CO emissions in most urban areas. This information can then be used to examine a number of interesting hypotheses with respect to vehicle CO emissions. Because there are no inexpensive devices available to test the CO output from vehicles, it was necessary for us to develop our own exhaust tester from readily available components. The exhaust tester we developed costs approximately $450 and can test up to 20 vehicles per hour. We have used this tester in several undergraduate classes to examine the CO emissions from vehicles arriving onto our campus. Using the CO data collected, and simultaneous survey data from each driver, the students are able to examine a variety of interesting hypotheses.

Introduction

Carbon monoxide (CO) is an important primary pollutant. Its health impacts result from the fact that it binds to hemoglobin in blood and interferes with our bodies' ability to transfer oxygen to our cells (Koenig 2000). At a mixing ratio of 1000 ppmv[1] (parts per million by volume) or 0.1 % (v/v), CO is toxic to humans, but even at much lower concentrations CO causes numerous health impairments. For this reason the U.S. Environmental Protection Agency has set the National Ambient Air Quality Standard (NAAQS) for CO at 9 ppmv for an 8 hour averaging period. In urban areas, the primary source of CO is auto exhaust [NRC 2001].

As a result of the U.S. Clean Air Act, vehicles in the U.S. must utilize emission control technologies to reduce CO, hydrocarbons and nitrogen oxides emissions. Two primary components of this system are an electrochemical oxygen sensor, which produces feedback to the fuel system to maintain the correct balance air-fuel ratio, and the catalytic converter, which convert CO to CO_2 in the exhaust stream. In many urban areas, annual or biennial emission tests are also required to check that the emission control system continues to work properly. A well-tuned vehicle, which has been warmed up and has properly operating emission controls will have a CO mixing ratio of 0.2 % by volume (2000 ppmv), or less. A cold or poorly running vehicle, or one where the emission controls are not working properly can have CO mixing ratios between 0.5% to ~15% (v/v). In regions that require a regular "Inspection and Maintenance (IM)" test for CO emissions, a typical passing level is 1% (v/v).

Several studies of on-road emissions have shown that a small fraction of high emitting vehicles emit the bulk of all CO. For example in the study by Beaton et al (1995), they found that 7% of the vehicles were responsible for 50% of the CO emissions. Similarly a National Research Council document (NRC 2001) reiterated this point in a recent review of this issue by stating "Typically less then 10% of the fleet contributes more then 50% of the emissions for any given pollutant". These vehicles are called "gross emitters", in that they have CO emissions that were well above the levels of most vehicles. The average age of the gross emitters is usually above average, but even some new vehicles, with modern emission controls, were found to be gross emitters. The authors concluded that these vehicles either had their emission controls tampered with or there was a serious malfunction in some component of the system. In addition the authors of these studies found that vehicles registered in areas that required participation in an IM program do not have lower on-road emissions, on average. In other words the IM programs don't seem to be effective in reducing CO emissions from these high emitters. In summary, then most vehicles are clean, a few are very dirty and better methods are needed to identify these high emitting vehicles (Beaton et al., 1995; Zhang et al., 1996; NRC 2001).

Previously we have developed several techniques for measurements of CO in auto exhaust and cigarette smoke [Jaffe et al. 1995; 1997; Jaffe and Chavasse 1999]. These methods were suitable for either secondary and/or college science classes. For auto exhaust, our previous method involves collection in small plastic "baggies" and analysis by gas chromatography. This method was found to be suitable for college chemistry classes. However this method is slow, only a few vehicles per hour could be tested, and was not really suitable for general environmental science classes. As a result, it is hard to use this method to conduct an interesting exhaust experiment for undergraduates. Therefore we sought to develop a fairly simple method that would work quickly, so we could obtain a larger database of exhaust CO values.

In this report, we describe a fast and relatively inexpensive method to test the CO mixing ratios in auto exhaust. The materials for the exhaust tester cost approximately $400 and can be used for many tests over a several year period. We have used this method in various classes to measure several hundred vehicles. Depending on the traffic, we can collect data at a rate of up to about 20 vehicles per hour. Students can then utilize the database to evaluate a wide range of hypotheses associated with CO emissions and vehicle type, age, mileage, maintenance, etc. The students conducting this experiment are usually quite excited to be involved and develop a strong interest in the hypotheses being evaluated.

Experimental

CO measurements in exhaust are done routinely at many gas stations and IM test locations. These devices use a non-dispersive infra-red spectroscopic technique. The sensors for this type of test typically cost several 10's of thousands of dollars. Several companies manufacture simple and inexpensive electrochemical sensors for CO, for homes and workplaces. These sensors detect CO in the parts per million range and typically last for several years. To date we have not found an inexpensive sensor that operates in the correct range for exhaust testing (0-15% by volume). So for this reason we developed a simple system that allows us to dilute the exhaust gas down so that we can use one of these low cost electrochemical sensors.

A diagram of the system is shown in Figure 1. It uses two rotameters (simple "floating ball" type flow meters) and two needle valves to control and measure the flow. A small, vacuum pump pulls exhaust and dilution air through the system and pushes it through to the CO sensor. A vent is necessary just before the sensor to avoid over-pressurization. The filter is a 47mm glass fiber filter in a filter holder. The filter helps keep the tubing clean from soot and other particulate matter in the exhaust and probably extends the life of the electrochemical CO sensor. The condenser is simply a section of tubing that goes through a plastic beaker holding crushed ice. The condenser drains via a "T" into a container of water. The condenser allows the large amounts of water in the exhaust to drain out prior to reaching the filter. In our earlier versions we used this system without a condenser, but found that the filter was constantly getting saturated with water and needed frequent replacement. The tubing is mostly Teflon, with some Tygon sections and stainless steel, for the portion that sits in the car's tailpipe. We have used two different sensors for these tests. The first is a model SGA70 from Universal Enterprises that was purchased from Cole Parmer Inc. (Chicago, IL). This sensor has a range of 0-3000 ppmv and lasted for approximately 3 years. A second sensor was purchased from Testo Inc. (Flanders NJ), Model 315-2. The sensors come pre-calibrated by the manufacturer and we have not attempted to recalibrate.

For simplicity, we run this system at a fixed dilution flow (9.6 liters/minute) and vary the exhaust flow (0.40, 0.55 and 0.84 liters/minute) to keep the final values on scale.[2] To calculate the actual exhaust CO mixing ratio, it is necessary to quantify the degree of dilution. To do this, we use:

CO (exhaust) = CO (sensor reading) /Dilution factor (1)

where;

Dilution factor = Exhaust Flow/(Exhaust flow + Dilution flow) (2)

So, for example, at a dilution factor of 25, our highest dilution factor (dilution flow of 9.6 liters/minute, exhaust flow of 0.4 liters/minute) a poorly running vehicle that has an exhaust CO mixing ratio of 6% by volume (60,000 ppmv) would result in a sensor reading of 2400 ppmv. This value is very high, but is readable by the sensor.

One way we have tested our exhaust system is by evaluating a vehicle during startup. The vehicle is started and continuous measurements are taken as the vehicle warms up. Because the exhaust CO is initially quite high, it is necessary to change the dilution flow several times. Figure 2 shows a typical warm-up pattern from a 1989 Volvo. Shown on the figure are both the true exhaust concentrations, as well as the raw CO data reported by the meter. The times where the dilution flow was changed are indicated on the graph. Initially the cold vehicle gave very high CO levels, but these came down considerably as the vehicle warmed up. When the dilution flow was changed, the meter reading changed, but the calculated exhaust values did not. This indicates that our dilution system was working properly.

To conduct the experiment, teams of students first review the literature on auto exhaust and to develop a set of hypotheses that they will test with their own data. The students then develop a survey form that will be given to each driver while their vehicle is being tested. The survey can ask any reasonable question, which will allow the students to evaluate their hypotheses. Each test, including filling out the survey form, takes no more then 2 or 3 minutes. To get participants, student teams stand by a stop sign near one of the main road entrances to our campus. Students wear bright orange vests and carry clipboards to look “official”. When a vehicle stops, the driver is asked if they would be willing to participate in the study. If they agree, the vehicle is directed to a pre-arranged spot for the test. Note that the test location requires power for the dilution pump, although this could be powered from a 12-volt battery. The CO sensor operates from a 9-volt battery. To obtain a uniform database of warmed up vehicles, we collect data only from vehicles entering campus that have been running for at least 10-15 minutes. Cold vehicles emit much higher CO levels (Jaffe and Herndon 1995). All operations are organized in advance and approved through campus security. Depending on the traffic, it is possible to test up to 20 vehicles in an hour.

The hypotheses the students develop are interesting and generally policy relevant. For example, some classes choose to evaluate who has the cleanest vehicles: faculty, staff or students. The assumption is that students have lower incomes, and therefore have older and more poorly maintained vehicles. Other students wish to evaluate the age of the vehicle, the time since the last tune-up or other factors. The survey form must reflect the data needed to evaluate the specific hypotheses. We also send study participants the results of their test by email, if they so choose.

Results

Students from the 1999 and 2000 Air Pollution and Health classes at the University of Washington Bothell collected data on campus. The 1999 class tested 112 vehicles, while the 2000 class tested 57 vehicles. A summary of the data is shown in Table 1.

Table 1. Summary data from 1999 and 2000 exhaust experiments

	N	Number of high emitters*	Mean % (v/v)	Median % (v/v)	Min % (v/v)	Max % (v/v)	Average model year
1999 Class data	112	11 (10% of vehicles)	0.37	0.05	0.0	5.6	1991.6
2000 Class data	57	3 (5% of vehicles)	0.56	0.04	0.0	12.0	1992.5

* We define a high emitter as a warmed-up vehicle which exceeds 1% CO (v/v) in the exhaust. This is the usual "passing" concentration for most state IM programs.

The data from the two classes are similar, but with some differences. The 2000 class found only 3 vehicles that exceeded the 1% (v/v) level. But 1 of these vehicles, a 1978 Porsche, was an exceptional polluter at 12% CO (v/v). This vehicle probably had no emission control equipment. The data from the 2000 class is perhaps a bit more representative in that 11 high emitting vehicles were identified, but the highest was "only" 5.6 % (v/v).

The mean exhaust mixing ratio from our studies, reported in Table 1, are comparable to means reported from other studies. For example Zhang et al. [1996] report mean CO exhaust mixing ratios from thousands of on-road tests in Denver of 1.03, 0.80, 0.64 and 0.53 % (v/v) for data collected in 1989, 1991, 1992 and 1994, respectively. Apparently the total CO emissions from all on-road vehicles is going down as emission control technology becomes more reliable. The average vehicle age from the Denver studies was 6.4-6.7 years, which is very similar to the average age of the vehicles in our study. The fact that the means for each year are much larger then the medians indicates that the data are significantly skewed, or non-Gaussian. This is typical of a wide variety of environmental data. As a result, any statistical tests must be based on methods that don't assume a normal distribution.

Discussion

The very low medians values shown in Table 1 indicate that most vehicles are very low emitting. In other words, for most vehicles the emission control devices are working properly. This then leads to the suggestion from previous studies that a small numbers of the vehicles on the road are responsible for a large fraction of the total emissions. To calculate the actual emissions for each vehicle it would be necessary to know the exhaust flow rate. This could be calculated from the engine size and speed (revolutions per minute). However since these were not measured in our study, we can roughly estimate the contribution of each vehicle to the total emissions by assuming that all vehicles have the same size engine, and therefore exhaust flow.

If each vehicle has the same exhaust flow, then the ratio of each vehicles exhaust concentration divided by the sum of the concentrations for all vehicles in the study gives the contribution by that vehicle to the total emissions. Figure 3 shows a plot of the cumulative emissions vs vehicle number. What this shows is that for the 1999 data, 6 vehicles (5 % of the 112 vehicles measured) emitted more then 50% of the total CO from all vehicles in the study and 23% of the vehicles emitted 90% of the total CO. The other 77% of the vehicles that we tested were so clean that, for practical purposes, they were essentially zero emitters of CO. This result is similar to that reported by Zhang et al [1996].

With these data, our students have been able to test a number of different hypotheses. One hypothesis considered is that there is a correlation between the age of the car and the concentration of CO in the exhaust. Another hypothesis is that there is a correlation between vehicle mileage and CO output. In general, we have found that a simple regression models fail to confirm these hypotheses. Instead, more complex data treatment or data segregation methods seem to be required. This can then lead into useful discussions on data treatment and the idea that real-life is always more complicated then theory. Students also benefit by applying statistical tools to their own data and observing the outcomes, which is not often integrated into statistics classes.

Summary

Because it is not possible to purchase an exhaust CO tester for student use, we decided to construct our own from readily available components. The device we constructed costs about $450 and can test up to 20 vehicles per hour. Using information obtained from the literature we designed an experiment to evaluate a variety of factors associated with CO in auto exhaust. Generally, our results confirm previous studies, which show that a small number of vehicles on the road are responsible for a large fraction of the automobile pollution. Conducting these experiments has given our students an interesting opportunity to understand an important environmental issue and helps them understand the nature of the scientific process and hypotheses testing.

References

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Tables

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Figures

Figure 1. Diagram of CO auto exhaust monitor.

Figure 2. Warm up data for a 1989 Volvo. Readings were taken every 20 seconds. Shown on this figure are the meter readings, the calculated exhaust mixing ratios and the times when the dilution flow was changed.

Figure 3. Cumulative distribution of total CO emissions vs ranked vehicle number.

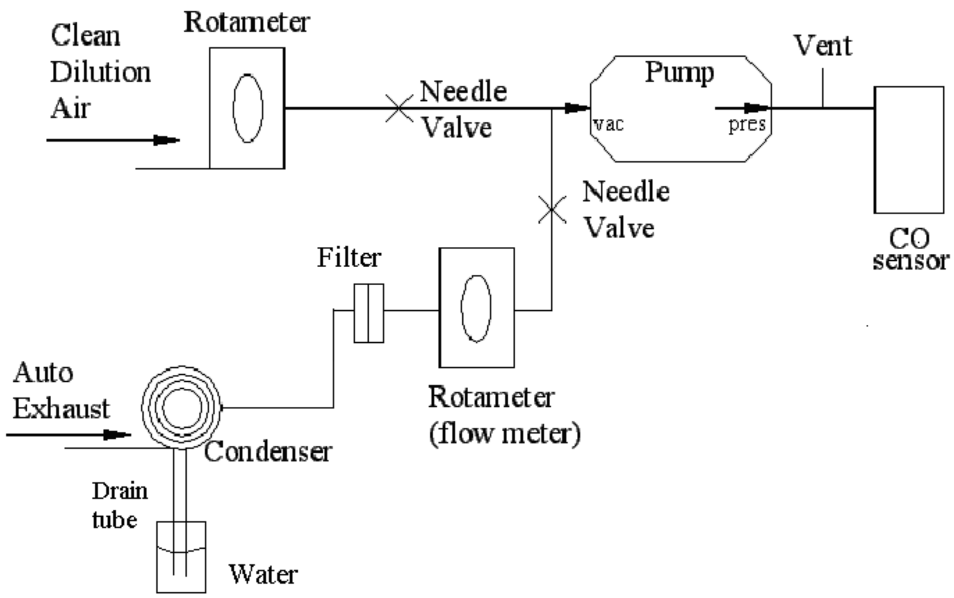
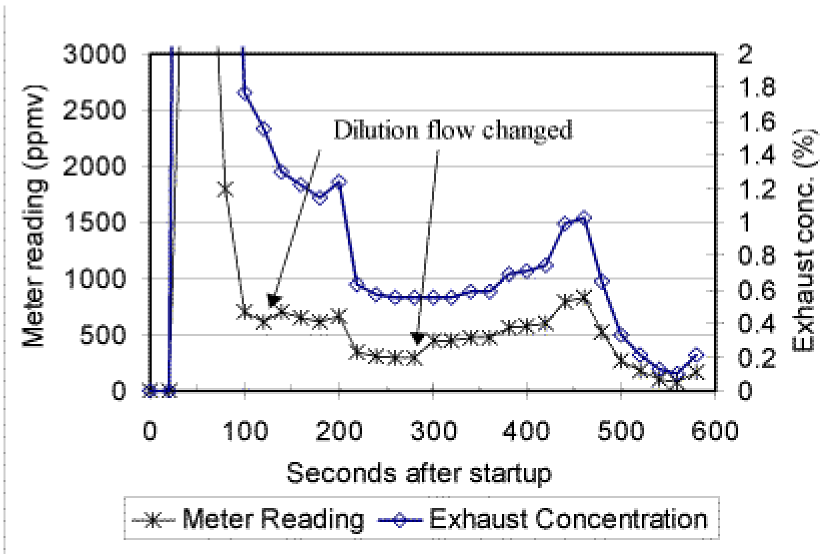


Figure 1. Schematic diagram of the CO exhaust monitor.



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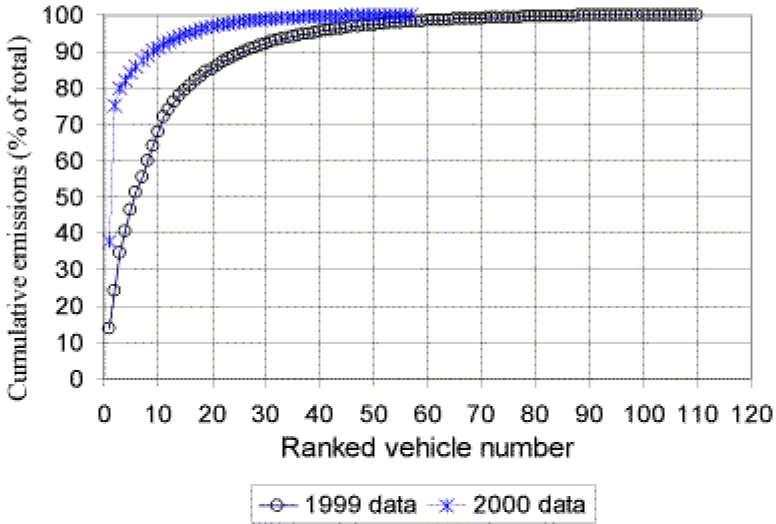

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Endnotes

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[1] Atmospheric concentrations are usually given as volumetric mixing ratios. So for example a mixing ratio of 1000 ppmv of CO is equivalent to 1000 liters of pure CO mixed into 1 million liters of air. Alternatively this could be thought of as 1000 moles of CO mixed into 1 million moles of air. A CO mixing ratio of 1% (v/v) represents 1 liter of CO mixed into 100 liters of air. The term "by volume" and the notation (v/v) are used interchangeably.

[2] Varying the dilution factor is probably not essential. For example using a dilution factor of 20 it should be possible to get coverage of the entire range of exhaust concentrations.