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Emissions Reductions as a Result of Automobile Improvement

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Remote sensing of light duty vehicle on-road tailpipe exhaust has been used to measure on-road mass emissions of automobile fleets in Denver for 13 years and in two other U.S. cities for 5 years. Analysis of these fleets shows that newer automobiles, during a period of fairly constant new car standards, have become continually less polluting independent of measurement location. Improving emissions control technology spurred by federal regulations is thought to have brought about these trends.

Introduction

The U.S. Environmental Protection Agency (EPA) estimates on-road motor vehicle emissions to be the single largest contributor of major atmospheric pollutants. As of 1998, automobiles contributed 60% of the carbon monoxide (CO), 44% of the hydrocarbons (HC), and 31% of the oxides of nitrogen (NO_x) to the national emissions inventory in the United States (*1*). In urban areas the contribution of motor vehicles is even higher; for instance, the Colorado 1998 Air Quality Data Report states that 86% of Denver's CO comes from motor vehicles (*2*).

Since the 1960s, various strategies have been employed to control automobile emissions in the United States. This control has been made more necessary by the substantial increase in automobile use since that time. A two-pronged approach was adopted. First, new vehicles were required to be built to be much lower emitting. Advances in emission control technology were often enabled by additional regulations controlling fuel composition. Second, emissions from older vehicles were to be reduced through scheduled, mandatory vehicle emission inspection, and maintenance (I/M) programs. In many states, including Colorado, Illinois, and California, new vehicles are exempt from I/M emissions testing for 4 years unless they change ownership.

In 1970, Congress adopted the first major Clean Air Act and established the U.S. EPA, which required new vehicles to meet certain emission standards. Throughout the next 2 decades, these emission standards were revised and new technologies were devised to meet the standards. Certification standards for new vehicles outside California remained constant from 1981 to 1999, with the exception that in 1994 the NO standard was reduced and a 100 000 mile, 10-year durability standard was phased in for NO, CO, and HC (*3*). By the 1996 model year, all light duty vehicles were required to have on-board diagnostic systems (OBDII). The intent of this system is early detection of potential emission control component failures (*4*). In 1990, congress made amendments to the Clean Air Act and required "enhanced" (I/M) programs involving loaded mode testing to "closely reflect how vehicles perform under actual driving conditions" (*4*).

Recent observations indicate that the 4 decades of regulations have made an impact. For example, Figure 1 illustrates that motor fuel consumption by the transportation sector has been increasing (*5*), while CO concentrations in the air have been decreasing (*6*). Note that in the past decade there has been a 4.1% annual decrease in average ambient CO concentrations in the United States. The EPA also reports a decrease in national average ambient NO_2 concentrations of 1.6% per year during the same time period (*6*). Furthermore, a recent review of ambient CO trends at various locations in California's South Coast Air Basin shows declines between 4% and 9% per annum over the last 12 years (*7*). This paper presents evidence based on on-road remote sensing that lower emitting newer vehicles have contributed to these reduced urban ambient pollutant concentrations even as fuel use has increased.

The on-road evidence comes from remote sensing measurements of vehicle emissions made over a decade in several U.S. cities. Remote sensing of automobile emissions involves the use of open-path infrared and ultraviolet spectroscopy to measure the concentration of pollutant species relative to the concentration of carbon dioxide (CO_2) in a section of the exhaust plume behind an automobile. From the ratio of pollutant to CO_2 one can then derive the fuel specific mass emissions of pollutant. Detailed discussions of remote sensing technology have been presented previously (*8*−*10*).

Using on-road remote sensing, we have measured fuel specific mass emissions of CO since 1989. Fuel specific emissions depend on load, HC and NO more so than CO. Load can be estimated from on-road speed, acceleration, and road grade measurements. Furthermore, CO and HC light-duty vehicle emissions may be large, even for well-maintained vehicles, if the vehicle is in cold start. A cold start is when a vehicle's catalytic converter and emission control systems have not reached operational temperature.

With careful site selection, measurement of high load and cold start driving modes can be prevented. By selecting measurement sites that are heavily trafficked, curved, uphill freeway off-ramps, we limit vehicles in cold start mode and those under high load. When light duty fleets are measured over several years at the same site with similar load distributions, fleet performance over time and under actual driving conditions can be studied.

Statistics from such measurements indicate that every year there exists a relatively small number of very high emitting vehicles, which are responsible for most of the total emissions of each pollutant (*11*). A "gross polluter" of a particular pollutant is defined (*11*) as one of the relatively few vehicles in the emissions category that together cause half the total on-road emissions of that particular pollutant. For example, in Denver in 2000, the 6% of the measured fleet that were CO gross polluters by this definition were measured with average emissions of 480 g CO/kg fuel, which is almost 9 times greater than the mean and 32 times greater than the median for the same fleet.

The fraction of gross polluters, however, has been decreasing over the years of measurement. This decrease is illustrated in Figure 2. In Denver in 1989, half of the total CO emissions came from about 9% of the vehicles (*12*). In 2000, half of the total came from only about 6% of the fleet (*13*).

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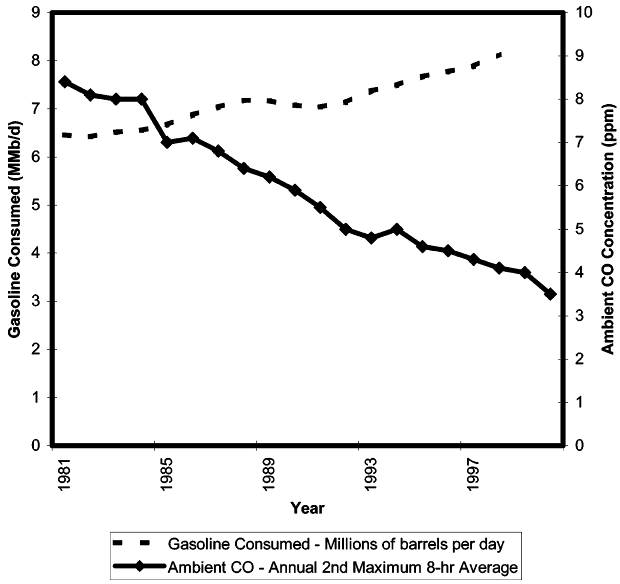

FIGURE 1. Opposite trends in gasoline consumption and CO ambient concentration. The decreasing plot shows EPA reported data on second maximum measured carbon monoxide concentrations in the air of the United States (*6*), while gasoline consumption by motor vehicles has been increasing (*5*).

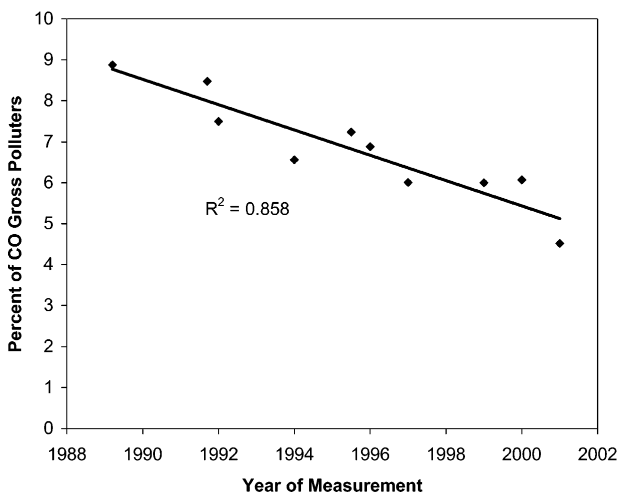

FIGURE 2. Decrease in fraction of CO gross polluters during measurements in Denver from 1989 to 2001. Gross polluters are defined as the percentage of the total measured fleet responsible for 50% of total measured CO emissions.

The average rate of decrease is 0.30 ± 0.10% per year, where the uncertainty is the 95% confidence interval. Thus, most automobiles are low emitting and collectively emit a relatively small portion of total emissions. Furthermore, the fraction of low emitting vehicles continues to increase with time.

When emissions are studied as a function of model year, the newest vehicles are always low emitting. Additionally, our most recent data suggest that emissions deterioration over time has slowed. This trend was first observed with remote sensing measurements between 1989 and 1995 (*14*), and the trend has continued (*13*). In 1989, the results, when plotted versus model year, showed a steep, approximately linear increase of CO emissions with age such that, after 10 years, the average emissions of 1979 model year vehicles was 240 g CO/kg of fuel. In 2000, the increase was much slower, and after 10 years 1990 model year vehicles (which in 1992 averaged 39 g CO/kg) emitted an average of only 80 g CO/kg. The remote sensing data also indicate that the small fraction of broken older vehicles has lower average emissions today than 13 years ago.

TABLE 1. Chicago Data Showing the Percentage of the Fleet and the Percentage of the Various Emissions from the Newest Four Years of Vehicles

measurement year	% of fleet	% of CO	% of HC	% of NO
2002	48	16	23	19
1999	49	20	32	24
1997	53	29	37	35

These observations led us to study our large remote sensing dataset using a new approach. We present here a study of the emissions of relatively new vehicles over several years of measurement. This approach highlights improvements in emission control strategies over the time period of the study.

Method of Data Collection and Mining

We have obtained large data sets of emissions measurements from busy curved uphill freeway ramps in Denver (*13*, *15*, *16*), Chicago (*17*), and Los Angeles (*18*). All of the Chicago and Los Angeles measurements and the Denver measurements since 1996 have been made at the exact same location in each city. The earlier Denver measurements were made on another very similar off-ramp three miles north on the same freeway near downtown Denver.

The timing of the yearly measurements has also been controlled. The Chicago, Los Angeles, and Denver data since 1996 were all obtained during measurement campaigns that lasted several days each. In Denver, these were days in late December or early January, the middle of mandatory oxygenated fuel season. The Denver mandate has been essentially unchanged from 1988 onward. We made measurements during September in Chicago and during June and July in Los Angeles. Measurements made during the same time of year help control for seasonal variables. Such variables include atmospheric temperature, presence of oxygenated fuels, and use of air conditioning.

The fleets analyzed are comprised almost entirely of passenger cars and light duty trucks. Furthermore, vehicles up to 4-years old are studied. Model years that are up to 4-years old comprise a large fraction of the on-road fleet in the United States and, thus, are most useful as subsets that have statistically significant sample sizes. Large sample size is crucial with automobile emissions data because of the highly skewed nature of their distribution, and the fact that, regardless of testing procedure, high emitters generally show very highly variable emissions results (*19*−*21*). Additionally, in the states of interest, vehicles up to 4 years of age are mostly exempt from I/M testing. Thus, in the study presented here, only vehicles up to 4-years old are analyzed. Analysis of the data is also limited to whole model year groups. Table 1 shows typical data from Chicago demonstrating that from 1997 to 2001, these newer vehicles contributed about 50% of the on-road measurements. Their contribution to the overall emissions however decreased significantly.

To observe the trend in average emissions of successive model year vehicles, the average emissions of vehicles of a certain age is studied over several years of measurement. For example, we look at how average CO emissions of 3-year-old cars and light duty trucks measured in Chicago between 1997 and 2000 have changed. Thus, we compare 1994 model year vehicles measured in 1997 to 1995 model year vehicles measured in 1998, etc. This type of analysis tracks the emissions improvement from one model year to the next without interference from the effect of deterioration. The grouping of the data in this study yields sample sizes between 1500 and 2500 emissions readings for all measurement

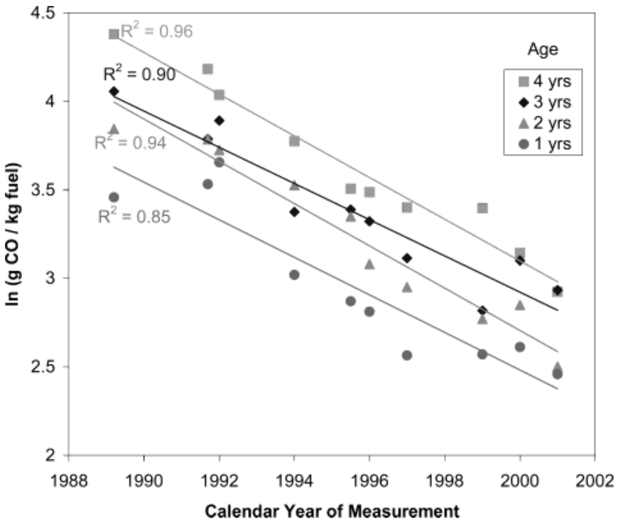

FIGURE 3. Decreasing CO emissions from new vehicles. The natural log of grams CO emissions per kilogram of fuel used is plotted by year of measurement for vehicles aged 1−4 years measured between 1989 and 2001 in Denver. Age of vehicle is calculated by subtracting model year from measurement year. Regression lines for each age are drawn and R^2 values are included. As a reference, the tier 0 and tier 1 federal 50 000 mile standard of 3.3 g/mi CO emissions for light duty vehicles transforms to 28 g CO/kg fuel, assuming a fuel economy of 23 mpg. This standard would appear at 3.3 on the log scale in the figure.

campaigns except for some of the older measurements in Denver, which had smaller sample sizes.

Three pollutants were measured in these studies: CO, HC, and NO. We have observed and reported a measurement offset, restricted to the HC channel (*13*, *17*, *18*), but diagnosis has proved difficult. In the absence of a true diagnosis of the problem, we proposed a remedy to remove the offset and obtain data that can be compared from the several years of study. This adjustment is to subtract a predetermined offset from the averaged data. The offset is determined as the average emissions of the cleanest model year and make of vehicles from each data set. Since we assume the cleanest vehicles to emit next to nothing, such an approximation will only err slightly toward clean because the true offset will be a value somewhat less than the average of the cleanest model year and make. This procedure is used to adjust the HC data so that measurements from different years can be compared without interference from an artificial offset.

Results

Figure 3 tracks the on-road, fuel specific CO emissions of vehicles that are less than 5-years old over a 13-year period in Denver. A trend of continually decreasing emissions during successive years of measurements is observed. In Figure 3, we plot the natural log of average grams CO emissions per kilogram of fuel used as a function of the year of measurement. We define the age of a vehicle as the year of measurement minus the model year. For example, during the 2001 Denver fieldwork a 2000 model year vehicle would be considered 1-year old.

A logarithmic scale is used because the natural log function most closely models the data. The slope of the best-fit regression line then shows the proportionate annual decrease in average emissions. For example, in Figure 3 the slope of the regression line to the CO data for 4-year-old vehicles in Denver is −0.12, which corresponds to an average annual decrease in CO emissions of 12%.

Similar studies of trends in average emissions of successive model year vehicles were conducted with data from Chicago

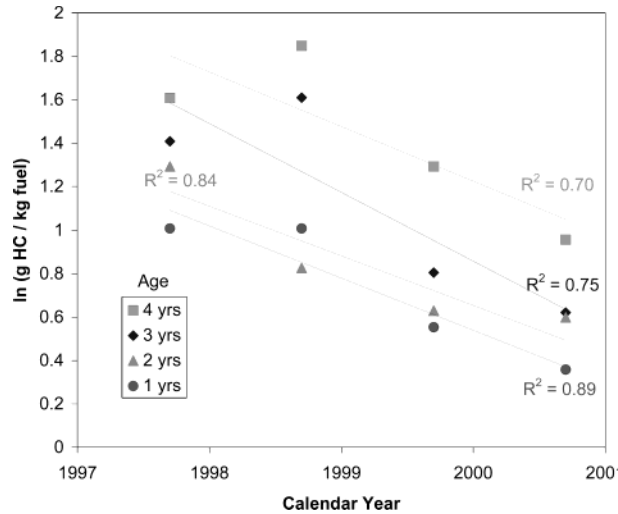

FIGURE 4. The HC data from four measurement campaigns in Chicago. As a reference, the tier 0 and tier 1 federal 50 000 mile standard of 0.41 g/mi HC emissions for light duty vehicles transforms to 3.4 g HC/kg fuel, assuming a fuel economy of 23 mpg. This standard would appear at 1.2 on the log scale in the figure.

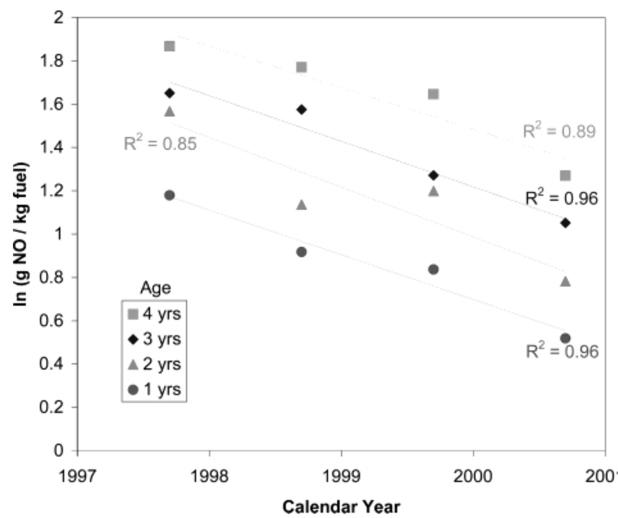

FIGURE 5. The NO data from four measurement campaigns in Chicago. As a reference, the tier 0 federal 50 000 mile standard of 1.0 g/mi emissions as (NO_2) for light duty vehicles transforms to 5.4 gNO/kg fuel, assuming a fuel economy of 23 mpg. This standard would appear at 1.7 on the log scale in the figure. The 0.4 g/mi Tier 1 standard would be 0.74 on the log scale.

and Los Angeles. We have made four sets of yearly measurements in Chicago starting in 1997 and three sets in Los Angeles beginning in 1999. Each year of measurement has been written up previously as a report, peer-reviewed by two levels of committee of the Coordinating Research Council, and published at the CRC Web site www.crcao.com and at www.feat.biochem.du.edu (*13*, *17*, *18*). The HC and NO emissions trends were also studied for all three cities. Figures 4 and 5 illustrate the HC and NO data from Chicago. Again, we can observe decreasing trends in both HC and NO emissions over successive years of measurement.

The average annual decreases in CO, HC, and NO emissions for light duty vehicle fleets aged 1−4 years in Denver, Chicago, and Los Angeles are tabulated in Table 2. The reported percentage values are obtained from the slopes of regression fits similar to and including Figures 3−5. The reported uncertainty values are derived from the standard errors of the slopes. Notice that almost every decreasing trend is significant. In Denver, the CO and HC rates of improvement

TABLE 2. Annual Percent Reductions in Emissions of Newer Vehicles during Their First 4 Years[a]

location (duration)	fleet age yr	annual % change in CO emissions	annual % change in HC emissions	annual % change in NO emissions
Denver	4	−12 ± 1	−10 ± 3	−15 ± 3
(1989−2001 for CO)	3	−10 ± 1	−9 ± 2	−19 ± 2
(1996−2001 for	2	−12 ± 1	−12 ± 3	−21 ± 2
HC and NO)	1	−11 ± 2	−15 ± 8	−18 ± 4
Chicago (1997−2000)	4	−29 ± 7	−25 ± 12	−19 ± 5
	3	−35 ± 6	−32 ± 13	−21 ± 3
	2	−29 ± 2	−23 ± 7	−23 ± 7
	1	−33 ± 7	−24 ± 6	−21 ± 3
Los Angeles (1999−2001)	4	−22 ± 5	−19 ± 0.1	13 ± 4
	3	−15 ± 5	−16 ± 6	−4 ± 8
	2	−16 ± 1	−19 ± 2	6 ± 4
	1	−24 ± 2	−48 ± 25	11 ± 24

[a] Data are grouped by age of vehicles. The period of measurement varies among locations and is indicated below the location names. There were 10 sets of CO measurements in Denver (five sets for HC and NO), 4 sets in Chicago, and 3 sets each in Los Angeles. Uncertainty values are standard errors of the mean. Note that only one of the regression fits indicates an emissions increase that is statistically significant.

are less than NO. In Chicago, the NO improvement rate is comparable to Denver, but the HC and CO rates are higher than NO. Los Angeles is intermediate, but relative uncertainties are high in the Los Angeles data because only three measurement campaigns have been conducted at that location.

Figures 3−5 can also be used to look at the deterioration in fleet emissions. Deconstruction of the plots reveals the trend in emissions of a specific model year fleet as it ages over the years of the study. This deconstruction involves ignoring the trend lines and tracking a specific model year from one calendar year to the next. For example in Figure 5, we see that the 1-year olds measured in 1997 (i.e. the 1996 model year fleet) have average NO emissions very close to that of 2-year olds measured in 1998 (again, the 1996 model year fleet). Thus, the 1996 model year vehicles' emissions did not deteriorate significantly as they aged 1 year between 1997 and 1998. We can follow the 1996 model year fleet through the 1999 and 2000 measurements and observe that there is only a sight increase in average NO emissions. This lack of significant deterioration holds true for other model year fleets and with CO and HC as well. It is also interesting that after 4 years of "deterioration" (or lack thereof) newer model year fleets are still lower emitting than older model year vehicles when they were only a year old.

Discussion

This analysis of on-road remote sensing data shows continual improvement in fleet average emissions of new vehicles over several years of measurement in three separate cities. Several factors may have contributed to these decreasing emissions. Three possibilities are that the states' I/M programs have become more effective, that gasoline supplied in these areas has become cleaner burning, and that vehicle technologies to reduce emissions have improved.

The effect of I/M programs have been effectively removed in this analysis by selecting vehicles that are up to 4-years old and, thus, mostly exempt from I/M testing and unaffected by I/M programs. The only notable exceptions were CO measurements made in Denver before 1995. Denver vehicles were subject to the Colorado annual idle I/M program between 1990 and 1995. During that time, there was only a 1-year exemption and then biennial testing for the next 2 years. While this I/M program may have influenced the average emissions of the fleets measured early on, the "enhanced" I/M program actually became progressively less involved in the newer vehicles, which nevertheless became lower and lower emitting. Thus, the enhanced I/M program cannot account for the decreased emissions.

The evidence of a lack of significant deterioration combined with the observation that newer vehicles that have aged several years are still lower emitting than new vehicles from a few years ago is important in discerning the influence of fuels on emissions. If cleaner burning fuels were the only cause of emissions improvements, one would expect emissions deterioration to offset the effect of cleaner burning fuels so that newer vehicles that have aged would have higher emissions than new vehicles measured a few years earlier.

These observations suggest that improvements in emissions control technologies have played a significant role in lowering fleet average on-road automobile emissions. Automobile manufacturers have made innovations in emissions control technologies in part to meet federal automobile emissions standards. The standards for new vehicles have remained fairly constant outside of California since the 1981 model year. Details are given in an NRC report (*3*) and by the EPA (*22*). The ability of the manufacturers to meet these standards on-road has apparently improved, however. New technologies continue to be developed to meet more stringent standards as discussed by Mondt (*23*). While the observed trends in Table 2 are mostly consistent from one age group to then next, they are different at the different locations. We do not know the cause of this difference. Further research will result in longer records at all locations which will lower the uncertainties and hopefully provide further insights.

Even as manufacturers meet current emission standards, they are compelled to produce cleaner technologies by the approach of future standards. OBDII has been installed on all 1996 and newer vehicles (*4*), and starting in the 2001 model year, new light duty vehicles will continue to have tighter emissions standards under a federal program called the national lower-emissions vehicle program (NLEV) (*3*, *22*). In fact, the motivation for auto manufacturers to produce cleaner vehicles may be also customer focused. They may not wish their customers to fail I/M tests and, with 1996 and newer vehicles, not have OBDII malfunction indicator lights go on.

Literature Cited

(1) U.S. Environmental Protection Agency. *National Air Quality and Emissions Trends, 1998;* EPA Publication 454-R-00-003; 2000.

(2) Colorado Department of Public Health and Environment. *Air Quality Data Report − 1998*; Publication APCD-TS-B1; CDPHE, Denver, 1998.

(3) *Evaluating Vehicle Emissions Inspection and Maintenance Programs*; National Research Council, National Academy Press: Washington, DC, 2001.

(4) U.S. Environmental Protection Agency. "Requirements For Preparation, Adoption, and Submittal of Implementation Plans"

(U.S. Code of Federal Regulations, Title 40, Part 51, 2002; http://www.epa.gov/epahome/cfr40.htm).
(5) U.S. Energy Information Administration. *Annual Energy Review*; EIA: Washington, DC, 2002; http://tonto.eia.doe.gov/aer/index2000.htm).
(6) U.S. Environmental Protection Agency. *Latest Findings on National Air Quality: 2000 – Status and Trends – Carbon Monoxide*; EPA: 2001; http://www.epa.gov/oar/aqtrnd00/carbon.html.
(7) Eisinger, D. S.; Chang, D. P. Y.; Kear, T.; Morgan, P. F. *J. Air Waste Manage. Assoc.* **2002**, *52*,1012.
(8) Bishop, G. A.; Starkey, J. R.; Ihlenfeldt, A.; Williams, W. J.; Stedman, D. H. *Anal. Chem.* **1989**, *61*, 671A.
(9) Zhang, Y.; Stedman, D. H.; Bishop, G. A.; Guenther, P. L.; Beaton, S. P.; Peterson, J. E. *Environ. Sci. Technol.* **1993**, *27*, 1885.
(10) Popp, P. J.; Bishop, G. A.; Stedman, D. H. *J. Air Waste Manage. Assoc.* **1999**, *49*, 1463.
(11) Beaton, S. P.; Bishop, G. A.; Zhang, Y.; Ashbaugh, L. L.; Lawson, D. R.; Stedman, D. H. *Science* **1995**, *268*, 991.
(12) Bishop, G. A.; Stedman, D. H. *Environ. Sci. Technol.* **1990**, *24*, 843.
(13) Pokharel, S. S.; Bishop, G. A.; Stedman, D. H. *On-road remote sensing of automobile emissions in the Denver area: year 3*; Technol. Rep. Coordinating Research Council E-23-4; University of Denver: Denver, CO, 2002; http://www.feat.biochem.du.edu.
(14) Slott, R. S. *Remote Sensing at the Speer Off Ramp, Denver, CO, 1989–1995*; Preprint extended abstract, American Chemical Society: New Orleans, LA, March 24–26, 1996.
(15) Stedman, D. H.; Bishop, G. A.; Aldrete, P.; Slott, R. S. *Environ. Sci. Technol.* **1997**, *31*, 927.
(16) Stedman, D. H.; Bishop, G. A.; Slott, R. S. *Environ. Sci. Technol.* **1998**, *32*, 1544.
(17) Pokharel, S. S.; Bishop, G. A.; Stedman, D. H. *On-road remote sensing of automobile emissions in the Chicago area: year 4*; Technol. Rep. Coordinating Research Council E-23-4; University of Denver: Denver, CO, 2001; http://www.feat.biochem.du.edu.
(18) Pokharel, S. S.; Bishop, G. A.; Stedman, D. H. *On-road remote sensing of automobile emissions in the Los Angeles area: year 3*; Technol. Rep. Coordinating Research Council E-23-4; University of Denver: Denver, CO, 2002; http://www.feat.biochem.du.edu.
(19) Zhang, Y.; Bishop, G. A.; Stedman, D. H. *Environ. Sci. Technol.* **1994**, *28*, 1370.
(20) Wenzel, T. P.; Singer, B. C.; Slott, R. *J. Transportation Statistics* **2000**, *3*, 1.
(21) Bishop, G. A.; Stedman, D. H.; Ashbaugh, L. L. *J. Air Waste Manage. Assoc.* **1996**, *46*, 667.
(22) U.S. Environmental Protection Agency. *Federal and California Exhaust and Evaporative Emission Standards for Light-Duty Vehicles and Light-Duty Trucks*; EPA Publication 420-B-00-001; 2000; http://www.epa.gov/otaq/stds-ld.htm.
(23) Mondt, R. J. *Cleaner Cars: The History and Technology of Emission Control Since the 1960s*; Society of Automotive Engineers: Warrendale, PA, 2000.

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