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■ The University of Denver's remote sensor for carbon monoxide has been used to perform a study of CO emissions from in-use vehicles during the State of Colorado's 1988–1989 Oxygenated Fuels program. More than 117 000 vehicle exhaust measurements were performed on warm vehicles at two locations in the Denver area, with more than 4900 vehicles identified by make and model year through license plate registration information. The results for the oxygenated fuels period show a statistically significant decrease in average CO emissions of 16 ± 3% at both locations. This decrease is shown to be independent of initial emissions for the dirtiest 25% of the fleet and not significant for the cleanest 75%. The decrease is shown not to be attributable to location, vehicle load, speed, fleet mix, fleet age, or age distribution changes. Less than 10% of the vehicles account for half of the CO emissions. Very few of these (0.3%) are less than 2 model years old, but a sizable fraction (26%) are 1983 model year and newer.

Introduction

The Clean Air Act of 1970 and subsequent amendments resulted in the Environmental Protection Agency establishing ambient air quality standards for several airborne chemical species (*1, 2*). Several cities in Colorado, including Denver, Colorado Springs, Greeley, and Fort Collins, have violated the federal standards for carbon monoxide, the majority of which is produced by automobiles (*3*).

The Colorado Department of Health (CDH) began evaluating CO reduction strategies in 1978. With the 1978–1987 database as the input to the EPA Mobile3 model, a 1988 mobile source CO reduction of 15.3% (in grams per mile units) was predicted for a fleet using 2% oxygenated fuel (*4*). In one of the CDH studies the effects of fuel oxygenation were compared to the effects of an emissions tune-up. The tune-up of only the dirtiest 20% of the vehicles led to more than double the improvement observed from fuel oxygenation.

In the fall of 1987 the State of Colorado enacted Regulation No. 13 mandating the wintertime sale of oxygenated gasoline along the Front Range of Colorado (*5*). The first winter of the program required that all gasoline sold during January and February 1988 have a minimum of 1.5% oxygen by weight. The second year was a 4-month program starting in November 1988 and continuing through February 1989 with the minimum oxygen content increased to 2.0% by weight. This required an 11% by volume methyl-*tert*-butyl ether (MTBE) blend. As in the previous winter, this fuel blend dominated the market with a 94% share of sales (*6*).

At the University of Denver we have designed and constructed a remote sensor that measures the CO/CO_2 ratio by infrared absorption from passing vehicles (*7*). With a knowledge of combustion chemistry, these ratios are converted to exhaust % CO emissions (corrected for excess air and water). The ratios can also be converted to grams of CO per gallon emission measurements.

During the first winter of oxygenated fuel usage, the remote sensing system was used to sample 60 000 tailpipe CO emissions during and after the program at an on-ramp located at the intersection of University Blvd. and Interstate 25 (I-25) (*8*). This paper describes a follow-up study performed during the second year of Colorado's Oxygenated Fuels program and increases the available data from actual "in-use" vehicles on the effectiveness of oxygenated fuels to reduce carbon monoxide emissions. Changes and improvements to the initial study include the following: increased sample rate with the use of an enhanced computer program, monitoring of an additional freeway ramp, additional data collection consistent with the increased program length, and use of a new video system that enables random vehicle samples to be identified, through the Colorado Department of Motor Vehicle Records (DMV), according to make and model year.

Experimental Section

The remote sensor consists of an infrared source located on one side of a roadway across from a detector unit with the spectral regions of interest (CO, CO_2, and a reference) isolated by filters. Span, zero, and data voltages are measured from each vehicle. In previous dynamometer, on-board monitoring, and test-track testing the remote sensor has shown precision and accuracy of better than ±1% CO over the entire range of measurements with no temperature dependence (*7, 8*).

A freezeframe video system was used to record the license plates of vehicles being measured. This system allows a picture of the car undergoing a measurement to be frozen on a video display terminal until the CO emissions have been determined, graphically written on the video picture, and saved to tape. In this way the measurement is permanently assigned to that vehicle. Due to the time required to manually read the plates, it was beyond the scope of this study to videotape every vehicle. Therefore, several time slots were picked to sample randomly the make and model year distributions at the two locations.

The remote sensor directly measures the ratio of CO to CO_2. For most of the results presented here, the ratio is converted to the exhaust % CO. The ratio can also be directly converted to a prediction of the vehicle emissions in grams per gallon of fuel used:

$$\text{g of CO/gal} = 5650(CO/CO_2)/[1 + 1.125(CO/CO_2)] \quad (1)$$

A major advantage of % CO or of grams of CO per gallon readings is that they depend only on the engine and emission systems operating characteristics. Gram per mile emissions (the current Federal standard) also depend on the vehicle transmission gear ratio and speed. The large variability of gram per mile emissions with speed, with an infinite singularity at zero speed, may have given real-time emissions monitoring a bad name. In our studies of individual vehicles on the road and on a dynamometer at moderate loads (*7*), the % CO varied little with speed and load.

During this study General Motors conducted two blind on-road quality control intercomparisons at the Speer Blvd. site. The first was an attempt to produce false high CO readings and the second was to obtain a correlation between the remote sensor and a vehicle of accurately known emissions. These comparisons utilized two specially instrumented cars with heads-up displays, which allowed control of the vehicles engine computer and included on-board exhaust gas monitors to record the % CO and % CO_2 exhaust emissions.

In the first test, a vehicle was driven erratically past the instrument (i.e., hard breaking, accelerating, coasting in neutral while gunning the engine, etc.) in normal traffic with all emission control systems operating normally. The remote sensor never recorded any false high CO readings.

The second car was used to obtain a CO correlation between the instrument and the on-board exhaust analyzers. The car was driven in normal traffic by the instrument 43 times, covering four different air/fuel engine settings. The CO emissions could be set at values ranging from 0 to ~12%. The correlation graph showed an R^2 of 0.93 with a slope of 1 (*9*).

A "case study" approach has been taken in this study since a true control is impossible to obtain because all of the vehicles are required to switch to the oxygenated fuels. A very large number of exhaust measurements at two different locations in the Denver area are compared during and after oxygenated fuel usage. The goal is to quantify the differences, if any, at these specific locations and to ascertain possible reasons for them.

The first site tested was located at the on-ramp to southbound I-25 from southbound University Blvd. in south Denver. The second was located at the off-ramp from southbound I-25 onto southbound Speer Blvd., a major artery from the northwest into the Denver central business district.

The University Blvd. site is the same location monitored in the 1987–1988 study and is characterized by an ~2% uphill gradient on a sharp curve (*8*). A variety of driving modes was observed with speeds averaging 25 mph. The remote sensing system made continuous automated measurements between the hours of 10:00 and 22:00 for the weekdays of October 14, 17–21, and 25, November 28–30, December 1, 2, 5, 6, and 9, 1988, and February 14–17 and 21–24, and April 4–7, 10–14, and 17–21, 1989, in which emissions from 82 389 vehicles were recorded. Freezeframe videotape of vehicles and their emissions were made on February 21 and 22 and April 18 and 19 between the hours of 15:00 and 17:00. During these periods 1936 vehicles were identified by license plates through DMV record matching.

The Speer Blvd. measurement site was on a 4–5% uphill gradient with a sharp curve. Average loads and speeds were higher (~30 mph) than those found at the University site. The Speer ramp is situated such that the vehicles measured have driven a minimum distance of 2 mi of high-speed driving. This ensures that the vehicles being sampled are fully warmed to operating temperature.

Sampling was carried out from 9:00 to 16:00, with the instrument being taken down and returned to the University of Denver at the end of each day. Measurements were made during the weekdays of January 18–20, 23, and 26 and May 4, 5, 8, 10, and 11, 1989, in which emissions from 35 156 vehicles were collected. Videotape of vehicles and their emissions were collected on January 19, 20, and 26 and May 4. During these periods, 2973 vehicles were identified by make and model year.

The instrument operated unattended at University Blvd. except for one to two service visits per day. Service included alignment checks, detector liquid nitrogen replenishment, and gas calibrations from three certified gas cylinders with CO/CO_2 ratios of 1:12.1, 1:1, and 4.96:1 (Scientific Gas Products, Longmont, CO; and Linde, Denver, CO). The results from the calibration gases were fit to a second-order polynomial equation, which was used to correct the data at each site. The operations were attended at Speer Blvd. with calibrations performed twice each day. All of the measurements were collected during dry roadbed conditions.

Table I

% CO category	University Blvd. oxy-fuel Nov/Dec	University Blvd. oxy-fuel Feb	University Blvd. non-oxy April	Speer Blvd. oxy-fuel Jan	Speer Blvd. non-oxy May
<1	14805	15537	23802	11899	12417
1	1476	1561	2777	1494	1731
2	897	949	1783	1029	1288
3	564	616	1232	715	949
4	405	467	811	500	702
5	260	283	552	363	483
6	168	199	399	238	346
7	124	137	269	160	229
8	75	92	187	91	161
9	41	55	111	53	121
10	34	44	67	32	62
11	22	29	32	23	29
12	15	16	23	8	13
13	9	10	4	8	5
14	0	2	1	1	3
≥15	2	3	1	0	3
total vehicles	18 897	20 000	32 051	16 614	18 542
mean % CO	0.82	0.86	0.99	1.09	1.33
SEM	±0.02	±0.02	±0.02	±0.03	±0.02
mean g/gal:	305	315	362	396	480
% vehicles responsible for 50% of CO emissions	7.0	7.0	8.2	8.9	10.2

Results

Some data (11 441 measurements) were collected at the University Blvd. site in October by use of the computer program for the previous study (this program collected 1 s of exhaust plume data from behind each vehicle before analysis began) to corroborate the final reading of the previous winter (1987–1988) measurements. The mean % CO and standard error, determined from a weighted average of the daily means, from the University Blvd. site for October 1988 is 1.16 ± 0.03%. This agrees with the April 1988 measurements of 1.14 ± 0.03% (*8*). Graphical analysis of the exhaust plume data from the previous study revealed that no significant data existed beyond time intervals greater than 0.5 s after the vehicle. Therefore the data collection routine was shortened to 0.5 s, which reduced the total analysis time to ~0.7 s per vehicle.

The use of this new program resulted in roughly a 15% decrease in the apparent average mean % CO value for April. This may be attributed to a more comprehensive sampling of vehicles, especially during periods of closely spaced, often slower moving, congested traffic. The new program also produced a significant increase in the daily number of vehicles measured and a 20% decrease in the variability of the daily mean % CO values. The 1988 comparisons were made with only the 1-s data collection program and in the current study only the 0.5-s program was used.

Table I shows the number of vehicles measured in each % CO category (i.e., 0–0.99%, 1–1.99%, etc.) for each of the measurement periods. The means, standard errors, and the fraction of vehicles responsible for 50% of the CO emissions (which we term gross polluters) are also tabulated. The overall means have been calculated by using a weighted average of the daily means with the weighting factor being the number of vehicles measured. The

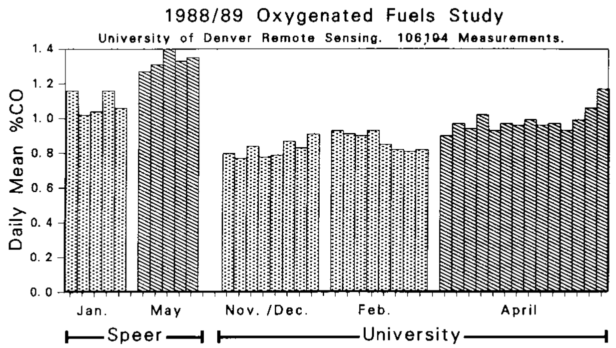

Figure 1. Daily means at Speer and University Boulevards, during (dotted bars) and after (cross-hatched bars) fuel oxygenation. The days for each month are identified in the text. 1% CO is equivalent to emissions of 365 g of CO/gal of fuel.

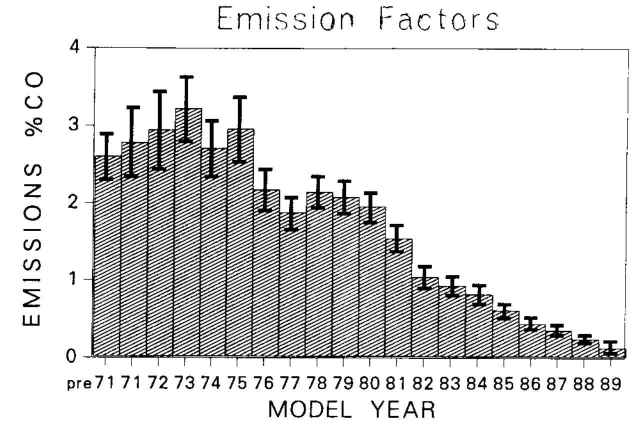

Figure 2. Emission factors by model year for all of the video data from both sites, regardless of fuel oxygenation; 4909 vehicles measured. Error bars are ±1 SEM.

Table II

	no. of vehicles (% of total)		% gross polluters (no. of vehicles)	
age group	University April	Speer Jan	University April	Speer Jan
1983 and newer	743 (72.2)	1195 (59.4)	3.77 (28)	3.43 (41)
1981–1982	104 (10.1)	223 (11.1)	13.46 (14)	9.87 (22)
1975–1980	135 (13.1)	454 (22.6)	28.15 (38)	16.96 (77)
1974 and older	47 (4.6)	139 (6.9)	23.40 (11)	24.46 (34)

standard errors for the means have been calculated by using the variance of the daily means about the overall mean. This method is more conservative than using the standard error of the mean as calculated from the entire distribution. Figure 1 shows the daily means.

Table II gives the distributions by model year obtained from the license registration information for the January data at Speer Blvd., the April data at University Blvd., and the percent of each age group in the gross polluting category (the few vehicles responsible for half of the CO). The age groupings are selected to correspond with emissions control technology (1974 and older, precontrol; 1975–1980, catalyst; 1981–1982, catalyst–closed-loop transition; and 1983 and newer, closed loop and three-way catalyst). Table III summarizes the means and standard error of the means for these distributions. Similar data were obtained for the other measurement periods. Figure 2 shows the average emissions by model year (emission factors) for the 4909 vehicles combined from the two sites. Vehicles registered as trucks made up 17.6% of the fleet at Speer Blvd. and 9.5% of the fleet at University Blvd.

The videotapes were reviewed for accuracy and self-consistency with the emissions database. The proportion of out-of-state registered vehicles, misread tags (by comparing DMV make with the make of the car on the videotape), and DMV misidentification collectively ranged between 2 and 6%. These were removed from the final database.

Discussion

Differences between the overall means at each of the locations were examined by using the Student's *t* test distribution at a significance level of 0.05. The null hypotheses can be rejected for the January to May comparison at Speer Blvd. It can also be rejected for the comparisons at University Blvd. between November/December and April and for February to April. It cannot be rejected (i.e., no significant difference) for the comparison between November/December and February. For this reason these two measurements periods (both collected during fuel oxygenation at University Blvd.) are combined with a resulting mean and standard error of the mean of 0.84 ± 0.01 % CO.

At the University Blvd. site a combined November/December and February mean is 15.2 ± 2% smaller than in April. At Speer Blvd. the measured January mean is 18.0 ± 2.6% smaller than for May. The lower mean % CO emissions found to exist during the oxygenated fuel usage is qualitatively in agreement with the expected goals of the program, which were to reduce carbon monoxide emissions. It was also expected that the 1988–1989 program would reap a larger benefit due to the increasing of the oxygen content to 2.0%. For the University Blvd. location the CO reduction is larger than the previous winter's measured reduction of 6.0 ± 2.5% (*8*).

Figure 3a is a quantile–quantile plot comparing the data collected at Speer Blvd. from before and after fuel oxygenation (*10*). If the two emission distributions had been identical, i.e., showed no effect attributable to fuel oxygenation, the data would have fallen along the 1:1 line. The 18% difference between the two means is shown to be accounted for by the May measurements being consistently higher than the January measurements for all vehicles above a CO emissions of ~1%. The change is constant within experimental error for all vehicles dirtier than 1% CO. The benefit to be attributed to fuel oxygenation cannot be shown to increase with increasing emissions. Figure 3b is a quantile plot of the January measurements from Speer Blvd. illustrating that the percent of vehicles benefiting from the oxygenated fuels (those vehicles having CO emissions above the line at 1%) is only 25%. The remainder of the vehicles show much lower emissions benefits.

These plots illustrate the very skewed nature of the emissions distributions observed. It is important to note that the majority of vehicles are low CO emitters, even

Table III Mean Model Year of Observed Vehicles (±1 SEM)

	University Blvd.				Speer Blvd.		
month	no. of vehicles	mean ± SEM	mean % CO	month	no. of vehicles	mean ± SEM	mean % CO
Feb	907	1983.6 ± 0.1	0.81	Jan	2011	1982.6 ± 0.1	1.04
April	1029	1983.8 ± 0.1	1.01	May	962	1982.8 ± 0.2	1.21

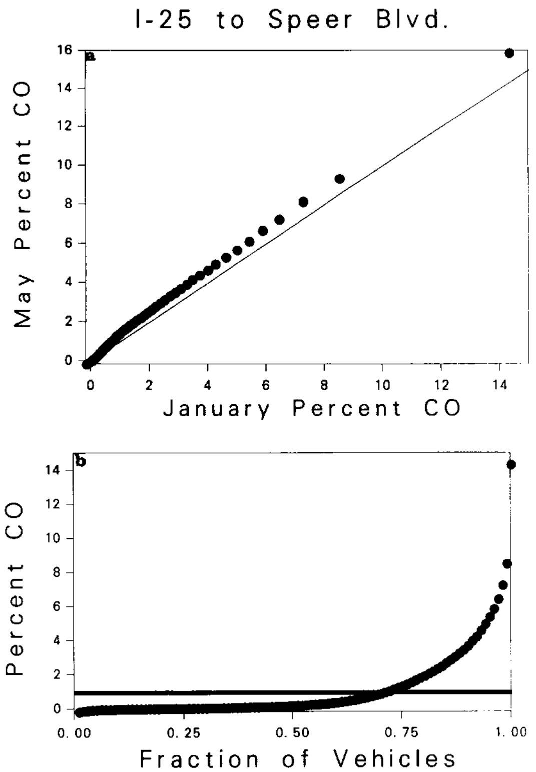

Figure 3. (a) Plot comparing the quantiles of the % CO emissions distribution measured in May (after oxy-fuels) with that observed in January (during). Note that the emissions increase is seen only in vehicles whose initial emissions are above ~1% CO and that the improvement is constant for the dirtier cars. (b) January measurements showing the fraction of vehicles that is above the 1% CO line.

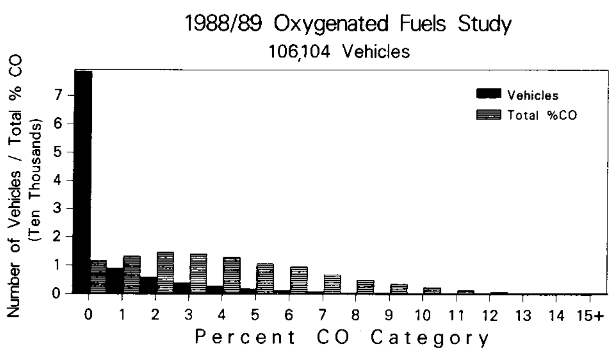

Figure 4. Observed histograms for the total number of vehicles, regardless of fuel oxygenation, and their CO contribution as a function of total % CO. The solid bars represent the number of vehicles in each measured category (i.e., 0–0.99%, 1–1.99%, etc.). The hatched bars represent the sum total of the % CO in each category. The 78 460 vehicles with % CO emissions less than 1% emit almost the same amount of CO as the 9039 vehicles in the 1–1.99% category.

among 1975 and older model years. Figure 4 further emphasizes the preponderance of clean cars. Table I highlighted the fact that between 7 and 10% of the vehicles are responsible for half of the CO emitted at these location, and Table III shows that these gross polluting vehicles occur in all of the age groups.

In-Use Variables. To validate that the observed differences are in fact caused by the change in the oxygen content of the fuels, factors such as location of sampling, fleet age, fleet mix, load, speed, and weather were considered in the study's design.

The two locations studied were chosen to provide different fleet age, vehicle mix (trucks vs cars), driving speeds, and loads. Different mean % CO values were observed at the two locations. The video samples taken at both locations after oxygenated fuel usage (April and May) show that the measured differences can be eliminated if the vehicle age distribution is normalized between the two locations. For example, if the May emission factors observed at Speer Blvd. are used for the fleet age distribution observed in April at the University Blvd. location, then the mean % CO is calculated to be 0.99%, in very good agreement with the measured University Blvd. mean of 1.01%. The fact that model year emission factors can be exchanged between these two sites with comparable results demonstrates their similarity. The lower absolute mean observed at University Blvd. is therefore not the result of similar cars having different average emissions (caused by load, speed, or fewer trucks), but a result of the younger fleet.

One potential source of variability in the measurements concerns the question of consistency in the age distribution of the vehicle fleet during oxygenated fuel usage compared to after. Table III documents that for the video fleets the average age is significantly different for the two locations; however, the average ages do not significantly change from one measurement period to the next at the respective sites. If corrections were made for the observed changes they would be on the order of 1–3%. This supports the conclusion that the CO reductions are attributable to the fuels.

All of the measurements were collected during times when the roads were dry, and during periods when it had been established that the passing vehicles were at normal operating temperatures (*8*). This should eliminate weather as any factor in the comparisons.

Model Comparisons. Remote sensing measurements of % CO have been converted directly to grams of CO per gallon of fuel by eq 1 with the results given in Table I. If the fleet-average fuel economy changed during the use of oxygenated fuels as compared with using the traditional fuels, this would have to be taken into account when comparing these measurements with the grams per mile based improvement published by the CDH.

The Colorado Department of Health reports a survey of available literature data that shows a consistent 1–3% decrease in overall fuel economy for the newest closed loop technology vehicles (*4*). The 1988 report gives direct test results obtained by CDH for MTBE blends at altitude of a 4.3% decrease in overall fuel economy for the newest closed loop technology vehicles (*5*). Overall fleet fuel economy estimates have also been reported in the economic analysis conducted during this year's program as covering a range of −0.22 to +0.28% (*6*). These calculations assumed a fleet mix of 25% closed-loop technology (1981 model year and newer), 41% catalyst equipped (1975–1980 model year), and 34% precontrol (1974 model year and older). These numbers, referenced to CDH, appear to be in error. The percentages are significantly different from the observed vehicle age distribution at either Speer or University Blvds. The new technology cars (1981 and newer used by CDH) are underestimated by a factor of 2 even when compared to the 2-year-old 1987 Motor Vehicle Manufacturers Association national vehicle registration data (*11*). Using the data in Table II for our fleet mix and assuming that all vehicles from 1975 to 1982 are catalyst-only equipped (which is not totally the case; many 1981–1982 vehicles contain closed loop control technology), a weighted average fuel economy correction would be −2.6% at University Blvd. and −2.0% at Speer Blvd. These estimates are made with the fuel economy values reported by CDH in their 1988 report for each technology class (*5*). Since fuel economy changes are estimated from the entire driving cycle, these corrections should serve as upper limits of the changes that might be observed at the particular monitoring site. In view of the fact that the 11% MTBE fuel contains ~2% less energy, we chose to correct the CDH grams per mile estimate by a 2% fuel effect. This increases the CDH estimate of the oxy-fuels benefit (in g of CO/gal) to 17.3%. A vehicle-weighted average of our data shows a 16 ± 3% difference, in very reasonable agreement.

Several inconsistencies exist between the current model used by EPA and CDH (Mobile3 at that time, now Mobile4) and these data. The first is the model assumes that vehicles at increasingly higher initial CO emissions will show a constant fractional benefit from the fuel blends. Data given in Figure 3a suggest a constant absolute improvement over the entire range of emissions above ~1% CO. Application of chemical thermodynamics to the combustion equations predicts this observed effect and shows that the EPA constant fraction model cannot be correct for the dirtiest vehicles. A second model assumption is that average vehicle emissions continue to increase with increasing age, and that vehicles produced before 1983 have much higher rates of deterioration than do 1983 and newer vehicles. On the basis of such models, one can predict that by 1993 emissions will decrease to the point that many areas of the nation will be in compliance with CO standards. If, by contrast, our data are more represntative and vehicle CO emissions increase linearly for the first 10 years as a vehicle ages and then are constant, there will be no further improvement in fleet average CO emissions unless the average age of the fleet decreases. It should be pointed out that the increase in average model year emissions with age is dominated by the change in the percentage of gross polluters in the 1983 and newer vehicles (3–4%) to a larger fraction (23–25%) in the 1974 and older model years (see Table II) and is not from an increase in the median vehicle emissions. Also, the model is based on measurements that cover an entire driving cycle, while these data only address a limited driving mode.

Finally, if we approximate the mean winter emissions at Speer Blvd. to 400 g of CO/gal and multiply by 3 million gal/day, the approximate Denver winter fuel use, we obtain a basinwide average CO emissions of 1200 tons/day. This number is close to the CDH predictions for Denver using their modeling approach (*4*). This calculation is not meant to imply that all vehicles in Denver behave in the same way as the limited sample we observed at Speer Blvd., but rather that the sample we observed is not unrepresentative of the basinwide emissions, particularly when the emissions are measured in grams per gallon, and the extrapolation is carried out via fuel sales statistics.

Conclusions

(1) Over 117 000 vehicle CO emissions were measured. More than 106 000 vehicle emissions were used in the oxy-fuel comparisons. Several of the findings duplicate the previous winter's results (*8*).

(2) Half of the CO emissions were produced by 7.0–10.2% of the vehicles, depending on location and measurement period.

(3) More than 70% of the vehicles were measured at less than 1% CO.

(4) A combined 16 ± 3% reduction in average % CO from warm vehicles was observed from during to after the oxygenated fuel program. This is similar to Colorado Department of Health model predictions corrected for lost fuel economy. This improvement was irrespective of location and fleet changes.

(5) This difference was dominated by measurable reductions in only 25% of the vehicle fleet whose emissions were above ~1% CO.

(6) Limited video data on make/model year show that agreement with the Colorado Department of Health model may be somewhat fortuitous, and that model predictions of future compliance arising from fleet turnover alone may not be correct.

Acknowledgments

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