Find and fix the polluters

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Fewer than 10% of the cars on the road produce half the CO exhaust emissions. Only fixing these cars can contribute to major reductions through any pollution control strategy. The oxygenated fuel programs that have already been mandated force everyone to pay in the form of higher fuel costs and, for most vehicles, reduced mileage.

We believe that a targeted repair program can achieve a greater improvement in air quality at much less cost than any oxy-fuels program. The cost estimates of oxy-fuels programs vary from $500 to $1500 per ton (t) of reduced CO emissions. These are direct costs to the driving public. We estimate the costs of a targeted repair program at $110/t.

Targeted repair programs can be merged with existing Inspection and Maintenance (I/M) programs. To do this requires that the gross polluters, who are responsible for most of the problem, be identified. We have developed a technique that will do just that.

With support from the Colorado Office of Energy Conservation, the University of Denver has developed a

The basics

A fuel-efficient automobile will burn most carbon to CO_2. Only the small, equilibrium amount of CO or hydrocarbon will appear in the exhaust plume. Because the carbon can only come from the gasoline, a measure of the engine's combustion efficiency can be determined from the ratio of CO or HC to CO_2 in the exhaust. Using the fundamentals of combustion chemistry, many of the parameters of the vehicle emission system can be accurately determined from these ratios, including the instantaneous air/fuel ratio, the gram/gallon emissions, and the percentage of CO that would be measured by a tailpipe probe. All our data in this paper are presented as grams CO per gallon (g/gal) of gasoline burned. The EPA units of grams of CO per mile traveled require a knowledge of miles per gallon, which varies with the individual car and is mostly dependent on vehicle weight. For CO inventory calculations total gasoline consumption is far more readily obtainable than total miles driven. The details are described elsewhere *(1–3)*.

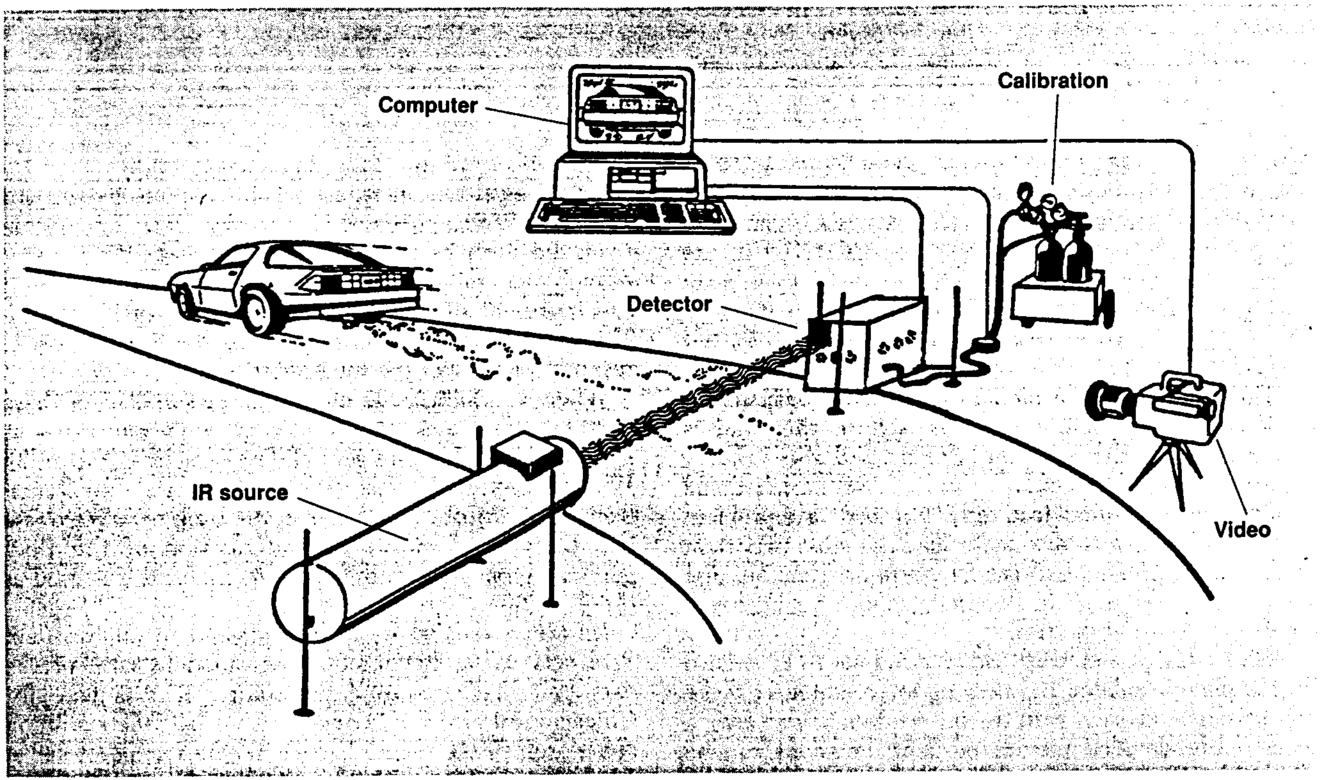

***Figure 1.* The University of Denver FEAT remote sensor.** Infrared rays from the source pass through the vehicle exhaust plume and detectors measure the light absorbed by exhaust components. The computer calculates pollutant concentration ratios and stores this along with a video image of the vehicle license plate.

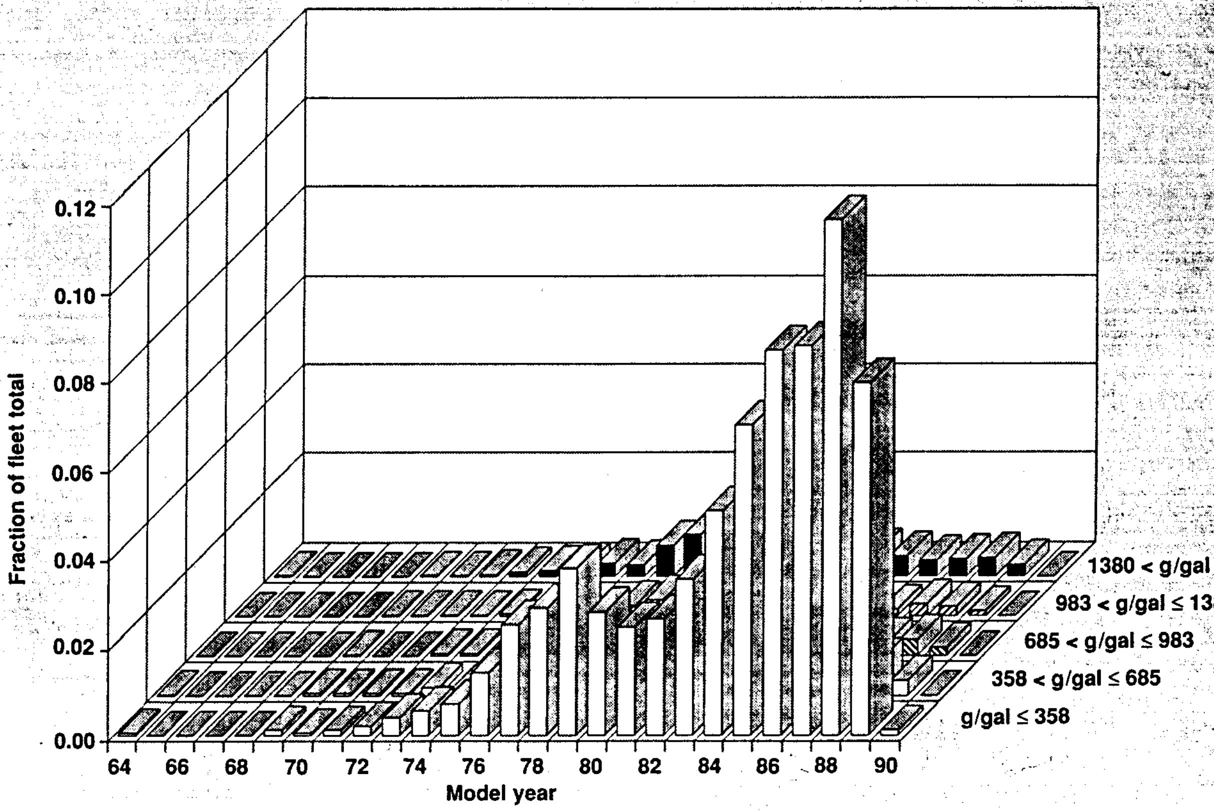

Figure 2. **Emission measurements from 11,818 vehicles on one on-ramp in Chicago on five consecutive days.** This graph represents the measured fraction of vehicles by model year within each CO emissions category. Model year 64 represents the total of all vehicles from 1964 and older, back to 1934.

remote monitoring system for vehicular exhaust emissions (Figure 1). The basic instrument measures the carbon monoxide to carbon dioxide ratio (CO/CO_2) and the hydrocarbon to carbon dioxide ratio (HC/CO_2) in the exhaust of any vehicle passing through an IR light beam directed across a single lane of roadway. This is the Fuel Efficiency Automobile Test (FEAT) that we used for our work.

FEAT readings are a random half-second snapshot of loaded-mode vehicle emissions, where the load is determined by the site, the driver, and the vehicle. Conventional I/M programs typically involve a scheduled (annual or biennial) no-load test. "No-load" is a problem because vehicle emissions under load are most important to air quality. "Scheduled" is a far worse problem because a scheduled test is an invitation to innovative ingenuity applied to "passing the test."

FEAT was joined with video equipment to record license plate numbers. By merging information from the motor vehicle division with the on-road emissions data, a much more detailed picture of fleet emissions can be obtained. When emissions data are broken down by model year, a clear picture of fleet characteristics emerges. Figure 2 shows the distribution of 11,818 cars by model year in the 1989 Illinois study (*4*).

Each model year in Figure 2 is broken into five groups in order of CO emissions. Graphically, as well as on the road, the sheer number of clean cars masks the number of high CO emitters. The dirty black bars in the farthest row represent all vehicles emitting more than 1380 g/gal. This group represents only 8.2% of the fleet, but it is responsible for half the total emissions.

When we multiply the number of cars in each of these bars by the mean g/gal value of their emissions as measured by FEAT, we get a different picture (Figure 3). What immediately jumps out is the black wall of pollution from the 8.2% of the vehicles in the back row. We chose the 1380 g/gal cutoff as that portion of the fleet generating one-half of the total emissions; this is used as the definition of gross polluters.

In every fleet we've measured, and in all the fleet data sets we've examined, approximately 10% of the cars emit half the total pollutants. This is true for Chicago and also for Denver, where half the pollution came from 9.1% of the cars, with the cut point set at 1240. In our high-altitude uphill study on Colorado's Ute Pass, half the pollution came from 14% of the cars, with a cut point at 1480 g/gal. The cleaner the fleet

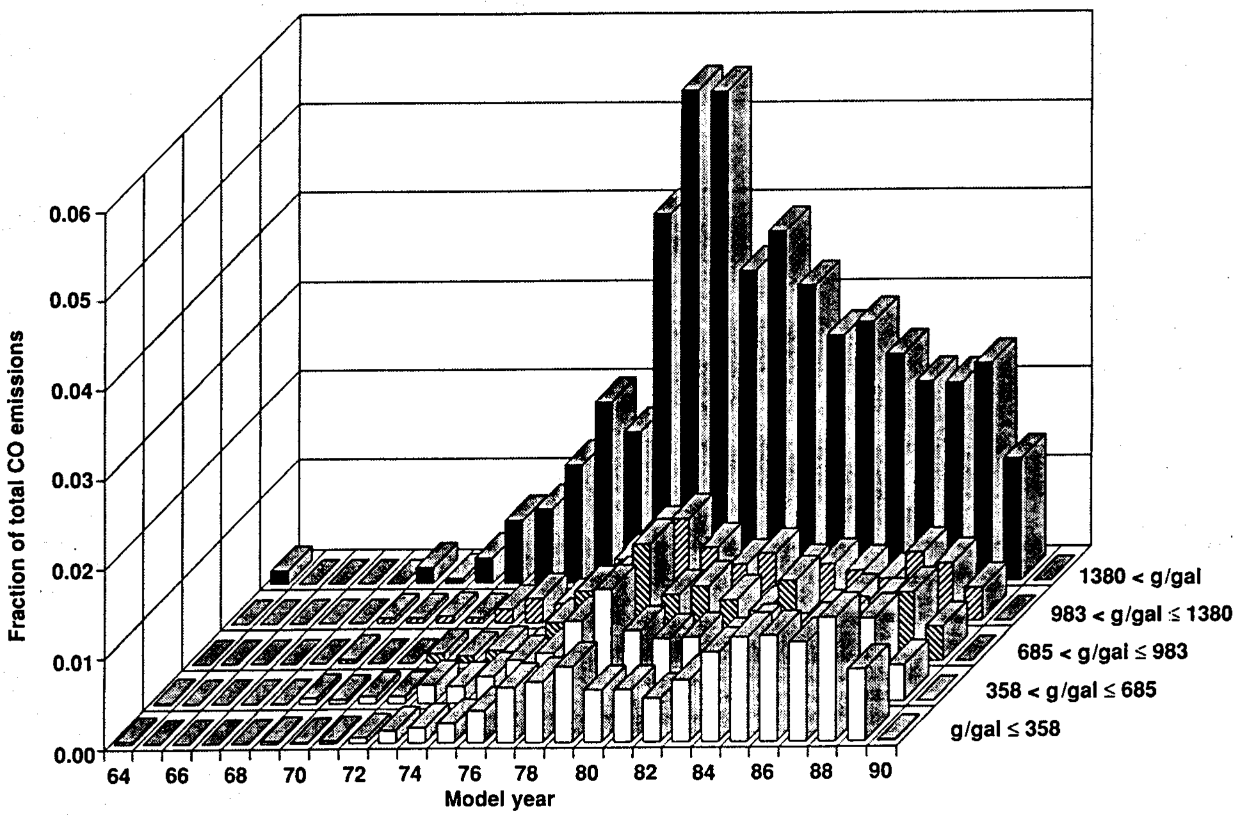

***Figure 3.* The CO emissions from the 11,818-vehicle Chicago fleet.** This is derived by multiplying the count in each bar by its mean emissions. One-half of the total fleet emissions are represented by the 9.1% of the vehicles with exhaust emissions greater than 1380 g/gal.

overall, the smaller the percentage of gross polluters, with the oldest cars not being a factor owing to their small numbers.

There is a non-trivial contribution from current model year cars, i.e., 1989 cars measured in 1989. Because the Chicago study was set up at an on-ramp to an interstate highway, some of these new-car gross polluters may be operating under hard acceleration in an off-cycle mode. The term off-cycle is used because the Federal Test Protocol (FTP) cycle used to certify a new vehicle does not include hard acceleration in its required dynamometer cycle. In this off-cycle mode, data from the exhaust sensors is disregarded by the on-board computer. Excess fuel is supplied to the engine for maximum power. However, it should be noted that the pollution from these new cars is more than the emissions from all the 1972 and older cars put together.

Is the analysis reasonable?

Are these gross polluters just "outliers" in the data? If you assume a Gaussian distribution, less than one-tenth of 1% of the values will exceed the mean ± 3.06 times the standard deviation. In the databases the EPA uses (OXY_EF_1 and OXY_EF_2) outliers are clearly marked and eliminated from all calculations. However, this treatment of data is wrong because the underlying population does not have a Gaussian or normal distribution, but has instead a gamma distribution because the largest group of cars will be very clean. There is, therefore, a significant probability that super-gross emitters exist. Gamma distributions are fully defined in statistics texts. They arise typically in populations subject to random mortality. A gamma distribution often looks like a normal distribution except that the tail only decreases exponentially.

Let's use the Chicago data as an example. The median of the Chicago database is 82 g/gal. Most of the cars are very low emitters. The fleet mean g/gal is 416; the standard deviation is 722. This gives us a mean plus three standard deviations of 2120 g/gal. Vehicles emitting >2120 g/gal are labeled as outliers, and there should be no more than about 11 of them if we had a normal distribution. In the Chicago fleet there were 258 of these super-gross polluters. They represented 2.2% of the fleet and contributed 20% of the pollution.

This picture is not unique to remote sensing data derived from CO/CO_2 measurements. The fleet emissions from FTP weighted grams per mile also show

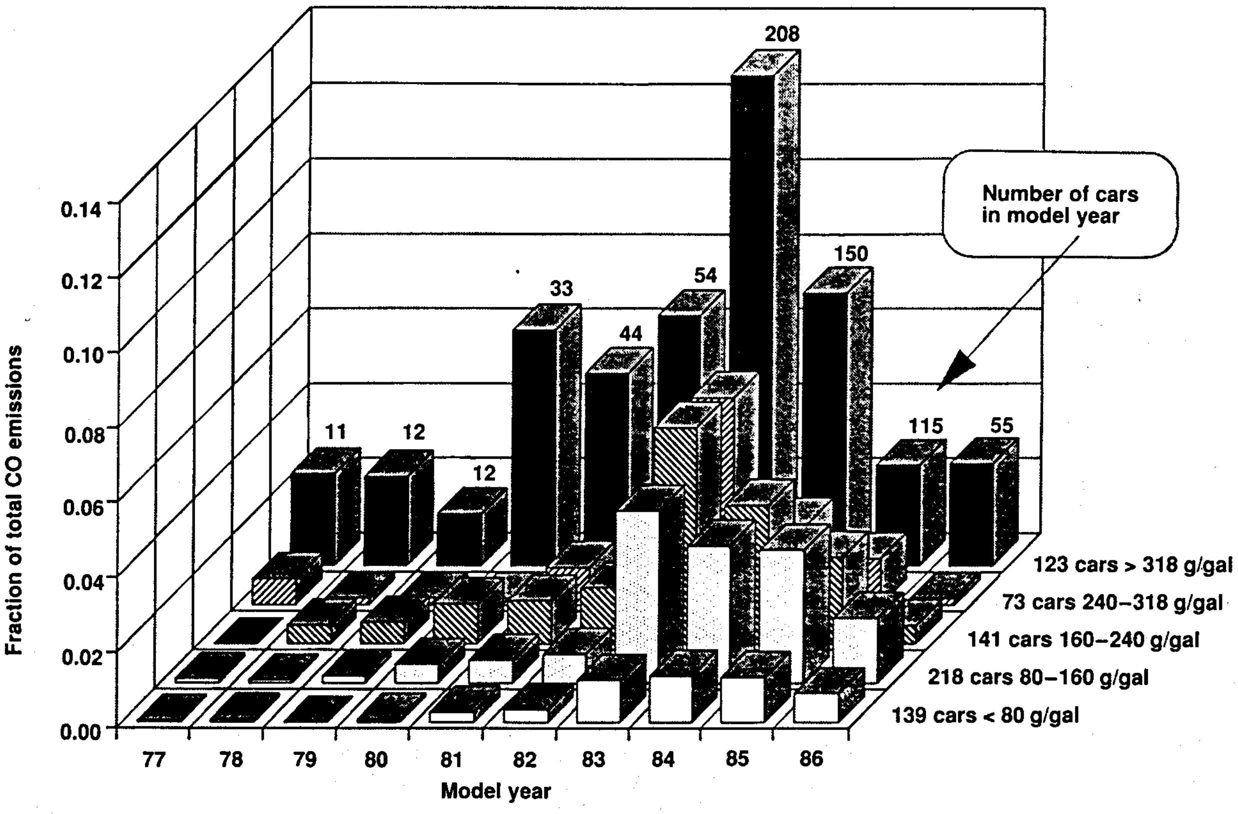

***Figure 4.* CO emissions from the CARB volunteer fleet tested as Project 9 in 1987.** This limited, very clean fleet shows the same general traits as road fleets. Half the emissions come from a small percentage of the vehicles. Most cars, even in the oldest category, are clean. A significant contribution comes from a very few cars in the newest model year.

that most cars are clean, with a few dirty cars contributing most of the emissions. California Air Resources Board (CARB) has conducted a series of FTP tests over a period of years. The ninth study, the largest (although only 694 cars), and most recent, was undertaken in 1987. Even though CARB acknowledged that they have difficulty recruiting really dirty cars, this Project 9 fleet (Figure 4) shows the same basic characteristics as the Chicago fleet. For the fleet, 50% of the emissions come from less than 18% of the vehicles. The black wall looms in the background.

There are some differences in Figures 3 and 4 that can be explained. The Project 9 fleet was a volunteer fleet from a random sample solicited by mail. The 10 model years and the number of cars in them were predetermined by CARB. Less than 1% of these cars would be gross polluters by Chicago standards and even fewer emission systems show signs of tampering. This is a very clean fleet, averaging only 233 g/gal compared with 416 g/gal in Chicago, but even so, the four dirty 1986 cars contribute half as many emissions as the 138 clean cars in all model years.

The high-emitting vehicles in the CARB study were diagnosed and repairs were made if possible. Repair work was done on 449 of the 694 vehicles, reducing total fleet emissions by 17%. However, more than 70% of the reduction came from repairing the 44 highest-emitting vehicles, those that would have met the FEAT criteria of contributing half the total emissions. Even in a fleet this clean, with mean g/gal less than 300, significant reduction in total fleet emissions can be achieved by repair of only 6% of the vehicles.

In order to control pollution, it is the black wall in figures 3 and 4 that must be singled out for attack. And it can be done. Video-linked remote sensing devices such as FEAT will identify these gross polluters. Currently, government-mandated Inspection and Maintenance (I/M) programs are supposed to do this, but from the measured picture of the Chicago on-road fleet, it is apparent that the Illinois centralized I/M program does not work as planned. In conjunction with a FEAT-type identification program, immediate I/M action could be required between licensing periods and the number of gross polluters reduced.

If half the gross polluters can be identified and repaired to the mean value of their model year, fleetwide emissions could be reduced by nearly 25%. The actual figure could be higher because high-mileage gross polluters are the most likely to be identified.

How would it work?

How would such a program work, how much would it cost, and what reduction in emissions could reasonably be expected? We will make certain assumptions in the proposed program. The principal objective is the reduction of CO emissions levels. This objective should be achieved with the least cost and inconvenience to owners and operators of clean vehicles. The program should be designed to minimize the burden on low-income car owners.

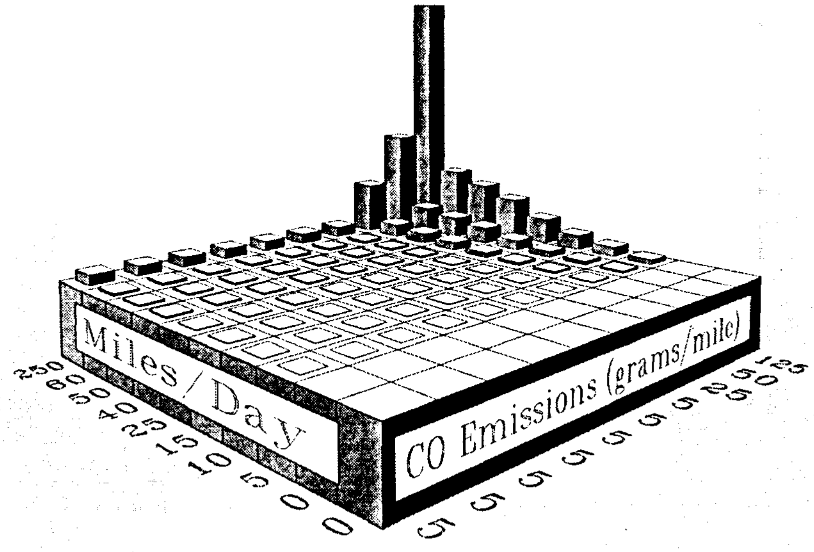

Figure 5. **Hypothetical fleet showing the effect of combining the measured emissions distribution with a realistically skewed miles-driven distribution.** A single high-mileage gross polluting vehicle could contribute 30% of the total emissions although it is only 1% of a 100-car fleet.

FEAT would identify the gross polluters. Incorrect identification of vehicles as gross polluters, when in fact they are cold or off-cycle, can be avoided by requiring multiple high measurements at different locations before any action is taken. Each collection site would have its own statistical determination of a gross polluter so as to eliminate unjust comparison between sites with greatly different driving conditions. An uphill grade would not have the same cut-off point as a level street. High off-cycle emissions could be avoided either by proper selection of sites where hard acceleration is unlikely, or by measurement of vehicle speed and acceleration.

In the Chicago fleet 641 cars were identified four or more times. Nine percent of these cars exceeded the cut point of 1380 g/gal two or more times. These cars accounted for 48% of total emissions from the 641 vehicles.

Even a grossly polluting car will not contribute to air pollution if it is not driven. Conversely, high-mileage gross polluters are the most significant targets and also the most likely to be multiply identified by FEAT. A thought experiment combining the effects of emissions distribution and mileage distribution (Figure 5) shows that it is possible for 1% of the fleet to be responsible for 30% of the total emissions, if the culprit vehicles are on the road much of the time. Such a vehicle would be measured by FEAT and would be among the first identified.

Once identified, the owner of the gross polluter would be notified by mail that repair or maintenance of the emissions system is required. To encourage immediate remedial action this notification could include a certificate equal to one-half the cost of repairs up to a specified dollar amount such as $100. Some provision would have to be made for those vehicles that reappear as multiple gross polluters after they have been certified as repaired, and referee repair and diagnosis sites should be established. Lemon laws could be applied to newly sold polluting vehicles. Only as a last resort should waivers be allowed. Legislators might declare the $100 incentive certificate to be invalid if the owner has tampered with the vehicle emissions system.

The costs of such a program are necessarily all estimates, but in the interests of fairness, we are using high estimates. It would cost $14.3 million to add FEAT sensing to an existing I/M program.

If half of the gross polluters can be identified and repaired to their model year mean, more than 25% of total fleet emissions can be eliminated. Using the Colorado Department of Health 1989 fleet average estimate of 55 grams/mile (6), the total CO emissions for the 21 billion miles driven in metro Denver each year is 1.2 million tons. Even if only half of the expected elimination occurs, that would mean a

How we calculated the costs of a Fuel Efficiency Automobile Test (FEAT) program

One FEAT sensor costing $75,000 can make 500,000 measurements per year. The operator and accompanying administrative pyramid will require 1.5 full-time-equivalent (FTE) personnel. The Colorado Department of Highways uses $60,000 per FTE *(5)*; we'll use $100,000 per FTE. The University of Denver currently pays about $0.03 for reading license data from the video screen and transferring them to the database. Using $0.10, the cost of reading 50,000 gross pollution records is $5,000. Only 10% of the valid measurements exceed the cut point; the other 90% are collected without video records for statistical analysis only. If more than one high reading is required, not more than 25,000 notifications will be generated. At $10.00 per notification and record keeping, this is an additional $250,000. The total cost per FEAT sensor is then $480,000 per year.

Denver has about 1.8 million cars in the metropolitan area. If a representative sample requires three times as many readings as vehicles, 5.4 million readings are needed. For Denver that is about 11 FEAT sensors for a total cost of $5.3 million. Assuming half of the polluting cars are identified, 5% of 1.8 million, and the maximum allowed $100 is spent on every notification, up to $9 million could be spent on repair. The cost of FEAT enhancement to an I/M program is less than $14.3 million.

Table 1. Cost estimates of existing oxygenated fuels programs (4)

Location	Season duration	Cost estimates, $ million/yr	Tons CO reduced	Effectiveness, $/ton
Arizona[a]				
Phoenix	10/01/89–03/30/90	29.5–37.8	21,485	1,372–1,760
Tucson[b]	10/01/90–03/30/91	3.2–9.1	5,392	603–1,693
Colorado[c]				
Denver	01/01/88–02/29/88	0.0–1.0–3.6	6,560–9,020	0–130–143
	11/01/88–02/28/89[d]	0.0–8.6–21.9	19,440	0–444–1,126
	11/01/89–02/28/90	3.9–8.2–19.3	19,440	198–423–992
Nevada[e]				
Las Vegas	11/01/89–02/15/90	5.6	7,350	766
New Mexico				
Albuquerque	12/01/89–02/15/90	0.6	3,905	160

[a] Arizona costs reflect only those incurred by state residents. [b] Tucson 1990–1991 data are projected. [c] Colorado costs are low-central-high original estimates. [d] Colorado 1988–1989 estimate revised from 0 to 5.1 to 16.7. [e] Nevada data are Milliken estimates.

reduction of 150,000 tons of CO, for a cost per ton of less than $100.

Oxyfuels are expensive

The per-ton costs of an oxy-fuels program are enormous to the owner of a properly functioning automobile. A clean car emitting less than 5 grams CO per mile will pay more than $2000/t for any CO emissions reduction. A gross polluter, one of the 10% emitting 200 g/mi, may pay less than $50/t for his cleanup. The gross polluter is the problem. In an oxy-fuels program everyone pays to clean up a few gross polluters.

The use of oxygenated fuels to control CO emissions from motor vehicles is one of the hottest projects of many state environmental agencies today. The 1990 Clean Air Act Amendments require the adoption of an oxy-fuels program for non-attainment areas. Colorado has the oldest oxy-fuels program in the western states, in effect since the winter season of 1987–88 and extended to continue for this winter. In 1989 Arizona, Nevada, and New Mexico initiated oxy-fuels programs.

How much does an oxy-fuels program cost? That question appears to have many answers (Table 1). The original low estimate for the Colorado 1987–88 program was nothing: $0.00 (5). The central estimate was $5.1 million. The central estimate in retrospect was revised a year later to $8.6 million by the same consultant. The Colorado Department of Health estimate spans from $198/t to $992/t. Other estimates run from a low of $160/t in Albuquerque to a high of $1760/t in Phoenix.

The major cost of an oxy-fuels program is the increased cost of fuel to the driving public. The estimates range from $0.00 in the RCG Hagler Bailly report (7) to $0.08 in Phoenix, where the oxygenated fuels are splash blended. Energy Analysts International, Inc. (8) suggests a reasonable current cost increase for Colorado fuels at $0.032 per gallon for 2% oxygenated fuel using methyl *t*-butyl ether (MTBE) (Table 2). This cost is predicted to rise to $0.073 per gallon for 2.6% MTBE oxy-fuel in 1991. The total is more than $30 million each winter to the Denver area driving public. (The state agencies would prefer to say only $5.00 per person statewide!)

The second major factor considered by every study is the loss of gas mileage. Oxy-fuels contain less energy value per unit mass. In general, each 1% oxygen content is a 1% loss in energy according to the theoretical models (*8*). On this basis most early mathematical models predicted about a 2% loss in fuel economy for 15% MTBE fuel. The tests that the EPA has run suggest that the fleet average decrease in mileage will be a bit less

Who does the accounting?

A large uncertainty in the agency estimates is the accounting stance chosen by the commissioning agency. This is a deliberate choice of exactly what is to be considered as a cost. And there are some interesting decisions made when making that determination.

In Arizona the cost of the program is reduced by 31% because 31% of the wintertime drivers are out-of-staters. Only 69% of the program costs accrue to Arizonans.

None of the agencies consider the full cost of U.S. Government subsidies for alcohol in gasohol. This money is transferred from the Highway Users Trust Fund and appears only as less money available for interstate highway maintenance. Gasohol subsidies in Arizona paid to distillers in Kansas appear as potholes in Ohio.

It has been suggested that Colorado prorate a portion of the gasohol subsidy based on its population, about 1% of the U.S. total. This accounting stance would be incorrect. Whatever the accounting stance chosen, the total cost to all 50 states caused by some adopting oxy-fuels programs must be the sum of the estimates of each state's cost.

***Table* 2. Cost increase for oxygenated fuel**

Oxygen content, wt%	Incremental gasoline costs, ¢/gal	Total costs (program), million $
1989		
2.0	3.21	14
2.6	5.06	22
3.0	5.81	25
1990–91 Projected		
2.0	5.66	24
2.6	7.36	32
3.0	8.46	37

Projected increase in fuel cost for an 80,000 BPD oxygenated fuels program utilizing MTBE as additive. Data from Milliken report.

than 2%; however, the mileage for clean cars will degrade more than that for dirty cars.

Other costs of an oxy-fuels program are considered as "unable to be documented," or simply ignored. Accelerated fuel system parts deterioration falls in the first category. This is not well documented because there has been no systematic attempt to document it. Colorado has printed public information brochures and hired gasoline sample collectors, and regularly analyzes gasoline for oxygen content during its program periods. For accounting purposes they originally claimed no administrative costs, because permanent staff administer the program and the costs are not directly applicable to the oxy-fuels program (*8*). A small minority of individuals report strong allergic reactions to MTBE. No one knows if there are health costs related to long-term exposure to low-level increases in aldehydes from oxy-fuels.

The results

Using the most optimistic of estimates, an oxy-fuels program will cost twice as much as a FEAT-enhanced I/M program. Most likely there is an order-of-magnitude difference in costs. More importantly there is a practical upper limit to both of the programs that favors the FEAT approach. The limit for oxyfuels is 12% as measured in the University of Denver study of more than 100,000 vehicles (*4*). Three to four times that reduction is achievable with a FEAT enhanced I/M program.

As currently implemented, the effectiveness of oxy-fuels programs is estimated by computer modeling; little real data exist. Any FEAT-based program would be able to monitor its own efficacy. To the extent that gross polluters are identified and corrective actions taken, the fleet emission characteristics would change and be measured. We would know how well the system was working and what changes were needed.

A program that identified the polluters and forced them to "clean up their act" would put the burden for action on those that were actually doing the polluting, not on those running properly tuned vehicles as cleanly as possible. FEAT, combined with an inspection and maintenance program, is one way to do just that.

Acknowledgments

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