Measuring the Emissions of Passing Cars

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Introduction

This Account discusses pollutants in motor vehicle exhaust and their measurement by means or on-road remote sensing, the results, and their policy implications. Pollutants found in car exhaust are formed in a number of different ways, depending on the pollutant. Fuel and air stoichiometry, heat transfer, fluid flow, thermodynamics, and kinetics all play a role.[1]

Hydrocarbons

A fly screen lowered into a candle flame extinguishes it above the screen although fuel and air are present. Taking the heat away puts the flame out. Likewise, the cold walls of the cylinder in a car engine extinguish the flame in a layer (the quench layer) within 1 mm of the walls. For this reason, a car engine is bound to emit some unburned fuel in its exhaust. There is also partially burned fuel, such that auto exhaust actually comprises a complex mixture. Typical capillary GC analyses show more than 300 peaks.[2]

Carbon Monoxide (CO)

CO formation depends mainly on air/fuel (A/F) stoichiometry. Fuel contains about two hydrogens for every carbon. Air is approximately one oxygen and four nitrogens. The majority of exhaust is therefore nitrogen, and the chemistry of a properly operating (stoichiometric) car is

$$CH_2 + 1.5(O_2 + 4N_2) \rightarrow CO_2 + H_2O + 6N_2$$

Not counting water, one-seventh of the exhaust (14%) by volume is carbon dioxide (CO_2), the rest nitrogen. Modern cars (since 1980) have a computer system and zirconia-based electrochemical oxygen sensor which, when hot, carefully measures a small excess of oxygen in the exhaust and meters the fuel in a feedback system so as to maintain close to exact stoichiometry.[3] The extra hydrocarbon caused by the cold walls in the engine is burned on the hot catalyst by the small excess of oxygen.

When a vehicle is operating exactly at stoichiometry, 14.7 lb of air is used to burn 1 lb of fuel. Thus, when you fill your car up with 50 lb (about 8 gal) of gasoline, this enables your car to process almost 750 lb of air.

If the car's computer and oxygen sensor feedback loop system are not working, then there may be too much air (fuel lean), or too little (fuel rich). Lean mixtures often cause misfiring, hesitation, "coughing", and thus poor fuel economy and poor performance. With rich mixtures, the car performs well except for loss of fuel economy and higher emissions. Vehicles in which the feedback loop system is broken, but there is still control of the fuel metering, are often programmed to default intentionally to rich mixtures. Suppose somehow 33% less air gets to the engine. The $1.5(O_2 + 4N_2)$ becomes just $O_2 + 4N_2$. The combustion equation then becomes

$$CH_2 + O_2 + 4N_2 \rightarrow CO + H_2O + 4N_2$$

All the carbon dioxide is gone and has been replaced by 20% CO. Most cars cannot run that rich, but notice how a relatively small deficit in air (or excess of fuel) leads to an infinite increase in CO. Even 10% CO is enough to kill someone breathing it in a few minutes. Another reaction, the "water gas shift" equilibrium

$$CO + H_2O \Leftrightarrow H_2 + CO_2$$

causes some hydrogen to be present in the exhaust too. For this reason automobiles are a major source of hydrogen to the atmosphere.

Nitric Oxide (NO)

NO contributes to photochemical smog/ozone when mixed with hydrocarbons and subjected to sunlight.[4] NO is formed mostly under heavy load, when the engine is running a little lean and when the catalyst and other NO control measures are not operating. The details of NO formation are complex,[1] but an overall picture can be obtained from a consideration of the thermodynamics of a heated mixture of N_2 and O_2 (for instance air).

$$N_2 + O_2 \Leftrightarrow 2NO$$

The reaction as written is very endothermic; however, at high temperatures entropy is the main driving force. The reason cars emit more NO under load than when coasting is that under load their manifold

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(1) Heywood, J. B. *Internal Combustion Engine Fundamentals*; McGraw-Hill: New York, 1988.
(2) Schuetzle, D.; Jensen, T. E.; Nagy, D.; Prostak, A.; Hochhauser, A. *Anal. Chem.* **1991** *63*, 1149−1159.
(3) Wiedenmann, H. M.; Hotzel, G.; Neumann, H.; Riegel, J.; Weyl, H. Exhaust Gas Sensors. Chapter 6 of Sensors and Actuators. In *Automotive Electronics Handbook*; Jurgen, R., Ed.; McGraw Hill: New York, 1994; Chapter 6.
(4) Finlayson-Pitts, B. J.; Pitts, J. N. *Atmospheric Chemistry*; John Wiley and Sons: New York, 1986; pp 2−64.

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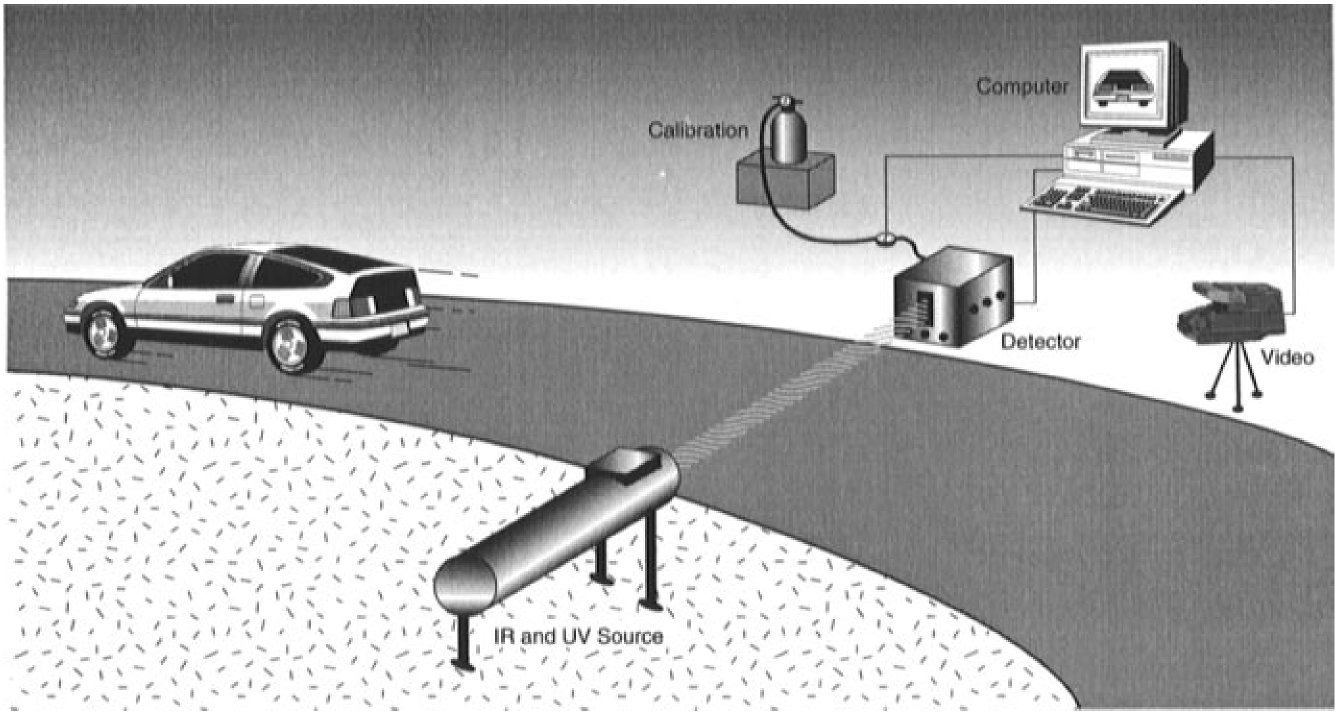

Figure 1. Typical layout of a remote sensing instrument observing vehicles across a single lane of traffic.

pressure is highest. The maximum possible adiabatic and exothermic temperature increase is called upon from every cylinder. The reason that cars running rich do not emit much NO even under load is that there is no excess oxygen for NO creation.

The Desire To Measure On-Road Emissions

By the mid-1980s it had become apparent that there was a discrepancy between the emissions standards to which motor vehicles were certified and the actual reductions seen by the network of ambient air monitors. New car CO emissions, for instance, had been decreased by 96% while ambient concentrations had gone down by perhaps a factor of 2. We also noticed that regulators were beginning to consider programs to reduce automobile emissions which had the potential to be both expensive and ineffective.[5−7] These factors, and the challenge of building novel methods to detect air pollutants wherever they are formed, caused us to propose the exhaust remote sensing system to the Colorado Office of Energy Conservation, arguing that decreased CO emission is well correlated with improved fuel economy. Significant improvements in fuel economy do result if rich-burning (high CO emissions) or misfiring (high HC emissions) vehicles are tuned to a more stoichiometric and more efficient A/F ratio. In one study[8] we showed that fuel economy improvements alone would pay for the cost of repairs to on-road gross polluters in under two years of typical driving.

The Remote Sensing System[9]

Figure 1 shows a diagram of the current system which measures CO, CO_2, HC, NO, and smoke opacity set up along a single lane of road. The IR source is a silicon carbide element powered by 110 V ac, available as the igniter for a gas clothes dryer. The make and model year of the vehicle are identified from the video picture.

Theory

The FEAT (Fuel Efficiency Automobile Test) instrument was designed to emulate the results one would obtain using a conventional nondispersive infrared (NDIR) exhaust gas analyzer. Thus, FEAT is also based on NDIR (NDUV for NO). An interference filter that transmits IR light of a wavelength known to be absorbed by the molecule of interest is placed in front of a cooled PbSe detector. Absorption of light produces a reduction in the detector's voltage output. Because the effective plume path length and amount of plume seen depend on turbulence and wind, one can only determine ratios of CO, HC, or NO to CO_2. These ratios, Q for CO/CO_2, Q' for HC/CO_2, and Q'' for NO/CO_2 are constant for a given exhaust plume. By themselves, Q and Q' are useful parameters with which to describe the combustion system. When the combustion equations are solved, as shown earlier, but using a more accurate formula for air, many components of the vehicle operating characteristics can be determined including the instantaneous air/fuel ratio and the % CO,% HC, and % NO which would be read by a tailpipe probe,

(5) National Academy of Sciences. *Rethinking the Ozone Problem in Urban and Regional Air Pollution*; National Academy Press: Washington, DC, 1991.
(6) Calvert, J. G.; Heywood, J. B.; Sawyer, R. F.; Seinfeld, J. H. *Science* **1993**, *261*, 37−41.
(7) Krupenick, A. J.; Portney, P. R. *Science* **1991**, *252*, 522−528. These authors carried out a cost/benefit assessment of the 1990 Clean Air Act Amendments and found that the costs exceed the benefits even when the EPA MOBILE computer model is used to estimate the benefits.
(8) Bishop, G. A.; Stedman, D. H.; Peterson, J. E.; Hosick, T. J.; Guenther, P. L. *J. Air Waste Manage.* **1993**, *43*, 2−8.
(9) Stedman, D. H.; Bishop, G. A. U.S. Patent No. 5,210,702, May 11, 1993, U.S. Patent No. 5,319,199, June 7, 1994. Bishop, G. A.; Starkey, J. R.; Ihlenfeldt, A.; Williams, W. J.; Stedman, D. H. *Anal. Chem.* **1989**, *61*, 671A−676A. Guenther, P. L.; Stedman, D. H.; Bishop, G. A.; Beaton, S. P.; Bean, J. H.; Quine, R. W. *Rev. Sci. Instrum.* **1995**, *66*, 3024−3029.

$$\% \ CO_2 = 42/(2.79 + 2Q + 0.42Q')$$

$$\% \ CO = Q(\% \ CO_2)$$

$$\% \ HC = Q'(\% \ CO_2)$$

$$\% NO = Q''(\% \ CO_2)$$

To derive mass emissions in g/gal of fuel from Q and Q' assuming a fuel density of 0.75 g/mL and the same CH_2 carbon/hydrogen ratio,

$$CO_2 \text{ mass emission (g/gal)} = 8381/(1 + Q + 3Q')$$

$$CO \text{ mass emission (g/gal)} = 5333Q/(1 + Q + 3Q')$$

$$HC \text{ mass emission (g/gal)} = 8000Q'/(1 + Q + 3Q')$$

The vehicle's instantaneous air to fuel ratio is

$$A/F \text{ by mass} = 4.93(3 + 2Q)/(1 + Q + 3Q')$$

All deisel and most gasoline powered vehicles show a Q and Q' near zero since they emit little to no CO or HC. To observe a Q greater than zero, the engine must have a fuel-rich air/fuel ratio and the emission control system, if present, must not be fully operational.

In the case of deisel combustion, misfire causes high HC readings. Since the overall air/fuel ratio is very lean, even when overfueling and sooting are taking place, CO emissions only arise from pockets of incomplete combustion, and are limited to about 3% CO, compared to a broken gasoline-powered vehicle which can exceed 12% CO.

Recently, the ability to measure nitric oxide (NO) has been added to the existing IR capabilities.[10] The light source, across the road, now contains a deuterium lamp and IR/UV beamsplitter which is mounted in such a manner that the net result from the source is a collimated beam of UV and IR light. As with CO and HC measurements, the NO measurements are possible by ratioing to the CO_2 measured in the plume. All pollutants except HC are a specific gas which can unambiguously be measured and calibrated. Exhaust HC is a very complex mixture of oxygenated and unoxygenated hydrocarbons. The filter chosen measures carbon−hydrogen stretching vibrations which are present, but not equally in all HC compounds. This system can easily distinguish gross polluters from low emitters, but the results on an individual vehicle cannot be expected to correlate perfectly with a flame ionization detector, with ozone-forming reactivity, or with air toxicity, since the three are not correlated to one another. For large fleets of vehicles, the lack of correlation appears to average out.[11]

Calibration

There are two separate calibration procedures performed on every remote sensing unit. The first consists of exposure in the laboratory at a path length of about 22 ft to known absolute concentrations of NO, CO, CO_2, and propane in an 8 cm IR flow cell with CaF_2 windows. The calibration curves are used to establish the fundamental sensitivity of each detector/filter combination to the gas of interest. Before each day's operation in the field, the instrument undergoes a quality assurance calibration performed with the system set up at the location. Several puffs of gas designed to simulate all measured components of the exhaust are released from a cylinder containing certified amounts of NO, CO, CO_2, and propane into the optical beam path. The ratio readings from the instrument are compared to those certified by the cylinder manufacturer. In this way the system never actually measures exhaust emissions; it is basically a comparator between the pollutant ratios in a known standard gas cylinder and those measured in the vehicle exhaust.

Operation

When a motor vehicle passes through the beam of a calibrated instrument on the road, the computer notices the blocked intensity of the reference beam. This beam block initiates two actions, the previous 200 ms of data (20 points) are stored in memory as the "before car" buffer. The blocked voltages are continuously interrogated both to remember the lowest values (zero offset) and to look for a beam unblock signal. When an unblock signal is recognized, the video picture is frozen into the video screen memory and thus goes to the video tape recorder, and the next 50 data points (1/2 s of exhaust) are placed in a data table. The zero offsets are subtracted from all data. The data stream is interrogated for the highest CO_2 voltage. This is the least polluted 10 ms average seen during the 0.7 s of data devoted to this vehicle. This set of data (often, but not always, in the before car buffer) then becomes the "clean air reference" (CAR) against which all other data are compared. After ratioing all signals to the reference channel, and ratioing the results to the CAR result for that channel, one now has a set of 50 postcar, corrected, fractional transmissions which are converted to gas concentrations such as would have been observed in the 8 cm cell. These concentrations are then correlated to CO_2 and the slope and error of the slope determined. These slopes (the ratios of the pollutants to CO_2) are corrected by the correction factors determined for that day by means of roadside calibration. These slopes now are the Q, Q' and Q'' described earlier.

The 420 data points (six channels at 70 points per channel as described above) obtained for each vehicle provide three pollutant ratios. The software written for these instruments now solves the combustion equation for the measured pollutant ratios, compares the errors to preset error limits, and, if acceptable, reports the measurements as % CO, % CO_2, % HC, and % NO such as would be measured by a tailpipe probe with the results corrected for water and for any excess air which may not have participated in combustion. In view of the fact that the instrument is calibrated with propane, we report percent HC as propane. The four derived concentrations, % CO, % HC, % NO, and % CO_2, are placed on the video screen together with the vehicle image (which has been waiting without results for about 0.8 s).

(10) Zhang, Y.; Stedman, D. H.; Bishop, G. A.; Beaton, S. P.; Guenther, P. L.; McVey. I. F. *Air Waste* **1996**, *46*, 25−29.

(11) Stephens, R. D.; Mulawa, P. A.; Giles, M. T.; Kennedy, K. G. Groblicki, P. J.; Cadle, S. H. Duncan, J. W.; Knapp, K. T. Coordinating Research Council Final Contract Report VE-11-4; CRC: Atlanta, GA, September 1994. Zhang, Y.; Stedman, D. H.; Bishop, G. A.; Guenther, P. L.; Beaton, S. P.; Peterson, J. E. *Environ. Sci. Technol.* **1993**, *27*, 1885−1891.

The video tapes are quite boring. A still video picture of the rear of a car or truck is overlaid in just under 1 s by the date, time, and derived emissions. This image now stays on the screen until the next vehicle comes by to repeat the process. If these results are to be compared to vehicles of known emissions, or gas cylinders puffed into the beam, it is important to compare to the three ratios and not the four derived concentrations since there are not actually four independent pieces of information. For example, if a person blocks the beam and exhales into it during the 1/2 s after they have unblocked the beam, the computer sees the exhaled CO_2, finds no CO, HC, or NO, and reports zeros for those pollutants and about 15% CO_2. Exhaled breath rarely contains even 2% CO_2, but the system only measures the ratios, and assumes (incorrectly in this case) that the emissions are from a fully stoichiometric automobile using gasoline as fuel. A puff from a cylinder which contains 50% CO and 50% CO_2 would be read as 8.6% CO and 8.6% CO_2 because the ratio is what is measured not the absolute concentration.

There are special software traps written to deal with two cars very close together. In this case, the before car buffer from in front of the first is used as a potential source of clean air reference for the exhaust of the second. The video picture of the first is replaced by the second before any data are overprinted. High pickup trucks thus often get two pictures, only the last of which has emissions data.

Other software traps reject data when the slope errors are too large, and when there is no sign of any significant exhaust plume (such as behind 18-wheel trailers whose tractors have elevated exhausts).

Operational Difficulties

Signal/Noise Considerations. Remote emissions measurements would all be very straightforward if one were able to measure directly behind the tailpipe of each passing car. Absorptions would be large, and the system signal/noise (S/N) would not be limiting. In fact, vehicle tailpipes point every which way, vehicle engine sizes differ enormously, and there is very rapid turbulent dilution of the exhaust behind vehicles which are moving faster than about 5 mph. Thus, one is forced to make engineering tradeoffs between the desire to measure all vehicles and the necessity to have an adequate S/N so as not to report incorrect exhaust emissions values.

The detection of gas absorption is based upon the reduction of signal on one detector versus the reference detector. Thus, the average car measured at an uphill freeway ramp in Denver shows an exhaust plume already diluted by a factor of about 10. This situation gives rise to an easily measurable 14% reduction in the CO_2 voltage. Because the average CO content is about 1/20th of the CO_2 and the HC 1/10th of the CO, the average total changes in CO and HC voltages are only 3 and 1 part in 1000, respectively. The NO channel shows a similar response to HC. Thus, the instrument builder's challenge is to build a system in which part per thousand changes in IR and UV intensity are accurately measured in all weather conditions beside a normal road at a measurement frequency of 100 Hz. At other locations, the plume dilution factor is 100 and a decision must be made whether the individual instrument's S/N is adequate for readings to be reported or if the data should be reported as "NO PLUME" invalid. This bleak outlook is somewhat mitigated by the fact that the source need only maintain a stable intensity for about 2 s for a complete measurement series and the fact that the data reduction process intrinsically "averages" all the 1/2 s data to only three ratios.

Weather. Measuring light intensities over a 10 m path to better than a few parts per thousand can be inhibited by bad weather. Ambient temperature and humidity variations are not a problem, but snowflakes and heavy rain add too much noise to all data channels. Wet or very dusty roadways cause a plume of spray or dust behind vehicles moving above about 10 mph. These plumes also add noise to the system, and generally increase the data rejection rate to an unacceptable level.

At the most productive sites, the remote sensor can gather data on 10 000 vehicles in a working day; thus, it often generates data faster than the operator can handle. In this case, taking the day off to analyze data when the weather conditions are not appropriate is no loss. Gross polluting vehicles are thought to be the same vehicles on dry as well as on wet days.

Interferences. The HC wavelength suffers from some interference from gas phase, and certainly from particulate phase, water (so-called "steam" plumes from colder vehicles operating at low ambient temperatures). When steam plumes are so thick that you cannot see through them (Fairbanks, AK, at forty below zero) the system no longer operates since all wavelengths are absorbed or scattered too much for useful data to be acquired.

Optical Alignment. If the instrument is not perfectly optically aligned, the voltages are likely to be very sensitive to equipment vibration. Since moving vehicles both shake the roadway and generate wind pulses, rigid instrument mounting is as important as perfect internal and external optical alignment. Software is written so that these noise sources generate "invalid" flags. Good alignment at a good site and more than 95% of passing vehicles obtain valid CO and HC readings. The current S/N of the NO channel is such that about 75% valid readings are reported.

The system is designed to operate on a single-lane road. Freeway ramps, turn lanes, and the inevitable road closures for sewer, gas, water, telephone, and road maintenance renders such sites quite easy to find. Multiple-lane operation has been reported[12] but is not recommended.

Emissions Variability. Emissions of motor vehicles are not constant from second to second or from day to day. Broken vehicles in particular often seem to have a large random component to their emissions irrespective of what test is used to make the measurement.[13] Some vehicle emission variability has known causes such as the initial operation of cold vehicles before the engine control system stabilizes and the catalyst begins operation, or when the vehicle is

(12) Bishop, G. A.; Zhang, Y.; McLaren, S. E.; Guenther, P. L.; Beaton, S. P.; Peterson, J. E.; Stedman, D. H.; Pierson, W. R.; Knapp, K. T.; Zweidinger, R. B.; Duncan, J. W. McArver, A. Q.; Groblicki, P. J.; Day, J. F. *Air Waste* **1994**, *44*, 169−175.

(13) Bishop, G. A.; Ashbaugh, L. L.; Stedman, D. H. *Air Waste* **1996**, *46*, 667−675.

accelerated at full throttle. Both situations give rise to large CO and HC emissions from well-maintained vehicles and can be avoided through careful site selection, or monitoring the speed, acceleration, and operating temperature of the passing vehicles.

Validation

The system has been tested since 1987 and at speeds between 2 and 152 mph. In 1991 in California the instruments were tested against a vehicle of known emissions. CO readings were found to be within +5% of correct, while the HC readings were within +15% (r^2 of 0.99 and 0.85, respectively).[14] The California Bureau of Automotive Repair is applying similar standards to the on-road certification of commercially available remote sensing units.[15] The NO system has not yet been subjected to blind intercomparisons.

Applications

Potential uses of the device which has been demonstrated worldwide[16] include immediate pullover of gross polluters (most of which turn out to have missing or tampered emission control systems); gross polluter identification to send to an alternative emission test; low emitter identification either on-road or in a special lane which exempts the low emitters from further testing; public information variable message billboards which inform passing drivers of their emissions; measurements at toll booths used to charge higher tolls for gross polluters; and measurements of employees arriving at work for employer-paid repairs.

The Rosemead High Emitter Study

The Rosemead High Emitter Study used remote sensing to identify gross polluting vehicles. A subset of the gross polluting vehicles was pulled over for an immediate, voluntary, roadside California smog check[17] in order to determine maintenance/tampering status. During the 10 weekdays of operation between June 3 and June 14, 1991, from 9 am to 3 pm, the remote sensors collected 60 487 measurements on 58 063 unique vehicles. A total of 3271 high emitters were identified. The two full-time teams conducting the voluntary roadside smog checks were able to check 330 vehicles. An EPA IM240 dynamometer team was able to test 70 vehicles during the same 10 day period.[18] Although we are not qualified as economists, we believe that these different productivity levels have cost/benefit implications.

Of the 307 vehicles with complete data sets,[19] 126 (41%) showed deliberate tampering, another 77 had defective or missing equipment which may not have been deliberate (such as missing air pump belts), and 261 (85%) of the vehicles failed the tailpipe test. Less than 5% of the vehicles identified as gross polluters by remote sensing passed the immediate roadside test. When random pullover studies are carried out in California,[20] approximately 60% of the vehicles pass the roadside test whether they are registered in a scheduled I/M (Inspection and Maintenance) program region or not.[21] These results show that vehicles identified as high emitters by the remote sensor are badly maintained; they are not a subset of normal vehicles temporarily high-emitting because they are cold or accelerating hard.[22]

If the 307 vehicles tested are representative of the high emitters identified from testing the 58 063 unique vehicles, we can estimate what would have resulted if all the high emitters could have been given a roadside inspection. In this case 3005 vehicles would have been pulled over and failed the roadside inspection, while only 0.5% of the on-road fleet would have been pulled over and passed.

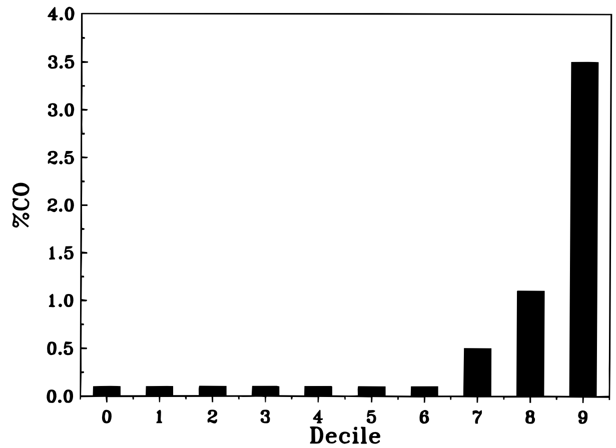

Figure 2. Ten bars whose heights represent CO emissions of 10 vehicles which resemble in mean and distribution typical vehicles on the road in Denver, CO, in 1996. The emissions of the lowest seven have been averaged because the small differences among the majority lowest emitters are not significant.

Age and Maintenance Effects

With so many cars easily measured, we started to look into the statistics. To our surprise, our data, USEPA data, indeed all the data we could find, showed half the pollution from less than 10% of the vehicles. These vehicles we call gross polluters. Figure 2 shows 10 blocks whose height matches the average CO emissions of 10% of the cars in Denver. Notice how much higher emitting are the gross polluters than the majority of the cars. Very few new cars are gross polluters (about 1% of 2-year-old cars), but for even the oldest cars (1974 and older, all without catalysts) the majority (60%) are *not* gross polluters. When a distribution this skewed is observed, it is easy to justify an air pollution program which identifies the gross polluters and targets them

(14) Ashbaugh, L. L.; Lawson, D. R.; Bishop, G. A.; Guenther P. L.; Stedman, D. H.; Stephens, R. D. ; Groblicki, P. J.; Parikh, J. S.; Johnson, B. J.; Huang, S. C. In *PM10 Standards and Nontraditional Particulate Source Controls*; Chow, J. C., Ono, D. M., Eds.; Air and Waste Management Association: Pittsburgh, PA, 1992; Vol. II, pp 720−739.

(15) Certification standards are spelled out in Contract No. 34909018-05 between the California Bureau of Automotive repair and Remote Sensing Technologies Inc. and amendments thereto, Oct 30, 1995.

(16) Zhang, Y.; Stedman, D. H.; Bishop, G. A.; Guenther, P. L.; Beaton, S. P. *Environ. Sci. Technol.* **1995**, *29*, 2286−2294.

(17) Beaton, S. P.; Bishop, G. A.; Zhang, Y.; Ashbaugh, L. L.; Lawson, D. R.; Stedman, D. H. *Science* **1995**, *268*, 991−993.

(18) Knapp, K. T. In *PM10 Standards and Nontraditional Particulate Source Controls*; Chow, J. C., Ono, D. M., Eds.; Air and Waste Management Association: Pittsburgh, PA, 1992; Vol. II, pp 871−884.

(19) Lawson, D. R. *Air Waste* **1994**, *44*, 121−130.

(20) California Air Resources Board, Mobile Source Division. Report on the ARB/BAR 1989 Random Roadside Inspection Survey. Report MS-90-14; July 1990.

(21) California Air Resources Board, Mobile Source Division. Report on the ARB/BAR 1990 Random Roadside Inspection Survey; Report MS-91-06; July 1991.

(22) Austin, T. C.; DiGenova, F. J.; Carlson, T. R. Analysis of the Effectiveness and Cost-Effectiveness of Remote Sensing Devices. Sierra Research, Inc., Report to USEPA; May 1994.

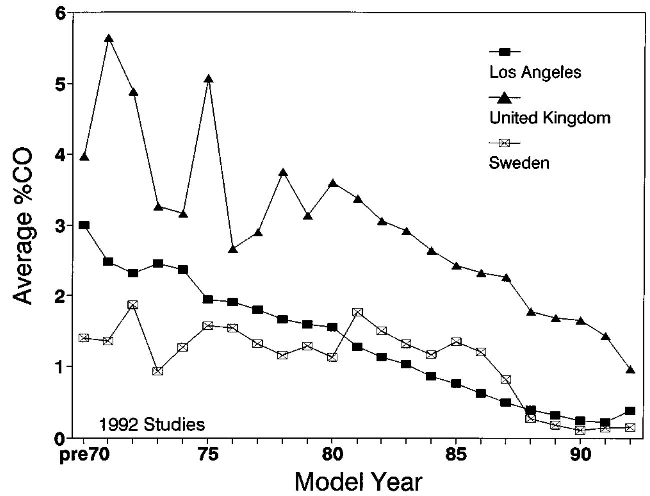

Figure 3. CO emissions versus model year measured in 1992, with results from three countries: filled squares, Los Angeles, CA; open squares, Gothenberg, Sweden; filled triangles, various locations in the U.K.

for treatment. It is correspondingly hard to justify programs which treat all cars as equal (oxygenated fuels, periodic mandatory emission testing, ride-sharing, etc.). All the studies show that fuel effects on emissions are very subtle compared to the emissions effects of broken vehicles.

Average results from three countries are shown in Figure 3. The black squares are data from 1991 in Los Angeles. New vehicles have low average emissions. As the vehicles get older, the average emissions increase. Notice that there is no discernable break in 1974 or 1980 when new technology (catalysts, 1974; closed-loop computer systems, 1980) was introduced. The line close to the Los Angeles data was obtained in 1991 in Sweden. Sweden introduced catalysts 50% in 1987, and 100% in 1988. The break is clearly discernable, and Swedish catalyst-equipped cars have lower average emissions (by half) than similarly equipped vehicles in Los Angeles. There are a number of social/personal reasons to expect better car maintenance in Sweden. Cars are relatively expensive, and my Swedish friends assure me that there is no word in Swedish for “tampering” with the emission control equipment.

If maintenance practices in Sweden are better than in Los Angeles, as cars get older, one might expect to see an age at which good maintenance is even more important than catalysts. This effect is observed in the 1975–1981 model years. The (apparently badly maintained) originally-catalyst-equipped cars in Los Angeles have higher emissions than noncatalyst cars in Sweden. Contrasting with the lower two lines is the upper line of data from the United Kingdom. The U.K. introduced catalysts in 1990, but it is apparent that the U.K. suffers from a combination of both poor technology and poor maintenance.

Mexico City and Kathmandhu are even worse than the U.K. However, in Mexico City they are trying to do something about their problem. One of the most elegant results of remote sensing programs to date

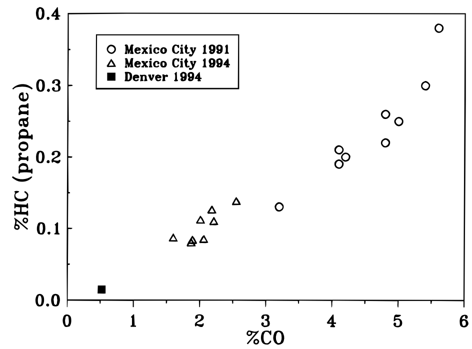

Figure 4. Average HC versus average CO readings measured in 1991 at various sites in Mexico City (open circles). Open triangles show the same data, mostly from the same sites measured in 1994. The filled square shows an average from Denver, CO, in 1995.

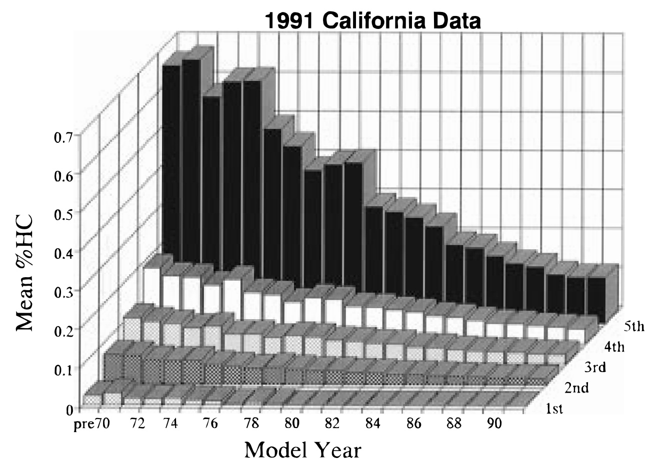

Figure 5. Average HC exhaust emissions from vehicles in California. Emissions for each model year were sorted into five groups (quintiles). The average emissions of the five quintiles for each model year are plotted from front to back, lowest to highest. Pre70 includes all 1970 and older vehicles.

shows the Mexico City success. Figure 4 shows as circles data from 1991 and as triangles data from 1994. The emissions reductions are readily apparent. We believe that a major cause is the introduction of closed-loop catalyst systems on the (mostly Volkswagon Beetle) taxi cab fleet.[23,24]

Despite these research results, there remain critics who believe that our results are random (*Pittsburgh Tribune Review*, May 15, 1995). This is hard to believe since we show new cars averaging lower emissions than old cars. The video camera and license plate data are independent of the emissions data; thus, these results could not be obtained with a random detector. The same age effects are observed for HC and NO,[11,25] but in both cases, the averages depend more upon vehicle speed and load.

With skewed distributions, average readings tend to obscure as much as they illuminate. When we divide each model year into five groups (quintiles) from lowest to highest emitting, a more startling result appears. The increase of average emissions with average age is overshadowed by the dramatic differences between well and badly maintained cars in a

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given model year. Thus, 20% of the early 1970s, noncatalyst cars have *lower* emissions than the broken 1990s cars.

These results are illustrated for HC in Figure 5. The pullover study showed that gross polluters identified by means of remote sensing usually have defective emissions control systems. The large difference between the majority front quintiles (low-emitting) and the back quintiles (high-emitting) of Figure 5 is thus shown to be caused by poor maintenance/tampering. We believe that the relatively small effect of age on average emissions is caused by a secondary correlation between increasing vehicle age and an increasing fraction of poorly maintained vehicles. The policy implications are discussed elsewhere;[17] however, we imagine that innovative uses will be found for a device which can distinguish the many low emitters from the few high emitters at 1000 tests per hour without driver inconvenience. Klein and Koskenoja[26] believe that the most cost effective vehicle emission testing programs would use mainly remote sensing, which Harrington and McConnell[27] believe can be carried out routinely for a cost of less than $0.16 per test.

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