Remote Sensing of Automobile Emissions

Many advanced traffic management integration projects now incorporate systems for sensing atmospheric pollution caused by vehicles. This article by D.H. Stedman, G.A. Bishop, Y. Zhang, and P.L. Guenther of the Chemistry Department, University of Denver, Colorado, USA, looks at a method of precisely measuring moving vehicle emissions.

A system has been developed that is capable of remotely measuring the exhaust carbon monoxide (CO), hydrocarbon (HC), and carbon dioxide (CO_2) from vehicles passing in single lane traffic in under one second per vehicle. On-road remote sensing of vehicle emissions and the remote sensor are fully described elsewhere [1,2]. Vehicles can be monitored at a rate of over 1,000 per hour with speeds ranging from two to 200 kph. A schematic diagram of the instrument can be seen in Figure 1. A computer video board freezes the image of the rear of the vehicle being measured. These images are stored on an optical disk along with that vehicle's emissions. When the license plates have been read, information from motor vehicle registration allows us to correlate vehicle emissions with make, model, and age of the vehicle. The emissions measurements have been validated by means of an exhaust gas analyzer with its probe inserted in the tail-pipe while the vehicle was being driven past the sensor. Instrument accuracy has been validated twice by means of double-blind studies conducted by the California Air Resources Board [2,3]. The measurements can be converted directly to mass emission units such as grams per litre of fuel consumed.

Recently, the abilities to measure nitric oxide (NO) and exhaust opacity have been added. NO is measured by ultraviolet (UV) absorption, while opacity is determined by means of infrared (IR) absorption at 3.9B. Diesel soot (black) or "steam" from cold cars both cause observable opacity.

FINDING THE PROBLEM

Many cities perceive that they have a problem caused by motor vehicles. On-road emissions monitoring by means of remote sensing offers a fast and cost effective technique to evaluate the extent of the problem. Table 1 shows the results of such studies for several world cities [1,5,6,7]. Mexico City and Kathmandu stand out as having CO and HC emissions far above those measured in Seoul or Denver. The efficiency of the system is demonstrated by the fact that the 11,000 measurements in Kathmandu were made in two and a half days. All of our observations point to the fact that fleet average emissions are strongly affected by the fleet average age, the presence or absence of new vehicle emission standards, and to a lesser extent the make of the cars. The effects of vehicle make can be further distinguished between the relatively minor effects of manufactured capability and relatively major effects of owner maintenance behaviour.

ANALYZING THE PROBLEM

Not all cars have equal emissions. Data from our measurements show that, a small fraction of the passing vehicles are responsible for half or more of the emissions in any given area. In Toronto half the emissions come from

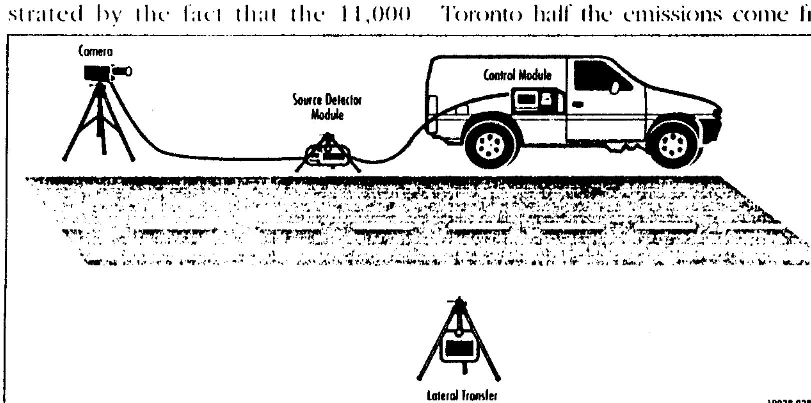

Figure 1: A schematic diagram of a typical roadside setup of a remote sensing instrument used for the measurement of vehicle emissions.

only eight per cent of the vehicles. In Kathmandu half the emissions come from 25% of the vehicles. The few vehicles emitting half of the CO and HC are referred to as "gross polluters". The overall characteristics of these fleets are very similar regardless of overall fleet age, location, or the presence or absence of inspection and maintenance (I/M) programs. Most vehicles, again regardless of location, show mean emissions of 1% CO and 0.1% HC (as propane) or less in the exhaust. The newer the fleet the more skewed the emissions [8]. This is because many more of the fleet have near zero emissions and thus, a smaller number of gross polluters strongly dominates the fleet emissions. Older vehicles are not all gross polluters. In fact, the majority of them are relatively low emitting. There is a correlation between fleet age and fleet emissions. This correlation has less to do with emissions control technology than it does with vehicle maintenance. Any well maintained vehicle regardless of age can be relatively low emitting.

For HCs, the fleet emissions tend to be less skewed than for CO, with more vehicles contributing to the overall fleet emissions. Only four cities, Bangkok, Hong Kong, Kathmandu, and Taipei, had half of the HC emissions produced by more than 15% of the fleet. Most of the same conclusions that are drawn regarding CO emissions and fleet characteristics hold true for HC emissions. This is true because HC emissions increase as engine combustion gets richer and produces more CO. Two cities in Asia, Bangkok and Kathmandu, stand out for HC emissions and this is due to the high percentage of two cycle engines, many of which are also badly tuned and badly maintained.

EFFECTS OF FLEET AGE AND EMISSIONS CONTROL PROGRAMS

Remote sensing can be used to determine how vehicle emissions change with the age of the vehicle fleet, and can be used to evaluate the effectiveness of emissions control programs. For instance, Figure 2 shows the emissions data from over 56,000 vehicle measurements at several locations in the USA. Each point is an hour of data which contains more than 100 vehicles, the %CO values have been averaged along with the age of the vehicle for which that measurement was obtained. From Figure 2 we obtain the following formula for predicting the emissions of a fleet of vehicles:

Mean CO emissions (gm/gal) = [(fleet avg. age(yr) - 0.28) * 74.0] ± 99

The equation predicts only the fleet mean CO emissions. It cannot be applied to individual vehicles. The equation is limited in that it applies only to fleets that have been subject to U.S. new vehicle standards since the

Table I ON-ROAD REMOTE SENSING DATA SUMMARY

Location	Date	#Records	Mean %CO	Median %CO	Mean %HC	Median %HC
Denver	91-92	35,945	0.74	0.11	0.057	0.033
Denver	Nov.93	58,894	0.58	0.13	0.022	0.013
Chicago	Oct.90	13,640	1.10	0.37	0.139	0.087
Chicago	Jun.92	8,733	1.04	0.25	0.088	0.064
Los Angeles	Jun.91	47,708	0.79	0.15	0.076	0.042
Provo	91-92	12,066	1.17	0.45	0.220	0.127
El Paso	Mar.93	15,986	1.22	0.37	0.073	0.044
Juarez	Mar.93	7,640	2.96	2.18	0.170	0.091
Mexico City	Feb.91	31,838	4.30	3.81	0.214	0.113
Gothenburg	Sep.91	10,285	0.71	0.14	0.058	0.046
Denmark	Oct.92	9,038	1.71	0.67	0.177	0.058
Melbourne	May 92	15,908	1.42	0.57	0.107	0.058
Thessaloniki	Sep.92	10,536	1.40	0.55	0.155	0.082
London	Nov.92	11,666	0.96	0.17	0.136	0.071
London	Nov.93	9,669	1.00	0.20	0.053	0.020
Leicester	Nov.92	4,992	2.32	1.61	0.212	0.131
Leicester	Nov.93	4,744	2.15	1.29	0.067	0.019
Edinburgh	Nov.92	4,524	1.48	0.69	0.129	0.084
Edinburgh	Nov.93	3,546	1.50	0.59	0.061	0.033
Bangkok	Aug.93	5,260	3.04	2.54	0.948	0.567
Hong Kong	Aug.93	5,891	0.96	0.18	0.054	0.037
Kathmandu	Aug.93	11,227	3.85	3.69	0.757	0.363
Seoul	Aug.93	3,104	0.82	0.26	0.044	0.019
Taipei	Aug.93	12,062	1.49	0.88	0.062	0.050

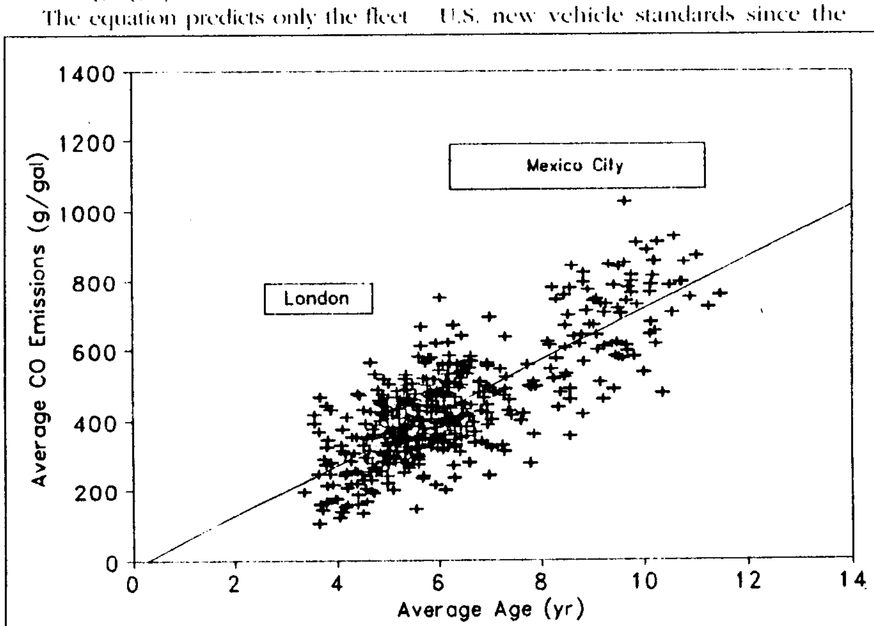

Figure 2: Each data point consists of the average of an hour of data containing more than 100 vehicles measured in the USA and Canada. The boxes for London and Mexico City are based upon measured emissions and estimated fleet age.

1970's. Vehicles monitored in London and Mexico City lie far above the line in Figure 2. Vehicles measured in Sweden lie slightly below the line. Factors influencing these differences include the presence or absence of mandated emissions control systems, mechanic competence, and the societal prevalence of tampering behaviour. Both of these factors are illustrated by the study from Sweden [7]. The emissions of on road vehicles in Sweden show a dramatic drop when catalysts were introduced in the late 1980s, but the non-catalyst equipped early 1980s vehicles on the road in Sweden have lower emissions than the catalyst equipped vehicles of the same model year found on the roads in Los Angeles. This result emphasizes the fact that maintenance and emissions technology are both important factors in controlling vehicle emissions. Emissions in London and Mexico City could be halved quickly and cheaply (making them comparable to those in the USA and Sweden) by successful enforcement of proper maintenance on current on-road gross polluting vehicles. Emissions in London and Mexico City could be halved slowly and more expensively by the introduction of catalysts on all new vehicles. Application of both new technology and proper maintenance and their emissions would be significantly lower than the current US fleet.

Remote sensing data taken year after year can be used to show whether emissions are decreasing from year to year. In Denver the decrease is apparent from Table one whereas in London there is no sign of any improvement.

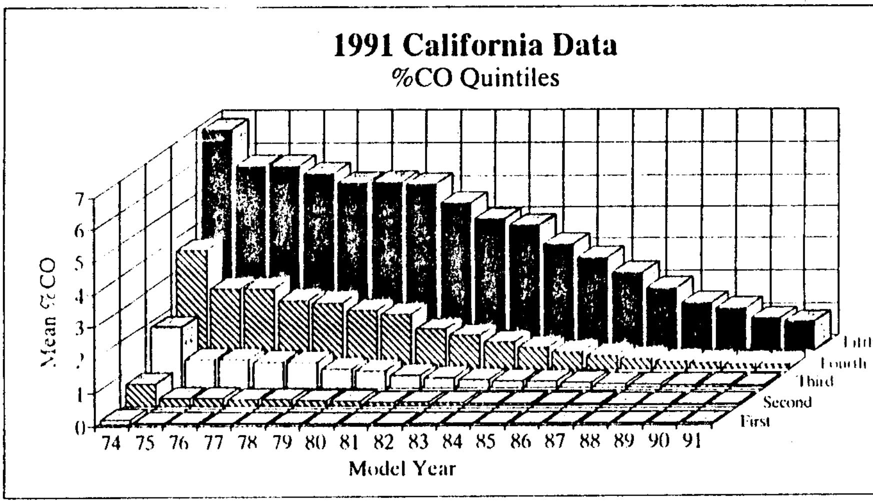

Figure 3a: Separation of the 76,244 1991 Los Angeles vehicles measurements into groups by model year. Each model year is rank ordered by %CO emissions and divided into quintiles. The emissions of each quintile are averaged.

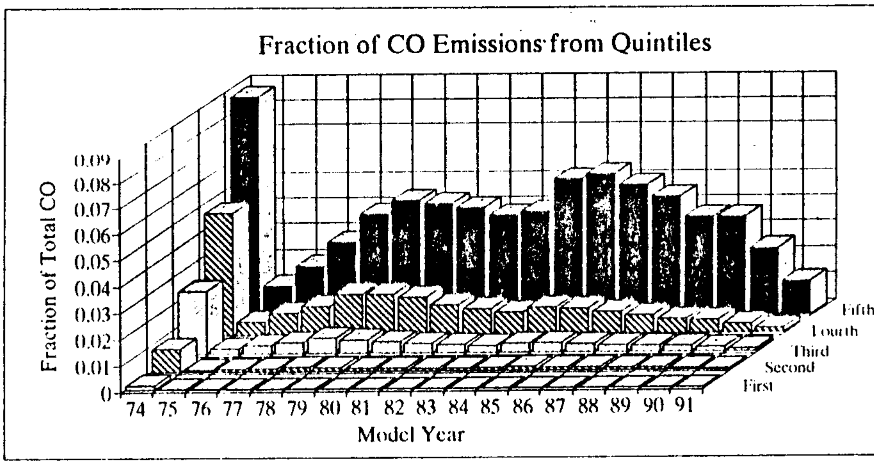

Figure 3b: Each quintile of Figure 3a multiplied by the number of vehicles in that quintile. Each quintile now shows its contribution to total fleet emissions. Late model high emitting vehicles dominate the fleet CO contribution.

THE IMPORTANCE OF MAINTENANCE

The use of remote sensing to characterize fleets emissions also lends itself to determining the type of strategy to employ in controlling vehicle emissions. In areas where only a relative handful of vehicles are responsible for the bulk of the emissions problem, targeting high polluting vehicles for repair would be effective [9]. Figure 3a shows the 76,244 vehicle 1991 Los Angeles measurement data set divided into year of production on the X axis. Within each year, the emissions of that part of the fleet have been rank ordered and then split into five equal sized sets (quintiles). Each quintile's emissions are then averaged and are presented as the height of the bar for that quintile. The bars in Figure 3 are directly proportional to emissions in grams per litre of fuel. If emissions in grams per kilometer are required then the emissions from each age group need to be multiplied by the average fuel economy for that age vehicle. Figure 3a shows the quintile emissions from each model year (per-catalyst 1974 and older vehicles are averaged together as 1974). Reading from front to back one can observe the effects of maintenance. The difference between the well maintained vehicles (front row) and the badly maintained vehicles (back row) is even larger than the effect of vehicle age increasing from right to left.

From Figure 3a it can be seen that the highest emitting quintile of the newest vehicles (1991) has much higher emissions than the lowest emitting quintile of the oldest vehicles (1974 and older). It can also be seen that the most rapid deterioration in emissions occurs during the first eleven years of ownership. After that time, the rate of increase of emissions slows down considerably. It is interesting to note that the vehicles with the most rapidly deteriorating emissions are all new technology vehicles with computer controlled fuel delivery systems and three-way catalysts (installed in the USA in 1980). All of our studies point to the fact that these vehicles have negligible emissions when first purchased, thus the problem is one of maintenance. Note that the well maintained vehicles (the front row) clearly show the effect of the new technology in that the emissions of the lowest quintile of the 1974 vehicles is significantly higher than the 1984 or newer model years.

Figure 3b is the same data multiplied by the number of vehicles in each model year, thus it represents the overall contribution of each vehicle to the air pollutant load. The highest block is the 1974 and older vehicles with about 9% of the total contribution, but notice that the highest emitting

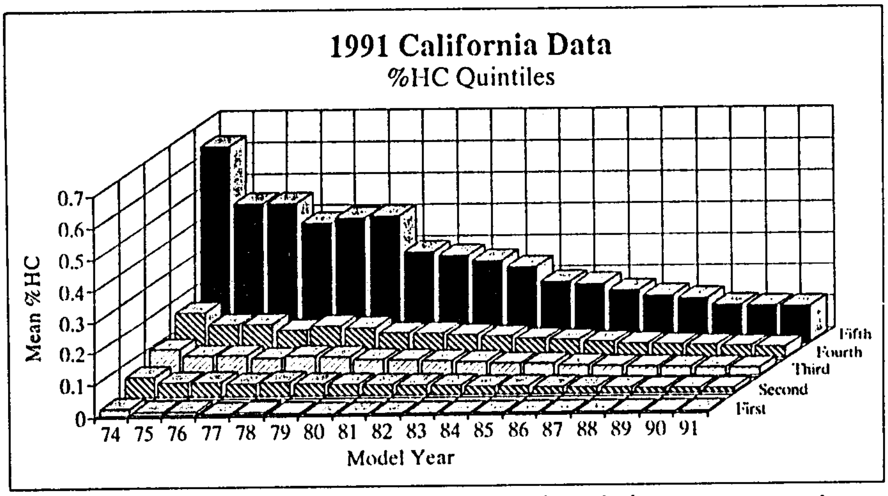

Figure 4a: Separation of the 76,244 1991 Los Angeles vehicles measurements into groups by model year. Each model year is rank ordered by %HC emissions and divided into quintiles. The emissions of each quintile are averaged.

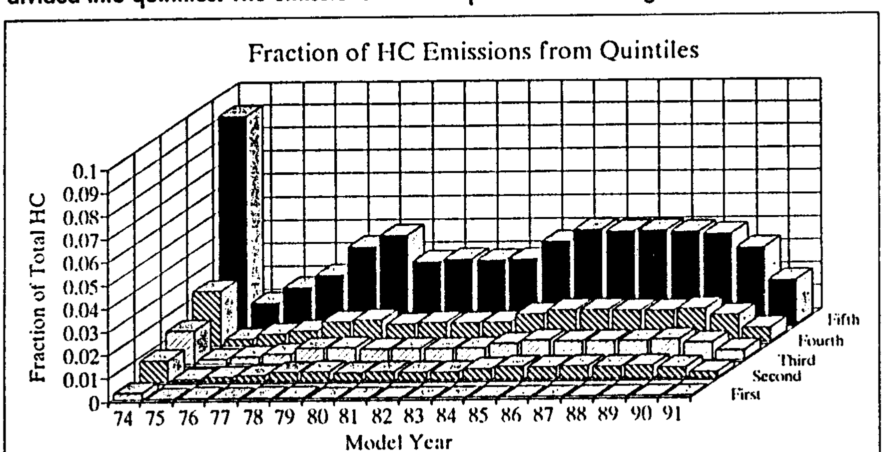

Figure 4b: Each quintile of Figure 4a multiplied by the number of vehicles in that quintile. Each quintile now shows its contribution to total fleet emissions. Late model high emitting vehicles dominate the fleet HC contribution.

1984, 1985 and 1986 vehicles when taken together contribute 15% of the total, with the model years either side also very significant. What this shows is that too much concern about the contribution of older vehicles is not warranted because there are relatively few of them out on the road.

Figures 4a and 4b show the same fleet but for the HC emissions. Notice that the emissions and contribution patterns are quite similar. The new vehicles have relatively similar low emissions. The average emissions of all fleets is dominated by a small percentage of high emitting vehicles The evidence points to the fact that the observations over time are caused by maintenance factors [4]. Sophisticated engine technology using alternative fuels, or catalytic converters and closed loop engine management systems will benefit only after considerable time and if the vehicle population experiences proper maintenance.

PUBLIC AWARENESS

We have shown in Utah, [4] that repairs (averaging about $200 each) of vehicles measured as on-road gross polluters results in an average gas mileage improvement of ten percent. This fuel saving would have paid for the cost of repairs in under two years at typical US gasoline prices (US$0.25 per litre). Public education and awareness of the relationship between emissions and fuel economy are early initiatives which can be taken using a remote sensor. Remote sensing can be used to operate a sign which tells drivers of the gross polluting vehicles their potential for improved fuel economy if their vehicle is properly maintained.

PROGRAM POSSIBILITIES

On-road remote sensing can be used to analyze the emissions of a large fleet of vehicles in a very cost-effective manner. The statistics of the data can be used to plan emissions control programs. The identification of gross polluters can be used as a component of a program designed to ensure that those vehicles receive effective repair (an inspection and maintenance program). High on-road readings have been used as evidence for pulling vehicles over to the side of the road to check for tampering with the emissions control system. More than 60% tampered or disconnected systems were found when this was carried out in Los Angeles [3].

Remote sensing can be applied at the same site under the same conditions periodically to determine how well emissions control programs are working to reduce on-road emissions. Since the correlation between low emissions and proper maintenance is high, most people operate vehicles which do not contribute significantly to pollution. These people could be rewarded for their socially responsible behaviour based on low on-road emissions readings. These rewards could consist of remote sensor operated "clean car only" lanes, or reduced tolls at toll plazas.

On road remote sensing of motor vehicle emissions is a new tool which has progressed from a University prototype to a commercially available system, either portable or mounted in a mobile van. Everywhere we have taken the system local air pollution officials have suggested new ways in which this tool could be applied to solving their mobile source emissions problems. ○

We would like to acknowledge the National Science Foundation, the American Petroleum Institute, the Coordinating Research Council, the Environmental Protection Agency, the Royal Automobile Club in the UK, the Institutet för Vatten- och Luftvårdsforskning in Sweden and other agencies who have helped sponsor this research. Our thanks also to the various members of the Phillipson Group at the University of Denver for their assistance.

REFERENCES

1 G.A. Bishop, J.R. Starkey, A. Ihlenfeldt, W.J. Williams, D.H. Stedman, Anal. Chem., 61 (1989) 671A.
2 D.R. Lawson, P.J. Groblicki, D.H. Stedman, G.A. Bishop, P.L. Guenther, J. Air Waste Management Assn., 40 (1990) 8.
3 D.R. Lawson and J.A. Gunderson, Presentation to I/M Review Committee, Sacramento, California, 29 January 1992.
4 D.H. Stedman, G.A. Bishop, J.E. Peterson, P.L. Guenther, Final Report to California Air Resources Board, Contract No. A932-189, August 1991.
5 J.F.S. Bidgood and J. Vanke, SAE Tech. Paper # 922385, Presentation to SAE International Meeting, San Francisco, California, October 19-22, 1992.
6 S.P. Beaton, G.A. Bishop, D.H. Stedman, J. Air Waste Management Assn., 42, (1992) 1424.
7 Å. Sjödin, report B-1042 to Institutet för Vatten- och Luftvårdsforskning, 1991-10-11.
8 J.E. Peterson and D.H. Stedman, Chemtech, 22 (1992) 47.
9 G.A. Bishop, D.H. Stedman, J.E. Peterson, T.J. Hosick, P.L. Guenther, J. Air Waste Management Assn., 43 (1993) 978.