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FINAL REPORT

to

COORDINATING RESEARCH COUNCIL

REMOTE SENSING OF ON-ROAD VEHICLE EMISSIONS

Contract No. VE-8-1

by

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ABSTRACT

The University of Denver has developed a remote sensor for in-use motor vehicle hydrocarbon (HC) and carbon monoxide (CO) emissions. Under this contract we have explored the possibility of using a police type radar unit to measure vehicle speed and acceleration in conjunction with that vehicle's remotely sensed HC and CO emissions. Vehicle speed was determined accurately, however, acceleration measurements need improvement. A fleet of vehicles in Toronto, Canada was characterized for its CO emissions. It is a very new and low emitting fleet despite the lack of a routine inspection and maintenance program. A subset of this fleet was propane powered and appears to have about double the emissions of the gasoline powered fleet. The possibility of adding a water vapor channel to the remote emissions sensor was examined. Full testing of this channel has yet to be done but there is hope that the sensitivity will be sufficient to allow separation of cold engine from warm engine operating modes.

ACKNOWLEDGMENTS

This project would not have been possible without the agencies and individuals which have shared the responsibility for the remote sensing program. These agencies have included the National Science Foundation, the Colorado State Office of Energy Conservation, the Illinois Department of Energy and Natural Resources, the California Air Resources Board, the American Petroleum Institute, the City of Toronto and others. The assistance of other members of the Phillipson Research group, and in particular, Ms. Marilyn Johnson is much appreciated.

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EXECUTIVE SUMMARY

A study for the Coordinating Research Council (CRC) entitled "Remote Sensing of On-Road Vehicle Emissions" was conducted. The primary goals were to investigate the possibility of using radar to monitor vehicle speed and acceleration in conjunction with remote sensing of that vehicle's CO and HC emissions; to analyze the data from a fleet of vehicles measured in Toronto, Canada; and to add the capability to measure water vapor to an existing FEAT unit.

The first goal has been accomplished. A radar system can be used to give speed and acceleration data along with a vehicle's emissions. Speed measurements to better than two miles per hour accuracy can be obtained on more than 80% of the passing vehicles. Due to problems with the manner in which the radar unit collects data successful acceleration measurements are made only about 50% of the time. Because the measurements are made while the vehicle's angle to the radar unit is changing, the accuracy of the acceleration data is limited.

The second goal has also been accomplished. The video tapes from the Toronto, Canada measurements have been transcribed to create a database of 4507 vehicles with their emissions and make, model, and model year information. This fleet was the newest and cleanest fleet observed anywhere in the world to date despite the fact that no routine I/M program exists there. This result arises partly because the location chosen was dominated by new vehicles which are inherently clean running, having had insufficient time to accumulate maintenance problems. The gasoline powered fleet averaged 0.77 %CO. The diesel fleet showed not only very low CO (0.11%), but also very low standard deviation (0.14 %CO). This illustrates not only that the diesel fleet has very low CO emissions, as expected, but that the FEAT unit has low noise on low CO vehicles. A small subset (28 vehicles) consisted of propane powered vehicles. In view of the gamma distribution of vehicle emissions, the size of the fleet is too small to make conclusive statements. Nevertheless, this fleet's emissions were double that of the gasoline powered fleet. This finding suggests that the conventional wisdom that propane is by definition "cleaner burning" needs further study.

The third goal has been partially accomplished. Calculations to determine the optimum wavelength for the water vapor interference filter have been made. This optimization is difficult because the system must be operational up to 40 foot pathlengths at sea-level in absolute H_2O humidities as high as 3-4% and yet be able to detect 20% H_2O from the exhaust added in a pathlength of only 5-10 cm. A filter of wavelength 2.79μ (3584 cm^{-1}) was purchased and installed. Initial tests show some promise, however, complete testing was not possible as funding had been fully expended by the other programs.

INTRODUCTION

With initial support from the Colorado Office of Energy Conservation, the University of Denver (DU) has developed an infra-red remote monitoring system for automobile carbon monoxide (CO) exhaust emissions. The University of Denver CO remote sensor has been given the acronym FEAT which stands for Fuel Efficiency Automobile Test. The reasoning behind the name lies in the fact that significant fuel economy improvement results if rich-burning (high CO), or misfiring (high HC) vehicles are tuned to a more stoichiometric (and more efficient) air/fuel (A/F) ratio. Our capabilities have now been expanded to include measurement of hydrocarbon (HC) emissions.

Some vehicles become high emitters under conditions of hard acceleration or prolonged power output. These effects are known as "power enrichment" or "off-cycle emissions" depending on whether the point of view of the author is founded in engineering or regulation. For this reason the ability to measure speed and acceleration while remotely sensing exhaust emissions was deemed important.

The City of Toronto had provided funds to carry out remote sensing and to generate video tapes of the measured vehicles. Funding was received from the CRC to read the video tapes and analyze the data for vehicle make, model year, and fuel type.

Motor vehicles in a cold-start mode require extra fuel in order to ensure that enough volatiles are present to guarantee combustion. While this fuel enrichment, provided by a choke or the modern equivalent, is normal and expected, it does lead to transitory high CO emissions. It would be a useful addition to on-road remote sensing to be able to determine whether a vehicle is in a cold-start mode. One potential means to carry this out is to look for water vapor in the exhaust. Until the exhaust system is heated to close to 100° C, the water will be present as liquid, not vapor, and thus will not be detected in the vehicle's exhaust.

REMOTE SENSING - HOW IT WORKS

THEORY

The FEAT instrument was designed to emulate the results one would see using a conventional non-dispersive infra-red (NDIR) exhaust gas analyzer. Thus, FEAT is also based on NDIR. An optical filter that transmits infra-red (IR) light of a wavelength known to be uniquely absorbed by the molecule of interest is placed in front of a detector. Reduction in the signal caused by absorption of light by the molecules of interest produces a reduction in the voltage output. One way of conceptualizing the instrument is to imagine a typical bench type NDIR instrument in which the separation of the IR source and detector is increased from 10 cm to 20-40 feet. Instead of pumping exhaust gas through a flow cell, the test vehicle drives between source and detector.

Because the effective exhaust plume path length and amount of plume seen depends on turbulence and wind, the FEAT instrument operates by measuring ratios of CO or HC to CO_2. These ratios are termed Q for CO/CO_2 and Q' for HC/CO_2 and are constant for a given exhaust plume. By themselves, Q and Q' are useful parameters with which to describe the combustion system. With the aid of a fundamental knowledge of combustion chemistry, many parameters of the vehicle's operating characteristics can be determined including the instantaneous air/fuel ratio, grams of CO or HC emitted per gallon of gasoline (g CO/gallon or g HC/gallon) emissions, and the %CO or %HC which would be read by a tailpipe probe. Most vehicles show a Q and Q' of nearly 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. A high Q' can be associated with either fuel-rich or fuel-lean air/fuel ratios coupled with a missing or malfunctioning emission control system. A lean air/fuel ratio while impairing driveability does not produce CO in the engine. If the air/fuel ratio is lean enough to induce misfire then a large amount of unburnt fuel (HC) is present in the exhaust manifold. If the catalyst is absent or non-functional then high HC will be observed in the exhaust without the presence of high CO. To the extent that the exhaust system of this misfiring vehicle contains some residual catalytic activity, then the HC may be partially or totally converted to a CO/CO_2 mixture.

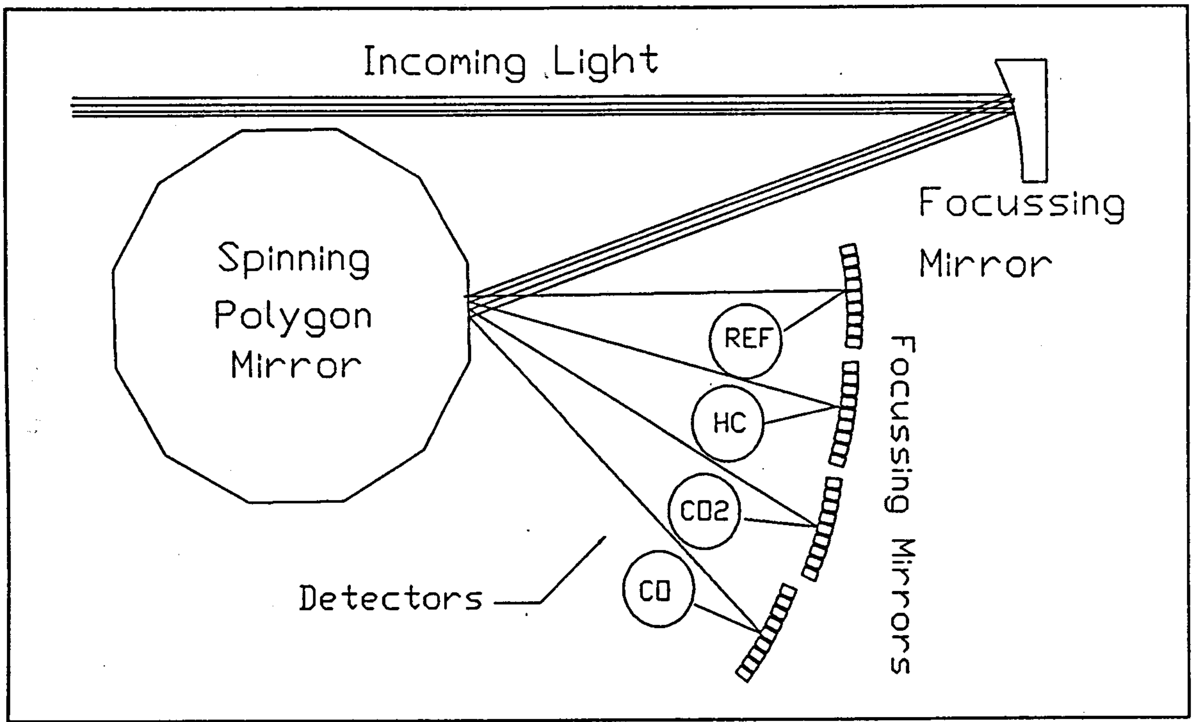

Figure 1 Schematic diagram showing the optical components of the FEAT 3000 series instruments. View is from above looking down. The detectors are Peltier-cooled Pb/Se and receive a chopped light beam from the spinning mirror.

INSTRUMENTAL DETAILS

The present design of FEAT instruments, of which there are now seven, incorporates CO (4.6μ), CO_2 (4.3μ), HC (3.3μ) and background (3.9μ) channels using interference filters, centered at the indicated wavelength, built into Peltier-cooled lead selenide (Pb/Se) detectors. The instrument uses a mirror to collect the light and focus it onto a spinning 12 faceted polygon mirror which provides a chopping frequency of 2,400 hz. The reflected light from each facet of the rotating mirror sweeps across a series of four focussing mirrors which in turn direct the light to the four detectors. Each detector thus gets a burst of full signal from the source in a sequential fashion for each measurement made. Figure 1 shows a schematic diagram of the arrangement.

Each detector provides a pulse train at 2,400 Hz equivalent to the intensity of the IR radiation detected at its specific wavelength. Electronic circuitry averages twenty four of these pulses, subtracts any background signal, and provides the averaged DC level to four signal ports. These are connected to the computer through an analog to digital convertor.

All data from the CO, CO_2, and HC channels are corrected by ratio to the reference channel. This procedure eliminates other sources of opacity such as soot, turbulence, spray, license plates, etc. from providing data that could be incorrectly identified as CO or HC.

Software written for these instruments reports our measurements as %CO, %CO_2, and %HC. The %HC is given as equivalent concentration of propane. This second step is not in accordance with normal I/M procedures. I/M instruments are tested for a single propane/hexane response ratio. All subsequent calibrations are performed with propane. The I/M data are reported as "hexane equivalent" by division by the propane/hexane response factor (a divisor usually close to two). A test of this response factor was performed using our calibration system and yielded a divisor of 1.8.

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 feet to known absolute concentrations of CO, CO_2, and propane in a 10 cm IR flow cell. The curves so generated are used to establish the fundamental sensitivity of each detector to the gas of interest, and to derive an equation relating the lowered voltages observed to those concentrations. As expected, CO and CO_2 curves are non-linear. Because of the small amount of HC to which the instrument is exposed, the HC curve is closer to linear and is approximated by a linear equation. This arises because of the small amounts of HC to which the instrument is exposed. The equation for the calibration lines become an empirical component of the instrument data analysis algorithm.

Before each day's operation in the field, the instrument undergoes a calibration performed with the system set up at the path length to be used at that location. A puff of gas designed to simulate all measured components of the exhaust is released into the instrument's path from a cylinder containing certified amounts of CO, CO_2, and propane. The ratio readings from the instrument are compared to those certified by the cylinder manufacturer. Because of the curvature of the response functions, particularly for CO_2, the field calibrations usually show higher ratios to CO_2 than those derived from the laboratory tests. The data for each day are adjusted by that day's correction factor.

SOFTWARE

The software which runs the system has been written with the concept that it is better to declare that a given vehicle's emission is not correctly measured than to let erroneous data into the database. The copyrighted software contains many checks that are used to detect potential errors. When errors are detected they lead to rejection of the measurement. A rejection sets an invalid data flag in the database. Two major criteria for rejection are not observing sufficient signal change to measure any exhaust components accurately and observing too much scatter in the HC or CO to CO_2 correlations from which the ratios are derived. The slope of the best fit straight line correlation is used for the ratio determination. The first rejection criterion could occur for passing pedestrians, heavy-duty diesel or gasoline vehicles with elevated exhaust, or any other instance in which the beam is blocked without the appearance of exhaust. The second criterion is set based on the expected signal/noise of the system. For CO a least squares slope error of less than 20% is allowed for all CO readings above 1%. For CO readings below 1% the rejection threshold is fixed at 0.2 %CO. Rejection criteria for the HC channel are currently set at less than 20% for HC readings of 0.375 %HC and greater and 0.075 %HC for readings less than 0.375 %HC (Bishop, 1989; Guenther, 1991).

VALIDATION

FEAT %CO readings have been shown by the Environmental Protection Agency and the California Air Resources Board (CARB) to accurately reflect on-road and on-dynamometer tailpipe probe readings. The study sponsored by CARB with collaboration from General Motors included a test of the instrument using a specially equipped GM vehicle. This vehicle had on-board controls to vary the air/fuel ratio and could thus produce a variety of CO levels in the exhaust which this vehicle was itself equipped to measure. The vehicle was used in a blind test in which the operators of the test vehicle randomly changed the engine operating parameters without informing the people operating the FEAT unit. The agreement between the test vehicle's on board instrument and FEAT was excellent, particularly when the vehicle was constrained to operating in a cruise control mode (Lawson et al., 1990). More recent CO and HC validation has been performed by CARB. The report is in preparation.

A side-by-side on-road comparison was carried out for CO data from the two differently designed FEAT units. The results show excellent agreement between them as seen in Figure 2. The new instrument agrees within the expected relative error with the older instrument which in turn has been validated by both EPA and the CARB (Guenther et al., 1991).

ON-ROAD REMOTE SENSING RESULTS (CO, HC, CO_2)

Studies which include measured CO emissions of more than 300,000 vehicles in Denver, Chicago, and California all indicate that about half the pollution comes from 10% of the vehicles. Separation of the data into individual cities or to sites within the cities does not alter this percentage. This 10% overall fraction includes almost no new cars, 4% of the vehicles built since 1983, and rises to a plateau of 30% of the 1975 and older fleet (Lawson et al., 1990; Stedman and Bishop, Illinois Report, 1990; Stedman and Bishop, EPA Report,1990). There is no sign of any break points in the remote sensing data corresponding to changes in vehicle emissions control technology. Since the mean emission is dominated by the few gross polluting vehicles, and those vehicles probably no longer have operating emissions control systems, this conclusion is not surprising. A similar pattern for HC emissions is evolving. For HC emissions it appears that about 14% of the fleet is responsible for half of the HC emissions with a gross polluter cut-off of around 0.23 %HC in propane equivalents (Stedman et al., Illinois report, 1991). There are two expected reasons for high HC emissions, vehicles operating with an excessively rich air to fuel ratio and vehicles which have an ignition misfire. Both conditions also require emission control systems that are not fully functional. The former condition results in both elevated HC and CO emissions. The later condition can produce both elevated HC and CO emissions but can also produce elevated HC emissions with no concommitant CO emission when the misfire is due to lean combustion operation.

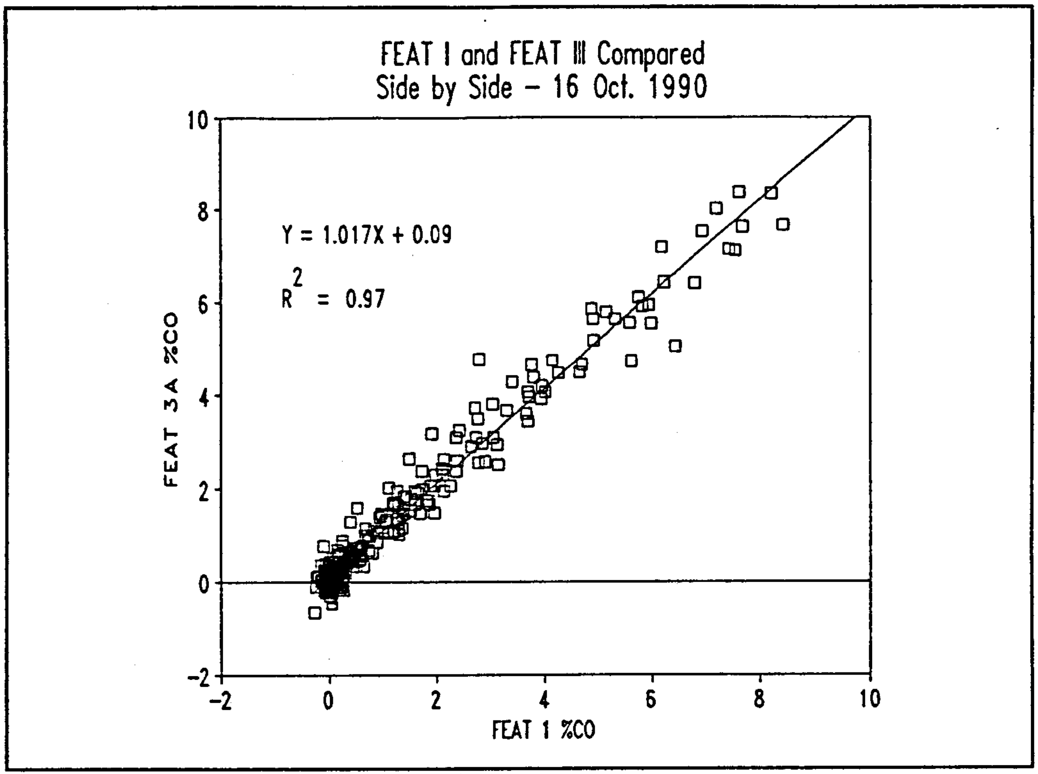

Figure 2 Comparison of %CO readings between FEAT 3000 and FEAT 1000 series instruments. FEAT 1000 series readings have been independently verified using vehicle with on board CO sensors and a variable air/fuel ratio.

THE CRC STUDY

INTRODUCTION

There were three parts to this $39,800 total program; 1) a study of the potential of a radar system to determine the speed and acceleration of passing vehicles; 2) the reading of videotapes and reporting on the emissions of vehicles in the Toronto area which data had been previously collected at the City of Toronto's expense; and 3) the specification and testing of a water vapor channel as a component of the remote sensing system. The channel to detect water vapor is designed to determine whether a vehicle's exhaust and catalyst system are warm enough for all the expected water of combustion to appear in the vapor phase. The goal of this component is not to monitor the details of water vapor in vehicle exhaust, but rather to find out whether the monitoring of water vapor in conjunction with CO_2 can be used to detect whether a vehicle is in a warm or cold operating condition.

RADAR SYSTEM

The need for speed and acceleration data is important because of the way new vehicles have their emissions certified during the EPA's Federal Test Procedure (FTP). Emissions during accelerations greater than four mph/second and speeds greater than 55 mph are not monitored due to the limitations of chassis dynamometers. It is known that some vehicles can exceed their standards while in these untested operating modes. It would be desirable to know when a vehicle is operating outside of the FTP standards to separate those vehicles which are truly dirty from those experiencing a temporary departure from their normal operating mode. The search for methodology to add to the existing FEAT unit for measuring speed and acceleration led us to try existing technology. We first investigated the possibility of using radar. MPH Industries, makers of a standard police radar unit (K15-2), informed us that they could provide us with a radar unit to meet our specifications. Those specifications entailed the ability to operate over a short range and produce an analog output. Unfortunately the unit provided failed to meet those specifications.

Despite the fact that MPH stated that this unit had an analog output which could be directly interfaced to our data acquisition system, there turned out to be a continuing series of difficulties which necessitated our rebuilding a number of the circuits which had been originally sold to us. The major problem was that the radar suffered from too much signal when looking at vehicles over the short range (20 to 50 ft) which we needed to measure. The option to go to longer ranges is not practical at busy ramps since the beam spreads quickly to the point where any one of a row of vehicles could be the one to which the radar is responding. The radar gun response to signal overload is to drop the output level to zero occasionally and then return the signal to the correct level. Since the internal gun logic provides a readout of the maximum speed in a given time interval, this dropout is not a problem for law enforcement. It is a major problem if one wishes (as we did) to take fifty speed readings in half a second and plot them versus time. The computer could then determine the slope of the resultant scatter plot and, if within acceptable error bounds, report a successful measurement of acceleration. When we rewired the system to decrease the input gain and, thus, partially eliminate the dropout problem, the system was then usable. Speed measurements can be obtained easily on more than 80% of the passing vehicles. Acceleration determination depends on the ability to determine, with reasonable accuracy, the first derivative of the already fairly noisy speed information. Acceleration is, therefore, reported on approximately 50% of the fleet.

A second problem developed because of the limited range that we employed in the measurement of the speed of the automobiles. This problem has to do with the change in angle of the vehicle relative to the radar unit during the time taken for the radar to collect the speed data. The computer starts to collect data when the IR light beam is blocked and continues the data collection for the duration of the half-second period after the beam is cleared by the automobile. A fifteen foot long automobile moving at 30 miles per hour (mph) can move 37 feet in the time that the data are collected. If the vehicle point of radar reflection is moving parallel to the side of the road at a distance of five feet, then the approach angle, Θ, to the radar gun will change from 5.7° to 21°. Since the measured speed is proportional to cosine Θ, the measured speed will change from 29.8 mph to 28.0 mph in the time that elapses during the data collection period of 0.84 seconds. A crude calculation lets us estimate that the approximate deceleration is 2.1 mph/second. However, if we do the same series of calculations for the same vehicle following the same path at 40 mph, then we get an apparent deceleration of 12 mph/second. These calculations are approximate since the radar reflection is not from an infinitesimal point nor is it necessarily from the same point with each data point collected. Similar apparent accelerations can be seen if the radar beam is looking at the rear of the vehicle as it recedes. Figure 3 shows a series of curves calculated for vehicles traveling at different speeds and distances from the side of the road. The apparent decelerations were determined from a series of points calculated for the vehicles as they moved along their path during the data collection period. The apparent deceleration effect becomes severe at higher speeds and greater distances from the side of the road.

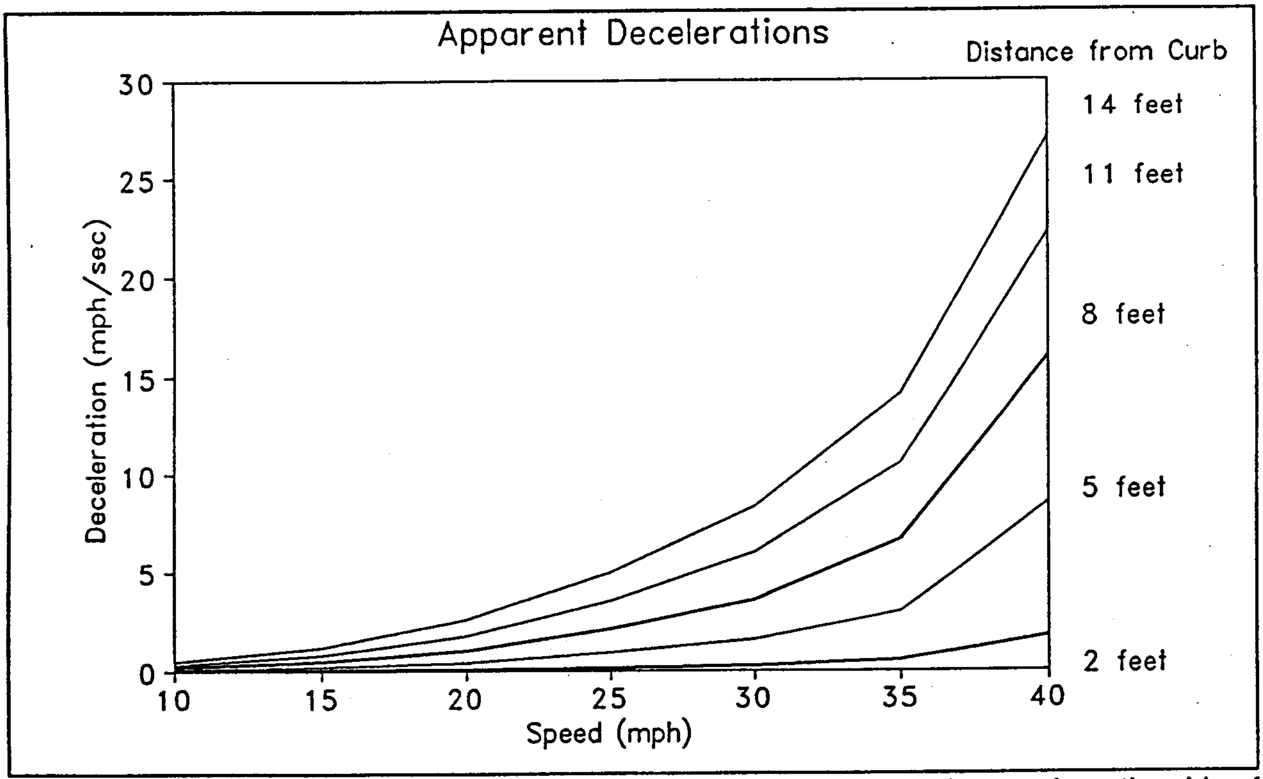

Figure 3 Graph showing the relationship between vehicle speed and distance from the side of the road to the apparent deceleration.

We conclude that the speed reported for the vehicles is largely unaffected by the cosine Θ effect since the difference in the speeds reported, except in extreme cases, is changed by only one or two mph. There is ample evidence that %CO or the equivalent gm/gallon CO mass emissions are affected very little by small changes in average vehicle speed. But the acceleration data, except for slow moving vehicles, do not have the degree of accuracy which one would like. In view of these difficulties and the fact that angle, change in angle, and heavy traffic also interfere with the data, we believe that a two-beam optical system would be an improvement. A two beam optical system could measure average speed using beam blocks from the front and then the rear of each vehicle. The difference between the speeds coupled with the change in measurement time would determine the acceleration. Further development of this system would be a valuable addition to the current CO and HC remote sensing capability.

Despite these problems we have recorded a large database of %CO and %HC measurements which include speed and acceleration from a study in Illinois (Stedman et al., Illinois report, 1991). Table I shows a summary of some of the data obtained. Accelerations are in mph/sec and speeds in mph. In this data set of over 3,000 vehicles the bias on the acceleration data is not large since most vehicles are observed between zero and two mph/sec. Not surprisingly, in view of the controlled nature of the on-ramp, there is a correlation between higher speeds and higher accelerations. What is interesting is that there is very little effect of either speed or acceleration on the observed CO or HC average emissions. The small effect observable from those fleets with a count over 50 indicates slightly lower HC and CO emissions on average with increasing speed/acceleration. No conclusive inferences can be drawn from average emissions numbers for data sets with less than fifty data entries. The fact that eight vehicles were assigned accelerations greater than seven mph/sec may represent errors in our ability to determine acceleration rather than a few high performance vehicles operating in a hard acceleration mode. Although no speed/acceleration correlations were observed at this particular site, there are likely to be other locations at which correlations would be observed and, thus, the development of a more reliable system is in order.

The reason for limiting conclusions to data sets containing at least 50 vehicles has to do with the nature of vehicle emission distributions. On-road motor vehicle CO and HC emissions show a gamma distribution. Half of the emissions come from on 10% of the fleet. When 50 vehicle subsets of a larger (10,000 vehicle) database are analyzed, there is a 17% probability of the 50 vehicle mean being a factor of two different from the 10,000 vehicle mean. For this reason we believe that any data from a fleet of 50 vehicles or less should only be treated as a qualitative indicator.

Range of Accel	Count	Speed Mph		Acceleration Mph/Sec		%CO		%HC	
		AVG	σ	AVG	σ	AVG	σ^2	AVG	σ^2
< -6	1	29.4		-6.7		1.01		0.1	
< -5	4	20.6	5.4	-5.5	0.3	0.59	0.4	0.15	0.02
< -4	3	15.3	3.5	-4.3	0.2	1.54	1.2	0.1	0
< -3	11	17.7	5.5	-3.3	0.2	1.64	1.3	0.28	0.14
< -2	56	18.1	3.8	-2.4	0.3	1.48	1.4	0.18	0.06
< -1	202	19.5	4	-1.4	0.3	1.72	1.5	0.19	0.07
< 0	581	19.5	3.9	-0.4	0.3	1.45	1.5	0.17	0.08
< 1	1260	20.8	3.4	0.6	0.3	0.89	1.2	0.11	0.04
< 2	1197	22.2	3.1	1.4	0.3	0.95	1.3	0.10	0.02
< 3	285	23.7	3.3	2.4	0.3	0.98	1.3	0.11	0.07
< 4	55	22.8	4.4	3.3	0.3	0.7	0.9	0.08	0.02
< 5	18	23.8	4	4.4	0.3	1.6	1.4	0.11	0.07
< 6	6	22.5	5	5.3	0.1	0.37	0.6	0.07	0.02
< 7	1	29.6		6.1		0.47		0.02	
< 8	4	21,6	6	7.3	0.3	0.7	0.6	0.07	0
< 9	3	20.7	3.3	8.4	0.4	3.32	2.1	0.14	0.02
< 10	1	23.3		9.1		4.05		1.07	

Range of Speed	Count	Speed Mph		Acceleration Mph/Sec		%CO		%HC	
		AVG	σ	AVG	σ	AVG	σ^2	AVG	σ^2
10-15	266	13.1	1.1	-0.1	1.5	1.24	1.4	0.15	0.13
< 20	920	17.9	1.4	0.3	1.2	1.17	1.4	0.11	0.17
< 25	1964	22.4	1.4	0.9	1.1	0.99	1.3	0.11	0.03
< 30	534	26.3	1.1	1.3	1.3	1.05	1.3	0.12	0.01
< 35	6	30.8	0.5	2.2	1.6	2.00	1.9	0.13	0.01

Table I Data summaries which show the effect of acceleration and speed on in-use CO and HC emissions in Chicago, 1990 at an on-ramp with traffic control at entry.

THE TORONTO TAPES

The University of Denver brought their instrumentation for the remote sensing of mobile source exhaust emissions to Toronto, Canada at the invitation of the City in late April of 1990. The original FEAT system (1000 series without HC capability) was used to collect data on CO emissions. As part of the data collected were video tapes allowing us to match vehicle emissions with make and model year by submitting license plate information to the local motor vehicle department. The system was set up on the ramp from northbound Bayview Extension to the Don Valley Expressway which had a 2% upgrade. FEAT collected 11,290 valid readings from 12,071 beam interruptions.

The part of the study that the city of Toronto paid for did not include reading of the video tapes and thus matching of emissions to specific vehicles. With funding from CRC all video tapes from this study have now been read. We sent data on 4,507 license plates to Ontario and received information on 4,274 vehicles regarding make, model, and model year. The matched fleet averaged 0.77 %CO with a variance of 2.01 %CO. The mean %CO for the entire fleet (11,290 vehicles) was 0.75 with a variance of 1.99 %CO.

The data collected show that the Toronto fleet was the cleanest fleet monitored by remote sensing anywhere in the world to date despite the fact that there is no routine I/M requirement in Ontario. This result arises partly because the location chosen was dominated by new vehicles which have not had a chance to deteriorate. It may also arise because a license to perform motor vehicle maintenance in Canada requires a four year apprenticeship with the attendant high level of training implied. The diesel fleet, consisting of 65 vehicles, showed not only very low CO (0.11%), but also very low standard deviation (0.14 %CO). This illustrates that the members of the diesel fleet are very low CO emitters, as expected. These data also show that the FEAT unit has low noise on low CO vehicles. Although the study was not designed to investigate the signal to noise ratio of the FEAT unit, noise has the property of being always positive and additive. Thus for any fleet, the observed standard deviation is the sum of the actual sample deviation plus the noise introduced by the detector. Therefore, the measurements herein represent a very conservative upper limit for the FEAT instrument noise for on-road low CO vehicles. The data also indicate that the diesel to gasoline engine switching, which occurs in California without proper reporting to authorities and involves about 75% of the GM diesel automobile fleet, does not occur to a significant extent in this particular fleet (Stedman et al., Report to CARB, 1991). There is no incentive not to report engine switching in Canada.

As illustrated Figure 4 shows a histogram summary of the Toronto data. Over 78% of the vehicles were emitting less than 1 %CO. The number of vehicles within each bin is multiplied by the mean emission of that bin to give the total emissions from that bin, also shown quantitatively on the Y axis. Eight vehicles were emitting over 10 %CO. Half of the total emissions came from 8.0% of the fleet and those vehicles were emitting over 2.9 %CO. At the University of Denver, vehicles contributing over half of the fleet emissions are called the gross polluters. Recent studies using FEAT 3000 series instruments with the HC channel show that high CO emissions are an indicator of high HC emissions. Gross polluters for CO are rarely low polluters of HC (Guenther, 1991).

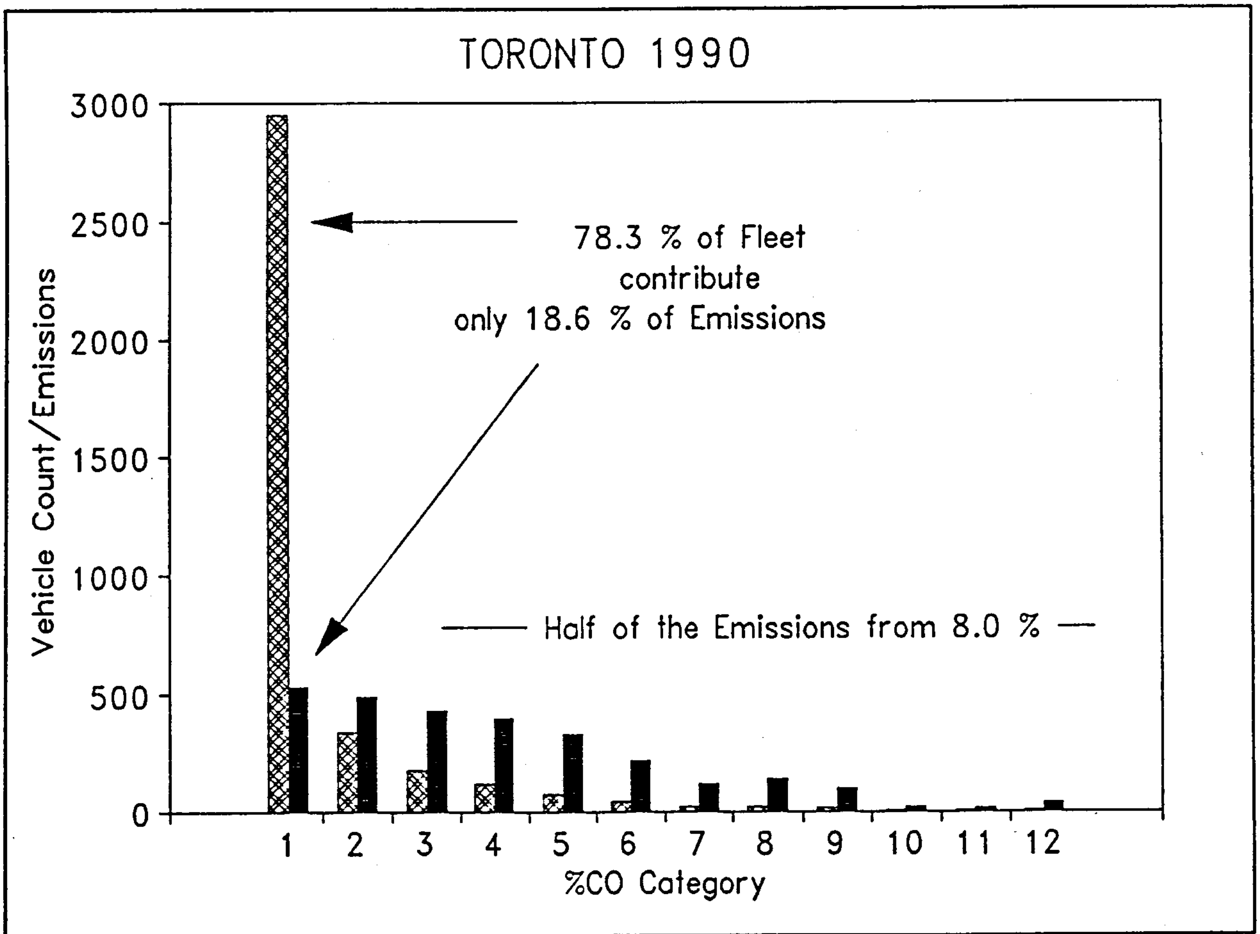

Figure 4 Histogram of vehicles and emissons from Toronto in April 1990. The light bar represents the number of vehicles in each %CO category. The solid bar is the emissions from those vehicles. The 8% with %CO > 2.9 emit ½ the fleet total.

As stated earlier, the average %CO emissions of all gasoline vehicles for which make and model year information was obtained was 0.77 %CO. For propane-powered vehicles the %CO emissions were 1.80. The average age of the propane fleet was only about one year older than the gasoline fleet. There were only 28 vehicles in this subset. The heavy tailed gamma distribution of emissions can produce great variation in small samples, thus there is insufficient information to draw any firm conclusions. The fact that %CO emissions from this small sample of propane powered cars is more than twice the fleet average, would suggest that the conventional wisdom that propane is by definition "cleaner burning" needs further study. Table II shows a listing of those vehicles, and indicates how the emissions of a small fleet of vehicles can be skewed by a very few dirty vehicles.

We were able to examine 116 vehicles that were measured more than once. Of the 240 measurements, only seven measurements exceeded our gross polluter definition (>2.9 %CO). In five of the seven cases the lower reading from the same vehicle was still double the fleet mean %CO. Two of the three highest readings came from one vehicle. This was a 1986 Dodge, 8 cylinder, commercially owned van. The two readings, which summed to 16.5 %CO, are 9.5% of the total CO emissions of all vehicles with multiple measurements. As a heavy, V-8 powered van it is not unreasonable to assume that the gas mileage of this vehicle is far less than the fleet average. As a commercially owned vehicle, the daily miles driven in the metropolitan area are likely to be more than double what an average cars travels. It is possible that this single gross polluting, low fuel economy, high usage vehicle may generate 30% of the emissions from the 116 vehicles. In this case, the identification and repair of a single vehicle will reduce overall emissions more than many fleet-wide programs could achieve.

WATER VAPOR CHANNEL

The desire to add a channel to the FEAT instrument to measure water vapor is based on the concern expressed in some quarters that we are unable to distinguish a gross emitter from a vehicle merely in a cold start mode. The channel does not have to be particularly sensitive as it need only provide an answer to the question, "Is there water vapor present in the exhaust plume?". A cold vehicle will have a cold exhaust system and the moisture produced in the combustion process will condense prior to reaching the exhaust outlet. A warm

Plate	Use	Year	Make/Model	Body	%CO	%CO$_2$
TRB404	Pas	89	CHEVCAP	4D	10.68	7.41
ZPF800	Pas	85	CHEVIMP	4D	6.65	10.3
SB5872	Bus	82	INTL172	BU	4.2	12.05
LA3792	Com	85	CHEVVAN	VN	3.97	12.21
WLA108	Pas	84	CHEVIMP	4D	3.89	12.27
XXN360	Pas	89	CHEVCAP	4D	3.64	12.45
YOM335	Pas	85	FORDLCV	4D	2.69	13.13
857CNS	Pas	85	CHEVIMP	4D	2.35	13.38
JY3432	Com	83	GMC FCC	CO	2.24	13.46
YNP641	Pas	88	PLYMG~C	4D	1.93	13.68
YNA149	Pas	84	CHEVIMP	4D	1.9	13.7
WTN674	Pas	85	CHEVIMP	4D	1.35	14.09
LT3301	Com	85	GMC VAN	VN	1.14	14.25
RZ9160	Com	89	FORDVAN	VN	0.97	14.37
YDN585	Pas	85	CHEVIMP	4D	0.77	14.51
LM1632	Com	82	DODGSPO	VN	0.4	14.78
JY3432	Com	83	GMC FCC	CO	0.35	14.81
939ECJ	Pas	87	CHEVCAP	4D	0.29	14.85
YBL308	Pas	85	CHEVIMP	4D	0.25	14.88
976EMY	Pas	88	CHEVCAP	4D	0.18	14.93
AE2259	Com	83	GMC P62	CO	0.17	14.94
ZVF363	Pas	84	CHEVIMP	4D	0.08	15
RD8262	Com	81	FORDE25	VN	0.08	15
LW8921	Com	85	FORDVAN	VN	0.08	15
TRR211	Pas	85	DODGDIP	4D	0.08	15.01
XXB686	Pas	87	CHRY5TH	4D	0.05	15.02
ZCM495	Pas	88	CHEVCAP	4D	0.03	15.04
ACX746	Pas	84	OLDSRBR	4D	0.02	15.05

Table II A listing of all 28 vehicles in the Toronto data base registered as propane powered.

vehicle will allow the vapor produced in the engine to be carried through the exhaust system and appear in the plume while still in the vapor phase.

We have carried out theoretical calculations to determine the optimum wavelength for the H_2O filter. This optimization is difficult because the system must be operational up to 40 foot pathlengths at sea-level in over 3% absolute H_2O humidity, and yet be able to detect 20% H_2O from the exhaust added in a pathlength of only 5-10 cm. The water vapor channel wavelength was chosen as 2.79μ (3580 cm^{-1}). The system has been built and shown to detect small increases in the ambient H_2O concentration. However, it has not been fully tested in view of the fact that the available funds were fully expended by the other programs.

The testing program which we have envisaged is to set the unit up at the entrance to a parking lot and test the readings from vehicles entering in the morning (mostly fully warmed up) and vehicles leaving in the afternoon, mostly in a fully cold operating mode. In addition, single vehicles, started cold, will be driven past the unit and data taken until the vehicle is fully warmed up. The data obtained would then be analyzed to determine if a cut point could be set for a Go/NoGo decision as to the likelihood that any given vehicle is (or is not) in a cold operating mode. The robustness of this cut point must then be tested under a number of different ambient humidity and temperature conditions, as well as at sea level.

At the outset it appears likely that such a channel will work provided the ambient absolute humidity does not exceed a certain level. Cold vehicle operation is more likely at colder ambient temperatures. The colder the ambient temperature, the lower the absolute humidity and, therefore, the more likely that a water vapor channel will be operational.

CONCLUSIONS

Funding from the CRC allowed us to achieve three goals; 1) to use a modified standard police radar unit to measure vehicle speed and acceleration in conjunction with remotely sensing that vehicles's CO, HC, and CO_2 emissions; 2) to read the video tapes from measurements made in Toronto, Canada which provided us with the means to fully describe the measured fleet there; and 3) to explore the addition of a water channel to an existing FEAT unit in order to separate cold from warm vehicles. The first goal was achieved in that a radar unit can be used to measure speed and acceleration. The speed data look to be quite good. However, due to problems with the nature of radar units and the effect that changing vehicle angle has on speed measurement, the acceleration measurement is often missed, and when not missed is likely to be inaccurate.

The data from Toronto show the vehicle fleet there to be the cleanest yet measured despite the absence of a routine I/M program. The fleet mean %CO was 0.77 with a variance of 2.01 %CO for the 4,274 vehicles with matched emissions and license plates and thus known make and model year information. A very small subset (28 vehicles) of the Toronto fleet consisted of propane-powered vehicles. Despite propane being touted as a "clean burning alternative fuel", this subset had over twice the mean %CO emissions of the 4,274 vehicle set. Such a finding warrants further research before additional claims are made for the utility of propane fuels in reducing mobile source CO emissions.

A channel to measure water vapor was installed on an existing FEAT unit. Funding ran out before the channel could be fully tested. However, preliminary indications are that under conditions of low absolute humidity, which is the case whenever the temperature drops below 45° F, the channel will work well enough to separate vehicles with cold exhaust systems (no water vapor) from warm vehicles.

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