1995

On-Road Remote Sensing of Vehicle Emissions in Monterrey, N. L. Mexico

Gary A. Bishop

Donald H. Stedman

ON-ROAD REMOTE SENSING OF VEHICLE EMISSIONS IN MONTERREY, N.L. MEXICO

Final Report

Prepared for:

The World Bank Group
Department of Environment & Urban Development
Washington, D.C. 20433

Submitted by:

University of Denver
Chemistry Department
Denver CO, 80208

Prepared by:

Gary A. Bishop
Donald H. Stedman

July 1995

EXECUTIVE SUMMARY

During the week of February 12, 1995 the University of Denver traveled to Monterrey, N.L. Mexico to monitor remotely the carbon monoxide (CO), hydrocarbons (HC) and nitric oxide (NO) emissions of the local vehicle fleet. In four days of monitoring at four different locations within the city, 26,534 vehicles passed the sensor. In all more than 24,000 valid measurements were obtained for CO, more than 23,000 for HC and more than 16,000 for NO. Mean values for each species were 1.69% CO (149 grams CO/liter of fuel), 0.067% HC as propane (9 grams HC/liter) and 0.143% NO (14 grams NO/liter).

Table A compares the on-road emissions measured in Monterrey with other cities that have been sampled in Mexico. The on-road emission averages are similar to the latest Mexico City data while being much lower than Juarez. In 1991 the nation of Mexico started requiring new vehicles to be manufactured to lower emissions standards which required the addition of catalytic convertors to all vehicles. This has resulted in a large decrease in fleet averaged emissions for Mexico City (between 1991 and 1994 overall CO and HC averages have decreased by a factor of 2). Juarez is likely to have seen less of a decrease because of the availability of older inexpensive vehicles from the United States. Emission levels in Monterrey remain two to four times larger than typical U.S. cities like Denver, CO.

Table A. Comparison of RSD on-road emission averages.

City and Date	Mean %CO (# vehicles)	Mean %HC[1] (# vehicles)	Mean %NO (# vehicles)
Mexico City, 1992	4.2 (31,838)	0.210 (31,838)	N/A
Mexico City, 1994	2.04 (38,440)	0.102 (38,440)	N/A
Juarez, 1993	2.96 (7,640)	0.17 (7,640)	N/A
Monterrey, 1995	1.69 (24,738)	0.067 (23,867)	0.143 (16,551)
Denver, 1994	0.52 (3,221)	0.015% (3,221)	0.048 (3,221)

[1]%HC values are reported in propane equivalent units and include methane.

One emissions observation which stands out in Monterrey as it does in the other Mexican

cities are vehicles which are emitting excessive amounts of HC. In Monterrey the highest HC emitting 1% of the vehicle fleet is responsible for 21% of the measured on-road HC emissions. Many of these vehicles smell of gasoline as they pass by on the street. This type of high HC emissions is not only indicative of fuel rich operation but must include some form of cylinder misfiring due to poor maintenance. These vehicles are operating despite Monterrey's vehicle inspection program. Targeting these vehicles for some form of immediate and mandatory maintenance action would be an extremely cost-effective way to reduce HC emissions and increase fuel economy in the Monterrey fleet. The repairs would actually save the owners money due to the fuel savings.

An initial survey of 4 hours of video taped data collected in Monterrey was made and vehicles were classified into eight categories. The groups consisted of all light duty passenger vehicles, which included vans and sport utility vehicles, light duty pickup trucks, Eco Taxis, post 1990 catalyst equipped VW Beetles (including any Eco taxis), pre 1991 non-catalyst equipped VW Beetles (including any Eco taxis), gasoline powered Micro transit buses, diesel powered transit buses and trucks larger than pickup trucks. The results are given in Table B. These data clearly show the emissions difference between new technology VW Beetles which are less than a factor of two lower emitting than the older VW Beetles. Of all the subfleets the taxis are the lowest emitting gasoline powered subfleet examined. The Micro buses had much higher than average CO emissions which may indicate that some of these have been converted to propane which is notorious in other parts of the world for high CO emissions when improperly tuned.

All of the exhaust species measured in Monterrey have been shown in other studies to have a strong dependance on vehicle age. As the Monterrey fleet has grown and included vehicles with new emissions control technology, such as catalytic convertors, the average fleet emissions have decreased. The continuation of this decrease will depend on the rate at which new technology vehicles continue to enter the fleet and how well they maintain their new car emissions levels. The maintenance issue is an important one in light of the devaluation of the peso and the resultant increase in interest rates and a tightening of credit. We would expect that this would slow new car sales in Mexico and possibly cause the average age of the vehicle fleet to increase. We also expect a higher misfueling rate to occur (using leaded gasoline in a catalyst equipped vehicle) since this fuel is less expensive and still readily available. This type of malmaintenance will quickly erase the many of the benefits of the new technology vehicles. This places a premium on proper maintenance of the new technology vehicles currently in the fleet. Without this maintenance the average fleet emissions will surely increase.

Table B. Emissions by vehicle classifications from 4 hours of data.

Vehicle Class	Mean %CO *Mean COg/lit*[1] (# Vehicles)	Mean %HC[2] *Mean HCg/lit*[1] (# Vehicles)	Mean %NO *Mean NOg/lit*[1,3] (# Vehicles)
LD Passenger Vehicles[4]	1.45 *132* (3,334)	0.051 *7* (3,287)	0.134 *14* (2,604)
LD Trucks[5]	1.67 *158* (580)	0.055 *8* (574)	0.131 *13* (478)
Eco Taxis[6]	1.10 *99* (581)	0.037 *5* (573)	0.109 *11* (425)
Post 90 VW's[7] (catalyst equipped)	1.09 *98* (340)	0.041 *6* (333)	0.096 *10* (240)
Pre 91 VW's[7] (non-catalyst)	2.64 *228* (188)	0.119 *15* (180)	0.220 *22* (113)
HD Trucks[8]	1.43 *133* (188)	0.079 *11* (153)	0.133 *14* (112)
Buses[9]	0.24 *24* (171)	0.020 *3* (153)	0.076 *8* (74)
Micro Buses[10]	2.00 *185* (44)	0.036 *5* (43)	0.118 *12* (37)

[1]Mean g/lit calculations assume a fuel density of 0.726 g/ml. [2]%HC values are reported in propane equivalent units and include methane. [3]NO emissions as grams of NO, not converted to NO_2. [4]Light duty passenger vehicles (includes taxis and VW Beetles), vans and sport utility vehicles. [5]Pickup trucks. [6]Green and white painted taxis. [7]VW Beetles only. [8]Gasoline and diesel trucks larger than pickup trucks. [9]Diesel powered transit buses. [10]Small gasoline powered transit buses.

INTRODUCTION

The University of Denver, under contract to The World Bank, was invited to the city of Monterrey, N.L., Mexico to monitor light-duty vehicle emissions. Monterrey is the capital of the State of Nuevo Leon and was founded by don Diego de Montemayor in 1596. The Monterrey metropolitan area is Mexico's second largest urban/industrial center with a population estimated at almost 3 million people. Due to the heavily industrialized nature of the area, the motor vehicle fleet is only one of a number of potentially large sources of emissions. Currently the motor vehicle fleet is estimated at 600,000 vehicles and it is projected to grow at an annual rate of 7%. The city currently exceeds Mexican air quality standards for particulate matter, ozone and nitrogen oxides and it is feared that emissions are increasing.

The city has instituted a twice yearly emissions inspection of all registered vehicles conducted by a central contractor at 9 locations around the city. This inspection is reported to consist of a 11 point visual inspection and a two speed idle test for gasoline vehicles and a snap idle smoke test for diesels. In tandem with Monterrey's inspection program the nation of Mexico in 1991 reduced the emission standards for new vehicles. This has resulted in all new light duty gasoline vehicles having catalyst-equipped emission control systems which are similar to US vehicles. These types of emissions control systems have been shown in the U.S. to be reliable and provide large reductions in tailpipe emissions provided proper maintenance practices are followed.

As a way to study a regions air quality it has become standard practice to conduct an analysis of all of a regions sources of air pollution and to obtain a region wide emissions inventory. This type of data has been routinely used by scientists and air quality officials to plan strategies which might help to mitigate future emissions and to lower the public's exposure to harmful levels of air pollutants. Estimating the emissions of a regional motor vehicle fleet is an important part of any inventory work and one to which the University of Denver is ideally suited to contribute.

ON-ROAD REMOTE SENSING

In 1987, with support from the Colorado Office of Energy Conservation, the University of Denver developed an infra-red (IR) on-road remote sensing device (RSD) for automobile carbon monoxide (CO) exhaust emissions (Bishop *et al.*, 1989). Significant fuel economy improvements result if rich-burning (high CO and HC emissions) or misfiring (high HC emissions) vehicles are tuned to a more stoichiometric and more efficient air/fuel (A/F) ratio. Therefore, the University of Denver CO/HC remote sensor is named Fuel Efficiency Automobile Test (FEAT). 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 infra-red light beam which is transmitted across a single lane of roadway. The addition of an ultraviolet source and detection system has enabled the instrument to simultaneously measure the nitric oxide (NO) to carbon dioxide ratio as well (Zhang *et al.*, 1995). Figure 1 shows a schematic diagram of the instrument (U.S. Patent No. 5210702).

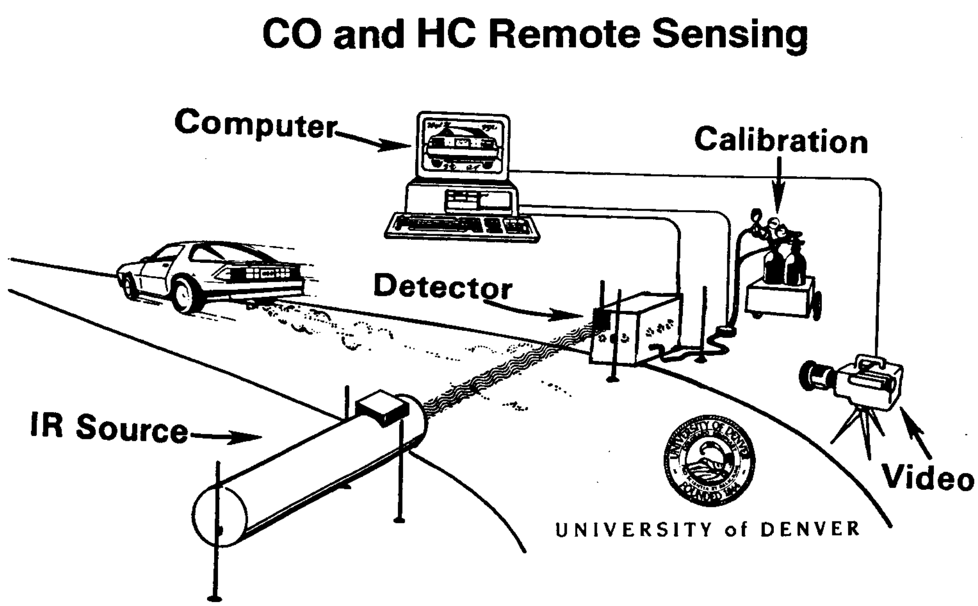

Figure 1 A schematic diagram of the University's of Denver remote automobile emissions detection system (FEAT). More than 1.5 million vehicles in 17 different countries have been monitored by the University.

Theory of Operation

The FEAT instrument was designed to emulate the results one would obtain using a conventional non-dispersive exhaust gas analyzer. An IR/UV source sends a collimated horizontal beam of radiation across a single traffic lane, approximately 10 inches above the road surface. This beam is directed into the detector on the opposite side and divided between five individual detectors; CO, CO_2, HC, IR reference, NO and UV reference (UV absorption detection is accomplished with a single detector). Each detector utilizes an optical filter that transmits light of a wavelength known to be uniquely absorbed by the molecule of interest, determining its specificity. Reduction in the light intensity caused by absorption of light by the molecules of interest reduces the voltage output.

Before each day's operation we perform a quality assurance calibration on the instrument with the system set up in the field. A puff of gas designed to simulate all measured components of the exhaust is released into the instrument's path from a cylinder containing industry certified amounts of CO, CO_2, propane and NO. On international trips a sealed calibration cell is employed in place of the high pressure cylinder. These measured ratios are used to adjust that day's vehicle exhaust measurements. In effect the instrument becomes a comparator, comparing the unknown exhaust ratios from passing vehicles with those of the known cylinder or calibration cell.

Because the effective plume path length and amount of plume seen depends on turbulence and wind, the FEAT can only directly measure ratios of CO, HC and NO to CO_2. With a fundamental knowledge of combustion chemistry, we can determine many parameters of the vehicle's operating characteristics, including the instantaneous air/fuel ratio, grams of CO, HC or NO emitted per liter of gasoline (gCO/liter, gHC/liter or gNO/liter) burned, and the %CO, %HC and %NO in the exhaust gas. Most U.S. vehicles show CO/CO_2 and HC/CO_2 of near-zero since they emit little to no CO or HC. To observe CO or HC values greater than near-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 HC/CO_2 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 will increase NO emissions but does not produce CO in the engine. If the air/fuel ratio is lean enough to induce misfire then a large amount of unburned 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, the HC may be partially or totally converted to a CO/CO_2 mixture.

Field Experience

The FEAT is effective across traffic lanes of up to 50 feet in width. It can be operated across double lanes of traffic with additional video hardware; however, the normal operating mode is on single lane traffic (Bishop *et al.*, 1993). The FEAT operates most effectively on dry pavement, as rain, snow, and spray from very wet pavement scatter the IR beam. These interferences cause the frequency of invalid readings to increase, ultimately to the point that all data are rejected as being contaminated by too much "noise". At suitable locations we have monitored exhaust from over two thousand vehicles per hour. The FEAT has been used to measure the emissions of more than 1.5 million vehicles in Denver (PRC Environmental Management Inc., 1992 and Bishop *et al.*, 1991), Chicago (Stedman *et al.*, 1991a), the Los Angeles Basin (Stedman *et al.*, 1991b), Toronto (Peterson *et al.*, 1991), Sweden (Sjödin, 1991), and Mexico City (Beaton *et al.*, 1992).

The FEAT has been shown to give accurate readings for CO, HC and NO in double-blind studies of vehicles both on the road and on dynamometers (Lawson *et al.*, 1990; Stedman and Bishop, 1991; Elliott *et al.*, 1992; Ashbaugh *et al.*, 1993; Zhang *et al.*, 1995).

Comparisons with Alternate Testing Methods

Glover and Clemmens (1991) compared mean on-road FEAT measurements with those obtained by traditional dynamometer testing. Using Corporate Average Fuel Economy (CAFE) estimates to convert remote sensing measurements of grams/gallon to grams/mile to compare fleet on-road emissions with IM240 grams/mile CO emissions for the same vehicles. The comparison of fleet emissions measured by on-road remote sensing to those made by IM240 is shown in Figure 2. Additional data collected during a pullover study of on-road gross polluters in California is also shown as a filled circle (●) in Figure 2 (Knapp, 1992). These data indicate that, even for small fleets of vehicles, average IM240 CO emissions agree well with average measured on-road emission data when the on-road grams/gallon data are converted to grams/mile using CAFE fuel economy estimates.

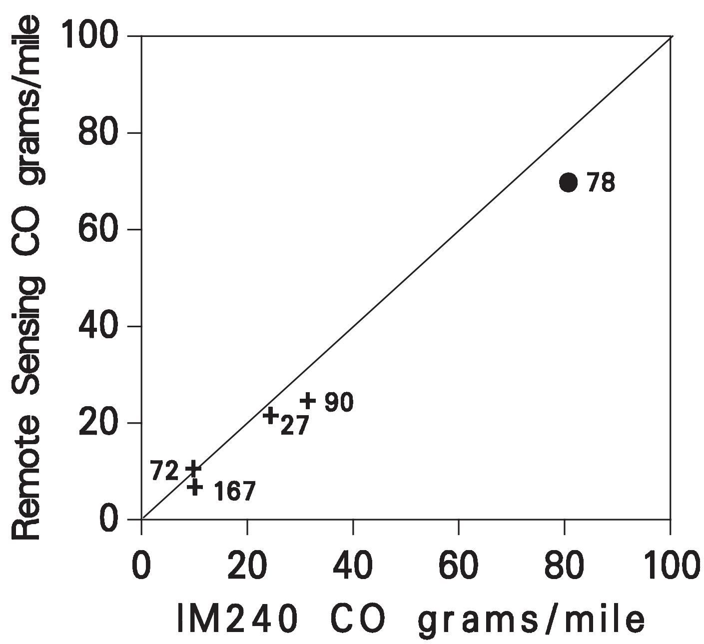

Figure 2 On-road fleet %CO emissions converted to grams/mile emissions compared to IM240 CO grams/mile emissions. The fleet sizes are noted next to the symbol.

A similar study has been conducted by the California Air Resources Board on a fleet of 554 vehicles (Schwartz, 1995). Remote Sensing CO and HC data were collected under controlled 25 mph driving conditions and compared with the new car certification test the Federal Test Procedure (FTP). The data were averaged and plotted by quintiles against one another and the excellent correlation is shown in Figure 3. Both studies show that average on-road concentration emissions can be used in lieu of mass emissions data.

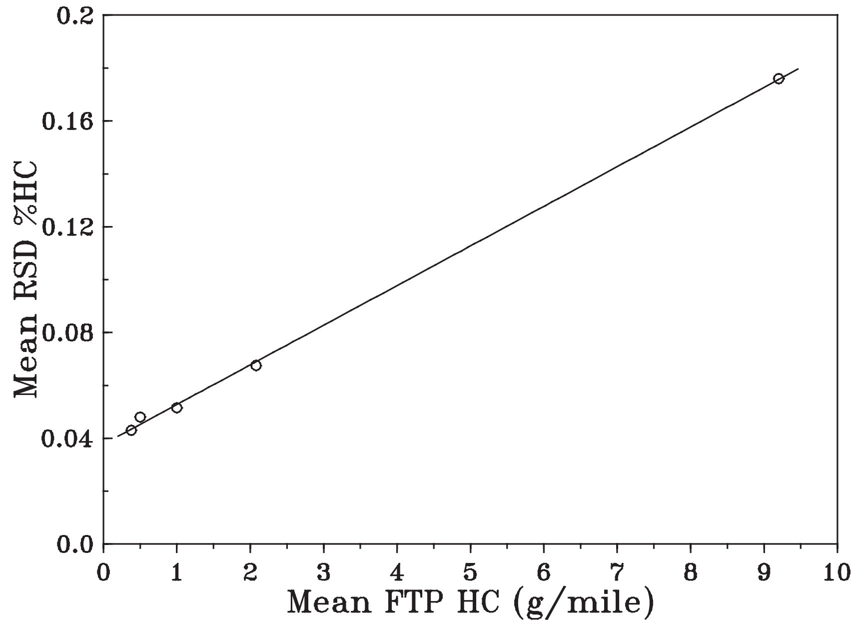

Figure 3. On-road HC emissions averaged by quintiles compared to Federal Test Procedure data for a 554 car California fleet (Schwartz, 1995). The r^2 for the regression is 0.999.

MONTERREY RESULTS

Remote sensing measurements were conducted in the Monterrey metropolitan area from February 14, 1995 to February 17, 1995. Site selection was conducted on Monday, February 13, 1995 and was heavily influenced by safety and convenience issues. Important criteria used in the site selection process were: 1) the desire for a single lane of traffic to monitor or two lane roads which could be safely restricted to a single lane; 2) sufficient roadway shoulders to safely park the support van, generator and remote sensing equipment; 3) sufficient flow of traffic (typically greater than 500 vehicles/hour); 4) sites with a contrasting mixture of vehicle types; 5) sites where vehicles were traveling uphill or flat roadways underload are an optimum remote sensing site (sites where the vehicles are traveling down a hill should be avoided) and were given a higher priority as the collection of NO data is more advantageous under these conditions. The only deviation from these criteria was for the final day of sampling when rainy weather forced us to abandon the planned monitoring site in favor or one which was covered. In all four locations were sampled and these sites have been marked on the map shown in Figure 4.

Table I provides the site specific on-road emissions measurement information for each of the locations sampled. The validation of remote sensing measurements involves a two step process. 1) The RSD first verifies the presence of a vehicle by analyzing the changes in CO_2

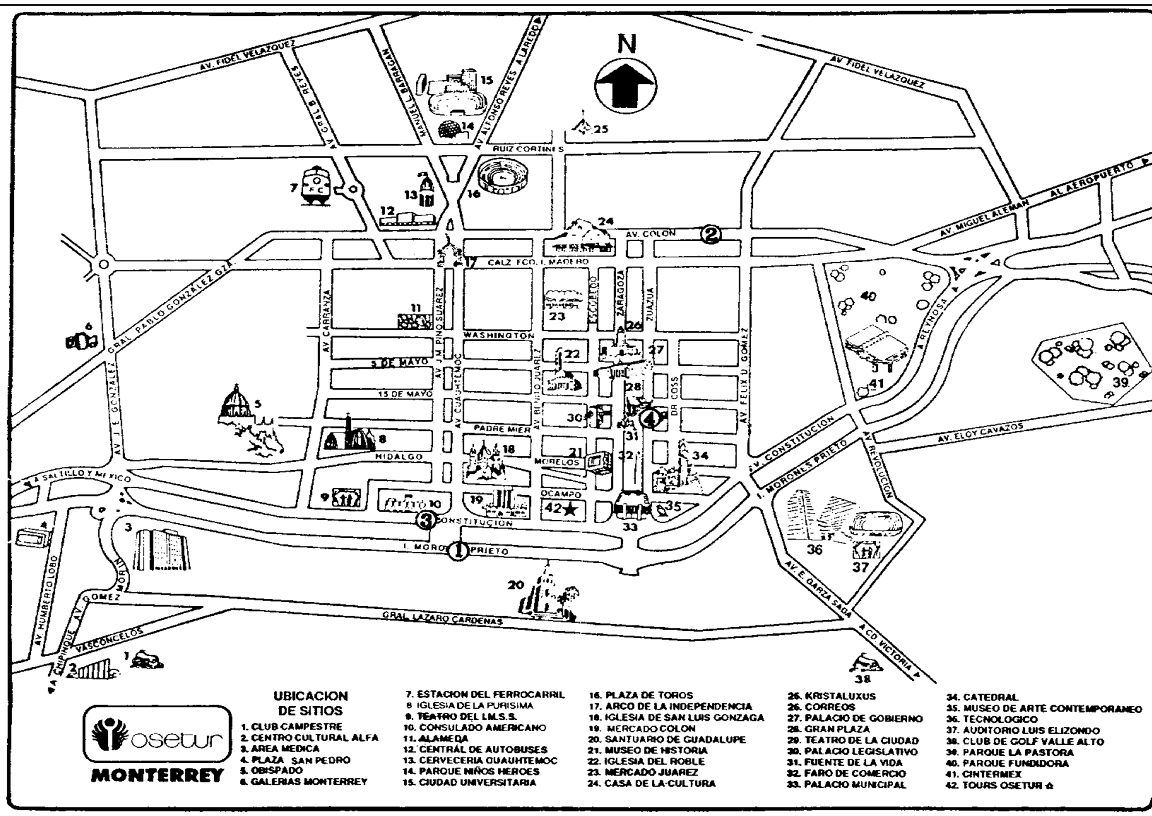

Figure 4. Area street map of Monterrey, N.L. Mexico with the four remote sensing sites numbered 1 to 4 to match the sites listed in Table I.

concentration from in front of the vehicle and behind the vehicle. It is assumed that all internal combustion engine powered vehicles will emit CO_2 from the tailpipe, a failure of the instrument to measure significant changes in CO_2 behind a vehicle results in an invalid readings for all species (Due to different sensitivities and noise constraints NO measurements are required to have 5 times the change in CO_2 concentration than CO and HC before calculations are performed. This results in the decreased capture rates for NO when compared to CO and HC.). Reasons for an invalid reading of this type range from vehicles with elevated exhausts (not emitted at ground level where we are monitoring), slow moving transit buses as measured on WB. AV. Colon (these vehicles have ground level exhaust pipes, but their slow rate of travel, high ground clearance and the RSD's measurement time, results in an attempted measurement which is usually started behind the rear wheels and completed before the end of the bus, and thus exhaust is reached), and people walking or bicycling through the measurement beam. 2) After the RSD determines that a sufficient change has occurred in the measured CO_2 concentrations the individual species concentrations and associated errors are calculated from the measured ratios. These values and their errors are compared against predetermined quality assurance limits and if they fall outside of these limits an individual measurement or all of measurements are invalidated.

Site Descriptions

On February 14 the equipment was located on a freeway entrance ramp from southbound AV. J. M. Pino Suarez to eastbound I. Morones Prieto. This was a two lane ramp which descended from Pino Suarez under a roadway and then ascended (approximately a 3% grade) to meet I. Morones Prieto. The remote sensing equipment was located at the midway point of the incline and traffic flow was only slightly effected by the single lane constriction. The traffic was predominantly light duty passenger cars and light duty trucks. Vehicle speeds were estimated at between 40 and 60 km/hr with the most of the vehicles being under load when they reached the RSD. The equipment was operated between 8:40 and 16:00 hours. A single generator was used which was located overhead on the cross street bridge.

Table I. Site and measurement statistics for Monterrey, N.L. Mexico.

Location (Date)	Vehicles	Valid CO (%)	Valid HC (%)	Valid NO (%)
1. SB. Av. J. M. Pino Suarez to EB. I. Morones Prieto (2/14)	9,414	8,898 (95)	8,388 (89)	4,899 (52)
2. WB. Av. Colon (2/15)	6,787	5,975 (88)	5,841 (86)	4,216 (62)
3. SB. Av. J. M. Pion Suarez to WB. Av. Constitucion (2/16)	7,118	6,746 (95)	6,607 (93)	5,316 (75)
4. NB. Zuazua (2/17)	3,215	3,119 (97)	3,031 (94)	2,120 (66)
All Sites	26,534	24,738 (93)	23,867 (90)	16,551 (62)

The second Site monitored on wednesday February 15 was on west bound Av. Colon between the intersections of streets of Av. Felix U. Gomez to the east and P. Sánchez to the west. The roadway is a flat two lane surface street which was constricted to a single lane for measurement purposes. The traffic at this location was a mix of light and heavy duty vehicles. Taxi cabs and pickup trucks were very common light duty vehicles and diesel transit, diesel powered over-the-road buses and delivery trucks dominated the heavy duty vehicles. Vehicle traffic at this location was controlled by a signal light at Av. Felix U. Gomez and low speed (25 to 40 km/hr) cruises were the dominant driving mode. Data were collected at this site between the hours of 9:00 and 16:00. A single generator was used and power was supplied to the opposite side of the road by an extension cord crossing the roadway.

On Thursday February 16 we attempted to use a site located in the north part of the city near the University. This site was too heavily congested for a single lane operation and after a brief attempt to install the equipment we agreed to abandon this location and move to our third site on an on-ramp located between SB. Av. J. M. Pino Suarez and WB. Av. Constitucion. This location offered a slight downgrade off of Av. J. M. Pino Suarez followed by a short incline (~2% grade) as it merged with Av. Constitucion with the equipment located at the top of this short rise. Data were collected between 10:00 and 16:00 hours.

The final day of measurements on February 17 was carried out on Zuazua street underneath the Gran Plaza. Working underneath the plaza was necessary because of a steady rain which had started overnight and continued for most of the day. This roadway is a level one way four lane cobblestone surface street. The RSD equipment was setup across a single outside lane. No lane closures were used at this location. The RSD source was setup between two active lanes of traffic protected by roadway cones allowing the traffic to use either lane. This reduced the number of vehicles monitored at this site, but was a necessary trade-off to avoid canceling measurements for the day. This site had the lowest overall volume with light to moderate cruise being the dominant driving modes with speeds between 25 and 40 km/hr. The vehicles were predominantly light duty passenger vehicles and light duty trucks with almost no transit buses or delivery trucks.

Daily Results

Tables II and III provide a summary of the fleet emission averages determined at the four Monterrey locations. As will be discussed later, interpretation and/or comparison of the differences in the averages from each locations must take into account the types of vehicles (gasoline versus diesel) and the average ages of the vehicles measured. These factors will greatly effect the meaningfulness of the differences.

Table II presents the mean and median fleet average molar tailpipe concentrations for CO, HC (propane equivalents), and NO. Table III provides the same data as fleet averaged grams of a particular species/liter of fuel consumed. Each of the values listed in Tables II and III are an average for the number of vehicles listed for each site and species in Table I. Figure 5 displays a decile plot for each of the measured species for the combination of all of the Monterrey sites. To produce this plot all valid emissions readings for each pollutant are sorted in ascending order. The average of the lowest 30% are plotted for the first three deciles (0,1 and 2). Each subsequent decile shows the average emissions of 10% of the measured fleet. For CO and NO the mean emissions are dominated by the highest 20% of the fleet. For HC the top 10% dominate the mean values. For all pollutants there is an

Table II. Fleet mean and median concentration measurements for Monterrey, N.L. Mexico

Location	Mean %CO[1] (Median)	Mean %HC[1,2] (Median)[2]	%NO[1] (Median)
1. Morones Prieto	1.80 (0.86)	0.076 (0.034)	0.188 (0.171)
2. Av. Colon	1.67 (0.79)	0.059 (0.026)	0.114 (0.097)
3. Av. Constitucion	1.45 (0.63)	0.054 (0.025)	0.141 (0.126)
4. Zuazua St.	1.93 (0.87)	0.089 (0.046)	0.102 (0.082)
All Sites %Total emissions from 10th decile	1.69 (0.78) 39%	0.067 (0.031) 57%	0.143 (0.123) 29%

[1]Fleet average molar concentrations for the number of vehicles given in Table I.
[2]%HC values are reported in propane equivalent units and include methane.

obvious contrast between the top 10-20% gross polluters and the lowest 30% low emitting vehicles.

We believe that the number of measurements, the mix of vehicles measured, and the observed driving modes provides a representative inventory for CO emissions. The measurement of CO is the most robust measurement of the three because it is influenced the least by driving conditions. The HC and NO data provide accurate information as to the fleets emissions distribution and relative size of its emissions. However, HC and NO are more load/site dependent than CO and for the purpose of HC inventories individual species emissions rates are often required. The RSD's HC measurements are most sensitive to paraffins (straight and branched chain alkanes in particular) with very little sensitivity for the aromatic compounds (most of which have high ozone formation potentials). It is assumed that gasolines in Monterrey have a high aromatic content, therefore the use of the RSD HC data for Monterrey's inventory will result in an ozone formation potential which is low and would need to be scaled upward to account for the aromatic emissions. The NO emissions will likely produce inventories which are statistically high because of our emphasis to test at sites where vehicles were being driven under load and NO emissions will be lower at other, less loaded locations in Monterrey.

Table III. Fleet mean and median grams/liter measurements for Monterrey, N.L. Mexico

Location	Mean gCO/liter[1] (Median)	Mean gHC/liter[1] (Median)	Mean gNO/liter[1,2] (Median)
1. Morones Prieto	158 (81)	10 (5.1)	19 (17)
2. Av. Colon	147 (75)	8 (3.9)	12 (10)
3. Av. Constitucion	128 (60)	7.3 (3.8)	14 (13)
4. Zuazua St.	168 (82)	11.8 (6.7)	10 (8)
All Sites[3] (± S.D.)	149 ± 17 (73)	9 ± 2 (4.5)	14 ± 4 (12)

[1]Fleet average grams/liter of fuel calculations assume a fuel density of 0.726g/ml.
[2]NO emissions as grams of NO, not converted to NO_2.
[3]Assuming a gas mileage of 6 km/l these averages translate into 24.8 g/km for CO, 1.5 g/km for HC and 2.3 g/km for NO. Current Mexican tailpipe standards (NOM-CCAT-004-ECOL/1993) for 1994 and newer model year automobiles is 2.11 g/km for CO, 0.25 g/km for HC and 0.62 g/km for NO. Truck standards are 8.75 g/km for CO, 0.63 g/km for HC and 1.44 g/km for NO.

For emission inventory purposes the average measured emissions (149 ± 17; 9 ± 2 and 14 ± 4 grams/liter) of CO, HC and NO respectively can be multiplied by total fuel sales in liters to obtain total mass. More detailed breakdown into vehicle/fuel classes can be obtained from Table IV using for instance the diesel bus emissions to estimate for all diesels. Mass emission values can be estimated from g/lit values but are highly dependent on the driving conditions monitored (especially speed) and the fleet fuel economy value used.

Emissions by Vehicle Class

Two of the video taped data were reviewed for vehicle type, and where possible vehicle make to provide a glimpse at emissions in Monterrey for the different classes of vehicles. A tape from Av. Colon (with data recorded between 12:06 and 14:19) and one from Av. Constitucion (between 12:07 and 14:14) were reviewed and vehicles were classified into 8 different groups. The groups consisted of all light duty passenger vehicles, which included vans and sport utility vehicles, light duty pickup trucks, Eco Taxis, post 1990 VW Beetles (including any

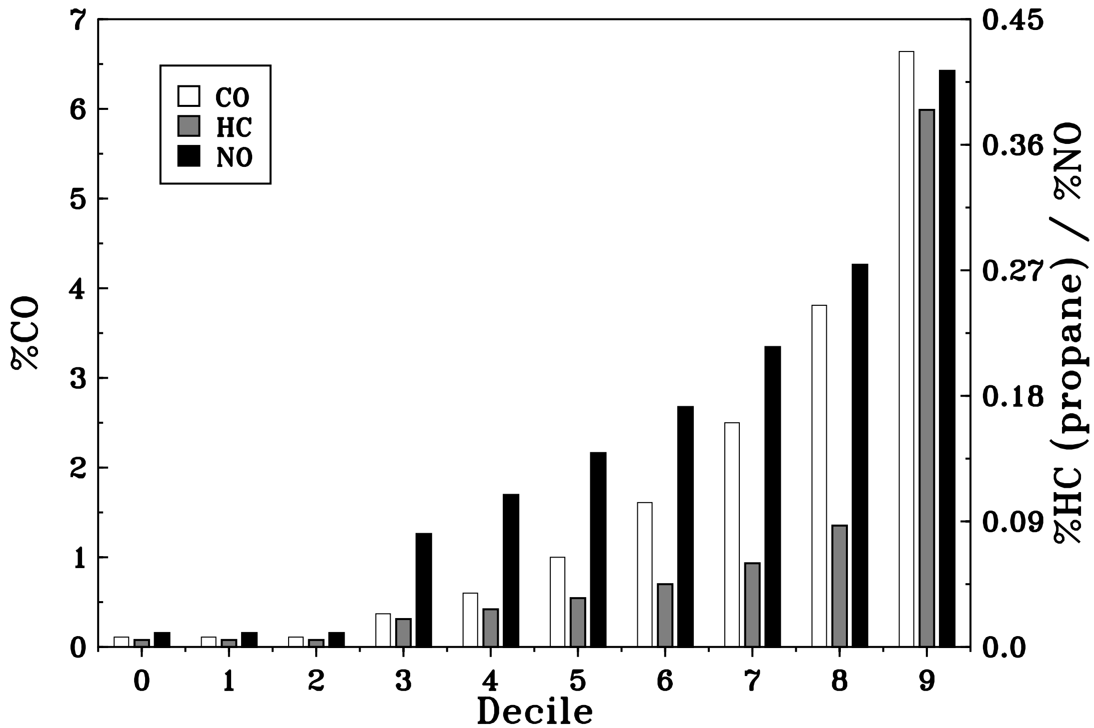

Figure 5. Average %CO, %HC (propane) and %NO plotted by deciles for the combined on-road RSD data collected in Monterrey, N.L. Mexico in February, 1995.

Eco taxis), pre 1991 VW Beetles (including any Eco taxis), gasoline powered Micro transit buses, diesel powered transit buses and trucks larger than pickup trucks. The designations were chosen for convenience and are not meant to be an exhaustive listing. The averages for light duty passenger vehicles includes the Eco Taxis and both pre 91 and post 90 VW Beetles. The averages for the pre 91 and post 90 VW Beetles also includes any Eco Taxis's of the same make and model. Eco Taxis are painted green and white and are required by law to be catalyst equipped post 1990 vehicles. The break out of the VW Beetles is possible due to the fact that model year designations can be determined from the number of tailpipe body openings which exist in the rear body panel of the Beetles. Dual tailpipe cutouts in the rear body panel designate a pre 1991 Beetle which is carbureted and has no emissions control equipment on the engine. A single tailpipe cutout indicates a post 1990 fuel injected Beetle which was originally equipped with a catalytic convertor. This designation provides a glimpse into how effective the changes in emissions controls have been.

Table IV. Emissions by vehicle classifications from 4 hours of data.

Vehicle Class	Mean %CO *Mean COg/lit*[1] (# Vehicles)	Mean %HC[2] *Mean HCg/lit*[1] (# Vehicles)	Mean %NO *Mean NOg/lit*[1,3] (# Vehicles)
LD Passenger Vehicles[4]	1.45 *132* (3,334)	0.051 *7* (3,287)	0.134 *14* (2,604)
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Buses[9]	0.24 *24* (171)	0.020 *3* (153)	0.076 *8* (74)
Micro Buses[10]	2.00 *185* (44)	0.036 *5* (43)	0.118 *12* (37)

[1]Mean g/lit calculations assume a fuel density of 0.726 g/ml. [2]%HC values are reported in propane equivalent units and include methane. [3]NO emissions as grams of NO, not converted to NO_2. [4]Light duty passenger vehicles (includes taxis and VW Beetles), vans and sport utility vehicles. [5]Pickup trucks. [6]Green and white painted taxis. [7]VW Beetles only. [8]Gasoline and diesel trucks larger than pickup trucks. [9]Diesel powered transit buses. [10]Small gasoline powered transit buses.

DISCUSSION

The vehicle fleet in Monterrey show emissions distributions which have similar characteristics as many other sites which we have monitored from around the world. Namely, that a disproportionate percent of the emissions is contributed by a small percentage of the vehicles. Table II and Figure 5 highlight the fact that the last decile for each species measured contributes a large percentage of the total emissions.

Carbon monoxide emissions in Monterrey are less skewed than found in U.S. fleets (i.e. in the U.S. the dirtiest 10% of the fleet account for approximately 60% of the total emissions). This means that in Monterrey more CO emissions show up in the middle deciles. The large majority of properly maintained vehicles in the USA with functioning catalytic convertors push the middle deciles much lower than found in Monterrey. It is possible that either rich operation in catalyst equipped vehicles or the presence of a higher percentage of pre-1991 models is responsible for this observation. In Sweden when catalysts had been introduced for three years a CO distribution more skewed (like the Monterrey HC distribution) than Monterrey was observed (Sjödin, 1991). Swedish vehicles have a reputation for being extremely well maintained. This would lead one to suspect that a number of new technology Mexican vehicles are experiencing problems and/or are having their emissions control equipment tampered with, i.e. by misfueling with leaded gasoline.

One attempt to measure the publics compliance with Mexican emission laws and perhaps their attitude toward their own vehicles emissions was to count the number of pre 1991 VW Beetles which are painted as Eco Taxis. The review of the four hours of videotape found a total of 581 Eco Taxis and their breakdown is shown in Table V. As can be seen from the table a small portion of the taxis's are now vehicles which do not meet the Eco taxis emissions technology requirement. The pre-1991 VW Beetles have emissions which are 3 times larger than non-Beetle taxis for CO and HC. The presence of these non-catalytic equipped VW Beetles, albeit small, should illustrate that a regulations emissions gain can be quickly eroded by non-compliance.

Hydrocarbon emissions are the most skewed with the last decile responsible for 59% of the total. High hydrocarbon emissions, as mentioned earlier, stem from rich engine operation (too much fuel for the amount of air in the engine) and misfires. Misfires can occur from a lack of fuel in the cylinder (called lean burn misfires) or from a poor mechanical state of the ignition components. Lean burn misfires are usually accompanied by low CO emissions. This situation is complicated by the presence of catalytic convertors which when functioning can partially oxidize the unburned fuel to CO even though the engine is not producing any CO. In Monterrey extremely high HC emissions are observed in the top 1% of the vehicles. This portion of the fleet is responsible for 21% of the measured on-road HC emissions. These vehicles average 10,400 ppm HC as propane (this translates into 5200 ppm HC as hexane) and 4.8% CO indicating very rich engine operation in conjunction with cylinder misfires. These are a significant source of emissions in Monterrey and are escaping repairs under the current inspection system. Targeting these vehicles for some form of maintenance action

Table V. Eco Taxis vehicle classifications.

Eco Taxis Type	Mean %CO (# Vehicles)	Mean %HC[1] (# Vehicles)	Mean %NO (# Vehicles)	Percent of Sample
Post 1990 VW Beetles (catalyst equipped)	1.12 (175)	0.046 (171)	0.096 (116)	30
Pre 1991 VW Beetles (non-catalyst)	2.91 (19)	0.073 (19)	0.168 (14)	3.3
All other makes and models	0.88 (387)	0.026 (383)	0.111 (295)	66.7
Totals	1.10 (581)	0.037 (573)	0.109 (425)	100

[1]%HC values are reported in propane equivalent units and include methane.

would be an extremely cost-effective way to reduce HC emissions from the Monterrey fleet. More information about the model year dependencies of these vehicles would provide needed information as to the types of potential maintenance problems.

Measured NO emissions are nearly normally distributed in Monterrey. The limited US data which we have collected shows NO emissions distributed similarly to CO and HC. It is obvious from tables IV and V that catalytic equipped vehicles have significantly lower levels of NO emissions. Most likely the large number of pre 1991 vehicles which are still operating in Monterrey account for this flatter and less skewed distribution.

Comparisons to other Locations

The University of Denver has conducted similar measurement programs in two additional Mexican cities for CO and HC. Data have been collected in Mexico City during February 1991 (Beaton *et al.*, 1991) and October 1994 at a variety of sites around the city, and in Juarez during March of 1993. Figure 6 displays the CO and HC emissions for these measurements and two U.S. cities, Denver and Baltimore, to compare with the Monterrey data. The data for the Mexican cities are also tabulated in Table VI for comparison. In general the Monterrey measurements are similar to the data collected in Mexico City in October of 1994 and are two to four times the averages for typical U.S. cities. The large reduction in emissions in Mexico City is most likely due to the introduction of catalyst assisted emissions control equipment with the 1991 model year vehicles.

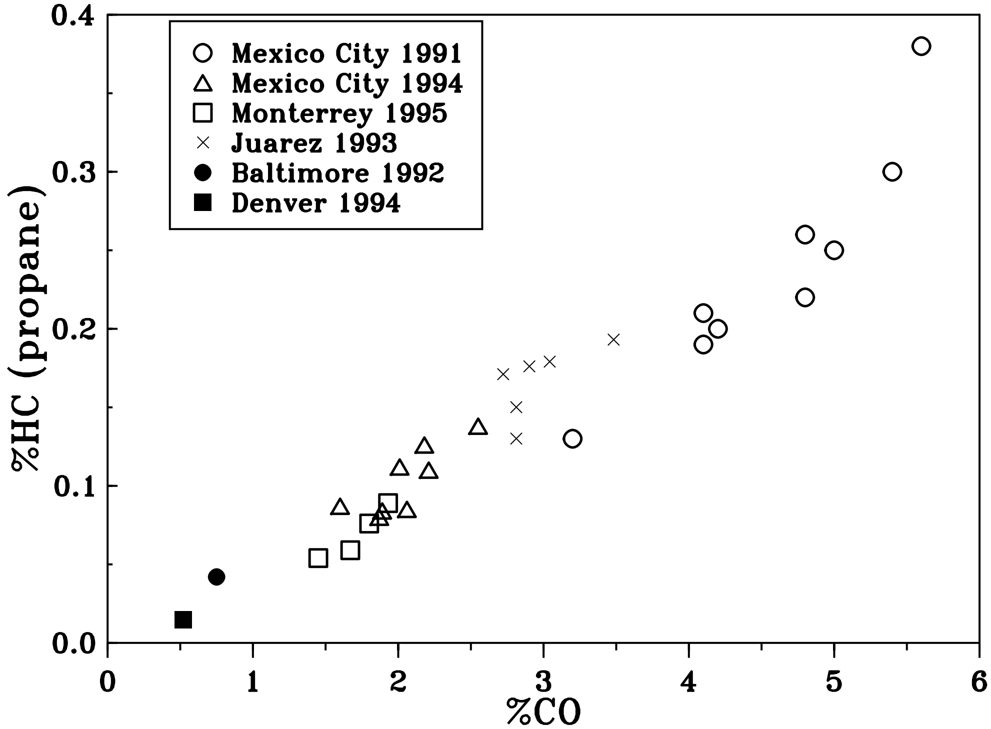

Figure 6. Comparison of CO and HC data collected in four Mexican cites since 1991 and measurements from two U.S. cities.

When comparing the Monterrey data with Mexico City there are several factors which can account for the slight differences which are observed. Vehicle emissions are greatly effected by the age and maintenance levels of the cars which are measured. When a country changes its vehicles emissions technology each new car purchased will usually displace a higher emitting vehicle. Provided the vehicle purchased remains low emitting this will start a downward trend in overall fleet emissions which, when observed at different times of the year, will continually be decreasing until some point in time when it reaches equilibrium. Figure 7 is on-road data collected in Sweden after that country implemented new emissions control technologies for vehicles. Starting with 50% of the 1987 model year vehicles, Swedish vehicles were equipped with 3-way catalytic convertors and closed-loop emissions control circuitry. The fact that the Monterrey data was collected 4 months after the latest Mexico City data probably accounts for the small difference. In addition it is apparent that Monterrey has many areas with a high standard of living and thus newer vehicles. Also while the VW Beetles are popular in Monterrey they are not as nearly as numerous as in Mexico

Table VI. Comparison of RSD CO and HC emission averages from Mexican cities.

City and Date	Mean %CO (# vehicles)	Mean %HC[1] (# vehicles)
Mexico City, 1992	4.2 (31,838)	0.210 (31,838)
Mexico City, 1994	2.04 (38,440)	0.102 (38,440)
Juarez, 1993	2.96 (7,640)	0.17 (7,640)
Monterrey, 1995	1.69 (24,738)	0.067 (23,867)

[1]%HC values are reported in propane equivalent units and include methane.

City, especially in the Taxi fleets. This is especially true for the pre 1991 model Beetles. Referring to Tables IV and V will convince you that these older vehicles would influence any overall emission averages. Model year profiles are lacking for both Monterrey and Mexico City which would be very valuable in further analysis of this question.

A major difference between Monterrey and Juarez is that in Juarez most of the vehicles are older vehicles which were originally manufactured for sale in the U.S. This probably makes the average age of the Juarez fleet older than the fleet in Monterrey, however, this also illustrates a key point. All of the used U.S. cars bought and sold in Juarez were manufactured with emissions control technology at least comparable to those now being sold in Monterrey. The point is that without proper maintenance, emissions control technology is not worth much to the environment. Most of the vehicles in Juarez have been abused to the point that the emissions control technology no longer functions properly, if it is still on the vehicle. Also it is obvious that the standard of living in Monterrey is higher than Juarez, especially in certain sections of the city. This provides Monterrey with a strong influx of new vehicles and thus lower overall fleet emissions.

When comparing the Monterrey fleet with most U.S. cities all of the pollutants of interest are much lower in the U.S. fleets. Figure 6 shows the difference for CO and HC being factors of 2 to 4 lower and NO data from Denver shows a similar pattern with mean NO emissions being about 50% lower in Denver at a similarly loaded site in Monterrey.

Anecdotal Comments and Observations

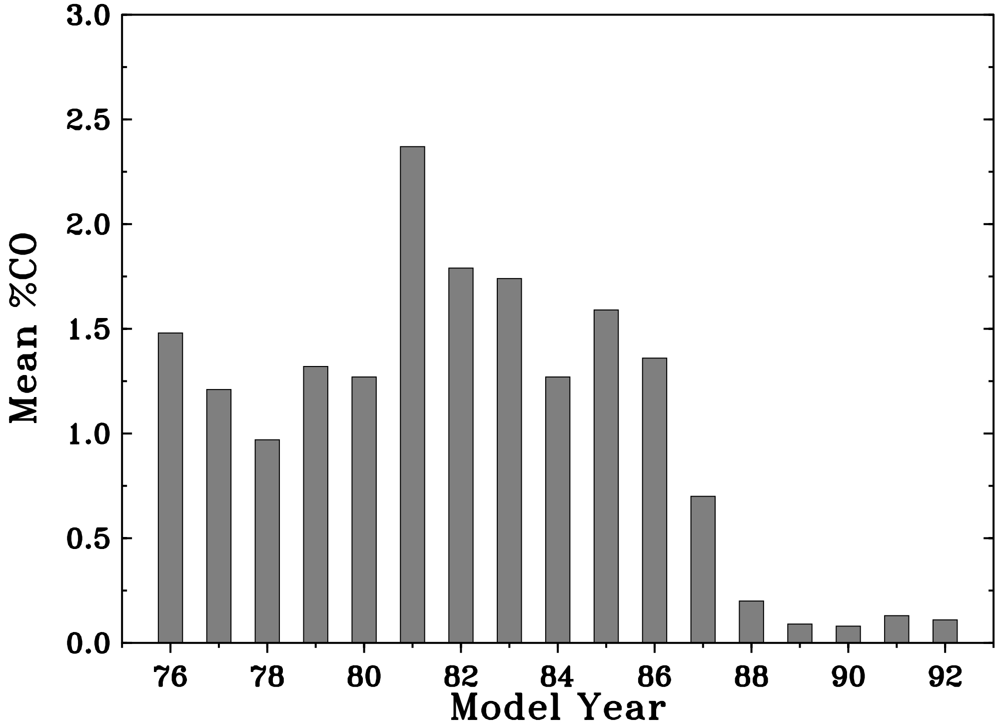

Figure 7. Average %CO by model year for vehicles measured in Göteborg, Sweden (Sjödin, 1991). Sales of new emissions equipped vehicles in 1987 were voluntary and approximately 50% of all sales.

This section is a synopsis of my impressions and observations that may help guide further research and or thinking toward particular areas of the vehicle fleet or public to further improve the environment in Monterrey.

I am constantly impressed with the Mexican peoples desire for sharp looking automobiles. In Mexico City and in Monterrey I have regularly observed people cleaning their vehicles, especially taxi drivers. In Monterrey at one street corner vendors were selling a large duster for cleaning vehicles and at a companion corner vendors were offering their services to dust you vehicle while we were stopped at the light. My point in this observation is that one might attempt to link the Mexican peoples desire for clean/shiny vehicles with tailpipe emissions. The message being that for a vehicle to truly be clean and shining requires the inside (the engine emissions) and the outside to be to be clean and shiny. A dirty tailpipe (i.e high emissions) means you have a dirty car which is also very bad for your neighbors air.

It is easy to look at Figure 6 and breath a sigh of relief that Monterrey's emissions are not as bad as they could be and this is a valid observation. However, after spending four days beside some of Monterrey's busies interchanges I can attest to the fact that auto emissions are very noticeable. At the site on Av. Constitucion I experienced a mild headache and a queazy stomach from the fumes. It can be generally uncomfortable to breath the air in Monterrey at certain times near the freeways. Mexico City in 1994 was worse than Monterrey, however Monterrey is noticeably worse than a similarly busy interchange we work at in Denver. My point is that emissions in Monterrey need to continue to decrease to around the 1% mean CO level to alleviate some of the obvious air quality problems which people who spend time outside will experience.

Monterrey is different from Mexico City in the number of diesel powered vehicles that are on the street, especially transit buses. Mexico City has gone almost exclusively to the small gasoline/propane powered Micro Buses while Monterrey's transit is dominated by large diesel powered buses. The diesel buses in Monterrey appear to be in excellent emissions condition. The Micro Buses have higher than average CO emissions when compared to the light duty fleet (see Table IV), however the sample analyzed so far is too small to draw definitive conclusions. I personally prefer the diesel buses because their emissions of CO and HC are insignificant, the engines are robust and easy to maintain, which is very important for a high mileage vehicle. Important diesel maintenance includes regular oil and filter changes and cleaning the fuel injectors when the engines start emitting visible smoke. I would certainly support a program to maintain these transit buses in good working order because of the amount of time they spend on the road each day.

The Micro Buses on the other hand are emitting excessive amounts of CO. It is possible that some of these buses are powered by propane, which is notorious for elevated CO emissions. Most propane fueled vehicles tend to be underpowered since the energy density available from propane is much lower than gasoline. This encourages people to increase the fuel input to the engine (peak power is obtained around 4% CO on the power curve) and thus higher CO emissions.

Monterrey officials have accomplished much in terms of public tolerance for its twice annually emissions testing program. I know of no US cities which would dare try to inconvenience motorist more than once annually. It is beyond the scope and data collected to provide any direct insights into how well this program is working at reducing emissions in vehicles in Monterrey. However, tailpipe emissions standards are relatively lenient for a program of this type. The most stringent standard is for 1994 and newer vehicles of 2% for CO and 200 ppm (hexane, 400 ppm propane) for HC which relaxes to 5.5% CO and 650 ppm HC for 1979 and older vehicles. My first hand experience was to observe that the 1994 VW Combi van which we were using to make measurements was not able to pass the inspection. This to me was alarming since the van was less than a year old and new vehicles spontaneously break very infrequently. The good news is that something was obviously wrong with the van and it was properly flunked. The bad news was that the workers were not overly alarmed at this and continued to operate the vehicle without a valid emissions sticker. This could also be an explanation for the existence of a significant number of vehicles operating on the street with extremely high HC emissions. I mention this to point out that respect for any program is generated from the top down. If government entities don't rigidly adhere to their own programs it is unfair to expect the general public to. The public learns quickly how to limit the inconveniences of any government program and will learn how, if possible, to circumvent Monterrey's emissions inspection program.

RECOMMENDATIONS

Vehicle emissions in Monterrey can be further reduced and it is likely that they will continue to trend downward without any additional intervention. A big question mark, however, is the effect that the looming recession surrounding the devaluation of the peso will have on new car sales and on present vehicle maintenance practices. Usually an economic downturn results in decreased levels of both of these key mobile source emission factors. It is possible that these factors alone could stop and/or partially reverse the improvements found in fleet vehicle emissions in Mexico City since 1991. This is a question which can be easily answered with on-road monitoring in subsequent years. Also the continued sales of leaded gasoline, which is less expensive at the pump, will eventually wreck havoc on the catalytic equipped vehicles and their emission levels and the sale of this fuel needs to be ended.

In addition, the maintenance that post 1990 vehicles are receiving should be of paramount importance to the people of Monterrey. We have conclusive proof that post 1990 vehicles are much cleaner than pre-1991 vehicles (see Table IV). The important concern is making sure they stay low emitting throughout their useful service life. The Taxi fleet provides the best example for making this point. Excluding the pre-1991 VW Beetles, which are masquerading as Eco taxis, the average %CO is 1.05. For this group of new technology vehicles half of the CO emissions are produced by 11.7% (66 out of 562) of the taxis with emissions exceeding 2.79% CO. More than half of this group of new technology vehicles (36 out of 66 or 6.4% of the taxis in Table IV and V) exceed 4% CO, a level at which serious emissions problems obviously exist. The rate at which these taxis are breaking and being properly repaired will dictate the average emissions for this important subfleet and its impact on the Monterrey airshed.

The taxi fleet should be looked at as important because of the number of taxis in Monterrey and the number of kilometers which they are driven annually. Also when a taxi driver decides to upgrade his vehicle it is highly likely that his old vehicle is sold to the highest bidder and remains in the fleet. The new technology vehicles remain low emitting only when they are not tampered with (i.e. the emissions control equipment is not removed or disconnected and only unleaded gasoline is used in the vehicle) and they receive regular maintenance. Since the taxi fleet is already regulated it is logical to try and target taxis for any new emissions reduction measures. My personal belief is that a rigorous anti-tampering program (perhaps RSD directed on-road pullovers with a visual inspection followed by a fix-it ticket which prevents a new taxi registration if not performed) combined with some type of maintenance aid, either through mechanic training or direct assistance to perform the regular maintenance, could be an extremely cost-effective way of maintaining this Monterrey subfleet. This would also provide an enforcement opportunity to remove the pre-1991 VW Beetle's from the fleet which are already defying the Eco taxis law by operating without the required emissions control equipment. Much of this same discussion applies to the Micro Buses.

Concerning the inspection and maintenance program in Monterrey. Their is a growing mountain of evidence that emissions inspection programs in the United States have been a complete failure (Lawson,1993; Calvert et al, 1993; Schwartz, 1995). It is therefore doubtful that Monterrey's program has been any more effective than those studied in the United States. As discussed with the taxis's the emission control equipment on the new vehicles must not be removed, disconnected or misfueled. Some type of directed (you stop all vehicles with measured on-road %CO emissions greater than 4%) on-road tamper inspection could go a long way to preserving the emissions reductions that have already been obtained in Mexico. Perhaps the centralized contractor could perform this type of service in exchange for reducing the I/M inspections to once per year.

ACKNOWLEDGEMENTS

The authors acknowledge the World Bank for providing its funding and support of this project. The office of the Subsecretaria de Ecologia of the Sate of Nuevo Leon especially Dr. Elicla Rizzo De Alanis, Ing. Julian De La Garza Castro, Ing. César Chávez and Dr. Pilar Tomás who provided invaluable local assistance. We would also like to thank Hugo Lopez, Ricardo Pérez, Jaime De Largarza, Gustavo Chacón, Fernando Sifuentes, Guadalupe Lozano and Hiram Salas for their tireless efforts in helping setup and move the equipment each day. The statements and conclusions in this report are those of the contractor and not necessarily those of the World Bank.

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