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On-Road Remote Sensing of Vehicle Emissions in Mexico

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In 1991, the nation of Mexico lowered light-duty vehicle emission standards leading to the introduction of catalytic convertors. On-road emissions were measured in Monterrey, Nuevo Léon, Mexico in 1995 from more than 24 000 vehicles. The Subsecretaría de Ecología's Office was able to provide vehicle registration information for 10 654 vehicles. These data show a steady emission reduction that coincides with the introduction of light-duty vehicle exhaust emission standards for Mexican vehicles and the implementation of Monterrey's I/M program. The 1995 models are emitting 75% less CO, 70% less HC, and 65% less NO than precontrol models. Pre-1995 models appear to experience a steady degradation in their emission control capabilities, but the cause of this observation cannot reliably be determined without additional data. Comparisons to other locations reveal that Monterrey and Mexico City have improved their fleet emissions when compared to Juárez despite a shorter time with access to vehicles manufactured with emission control systems. The Monterrey data set can also be used to help explain some of the large on-road reductions observed in Mexico City between 1991 and 1994. Sweden's experience in introducing three-way closed-loop emission control systems suggests that the service life of Mexican vehicle emission control systems can be improved.

Introduction

The deterioration of urban air quality is considered a serious problem for many cities throughout the world (*1*). This is especially true for developing countries such as Mexico where large influxes of people into the major urban/industrial centers have resulted in large increases in all of the airborne pollutants. The Monterrey Metropolitan Area is no exception to this, and the state environmental authorities have been working together with higher education institutions, members from the industry sector, and non-governmental organizations for the last 6 years to find solutions. The result of this is the development of an air quality management program that will be finalized in 1997.

As in many cities, the automobile and its internal combustion engine is one of the prime contributors to poor urban air quality in Mexican cities. In 1990, the estimated 3 million vehicles were thought to emit 76% of the total emissions within the Mexico City Metropolitan Area (MCMA) (*2*). While Monterrey has a smaller vehicle fleet (its 1995 vehicle population was estimated at approximately 600 000 vehicles) than the MCMA, it is predicted to grow at a 7% annual rate (*3*). Information about on-road motor vehicle emissions and how they are changing with time is necessary to help in Mexico's campaign to improve its urban air quality.

The University of Denver (DU) first monitored the on-road emissions of light-duty vehicles in the nation of Mexico in 1991. This initial study monitored more than 31 000 vehicles in Mexico City, Distrito Federal, as a part of a basin wide study of air quality (*4, 5*). District registration information found that private automobiles averaged 8 years old while the commercial taxi fleet was at least 3 years older (*6*). We returned to Mexico City in the fall of 1994 and revisited the same sites surveyed in the 1991 study. Figure 1 shows the large drop (around 50%) that occurred in carbon monoxide (CO) and hydrocarbon (HC) emissions in the intervening years. Note also that there is still an excellent linear HC/CO fleet average correlation that was first shown by Beaton (*4*). An insufficient amount of vehicle information is available for the 1994 data set to fully explain the large decrease.

During the period 1991–1994, Mexico City and the country of Mexico have instituted many new initiatives to reduce light-duty vehicle emissions including an aggressive program to renew the commercial taxi fleets and a nationwide phased-in reduction in emission standards for new gasoline vehicles beginning with 1989 models (see Table 1) (*7–9*). These standards led to the introduction of oxidation catalytic converters on private automobiles beginning in 1991 and three-way catalytic converters with closed-loop controls in 1993. These standards follow the pattern established in the United States but over a shorter time frame.

Soon after our 1994 work in Mexico City, DU was invited to be a part of an emission inventory project in Monterrey, NL, Mexico, sponsored by the World Bank. Due in large part to the local participation of the Subsecretaría de Ecología of the Nuevo Leon government, critical access to vehicle registration information was made possible. The importance of this added information cannot be underestimated for those interested in understanding the effects of the changing Mexican vehicle fleet.

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 located in the northeast corner of Mexico due east of Brownsville, TX. It is Mexico's second largest urban/industrial center with a population estimated at 3 million. Due to the heavily industrialized nature of the area, the motor vehicle fleet is only one of many sources of emissions. The city currently exceeds Mexican air quality standards for particulate matter, ozone, and nitrogen oxides, and it is feared that emissions are increasing. This paper will focus on the analysis of the data from Monterrey, NL, and several of the important findings that help to understand data collected from other Mexican cities.

Experimental Section

The DU instrument for the remote analysis of light-duty vehicle exhaust has been described in detail elsewhere (*10–12*). The instrument used in this study measured carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC, utilizing a non-dispersive filter centered at 3.4 μm), nitric oxide (NO), and opacity. Each vehicle's emission measurement results were recorded along with a video image of the vehicle's license plate. License plate transcription and vehicle

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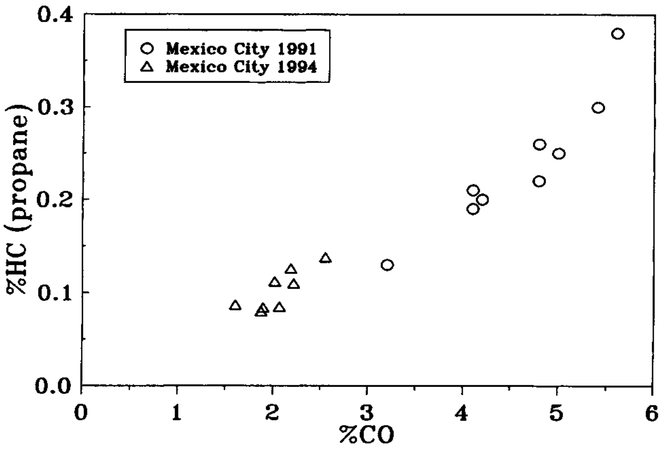

FIGURE 1. Comparison of on-road emission measurements collected in Mexico City, Distrito Federal, at various sites around the city in February 1991 and October 1994.

TABLE 1. Applicable Mexican Light-Duty Emission Standards by Model Year and Vehicle Type[a]

vehicle type	HC, g/km (g/mi)	CO, g/km (g/mi)	NO_x, g/km (g/mi)	$HC_{evaporative}$, g/test
1989 private cars	2 (3.2)	22 (35.2)		
1990 private cars	1.8 (2.88)	18 (28.8)		
commercial[b]	2 (3.2)	22 (35.2)		
light-duty trucks[c]	3 (4.8)	35 (56)		
1991 private cars	0.7 (1.12)	7 (11.2)		
commercial[b]	2 (3.2)	22 (35.2)		
light-duty trucks[c]	3 (4.8)	35 (56)		
1992 private cars	0.7 (1.12)	7 (11.2)		
commercial[b]	2 (3.2)	22 (35.2)		
light-duty trucks[c]	2 (3.2)	22 (35.2)		
1993 private cars	0.25 (0.4)	2.11 (3.4)		
commercial[b]	2 (3.2)	22 (35.2)		
light-duty trucks[c]	2 (3.2)	22 (35.2)		
1994 private cars	0.25 (0.4)	2.11 (3.4)	0.62 (1)	
commercial[b]	0.63 (3.2)	8.75 (14)	1.44 (2.3)	
light-duty trucks[c]	0.63 (3.2)	8.75 (14)	1.44 (2.3)	
1995 private cars	0.25 (0.4)	2.11 (3.4)	0.62 (1)	2.0
commercial[b]	0.63 (3.2)	8.75 (14)	1.44 (2.3)	2.0
light-duty trucks[c]	0.63 (3.2)	8.75 (14)	1.44 (2.3)	2.0

[a] Refer to refs 7–9. [b] Commercial vehicles (i.e., Nissan van & Combis) with GVW up to 3857 kg (8500 lb). [c] Light-duty trucks with GVW up to 2728 kg (6000 lb).

registration matching was carried out by the office of the Subsecretaría de Ecología in Monterrey. Registration information returned make, model, and model year.

Calibration of the remote sensor was conducted before and after each day's measurement period. The instrument was calibrated with the use of a special calibration cell of our design. The cell eliminates the need to purchase or import precision standard gases. The cell is constructed out of aluminum (5 in. × 2.375 in. × 0.375 in.) and contains two 2 in. diameter holes. Each hole is sealed by two sapphire windows that are epoxied into the aluminum, creating two sealed compartments. The first compartment (used as an optical reference) is filled with room air while the second one is filled with a mixture of CO_2, CO, propane, and NO. The reference cell is used to correct for signal attenuation from any background levels of the gases of interest as well as for the two sapphire windows. After construction, the cell was allowed to age for several months until the gas mixture stabilized before field use. We are less interested in the absolute concentrations of the gases contained in the cell than we are that the concentrations remain constant. The cell gas ratios are measured in the laboratory by our remote sensing unit before and after each trip. These measurements are compared to a certified gas mixture of known contents. The cell provides a direct link to a traceable gas mixture that is ultimately used to correct the exhaust emissions measurements made in Monterrey.

Remote sensing measurements were conducted in the Monterrey Metropolitan Area from February 14 to February 17, 1995, at four locations in the downtown area. Two of the sites were freeway on-ramps, and the other two were local surface streets. A brief description of each monitoring site follows.

Emissions measurements on February 14 were made on a freeway connector ramp from southbound Av. J. M. Pino Suárez to eastbound Av. I. Morones Prieto. This two-lane ramp constricted to a single lane with the remote sensing equipment being located at the midway point of the incline (approximately a 3% grade). The traffic was predominantly light-duty passenger cars and light duty trucks measured under load with speeds estimated at between 40 and 60 km/h.

The February 15 measurements took place on west bound Av. Colón between the intersections of streets of Av. Félix U. Gómez to the east and Av. P. Sánchez to the west. The roadway is a flat two-lane surface street that was constricted to a single lane for measurement purposes. The traffic at this location was a mix of light- and heavy-duty vehicles. This location included a large number of diesel-powered transit buses. Vehicle traffic at this location was controlled by a signal light at Av. Félix U. Gómez two blocks east, and low speed (25–40 km/h) cruises were the dominant driving mode.

On February 16, we monitored an on-ramp located between southbound Av. J. M. Pino Suárez and westbound Av. Constitución. This location offered a slight downgrade off of Av. J. M. Pino Suárez followed by a short incline (~2% grade) as it merged with Av. Constitución with the equipment located at the top of this short rise. Traffic composition and speeds at this location were similar to the Av. I. Morones Prieto site monitored on February 14th.

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 that had started overnight and continued for most of the day. This roadway is a level, one-way, four-lane cobblestone surface street. The remote sensing equipment was set up across a single outside lane. No lane closures were used at this location. This site was predominantly light-duty passenger vehicles and light-duty trucks with almost no transit buses or delivery trucks. Low speed cruises between 25 and 40 km/h were the predominant driving mode.

Results

In the four days of measurements, more than 26 000 vehicles were driven past the sensor, and the details of this sampling are provided in Table 2. The data are expressed as mole percents and as grams of pollutant per liter of fuel where the gram per liter conversions assume a fuel density of 0.726 g/mL. The hydrocarbon data are expressed in propane equivalents (the gas that the instrument is calibrated against), and the NO data are expressed as grams of NO and have not been converted to NO_2. The collection of NO data is restricted by a requirement of a minimum exhaust plume strength (to minimize instrument noise) and limits on vehicle hydrocarbon emissions (NO data are not accepted for hydrocarbon measurements in excess of 0.15% HC). The hydrocarbon limit arises because of strong UV absorption by aromatic hydrocarbons in the exhaust of vehicles emitting excess amounts of HC. This interference is negligible when monitoring U.S. fleets, but Mexican fleets on average emit larger amounts of fuels that have higher aromatic content than do U.S. fleets. The overall measurements include a number of heavy-duty vehicles, many of which are local and over-the-

TABLE 2. Fleet Mean Percent and Gram/Liter Measurements for Monterrey, NL, Mexico

site (date)	Morones Prieto (2/14/95)	Av. Colón (2/15/95)	Av. Constitución (2/16/95)	Zuazua St. (2/17/95)	totals[a]
attempts	9414	6787	7118	3215	26534
mean %CO	1.80	1.67	1.45	1.93	1.69 ± 0.20
g of CO/L[b]	158	147	128	168	149 ± 17
(no. of vehicles)	(8898)	(5975)	(6746)	(3119)	(24 738)
mean %HC[c]	0.076	0.059	0.054	0.089	0.067 ± 0.016
g of HC/L	10	8	7	12	9 ± 2
(no. of vehicles)	(8388)	(5841)	(6607)	(3031)	(23 867)
mean %NO[d]	0.188	0.114	0.141	0.102	0.143 ± 0.038
g of NO/L	19	12	14	10	14 ± 4
(no. of vehicles)	(4899)	(4216)	(5316)	(2120)	(16 551)
Plate Matched Data					
mean %CO	1.86	1.73	1.51	2.01	1.76 ± 0.21
g of CO/L[b]	164	153	135	174	155 ± 17
model year	1987.4	1987.2	1988.5	1988.1	1987.8
(no. of vehicles)	(4446)	(1750)	(2965)	(1493)	(10 654)
mean %HC[c]	0.076	0.059	0.054	0.087	0.069 ± 0.015
g of HC/L	10	8	7	12	9 ± 2
model year	1987.4	1987.2	1988.5	1988.2	1987.8
(no. of vehicles)	(4191)	(1727)	(2922)	(1456)	(10 296)
mean %NO[d]	0.194	0.109	0.140	0.107	0.148 ± 0.041
g of NO/L	20	11	14	11	15 ± 4
model year	1987.8	1987.5	1988.7	1988.5	1988.2
(no. of vehicles)	(2362)	(1282)	(2367)	(982)	(6993)

[a] Standard deviations are calculated using the four daily averages. [b] Fleet average grams of pollutant/liter of fuel calculations assume a fuel density of 0.726 g/mL. [c] HC values are reported in propane equivalents and include methane. [d] NO emissions reported as grams of NO, not converted to NO_2.

road transit buses. The vehicle registration information has very limited heavy-duty vehicle information and no information on the transit buses.

Figure 2 displays the emission measurements for all identified vehicles as a function of model year. Model year 1979 includes all emission measurements of vehicles 1979 and older. The average age of the fleet is approximately 8 years.

Two of the video tapes (4 h) were visually 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. Colón and one from Av. Constitución were reviewed, and the vehicles were classified into eight different groups as listed in Table 3. The groups consisted of all light-duty passenger vehicles, which included vans and sport utility vehicles; light-duty pickup trucks; Eco taxis (ecological taxis are taxis for hire that are required by the Mexican government to be post-1990 gasoline powered and are painted green and white to signify this); post 1990-VW sedans (including any Eco taxis, nicknamed Beetles in the United States); pre-1991 VW sedans (including any painted as if an Eco taxi); 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 average for light-duty passenger vehicles includes the Eco taxis and all models of VW sedans. The averages for the pre-1991 and post-1990 VW sedans also include any Eco taxis of the same make and model. The breakout of the VW sedans is possible due to the fact that model year designations can be determined from the number of tailpipe body openings that exist in the rear body panel of the VW sedans. Dual tailpipe cutouts in the rear body panel designate a pre 1991-VW sedan, which is carbureted and has no emissions control equipment on the engine. A single tailpipe cutout indicates a post-1990 fuel-injected VW sedan, which was originally equipped with a catalytic converter.

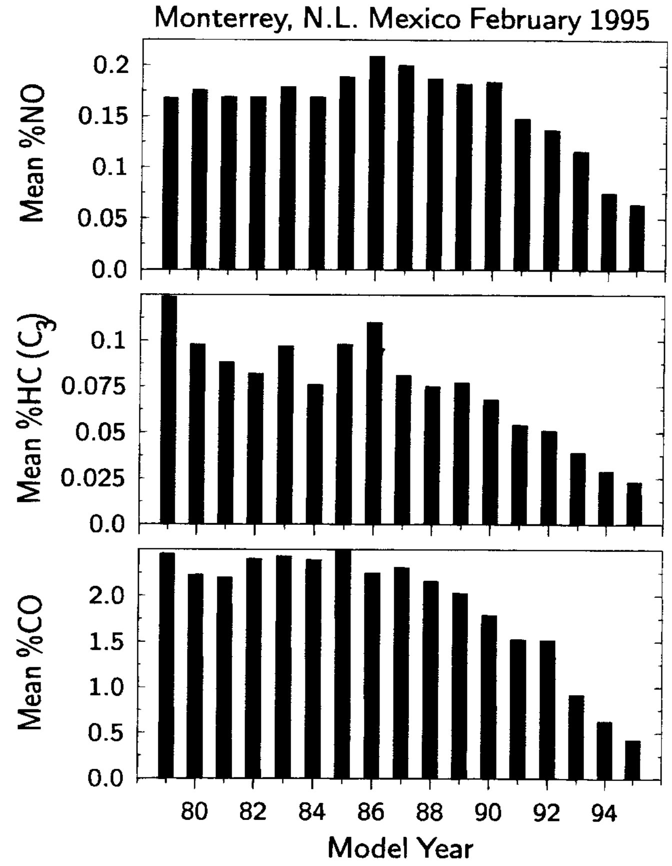

FIGURE 2. Emissions by model year of data collected in Monterrey, NL, Mexico during February 1995. Model year 1979 also includes emissions from vehicles older than 1979.

The quality of the registration information has been qualitatively evaluated for internal consistencies and against other available data. The results suggest that the emissions data matched to registration information are slightly older than the total Monterrey sample. When comparing light-duty passenger vehicles with light-duty pickup trucks identified by model information, we obtain average %CO values of 1.73 and 2.04, respectively. The difference is very similar to that shown for these types of vehicles listed in Table 3, which were visually typed; however, the absolute values are significantly higher, again indicating an older sampling. Internal

TABLE 3. Emissions by Vehicle Classifications from 4 h of Reviewed Video Data

vehicle class	mean %CO *mean CO (g/L)*[a] (no. of vehicles)	mean %HL[b] *mean HC (g/L)*[a] (no. of vehicles)	mean %NO *mean NO (g/L)*[a,c] (no. of vehicles)
LD passenger vehicles[d]	1.45 *132* (3334)	0.051 *7* (3287)	0.134 *14* (2604)
LD trucks[e]	1.67 *158* (580)	0.055 *8* (574)	0.131 *13* (478)
Eco taxis[f]	1.10 *99* (581)	0.037 *5* (573)	0.109 *11* (425)
post-1990 VW sedans[g] (catalyst equipped)	1.09 *98* (340)	0.041 *6* (333)	0.096 *10* (240)
pre-1991 VW sedans[g] (non-catalyst)	2.64 *228* (188)	0.119 *15* (180)	0.220 *22* (113)
HD trucks[h]	1.43 *133* (188)	0.079 *11* (153)	0.133 *14* (112)
buses[i]	0.24 *24* (171)	0.020 *3* (153)	0.076 *8* (74)
micro buses[j]	2.00 *185* (44)	0.036 *5* (43)	0.118 *12* (37)

[a] Mean g/lit calculations assume a fuel density of 0.726 g/mL. [b] %HC values are reported in propane equivalent units and include methane. [c] NO emissions as grams of NO, not converted to NO_2. [d] Light-duty passenger vehicles (includes taxis and VW sedans (Beetles)), vans, and sport utility vehicles. [e] Pickup trucks. [f] Green and white painted taxis. [g] VW sedans (Beetles) only. [h] Gasoline and diesel trucks larger than pickup trucks. [i] Diesel-powered transit buses. [j] Small gasoline-powered transit buses.

consistency checks between make and model information proved accurate, and the critical information, namely, the vehicle model year, is consistent with the expected emission distributions.

Discussion

Table 2 shows that the registration-matched data has higher emissions for all three measured pollutants. This most likely indicates an older fleet for the plate-matched data since prior research has shown a strong dependence between fleet age and emissions (*13*). Private vehicle plates remain with the vehicle throughout its lifetime; however, commercial plates can be sold separately (*6*). Also, differences do exist between the two samples such as the lack of all of the transit buses and the majority of the heavy-duty trucks from the registration-matched data. On an emissions basis, this fleet difference should be small since the low emissions of the diesel-powered transit buses are offset by the higher emissions of the micro-buses and the heavy-duty trucks. The overall effect of these differences is not known.

The post-1990 Monterrey fleet has significantly lower emissions for all three pollutants measured when compared to the uncontrolled pre-1990 fleet. This reduction was also confirmed by the visual comparisons of vehicle types listed in Table 3. Large, stepwise emission reductions do not appear to align with the introduction of emission control technology, which began with the 1991 models and again with 1993 and 1994 models. Some of these reductions may be obscured due to the different standards for the various vehicle types (see Table 1). What is apparent is a steady decline in each of the three measured species commencing around the 1991 models. This is observable in spite of the effects of aging. All of the measured species show essentially unchanging emissions with increasing age for model years older than 1988.

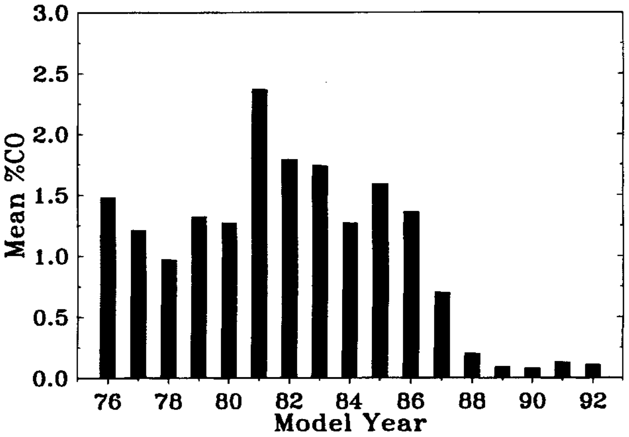

FIGURE 3. Average %CO by model year for vehicles measured in Göteborg, Sweden (*17*). Sales of new emissions equipped vehicles in 1987 were voluntary and approximately 50% of all sales.

The lack of a clear stepwise reduction in emissions as a result of the new emissions technology introduced into the Mexican fleet beginning with 1991 models follows a pattern seen previously in the United States. Introduction of this control technology in the United States in the mid 1970s resulted in high tampering (removing/disconnecting emission control devices) and misfueling (using leaded fuel instead of unleaded) rates (*14, 15*). One would expect a large drop in emissions if the new technology is effective, robust enough to last for 4 years, and has not been disconnected or misfueled. There is a large reduction between the 1990 and 1995 model years as more advanced emission control equipment is introduced. However, the loss of this difference in the intervening years could result from a number of pathways. On-road remote sensing measurements provide an emissions picture looking back in time at an aged fleet. With only one picture, we have no information about the pathway the fleet has taken to arrive at its current state. This makes it difficult to answer all of the questions one has about the dynamics of the Mexican fleet. For example, are the modern engines getting more robust with each new model or are they deteriorating rapidly to the same level as the earlier models? If we are observing rapid deterioration, it could be due to any number of reasons such as malmaintenance (leaded fuel is still sold in Mexico), lack of technical service necessary to repair emission problems, or problems originating with the manufacture of the vehicles. Repeat measurements at the same sites with model year information could help to distinguish improvements in technology from deterioration (*16*).

Comparisons to Other Locations. We do know that three-way closed-loop emission control systems are now a mature control technology and have proven in many countries around the world the capability to provide large emission reductions if properly cared for. For example, Sweden made a similar, though not identical, switch to three-way closed-loop emission controlled vehicles as Mexico. Figure 3 shows CO data (HC data are very similar) collected in Göteborg, Sweden, in the summer of 1992, which is approximately 4 years after Sweden introduced new emissions technology (*17*). Sweden began introducing three-way closed-loop equipped light-duty vehicles in 1987. Economic incentives were offered for people to buy the vehicles on a voluntary basis in the first year. This resulted in approximately a 50% market share for these vehicles. Beginning with the 1988 model year, all vehicles sold were so equipped. The Swedish vehicles experienced drastic reductions in emissions, and 1988 model year vehicles still had emissions within 25% of their 1992 siblings even after 4 years of use.

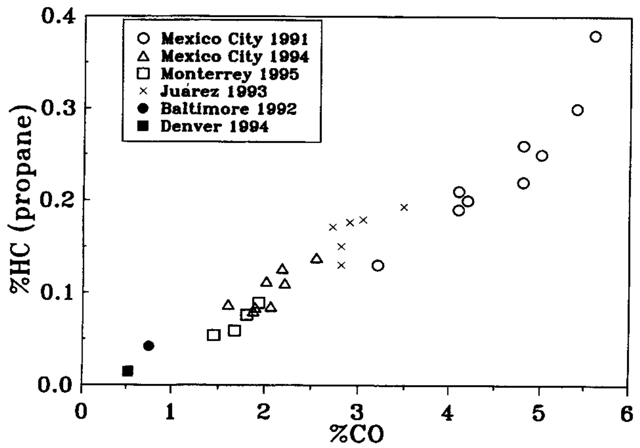

FIGURE 4. Comparison of daily averaged CO and HC data collected in four Mexican cites since 1991 and representative averages from two U.S. cities.

We do not intend to compare Mexico with Sweden. There are too many differences for that to be a viable comparison (notice that uncontrolled Swedish vehicles have emissions comparable to early controlled Mexican vehicles). What we would like to do is hold up the Swedish data as an ideal and point out that emission control equipment on 1991 and newer Mexican vehicles appears to lose effectiveness very quickly for whatever reason. The data show 1991 model year emissions almost back up to pre-controlled models by the time they were measured in 1995. If this loss of effectiveness continues with the current and future models, then fleet turnover rates, which do not alter the average age (about 8 years in Monterrey), will not allow for any further emissions improvement.

Emissions by model year for the Mexico City fleet measured in the spring of 1991 show slight CO and HC reductions beginning with 1989 models and a larger reduction with the 1991 models (average CO emissions declined from $\sim$4% in 1990 models to $\sim$1.5% for 1991 models; average HC emissions declined from $\sim$0.14% propane to $\sim$0.075% propane). For models older than 1989, the emissions do not change with model year and average 4.75% CO and 0.23% HC (propane) (*6, 18*). Emissions of the 4-year-old 1991 models in Monterrey are only slightly higher for CO with lower HC emission than the less than 1-year-old 1991 models first observed in Mexico City. Older Monterrey models (pre-1991) show similarly unchanging emissions for all species prior to 1990 but with absolute emissions less than half of those found 4 years earlier in Mexico City.

Figure 4 compares the daily CO and HC emission averages for all of the data collected in Monterrey against average daily CO and HC emissions collected in Mexico City during February 1991 and October 1994, in Ciudad Juárez during March of 1993, and in two U.S. cities (*4, 19*). In general, the Monterrey measurements have similar averages when compared to the data collected in Mexico City in October 1994 and are 2–4 times the averages for the U.S. cities.

There are numerous fleet and economic differences between the three Mexican cities. Monterrey and Mexico City fleets comprise predominantly vehicles manufactured to Mexican standards while the Juárez fleet is almost entirely vehicles originally manufactured to U.S. standards. In Mexico City, many of the monitoring sites have significant percentages of taxi cabs and thus fewer private automobiles. Also while the VW sedans are popular in Monterrey, they are not nearly as numerous as in Mexico City, especially in the taxi fleet. The Mexico City taxi fleet is noticeably older than in Monterrey due to the large number of pre-1991 models (which are painted yellow and white to distinguish them from the Eco taxis). Ciudad Juárez has only a small taxi fleet and very few VW sedans of any vintage, and Mexican import laws favor the importation of older (5-year-old; newer vehicles are taxed at 100% of import value) vehicles (*20*).

However, as we alluded to in our Introduction, we would very much like to account for the large change in emissions observed in Mexico City between 1991 and 1994. The new emissions control equipment on 1991 and newer vehicles may be responsible. While the Monterrey registration data confirm that the newer models have lower emissions, it is impossible to reconstruct with Monterrey vehicles the overall CO and HC fleet averages that were first reported for Mexico City in 1991. Even if every car in Monterrey were a pre-control VW sedan as measured in 1995, the emissions would not come close to the 1991 Mexico City data.

The lack of model year information for the 1994 Mexico City data prevents a more thorough examination. However, the implication is that this Monterrey fleet is not able to provide a complete parallel story with which to interpret the changes in Mexico City. Additional Information about factors and influences such as the altitude difference (Mexico City at 2240 m and Monterrey at 540 m), oxygenated fuel usage, inspection and maintenance programs, forced no-drive days, and fleet turnover rates are needed along with the changes in vehicles emissions control equipment to explain the large reduction observed in Mexico City between 1991 and 1994.

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