Measurement of In-Use Passenger Vehicle Emissions in Three Urban Areas of Developing Nations

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I. Abstract
Second by second emissions of CO, CO2, NO, and THC were measured for 324 gasoline fueled passenger vehicles over a two week period in each of three cities: Mexico City, Mexico (11/04); Sao Paulo, Brazil (12/04), and Nairobi, Kenya (3/05). The measurements included a vehicle cold start and about 30 minutes of driving. A circular driving route was selected with a variety of driving situations including low speeds on congested arterials and higher speeds and accelerations on highways. A Sensors SEMTECH-G portable emissions monitor and exhaust flow measurement system was used for the on-road emission and position, speed, and acceleration measurements providing in-use emissions information for vehicles operating in the three study areas. Subsequent analysis of the data provided second by second vehicle power demand in association with the measured emissions. By normalizing this data, it is possible to obtain estimates of emissions that would have occurred on an LA-4 cycle. These calculated emissions were used to improve the performance of the International Vehicle Emissions (IVE) model in conjunction with fleet and activity information previously collected to create an on-road emissions inventory for each of the three cities.

II. Background

On-road vehicles are responsible for a significant and rapidly increasing portion of the air pollution in the urban areas of developing nations. Many nations have recognized the health and environmental degradation from the use of these vehicles and have begun efforts to control the amount of emissions from their fleets. The process of reducing vehicular emissions is not straightforward; in general consisting of a combination of implementing stricter emission levels on new vehicles, tighter fuel standards, and implementing behavioral policies such as limiting driving in certain areas or days. While it is easy to conclude that these efforts should improve the situation, it is unclear to what extent these decisions have actually reduced in-use emissions, and what additional efforts will be needed to adequately address the urban air pollution problem. To provide answers to these types of questions, a complex and accurate vehicular emissions model is needed for estimating vehicular emissions, its contribution to the total inventory and air pollution, and forecasting emission reductions under various policy implementations. This model requires significant data inputs on the specific fleet of interest, including the type and quantity of vehicles, their behavior and amount of use on the roadways, and their in-use emissions under various conditions. Existing or easily obtainable information on the fleet and its emissions (for example, the registration database or emissions certification values) have shown to be exceptionally inadequate for this purpose. Both the development of a model and gathering necessary fleet information require significant financial and time investment that is not readily available in many locations. Moreover, the need for this information sooner rather than later is important, since even a few years delay in implementing emission reduction strategies could have a catastrophic impact on the air quality for years to come.

In response to this situation, the International Sustainable Systems Research Center (ISSRC) has developed a study process to gather the information and build the tools and capacity to properly estimate and predict vehicular emissions in any location worldwide. This process has several parts. First, the US EPA international offices funded the development of the International

Vehicle Emissions (IVE) model that can be applied to any area to estimate emissions. This model is designed with the flexibility to accommodate a wide variety of vehicle types, fuels, and driving behavior. The model is available free from the internet and requires minimal training to use. However, information specific to each local area is still needed to accurately estimate emissions using the model. In recent years, the US EPA, the Hewlett, and the Energy Foundations have funded ISSRC to collect information on the type, quantity, and driving behavior of the fleet in 11 cities worldwide. More information on these studies can be found on the ISSRC website (www.issrc.org/ive). The last required piece of information is the actual in-use emissions from the specific vehicle fleet. This report documents the procedure and results of collecting in-use light duty gasoline emissions in several developing nations and applying this information to the IVE model.

III. Study Design

III.A. Overview

The core purpose of the study was to collect real-world second by second emissions data from a representative sample of on-road gasoline fueled vehicles under a wide variety of driving conditions, including cold and hot starting conditions. A previous study by ISSRC (www.issrc.org/ive) established typical driving patterns in each city between the hours of 07:00 and 21:00. Thus, there was no need in this study to attempt to collect typical driving patterns. Instead, the goal was to collect vehicle emissions data from as large a variety of driving situations as might occur in the city within the constraints of safety, road conditions, and congestion. Clearly, since the study involved actual on-road driving, the test vehicle driving patterns will vary from vehicle to vehicle as traffic congestion changed throughout the test period. In order to compare measurements from the different vehicles, second by second vehicle speed and road altitude data was collected using GPS technology simultaneous with the emissions measurement. Altitude information can be used to estimate road grade and combined with vehicle speeds the power demand per unit weight, denoted VSP, on the vehicle can be determined. VSP is one of the best predictors of emissions variation with changes in driving behavior and speed. (Figure 1). With a complete map of emissions versus VSP collected, this information can be used to recreate emission estimates from any driving patterns. To enable the collection of cold-start conditions, the vehicles were procured the day before they were to be tested so that they could soak overnight. The vehicles were also stopped halfway through the on-road driving test and allowed to sit with the engine turned off for 10 minutes for the first two studies (Mexico City and Sao Paulo). The vehicle was then started and the driving route concluded. After some testing, it was determined that the amount of emissions from a hot start was too small to detect in this measurement system, therefore the ‘hot’ start was eliminated and replaced with additional driving for the study in Nairobi. Together, these data were used to estimate cold-start information along with running emissions.

III.B. Route Selection

The driving route selected needed, of course, to begin at the test setup location and to return the vehicle to the test setup location in order to remove the test equipment to the next vehicle. In addition, a driving route that exercised the vehicle under many different driving conditions, including slow, steady driving, fast speeds, and hard accelerations was required. Thus, the driving route needed to include opportunities for driving in congestion as well as opportunities for driving in high speed situations. It is difficult in urban areas such as Mexico City to find a route that would allow many high speed opportunities due to the ubiquitous traffic congestion. The route also needed to be completed in 30-45 minutes depending upon the traffic situation at the time of testing. The route selection is further compromised due to the need to be located near a secure place to park the vehicles overnight. These routes allowed a significant, although not complete variety of driving patterns for the vehicles tested. In general, a reasonable range of driving patterns was collected as will be shown in the data analysis section.

III.C. Vehicle Procurement

The intent of the study was to test a variety of vehicle technologies found in each city. It was not intended to develop an exact representation of the local light-duty gasoline fleet. However, the vehicle procurement process did result in a fairly typical light-duty gasoline fleet in all three cities. A combination of ads placed in a few periodicals and newspapers and word of mouth was used to find vehicle donors. A US$50 payment was paid to the vehicle donor to drive their vehicle to the test location and leave it for 24 hours and then pick it up. The owner was required to sign a waiver that the vehicle had liability and collision insurance and to agree that the maximum liability of ISSRC for each tested vehicle was US$1,000. Vehicle procurement was slow, particularly in Mexico City, before the beginning of actual testing due partially to concern that the testing was a rouse to get peoples cars for removal of parts. However, early donors finding that their car was returned safely and driven less than 10 kilometers told their friends and by the third day of the studies, vehicles were typically being turned away.

In Mexico, a SEMARNAT (Mexico EPA) facility was used as the vehicle staging area. This particular facility was fenced and had 24-hour guards providing vehicle donors with a sense of security concerning their vehicles. In Sao Paulo, a secure garage located on the campus of Sao Paulo University was used, and in Nairobi a service station owned by the United Nations was used, which had 24-hour guards.

Each vehicle was inspected upon arrival and was rejected if it did not appear to be safe to operate for the test or if the exhaust had leaks. For example, some vehicles had tires with large bulges that could contribute to a blow-out and at least one vehicle had significant steering and brake problems. In Mexico City, a total of 112 vehicles were procured and tested and 101 vehicles were successfully tested. 2 vehicles ceased to function during testing and previously unnoted safety issues occurred with 5 vehicles, and the testing equipment failed to operate properly on 4 vehicles due to operator error or undetermined cause. In Sao Paulo, a total of 111 vehicles were successfully tested in the 2 week study, and for Nairobi, 113 vehicles were successfully tested. Table III-1 lists the variety of vehicles that were tested in each study. The vehicles were randomly selected from the volunteered fleet and therefore should be somewhat representative of the real-world fleet in each city.

Table III-1 Overview of Light Duty Gasoline Vehicles Successfully Tested in Mexico City

Vehicle Air/Fuel System	Vehicle Emissions Control Technology	Range of Model Years	Number of Vehicles
Carburetor	None	1975-1992	20
Carburetor	2-Way Catalyst	1991	1
Carburetor	3-Way Catalyst	1992	1
Single Point (Throttle Body) Fuel Injection	None	1986	1
Single Point (Throttle Body) Fuel Injection	3-Way Catalyst	1992-2001	8
Single Point (Throttle Body) Fuel Injection	No Catalyst and EGR	1989	1
Multipoint Fuel Injection	3-Way Catalyst	1986-2004	48
Multipoint Fuel Injection	3-Way Catalyst and EGR	1991-2004	21
Average Age of Vehicle Fleet Tested		**MY 1996 (9 yrs)**	**101**

Table III-2 Overview of Light Duty Gasoline, Natural Gas and Alcohol Vehicles Successfully Tested in Sao Paulo

Fuel Type	Vehicle Air/Fuel System	Vehicle Emissions Control Technology	Range of Model Years	Number of Vehicles
Petrol	Carburetor	None	1988-1994	5
Petrol	Carburetor	3-Way Catalyst	1991,1995	3
Petrol	Single Point (Throttle Body) Fuel Injection	None	1993,1996	2
Petrol	Single Point (Throttle Body) Fuel Injection	3-Way Catalyst	1995-2002	3
Petrol	Multipoint Fuel Injection	3-Way Catalyst	1996-2004	82
Natural Gas	Carburetor	3-Way Catalyst	1995	1
Natural Gas	Multipoint Fuel Injection	3-Way Catalyst	1997-2004	6
Alcohol	Carburetor	None	1986,1990	3
Alcohol	Single Point (Throttle Body) Fuel Injection	None	1994	1
Alcohol	Multipoint Fuel Injection	3-Way Catalyst	2004-2005	5
Average Age of Vehicle Fleet Tested			**MY 1999 (6 yrs)**	111

Table III-3 Overview of Light Duty Gasoline Vehicles Successfully Tested in Nairobi

Vehicle Air/Fuel System	Vehicle Emissions Control Technology	Range of Model Years	Number of Vehicles
Carburetor	None	1986-1995	38

Single Point (Throttle Body) Fuel Injection	None	1989,1992	2
Single Point (Throttle Body) Fuel Injection	3-Way Catalyst*	1986	1
Multipoint Fuel Injection	None	1989-2001	45
Multipoint Fuel Injection	3-Way Catalyst*	1991-1999	27
Average Age of Vehicle Fleet Tested		**MY1993 (12 yrs)**	**113**

*Of the 28 vehicles equipped with 3-way catalysts, only 10 were considered functional because the rest were using leaded fuel. It is suspected from the emission factors, that even some of the 10 vehicles that had indicated they had only used unleaded fuel may have sometimes used leaded fuel as well.

In each of these three cities, a vehicle activity study was previously conducted by ISSRC that collected information on over 1000 passenger vehicles operating within the city. This information was used to create fleet files of the exact mix of vehicles operating on the road in each of the cities, and can be used to compare with the vehicles recruited in the emissions testing study to assess how representative the recruited vehicles are to the general passenger fleet. The ISSRC Mexico City activity study determined that the average age of the on-road Mexico City passenger vehicle fleet is 6.4 years. Thus, the average age of the vehicle fleet tested in this study, 9 years, was slightly older than the observed on-road fleet. However, in Sao Paulo, the average age of the fleet 6 years old, where the activity study conducted previously indicated that the passenger fleet average age is actually 7.4 years. And for Nairobi, the average age of the fleet tested is 12 years, while the activity study conducted measured a fleet age of 13.4 years. These differences in average age of the fleet indicate that the recruitment process is not an exact replica of the actually fleet, however, it roughly approximates the fleet mix found in the city. In this paper, references to the average emissions of the fleet tested will be listed. These averages are of the tested vehicles, which only roughly represent the true passenger fleet. In the last section, the exact fleet mix of vehicles as determined in the activity study will be used in conjunction with the corrected emission factors to estimate a fleet-wide inventory for each city.

III.D. Emission, Speed, and Altitude Measurements

A SEMTECH-G portable emissions test unit was used to make emission measurements. This unit, shown in Figure III-1, weighs 40 kilograms equipped for testing (http://www.sensors-inc.com/semtech.htm). A separate flow measurement device manufactured by Sensors, Inc. that integrated with the SEMTECH-G unit was used in order to make mass emissions measurements. This unit weighed about 5 kilograms. An integrated Garmin GPS unit was used to estimate vehicle speeds and altitude. The SEMTECH-G unit also contained a temperature and humidity measurement device that was placed on the exterior of the vehicle to proved information concerning the vehicle intake air. A 100 amp-hour, 12 volt lead acid battery was used to power the system during on-road testing. Combined, the test equipment and battery added about 70 kilograms of weight to the vehicle, which is similar to an extra passenger. Thus as tested, the vehicles were transporting the rough equivalent of two persons counting the vehicle operator.

Figure III-1 SEMTECH-G Portable Emission Measurement Unit

The SEMTECH-G uses an NDIR for CO and CO_2 measurement, a NDUV for NO measurement, a FID for THC measurement, and an electrochemical O_2 sensor. Further information on the exact specifications for the measurement technology can be found in Appendix A of this report.

III.D.1. Calibration in Mexico City

Four bottles of calibration gases were obtained from a respected Mexico City gas vendor. Questions about the accuracy of the calibration of the test gases resulted in delivery of a second set of test gases half way through the testing process. Table III-4 lists the concentrations of the test gases as indicated by the supplier.

Table III-4 Concentrations of Calibration Gases Used in the Mexico City Study

	First Week of Testing				Second Week of Testing			
Gas	**CO %**	**CO_2 %**	**NO ppm**	**C_3H_8 ppm**	**CO %**	**CO_2 %**	**NO ppm**	**C_3H_8 ppm**
Span	8.01	12.02	2998	3203	8.01	12	3001	3403
High-Audit	0.1199	12.0	1503	200	0.12	12	1478	206
Low-Audit	0.02	5.99	302	50	.020	6	292	52
Zero	0	0	0	0	0	0	0	0

The manufacturer guaranteed the accuracy of the gases to within 2%. Each morning, the unit was zeroed and then spanned using the Zero and Span gases. The zero and span process was then followed by an audit of the SEMTECH-G unit using the High-Audit and Low-Audit gases. This process resulted in agreement of better than 4% for all gases when attempted in Los Angeles using US supplied gases. However, on using the locally obtained gases, after the span, the High-Audit and Low-Audit gases did not produce audits within 4% as was the case in the United States. The audits produced readings from the instruments that were 7% to 30% different from the certified contents of the gases. Table III-5 indicates comparisons of the daily audits.

Table III-5 Typical Morning Audits

		CO (%)		CO2 (%)		NO (ppm)		THC (ppm)	
	Day	Reported	Measured	Reported	Measured	Reported	Measured	Reported	Measured
Low Audit	1	0.0200	0.0250	6.00	5.67	302	239	50	No FID
Low Audit	2	0.0200	Not Rec	6.00	5.53	302	234	50	No FID
Low Audit	3	0.0200	0.0239	6.00	5.60	302	239	50	47.3
Low Audit	4	0.0200	0.0230	6.00	5.59	302	226	50	41.0
Low Audit	5	0.0200	0.0190	6.00	5.45	302	236	50	44.5
Low Audit	6	0.0200	0.0326	6.00	6.24	292	Not Rec	52	Not Rec
Low Audit	7	0.0207	0.0253	6.00	6.06	292	Not Rec	52	Not Rec
Low Audit	8	0.0207	0.0248	6.00	6.09	292	255	52	39.6
Low Audit	9	0.0207	0.0260	6.00	6.10	292	260	52	54.1
Low Audit	10	0.0207	0.0240	6.00	6.13	292	263	52	51.3
High Audit	1	0.120	0.115	12.0	11.7	1503	1365	200	No FID Gas
High Audit	2	0.120	Not Rec	12.0	Not Rec	1503	Not Rec	200	No FID Gas
High Audit	3	0.120	0.117	12.0	11.7	1503	1368	200	197.0
High Audit	4	0.120	0.113	12.0	11.8	1503	1366	200	191.0
High Audit	5	0.120	0.113	12.0	11.7	1503	1366	200	195.6
High Audit	6	0.120	0.147	12.0	11.8	1478	Not Rec	206	Not Rec
High Audit	7	0.120	0.137	12.0	11.7	1478	Not Rec	206	Not Rec
High Audit	8	0.120	0.138	12.0	11.6	1478	1378	206	198.0
High Audit	9	0.120	0.140	12.0	11.6	1478	1379	206	207.6
High Audit	10	0.120	0.137	12.0	11.7	1478	1388	206	204.1

The large differences between reported values and measured values for the audit gases indicated that there was some non-linearity in the Sensor's measurement device that were not observed in Los Angeles or that the supplied span and audit gases were not within specified tolerances guaranteed by the supplier. Because of the accuracy of the instrument when used in Los Angeles, it was believed that the span and audit gases may not be accurate. The supplier was contacted and agreed to supply a new set of gases for the second week of the study. These gases did not provide improved performance.

At the end of testing, the SEMTECH-G unit was zeroed and spanned using the locally supplied gases before crating it for return to the United States. Upon return to Los Angeles, the SEMTECH-G unit was warmed up and immediately audited using the original US supplied gases with out zeroing or spanning the unit in an attempt to better understand the locally obtained gases. The SEMTECH-G produced CO and CO2 measurements that were within 5% of the reported values for the US gases; however, for NO and THC the SEMTECH-G produced readings that were 20% to 25% too low. The SEMTECH-G unit was then zeroed and spanned on the US gases with resulting audits that met the 4% accuracy requirement. This leads us to believe that the locally obtained gases may have been inaccurate for NO and THC such as to produce measurements that were around 20% too low. While it can never be absolutely established what the true concentrations were in the Mexico supplied gases, for purposes of this study, NO and THC values will be increased by 20% for development of emissions factors.

This was not the only measurement problem in the study. Many of the tested vehicles, especially at cold start, produced THC concentrations that were over the maximum measurement capability of the FID. This caused the FID to peg at a maximum value of about 11,500 ppm THC. This problem will cause the THC measurements reported for this study to potentially be low beyond the 20% discussed in the previous paragraph. Even with the highly polluting vehicles, the fraction of time above the FID cutoff point was a small fraction of the total testing. In order to bracket the range of possible THC emissions, all reported THC concentrations above 11,500 ppm were set to 30,000 ppm, which was felt to be the maximum value that would have been observed. The THC data was then reevaluated and a likely maximum THC concentration was established. Thus, in this report, the THC data will be presented as a low and a high value.

III.D.2. Calibration in Sao Paulo

In Sao Paulo, CETESB arranged to have the gases supplied by a local vendor. CETESB has vehicle and ambient testing equipment and is familiar with using these gases. The gases calibrated within expected limits and there were no problems with the SEMTECH calibration or calibration gases.

III.D.3. Calibration in Nairobi

In Nairobi, ambient and vehicle testing is not common and it was difficult to locate an adequate gas supplier that could provide accurate mixtures of the gases needed for audit and calibration of the equipment. Therefore, Scott Gasses were shipped from the US to Nairobi prior to the testing. The gases used passed quality checks and there were no problems with the calibration or testing process.

IV. Data Analysis Process

IV.A. Time alignment

The time alignment between the vehicle speed, tailpipe flow measurement, and gas concentrations is critical for producing accurate second by second emission estimates. Vehicle speed was estimated using a GPS unit attached to the vehicle that was supplied by Sensors. Flow measurements were made by a pitot tube flow measurement device provided by Sensors, Inc. (http://www.sensors-inc.com/semtech.htm). The time alignment was initially established by observing the flow measurements and comparing them to concentration and vehicle speed measurements. This allowed an approximation of the appropriate time alignment between the speed, flow, and concentration measurements. The time alignment was further refined by comparing the total carbon out of the tailpipe with the power demand (VSP) determined by the GPS unit. The total carbon relates to fuel use and should correlate with the power demand on the vehicle. Delay times were refined by selecting the values that gave the best total carbon to vehicle power demand correlations.

IV.B. Running Emissions

Two approaches for analyzing running emissions were used in this study. First, the emissions as collected are reported directly. Second, the emission rates were corrected to represent emissions from a standard driving pattern (the LA4 driving cycle).

IV.B.1. Study Measured Emission Rates

With the limited testing time, this study did not attempt to replicate typical citywide driving patterns. Instead, driving in all types of conditions was attempted to be collected. Therefore, the raw emissions reported from each test will not be exactly the same emissions as would be observed for a daily typical operation in each city. To compare how similar the driving pattern from the emissions study is to the real world, Figure IV-1 presents the study's driving trace and the actual arterial driving pattern as determined in previous studies. As shown in the figure, the driving pattern used in the emissions study ('study') compared to the driving pattern measured on arterials in the activity data collection ('art') is fairly similar with the exception of Nairobi. Thus, there will be some small errors when assuming the average emissions data collected in this study is the same as the average emissions of a typical vehicle operating on road. The reader should note these small differences when reporting the directly measured values as typical emission rates for each area. However, the corrected and raw emission values should not be very different, and the raw emission values should give one a ballpark idea of actual gasoline fleet emissions in each area.

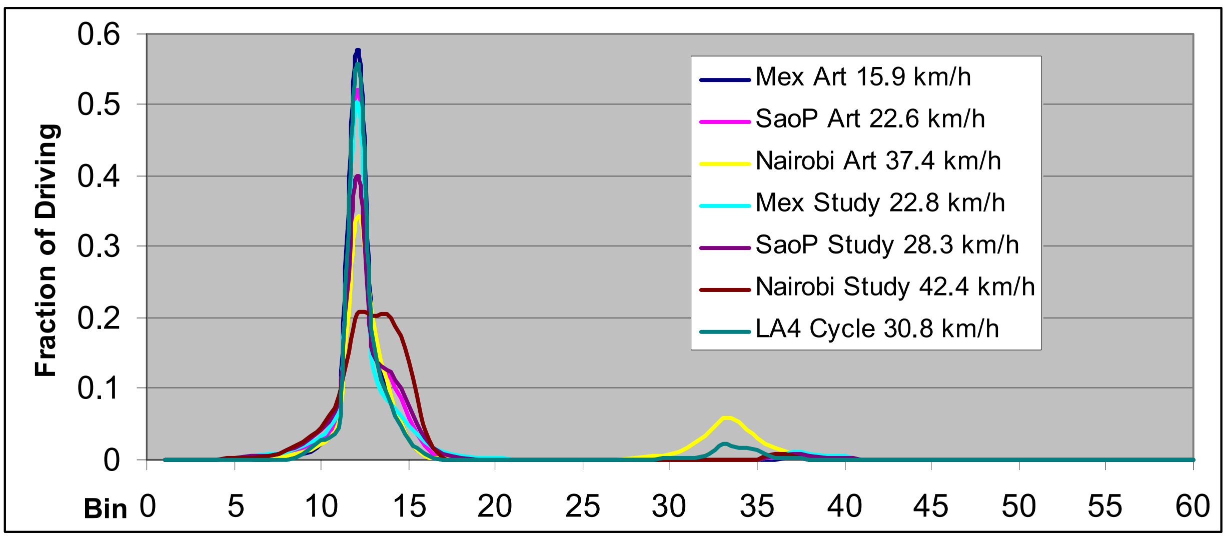


Figure IV-1 Distribution of Driving Among the 60 IVE Bins for a Typical Vehicle Compared to Daytime Distribution of Arterial City Driving

As can be seen in Figure IV-1, the driving was restricted primarily to the first 20 bins (power demand groupings) with only a small amount of driving in bins above 20. The bins above 20 are referred to as higher stress bins in the IVE model. The emissions study vehicles achieved a higher average speed than was observed in the original vehicle activity study but this was on purpose to gather as large a variety of data as possible. Even with the increased driving speeds there was still little data collected outside of bins 5 through 16, making it difficult to yield reliable emissions trends in these higher bins.

IV.B.2. Corrected Emission Rates for City Driving

The second approach used to analyze the running emission data is more complex. To estimate a more realistic on-road emission factor, the driving patterns of arterial, residential, and highway driving should be applied instead of the driving pattern during the limited emissions test. To extrapolate the collected emissions data to other driving patterns, the average emissions in each driving condition (termed 'bin') is determined. Once the emission rate for each individual bin is determined, emissions from any driving cycle can be recreated by multiplying the fraction of driving in each bin by the emission rate in each bin. The IVE model uses 60 bins to represent urban and rural driving. The emissions variation from bin to bin is what ultimately accounts for the variation in emissions from different driving patterns. There are default values for each pollutant built into the IVE model (named Driving Pattern Correction Factors). These corrections were developed based on second by second emissions data collected on a variety of US vehicles. Figure IV-2 - Figure IV-5 presents the variation in emissions for bins 1-20 for the IVE model and the data collected in each of the cities for multipoint fuel injected gasoline vehicles. From the figure, it indicates that the driving corrections in the IVE model are representative of the collected data for bins 1-15. After that, the IVE model correction factors are larger than the measured values for all pollutants. This indicates that the model is reporting larger emissions from driving in these high power bins. It is unknown whether this overestimation of the emissions during high power situations is a real phenomenon or not. Unfortunately, the number of data points in the three cities in bins 16-20 are very small compared to the number of data used in the development of the IVE model. Also, time alignment becomes very critical for gauging these higher bins and more work needs to be done to understand this impact. For this reason, the IVE bin corrections were not modified based on these results at this time. Additional studies to collect emissions data for the larger bins are planned in the future, and the results will indicate whether the IVE correction factors should be modified. At any rate, the fraction of actual driving occurring in these bins is a tiny portion of the driving (see Figure IV-1), and therefore making changes to the corrections would not result in a large change in overall emission rates.

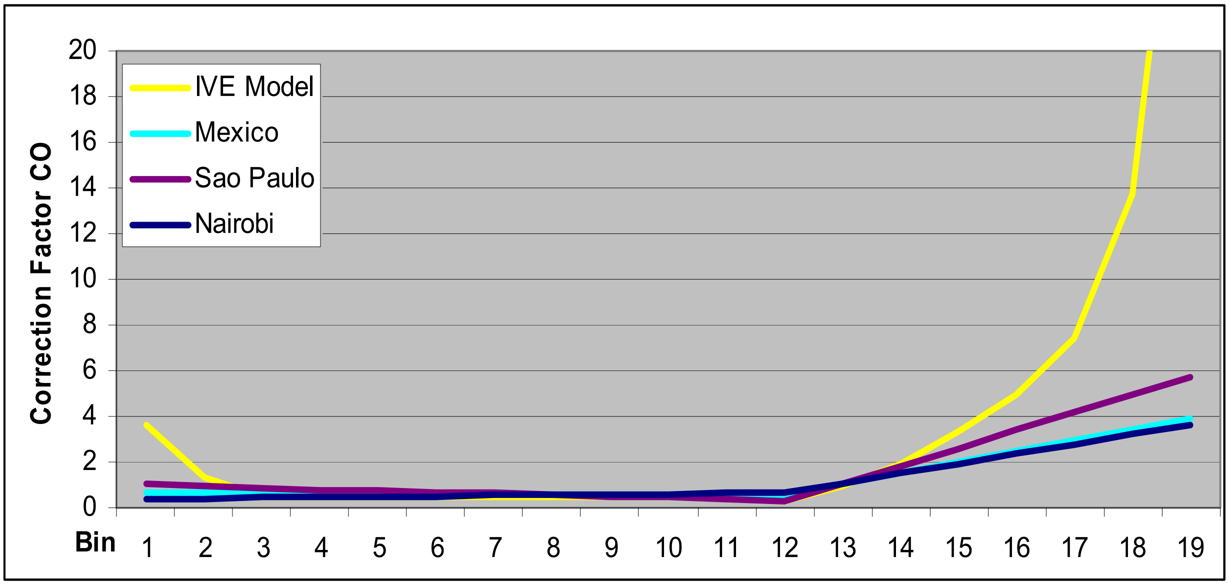


Figure IV-2 CO Corrections for the Driving Bins for the New Multipoint Fuel Injected Vehicle with a 3-Way Catalyst Observed in this Study

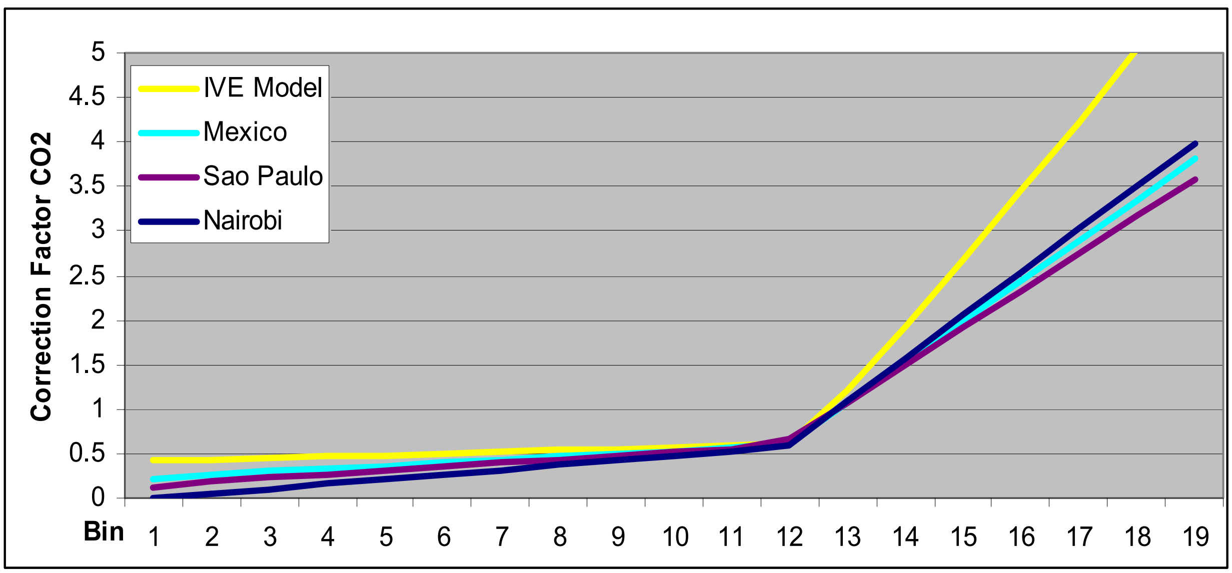


Figure IV-3 CO2 Corrections for the Driving Bins for the New Multipoint Fuel Injected Vehicle with a 3-Way Catalyst Observed in this Study

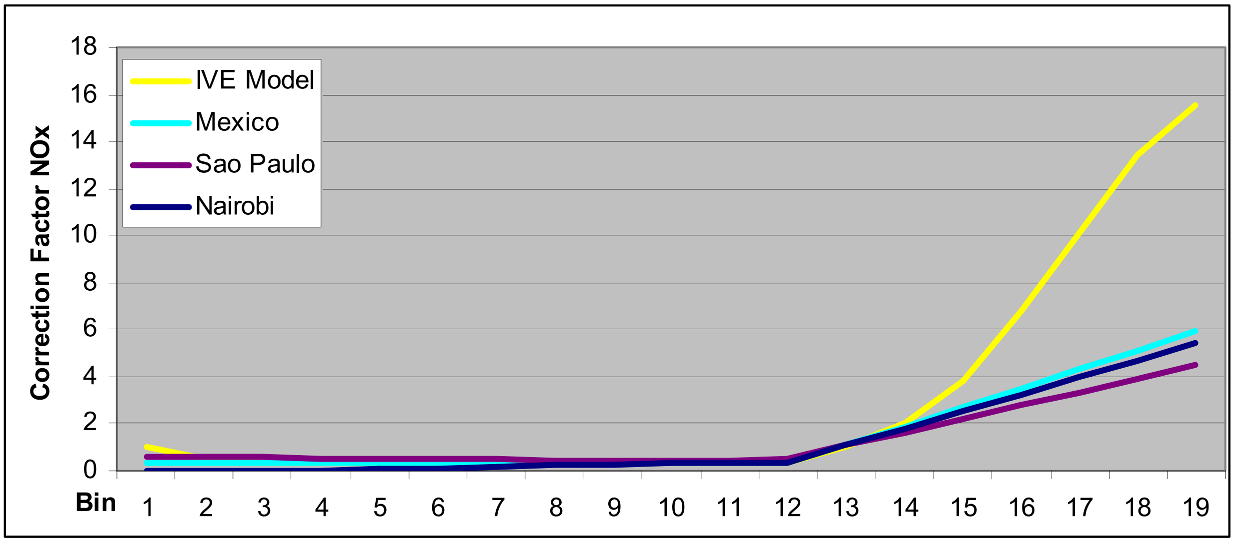


Figure IV-4 NOx Corrections for the Driving Bins for the New Multipoint Fuel Injected Vehicle with a 3-Way Catalyst Observed in this Study

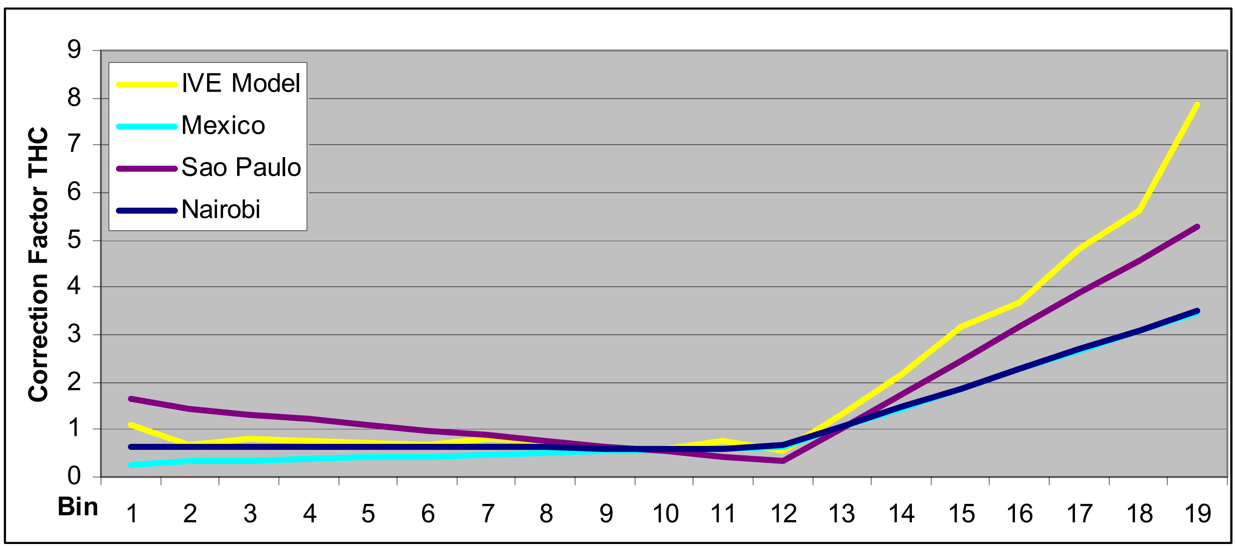


Figure IV-5 THC Corrections for the Driving Bins for the New Multipoint Fuel Injected Vehicle with a 3-Way Catalyst Observed in this Study

Due to traffic congestion during parts of the day, driving could not be achieved in all of the necessary running bins. Thus there were no emission estimates for these bins. In all cases, the bins missed were the bins were the smallest fraction of driving was taking place. Thus, an estimate of emissions for these bins would not produce a major change in the resulting emission estimates. A linear fit was made to the data in bins 0 to 11 (these are the bins were the vehicle is slowing down), and a second linear fit was made for bins 11-19 (these are the bins were the vehicle is accelerating or driving at a steady rate). Similar linear fits were made to the higher stress bins. These linear fits were used to fill in data where no driving was observed.

The LA4 test cycle, which represents the hot running portion of the FTP test procedure, is a standard test cycle used all over the world and is used in the IVE model to establish the base emission factors. It is easy to divide the driving trace of the LA4 cycle into the fractions of time spent in each of the 60 IVE VSP bins. The result is the LA4 driving pattern as shown in Figure IV-1. These fractions can be used in conjunction with the emission rates measured for the various IVE VSP bins (Figure IV-2) to determine the approximate emissions that would result had the tested vehicle been driven on the LA4 cycle. Thus, the emission rates for different vehicles can be normalized as if the vehicle had been tested on a LA4 cycle. This will not be a perfect conversion, and as noted earlier, the observed changes in emissions in the higher bins were not totally consistent with our U.S. results. Until this can be better understood a different approach to LA4 normalization will be used as described in the next paragraph.

In order to make comparisons with the base emission factors in the IVE model, and because of the inconsistency in higher bin emissions, a second normalization approach was used. In this approach, the IVE driving correction factors as illustrated in Figure IV-2 are multiplied by the fraction of observed driving illustrated in Figure IV-1. This process results in a driving correction factor that indicates the difference in emissions predicted by the IVE model from an LA4 cycle to the actual cycle used to measure the emissions. This value is divided into the measured running emissions from each test to obtain an estimate of the vehicle's emissions if it was driven over the LA4 cycle (the running base emission factor). This value is important for developing improved base emission factors for the IVE model. These results will be presented in the results section as the LA4 corrected emissions.

IV.C. Starting Emissions

Cold-Start emissions are defined to be the excess emissions that occur in the first 200 seconds after the vehicle sits for 12 or more hours. When the vehicle is started, there will be both starting emissions and running emissions for the first 200 seconds. The cold start emissions can be obtained by subtracting the running emissions that occur during the first 200 seconds from the total emissions that occur during that period. Similarly, Warm-Start emissions are defined to be the excess emissions that occur from an already warmed up vehicle in the first 200 seconds after the vehicle rests for 10 minutes.

The estimation of start emissions is not an exact exercise. The estimated running emissions that occurred during the start up phase can be a little too high or a little too low. Since the Cold-Start and Warm-Start emissions are calculated as the difference between two values, an error in the estimation of one of the values will exacerbate the error in the calculation of Cold-Start and Warm-Start emissions. However, when applied over several vehicles, the errors should average out to produce a representative emission rate depending upon the number of vehicles tested.

V. Results

V.A. Running Emission Rates for Individual Technologies

Table V-1 - Table V-3 lists the technologies that participated in the testing, the number of vehicles tested in that technology category, and the 90% confidence intervals for the vehicle categories where applicable. For example, for IVE category 4 in Mexico City, there is a 90% probability that a similar vehicle tested would fall within ± 43% of the reported value for CO.

The large range in the 90% confidence interval results from the fact that similar vehicles can have a large spread in actual emissions. This fact emphasizes the point that many vehicles need to be tested to fully understand vehicle emissions in an area, and further studies need to be completed in all of the urban areas where we worked. Appendix B contains the numerical values for the measured emissions from each vehicle as well as the FTP corrected values.

Table V-1 Description of Vehicles Tested in Mexico City and the 90% Confidence Intervals for Average Values Computed for each IVE Class

IVE Category	IVE Description	# Tested	CO	CO2	NOx	THC
4	med carb med mi	5	43%	13%	68%	56%
5	med carb high mi	12	22%	9%	39%	18%
8	heavy carb high mi	2	2%	17%	32%	164%
19	light carb 2w med mi	1	n/a	n/a	n/a	n/a
31	med carb 3w med mi	1	n/a	n/a	n/a	n/a
53	heavy spfi high mi	1	n/a	n/a	n/a	n/a
59	heavy spfiegr high mi	1	n/a	n/a	n/a	n/a
84	med spfi 3w low mi	1	n/a	n/a	n/a	n/a
85	med spfi 3w med mi	6	82%	10%	25%	52%
86	med spfi 3w high mi	1	n/a	n/a	n/a	n/a
104	heavy spfi 3w high mi	1	n/a	n/a	n/a	n/a
117	light mpfi 3w low mi	2	102%	13%	40%	
85	med mpfi 3w low mi <2000	4	45%	5%	32%	57%
120	med mpfi 3w low mi 2000+	22	19%	5%	29%	25%
86	med mpfi 3w med mi <2000	10	46%	4%	49%	53%
121	med mpfi 3w med mi 2000+	5	16%	3%	49%	27%
124	heavy mpfi 3w med mi	2	63%	20%	63%	n/a
125	heavy mpfi 3w high mi	2	7%	2%	106%	32%
129	med mpfi 3wegr low mi	8	52%	7%	52%	60%
130	med mpfi 3wegr med mi	2	54%	15%	11%	n/a
131	med mpfi 3wegr high mi	2	85%	19%	71%	64%
132	heavy mpfi 3wegr low mi	4	42%	26%	53%	64%
8	heavy mpfi 3wegr med mi <1998	2	40%	40%	117%	95%
133	heavy mpfi 3wegr med mi 1998+	2	71%	41%	10%	115%
134	heavy mpfi 3wegr high mi	1	n/a	n/a	n/a	n/a
	All Vehicles	100	24%	4%	18%	22%

Table V-2 Description of Vehicles Tested in Sao Paulo and the 90% Confidence Intervals for Average Values Computed for each IVE Class

IVE Category	IVE Description	# Tested	CO	CO2	NOx	THC
2	light carb high mi	1	n/a	n/a	n/a	n/a
5	med carb high mi	4	49%	29%	119%	70%
28	carb 3w med mi	1	n/a	n/a	n/a	n/a
29	carb 3w high mi	1	n/a	n/a	n/a	n/a
50	med spfi high mi	1	n/a	n/a	n/a	n/a
58	med spfi egr med mi	1	n/a	n/a	n/a	n/a
81	light spfi 3w low mi	1	n/a	n/a	n/a	n/a
84	med spfi 3w low mi	1	n/a	n/a	n/a	n/a
85	med spfi 3w med mi	1	n/a	n/a	n/a	n/a
117	light mpfi 3w low mi	36	26%	4%	25%	25%
118	light mpfi 3w med mi	11	54%	5%	34%	46%
120	med mpfi 3w low mi	22	22%	5%	44%	36%
121	med mpfi 3w med mi	10	72%	7%	64%	81%
122	med mpfi 3w high mi	2	37%	15%	36%	104%
124	heavy mpfi 3w med mi	2	125%	14%	50%	51%
244	retrofit ng light carb 3w med mi	1	n/a	n/a	n/a	n/a
306	light ng fi 3w low mi	1	n/a	n/a	n/a	n/a
307	light ng fi 3w med mi	1	n/a	n/a	n/a	n/a
309	med ng fi 3w low mi	1	n/a	n/a	n/a	n/a
310	med ng fi 3w med mi	1	n/a	n/a	n/a	n/a
313	heavy ng fi 3w med mi	2	154%	19%	116%	26%
572	etoh retroift med 2w high mi	1	n/a	n/a	n/a	n/a
575	etoh retroift heavy 2w high mi	1	n/a	n/a	n/a	n/a
606	etoh retrofit med 3w low mi	4	119%	12%	93%	44%
635	oem etoh carb high mi	2	86%	5%	65%	62%
675	oem etoh light fi 3w low mi	1	n/a	n/a	n/a	n/a
	All Vehicles	111	31%	3%	22%	34%

Table V-3 Description of Vehicles Tested in Nairobi and the 90% Confidence Intervals for Average Values Computed for each IVE Class

IVE Category	IVE Description	# Tested	CO	CO2	NOx	THC
4	med carb med mi	6	28%	10%	37%	34%
5	med carb high mi	32	11%	7%	33%	15%
49	med spfi med mi	2	29%	3%	4%	13%
50	med spfi high mi	1	--	--	--	--
102	med mpfi low mi	15	20%	7%	26%	25%
103	med mpfi med mi	33	18%	4%	13%	14%
104	med mpfi high mi	14	24%	7%	21%	17%
120	med mpfi 3w low mi	6	27%	8%	45%	56%

121	med mpfi 3w high mi	4	20%	4%	47%	40%
	All Vehicles	113	17%	3%	11%	15%

As noted earlier, these data show a clear indication of the need to collect larger samples of vehicles to have an improved confidence in the results of the testing. Although data was successfully retrieved from over 100 vehicles in each location, very few vehicles were left in a technology group by the time it was categorized. A combination of the innate nature of the variation in emissions from vehicle to vehicle and the limited number of tests render quite large confidence limits in many cases. Overall, the Nairobi data set contains the best confidence, probably due to the larger quantity of vehicles within each grouping, and the less complicated control technology. There are only 9 different vehicle types tested in Nairobi, compared to 26 in Sao Paulo Mexico City. Looking at all vehicles combined, the confidence interval improves somewhat and looks similar between cities. Confidence intervals for CO2 remained 3-4%, ranged from 15-30% for CO and THC, and 7-15% for NOx.

The vehicles tested in each city should roughly represent a random selection of the light duty passenger fleet as found in each city. Thus, the overall results should provide a reasonable estimate of the light duty fleet emission rates, but again caution should be employed when looking at individual classes with few vehicles tested.

Table V-4 - Table V-6 lists the average running emissions for all vehicles tested in each city operating over the LA4 cycle. Because the LA4 cycle could not be replicated for every vehicle tested since this was an on-road experiment, the IVE model was used to adjust the actual emissions to emissions from an LA4 cycle as explained in the data analysis section.

Table V-4 Mexico City Average Running FTP Emissions Rates for each Technology Type Tested[1]

IVE Class	Description	CO (g/km)	CO2 (g/km)	NOx (g/km)	THC (g/km)
4	med carb med mi	37	234	1.5	3.8
5	med carb high mi	42	211	1.2	4.8
8	heavy carb high mi	64	344	2.1	2.2
19	light carb 2w med mi	22	168	0.8	1.8
31	med carb 3w med mi	25	192	1.2	6.3
53	heavy spfi high mi	25	317	6.0	4.0
59	heavy spfiegr high mi	32	281	3.8	4.4
84	med spfi 3w low mi	1	200	0.3	0.3
85	med spfi 3w med mi	14	193	0.8	1.6
86	med spfi 3w high mi	4	225	1.4	1.0
104	heavy spfi 3w high mi	17	313	3.6	2.2
117	light mpfi 3w low mi	1	150	0.2	0.1
85	med mpfi 3w low mi <2000	7	206	0.7	0.8
120	med mpfi 3w low mi 2000+	2	219	0.2	0.2
86	med mpfi 3w med mi <2000	15	229	1.3	2.1
121	med mpfi 3w med mi 2000+	5	203	0.4	0.5
124	heavy mpfi 3w med mi	7	343	1.2	0.3

125	heavy mpfi 3w high mi	8	254	2.0	1.0
129	med mpfi 3wegr low mi	1	201	0.3	0.2
130	med mpfi 3wegr med mi	3	257	1.6	0.5
131	med mpfi 3wegr high mi	11	214	1.7	2.4
132	heavy mpfi 3wegr low mi	2	259	0.3	0.3
8	heavy mpfi 3wegr med mi <1998	31	335	1.6	4.7
133	heavy mpfi 3wegr med mi 1998+	5	331	0.7	0.7
134	heavy mpfi 3wegr high mi	7	414	0.8	1.3
Average of All Light Duty Vehicles Tested		16	228	0.9	1.7

[1] The measured emissions values were normalized to the FTP cycle using the IVE model for comparison purposes. It should be noted that the FTP referred to here includes only the running part of the FTP cycle (bags 2 and 3). The value was not normalized for altitude, fuel, temperature, humidity; although, the temperature and humidity were somewhat close to those called for in the standard FTP testing cycle on the days of testing.

Table V-5 Sao Paulo Average Running FTP Emissions Rates for each Technology Type Tested[1]

IVE Class	Description	CO (g/km)	CO2 (g/km)	NOx (g/km)	THC (g/km)
2	light carb high mi	87	139	0.5	8.2
5	med carb high mi	69	193	2.8	12.2
28	carb 3w med mi	113	112	0.2	11.1
29	carb 3w high mi	50	157	0.5	4.9
50	med spfi high mi	26	231	0.8	3.4
58	med spfi egr med mi	13	258	1.4	2.5
81	light spfi 3w low mi	6	213	0.3	0.4
84	med spfi 3w low mi	6	235	0.4	0.6
85	med spfi 3w med mi	19	254	2.0	2.1
117	light mpfi 3w low mi	3	200	0.4	0.2
118	light mpfi 3w med mi	8	189	1.1	0.9
120	med mpfi 3w low mi	2	245	0.5	0.3
121	med mpfi 3w med mi	12	218	0.9	2.1
122	med mpfi 3w high mi	6	236	1.3	0.7
124	heavy mpfi 3w med mi	37	335	0.9	2.8
244	retrofit ng light carb 3w med mi	1	206	2.3	2.1
306	light ng fi 3w low mi	3	180	0.9	0.9
307	light ng fi 3w med mi	9	156	0.8	1.2
309	med ng fi 3w low mi	1	196	0.3	0.6
310	med ng fi 3w med mi	17	206	1.9	2.7
313	heavy ng fi 3w med mi	10	302	2.0	2.0
572	etoh retroift med 2w high mi	17	205	1.2	6.8
575	etoh retroift heavy 2w high mi	38	156	0.7	7.7
606	etoh retrofit med 3w low mi	1	244	0.2	0.2
635	oem etoh carb high mi	31	189	1.1	5.2
675	oem etoh light fi 3w low mi	2	230	0.3	0.1

Average of All Light Duty Vehicles Tested	11	215	0.8	1.5

[1] The measured emissions values were normalized to the FTP cycle using the IVE model for comparison purposes. It should be noted that the FTP referred to here includes only the running part of the FTP cycle (bags 2 and 3). The value was not normalized for altitude, fuel, temperature, humidity; although, the temperature and humidity were somewhat close to those called for in the standard FTP testing cycle on the days of testing.

Table V-6 Nairobi Average Running FTP Emissions Rates for each Technology Type Tested[1]

IVE Class	Description	CO (g/km)	CO2 (g/km)	NOx (g/km)	THC (g/km)
4	med carb med mi	69	147	0.7	9.6
5	med carb high mi	73	159	0.8	8.4
49	med spfi med mi	13	174	2.2	3.1
50	med spfi high mi	63	273	1.8	14.7
102	med mpfi low mi	9	179	1.7	1.5
103	med mpfi med mi	10	175	1.7	2.1
104	med mpfi high mi	17	177	1.3	3.8
120	med mpfi 3w low mi	5	175	1.2	1.0
121	med mpfi 3w high mi	5	180	1.4	1.4
Average of All Light Duty Vehicles Tested		32	171	1.3	4.5

[1] The measured emissions values were normalized to the FTP cycle using the IVE model for comparison purposes. It should be noted that the FTP referred to here includes only the running part of the FTP cycle (bags 2 and 3). The value was not normalized for altitude, fuel, temperature, humidity; although, the temperature and humidity were somewhat close to those called for in the standard FTP testing cycle on the days of testing.

From all three tables, it is clear that the emissions follow the expected trend when looking on a gross scale, but there are not enough tests to see the expected trends on the disaggregated scale in all cases. For example, in Table V-7, you would expect the class 5 with high mileage to have higher THC emissions than class 4, but it does not. Because the vehicle to vehicle variability is large compared with sample sizes, it is necessary to take into account and average effects until more data can be collected.

Table V-7 - Table V-9 are similar to the previous tables in that it shows the running emissions from all vehicles tested, but these have not been corrected to be for the LA4. Instead, this is the result of the actual driving cycle at the time each vehicle was tested. Therefore, no two driving cycles are alike, and will affect emission rates differently for each vehicle, which makes it difficult for exact comparison between vehicles and classes. However, it is useful to observe the actual emissions, and these emissions should more closely represent real-world conditions than the LA-4 corrected emission rates, and be similar to what would be used in an emissions inventory. Note that in most cases, the actual on-road emissions are larger than the LA4 corrected emission rates shown in Table V-4-Table V-6. This is expected since the LA4 is considered to be a non-aggressive cycle that does not represent real-world driving conditions. The exception is Nairobi, whose on-road running emissions are lower than for the LA4 cycle.

This is consistent with what was observed from the driving patterns during testing, where high velocities and accelerations were not achieved consistently. The last row in Table V-7 - Table V-9 is the average of all the vehicles tested. Although the mix of vehicles used in this test is not exactly representative of the real-world fleet, this emission rate should give a rough approximation of the actual emissions of the light duty fleet, keeping in mind the confidence intervals from Table V-1 - Table V-3. Additionally, these emissions are for the cycles that operated during testing, which is slightly different than the cycles operating within the city on a daily basis. Emissions corrected for the cycle is discussed in the next section.

Table V-7 Mexico City Average On-Road Running Emissions Rates for each Technology Type Tested

IVE Class	Description	CO (g/km)	CO2 (g/km)	NOx (g/km)	THC (g/km)
4	med carb med mi	47	278	2.1	4.4
5	med carb high mi	59	283	1.8	7.5
8	heavy carb high mi	74	407	1.7	2.3
19	light carb 2w med mi	32	297	1.2	3.0
31	med carb 3w med mi	51	243	1.8	8.5
53	heavy spfi high mi	28	343	6.8	4.3
59	heavy spfiegr high mi	32	282	3.6	4.6
84	med spfi 3w low mi	3	335	0.5	0.4
85	med spfi 3w med mi	22	246	1.2	2.1
86	med spfi 3w high mi	16	308	2.5	1.5
104	heavy spfi 3w high mi	37	363	4.7	2.8
117	light mpfi 3w low mi	3	211	0.3	0.1
85	med mpfi 3w low mi <2000	22	281	1.2	1.1
120	med mpfi 3w low mi 2000+	6	316	0.4	0.3
86	med mpfi 3w med mi <2000	32	322	2.0	2.9
121	med mpfi 3w med mi 2000+	15	323	0.7	0.8
124	heavy mpfi 3w med mi	11	469	1.7	0.4
125	heavy mpfi 3w high mi	15	319	3.0	1.4
129	med mpfi 3wegr low mi	4	280	0.6	0.4
130	med mpfi 3wegr med mi	7	323	2.6	0.6
131	med mpfi 3wegr high mi	32	360	3.3	4.2
132	heavy mpfi 3wegr low mi	7	366	0.4	0.4
8	heavy mpfi 3wegr med mi <1998	47	435	2.0	6.0
133	heavy mpfi 3wegr med mi 1998+	10	418	1.1	1.0
134	heavy mpfi 3wegr high mi	12	486	1.0	1.6
Average of All Light Duty Vehicles Tested		26	313	1.4	2.5

Table V-8 Sao Paulo Average On-Road Running Emissions Rates for each Technology Type Tested

IVE Class	Description	CO (g/km)	CO2 (g/km)	NOx (g/km)	THC (g/km)
2	light carb high mi	105	164	0.7	9.6
5	med carb high mi	81	224	3.5	14.4

28	carb 3w med mi	136	124	0.3	12.8
29	carb 3w high mi	66	194	0.6	6.1
50	med spfi high mi	35	277	0.9	4.4
58	med spfi egr med mi	19	366	1.7	4.1
81	light spfi 3w low mi	13	297	0.5	0.6
84	med spfi 3w low mi	12	362	0.8	0.9
85	med spfi 3w med mi	25	322	2.6	2.7
117	light mpfi 3w low mi	4	241	0.6	0.3
118	light mpfi 3w med mi	10	238	1.5	1.1
120	med mpfi 3w low mi	4	303	0.7	0.4
121	med mpfi 3w med mi	20	275	1.3	2.8
122	med mpfi 3w high mi	13	274	2.0	0.9
124	heavy mpfi 3w med mi	51	391	1.2	3.3
244	retrofit ng light carb 3w med mi	1	230	2.7	2.3
306	light ng fi 3w low mi	5	254	1.4	1.4
307	light ng fi 3w med mi	12	194	1.1	1.5
309	med ng fi 3w low mi	1	226	0.3	0.7
310	med ng fi 3w med mi	30	272	3.0	3.7
313	heavy ng fi 3w med mi	15	356	2.5	2.5
572	etoh retroift med 2w high mi	22	237	1.7	7.5
575	etoh retroift heavy 2w high mi	46	182	0.8	9.3
606	etoh retrofit med 3w low mi	1	312	0.3	0.2
635	oem etoh carb high mi	41	230	1.7	7.0
675	oem etoh light fi 3w low mi	2	260	0.4	0.1
Average of All Light Duty Vehicles Tested		15	264	1.0	1.9

Table V-9 Nairobi Average On-Road Running Emissions Rates for each Technology Type Tested

IVE Class	Description	CO (g/km)	CO2 (g/km)	NOx (g/km)	THC (g/km)
4	med carb med mi	68	140	0.9	7.9
5	med carb high mi	68	149	0.7	6.9
49	med spfi med mi	14	182	2.4	3.3
50	med spfi high mi	82	284	2.3	16.4
102	med mpfi low mi	9	179	2.0	1.4
103	med mpfi med mi	11	176	1.9	2.1
104	med mpfi high mi	19	179	1.5	3.7
120	med mpfi 3w low mi	5	176	1.4	1.0
121	med mpfi 3w high mi	6	181	1.9	1.5
Average of All Light Duty Vehicles Tested		31	169	1.5	4.0

V.B. Running Emissions by Technology Groups

It can be useful to group emissions from similar classes together to observe trends and to increase sample size and minimize random error. For comparisons between classes, vehicles in more than a single IVE class were aggregated for a larger sample size between comparable vehicle types. For this section of the analysis, the vehicles from the following classes were aggregated into seven general technology and age classes (Table V-10-Table V-12). It can be noted from the table that some IVE classes were separated by model year, due to the disparate emissions results within these classes. This is discussed further in the next section.

Table V-10 Mexico City Grouped IVE Classes for Technology Comparisons

Description	# of Vehicles	IVE Classes
carb high mi	14	5,8
carb med mi	5	4
mpfi 3w med mi & old	18	121 (<2000), 124, 125, 131, 133(<1998)
Spfi 3w	7	85,86
mpfi 3w low mi & old	3	120 (<2000)
mpfi 3w med mi & new	9	121 (>1999), 130, 133 (>1997)
mpfi 3w low mi & new	40	117, 120, 129, 132

Table V-11 Sao Paulo Grouped IVE Classes for Technology Comparisons

Description	# of Vehicles	IVE Classes
carb	7	2,5, 28, 29
spfi, high mileage	3	50,58,85
mpfi med/hi mi	20	118, 121, 122, 124
spfi low mi	2	81, 84
mpfi low mi	55	117, 120
cng, fi med mi	3	310, 313
cng, fi low mi	3	306, 307, 309
etoh high mi	4	572, 575, 635
etoh low mi	5	606, 675

Table V-12 Nairobi Grouped IVE Classes for Technology Comparisons

Description	# of Vehicles	IVE Classes
carb	38	4,5
spfi, high mileage	3	49, 50
mpfi hi mi	14	104
mpfi low mi	48	102,103
mpfi 3w	10	120, 121

Figure V-1- Figure V-12 shows the FTP corrected running emissions for the technology groups shown in Table V-10- Table V-12. The FTP corrected emissions were used because they provide a fairer comparison between vehicles because the actual emissions have been normalized to the same driving trace. In the actual tests, the vehicles are not constrained to specific driving patterns and thus can produce a variety of emissions depending upon the traffic situation at the time of testing.

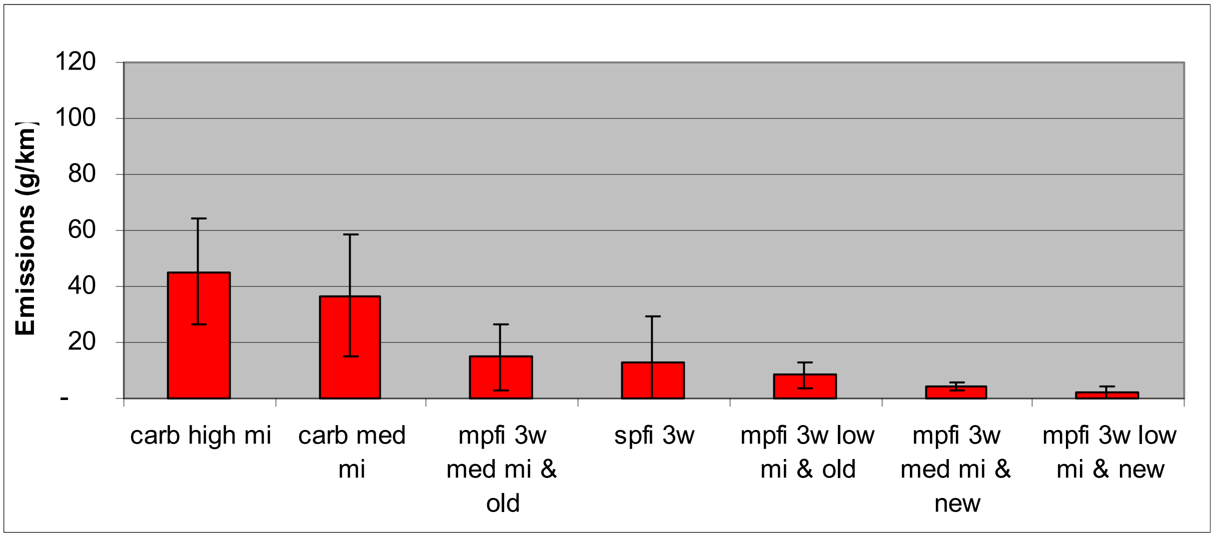


Figure V-1 Comparison of FTP corrected carbon monoxide emission values for the predominant Mexico City vehicle technologies

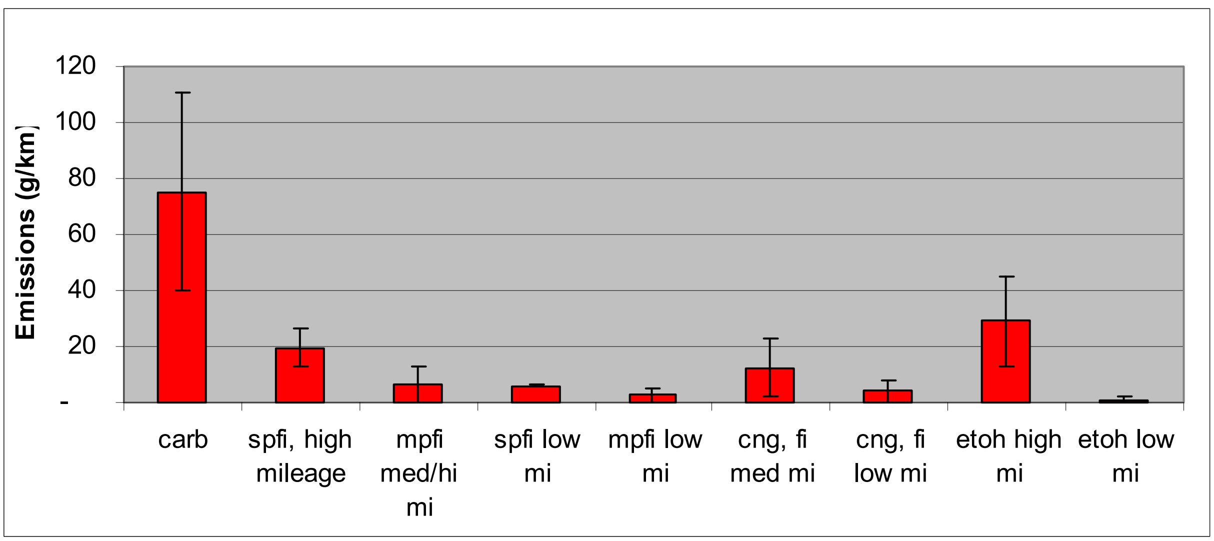


Figure V-2 Comparison of FTP corrected carbon monoxide emission values for the predominant Sao Paulo vehicle technologies

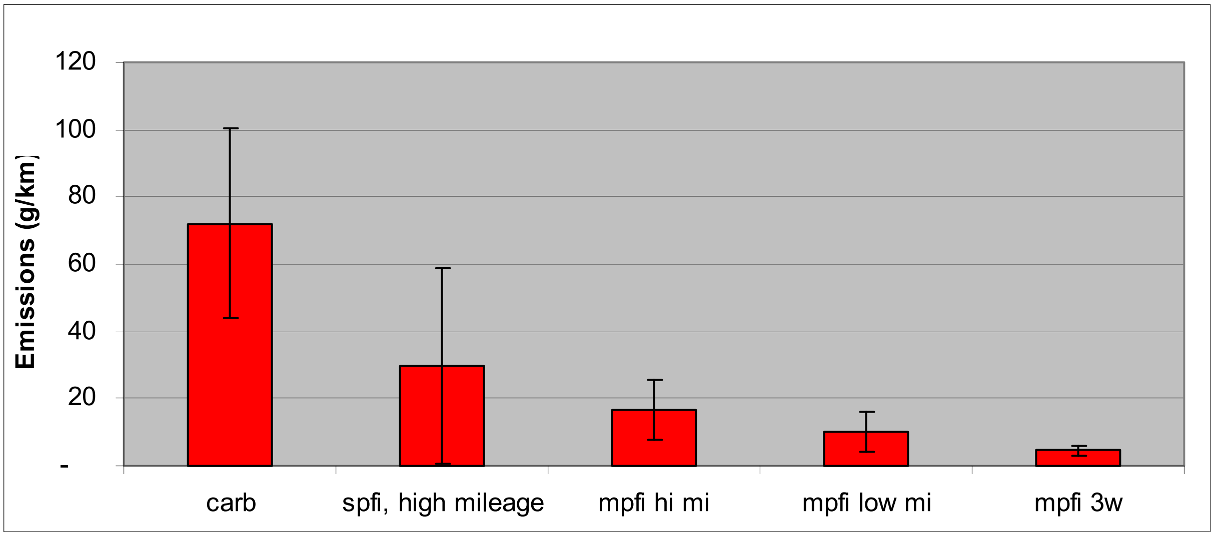


Figure V-3 Comparison of FTP corrected carbon monoxide emission values for the predominant Nairobi vehicle technologies

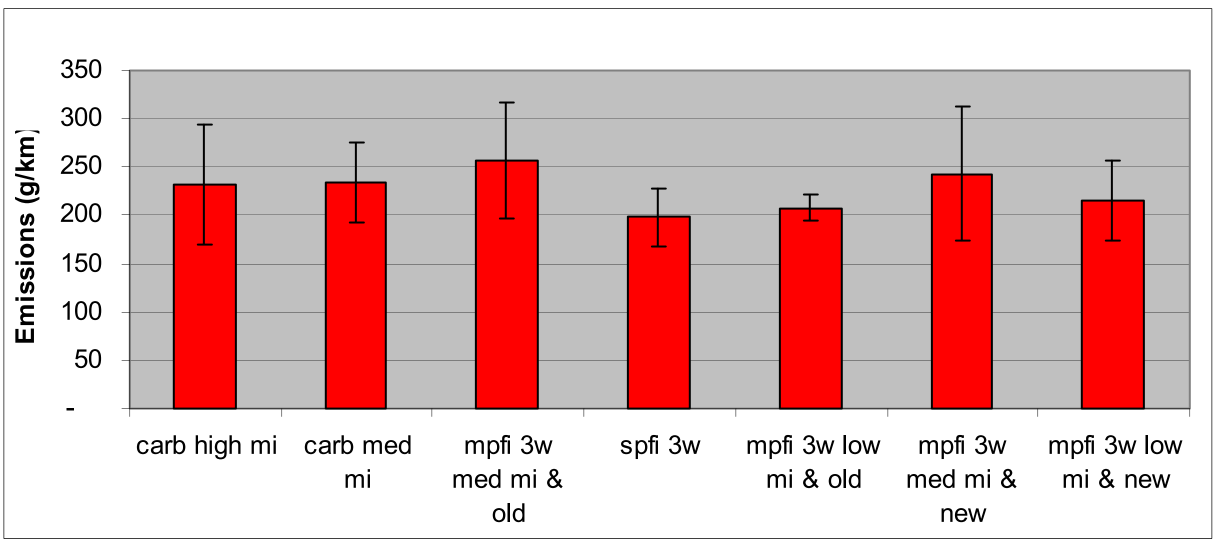


Figure V-4 Comparison of FTP corrected carbon dioxide emission values for the predominant Mexico City vehicle technologies

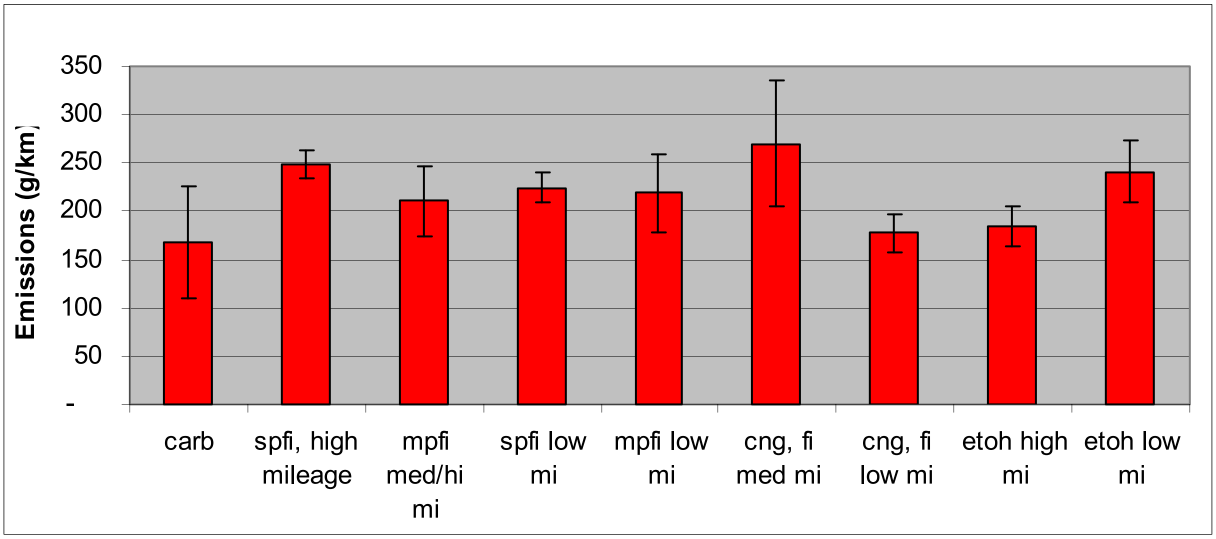


Figure V-5 Comparison of FTP corrected carbon dioxide emission values for the predominant Sao Paulo vehicle technologies

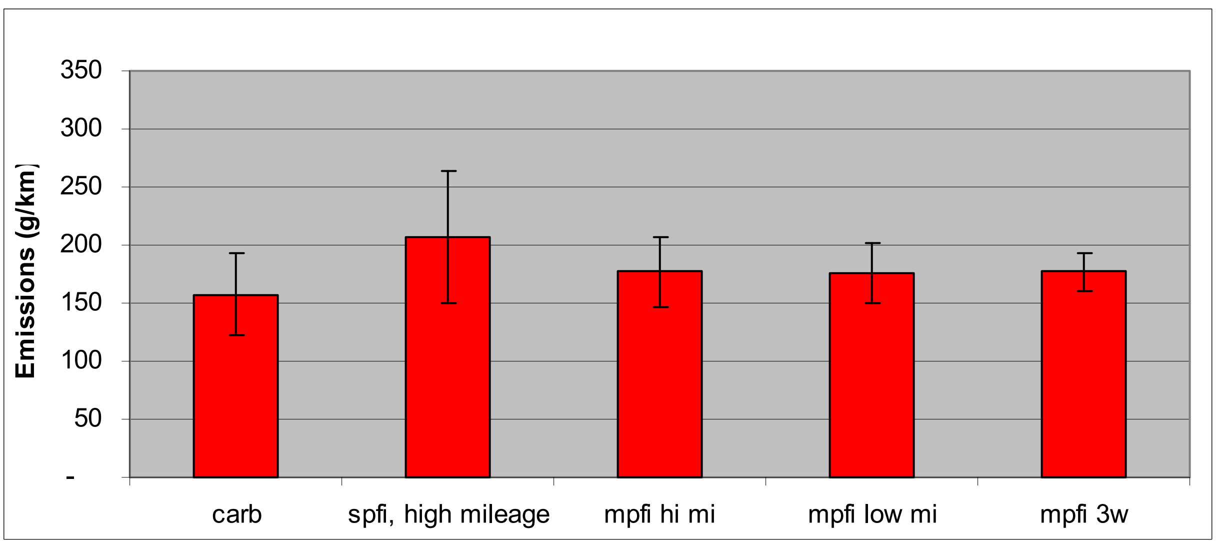


Figure V-6 Comparison of FTP corrected carbon dioxide emission values for the predominant Nairobi vehicle technologies

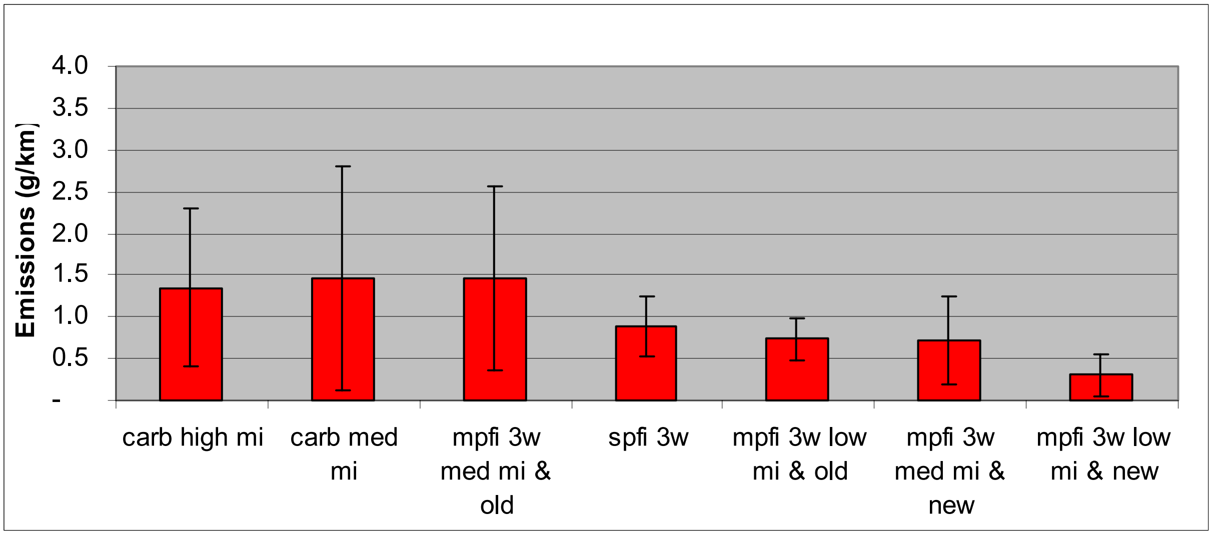


Figure V-7 Comparison of FTP corrected nitrogen oxide emission values for the predominant Mexico City vehicle technologies

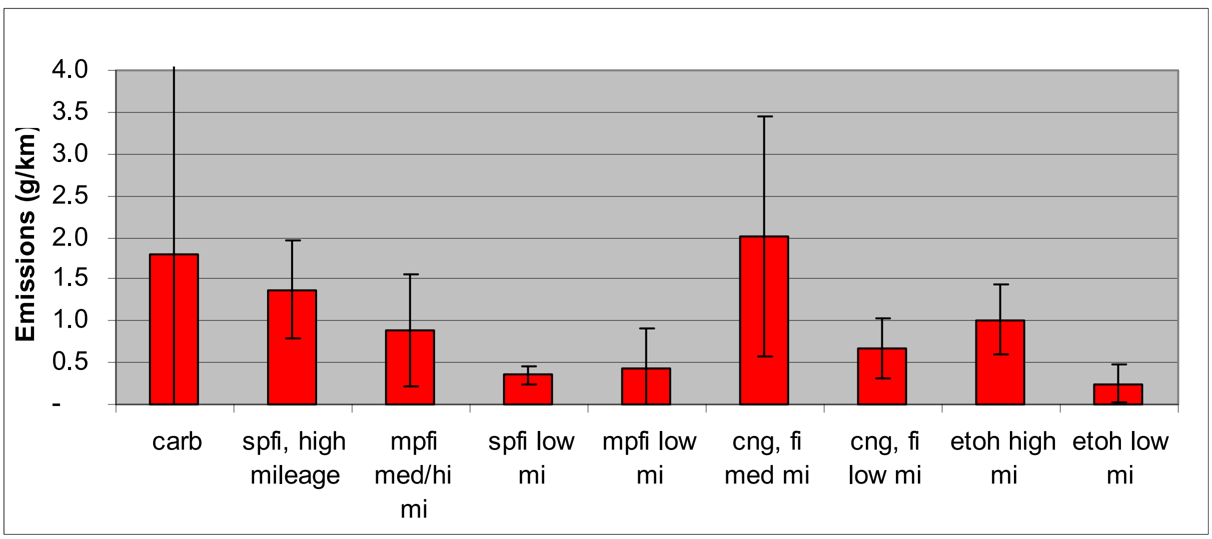


Figure V-8 Comparison of FTP corrected nitrogen oxide emission values for the predominant Sao Paulo vehicle technologies

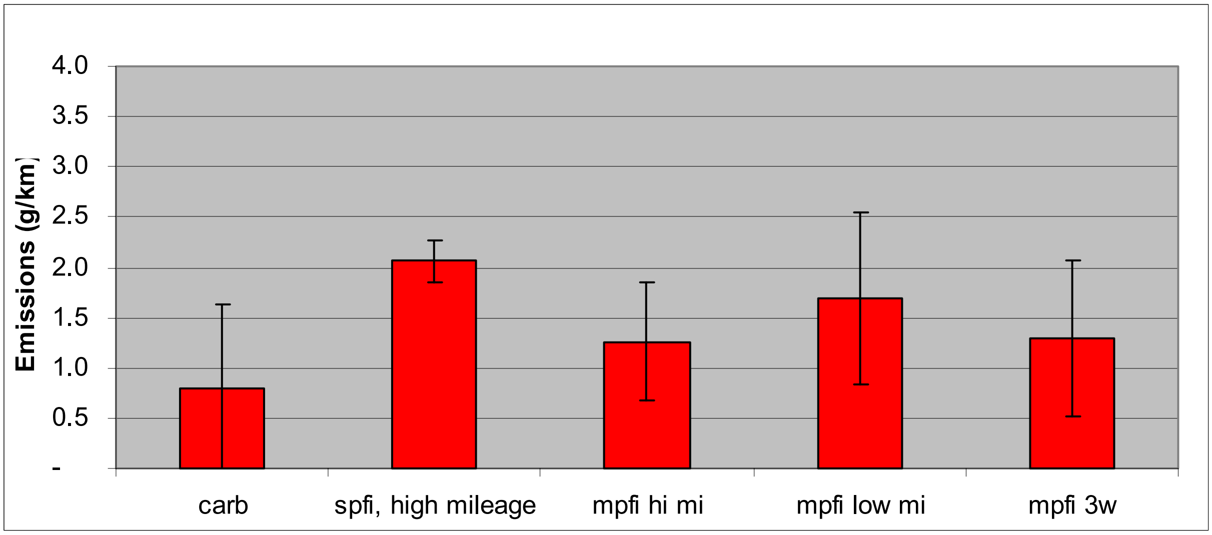


Figure V-9 Comparison of FTP corrected nitrogen oxide emission values for the predominant Nairobi vehicle technologies

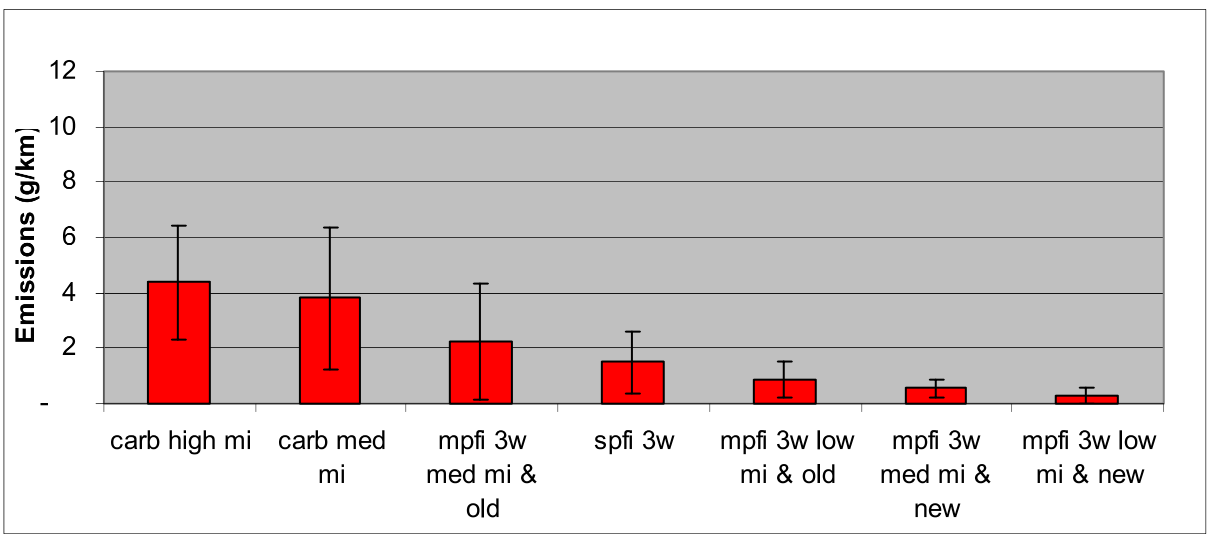


Figure V-10 Comparison of FTP corrected total hydrocarbon emission values for the predominant Mexico City vehicle technologies

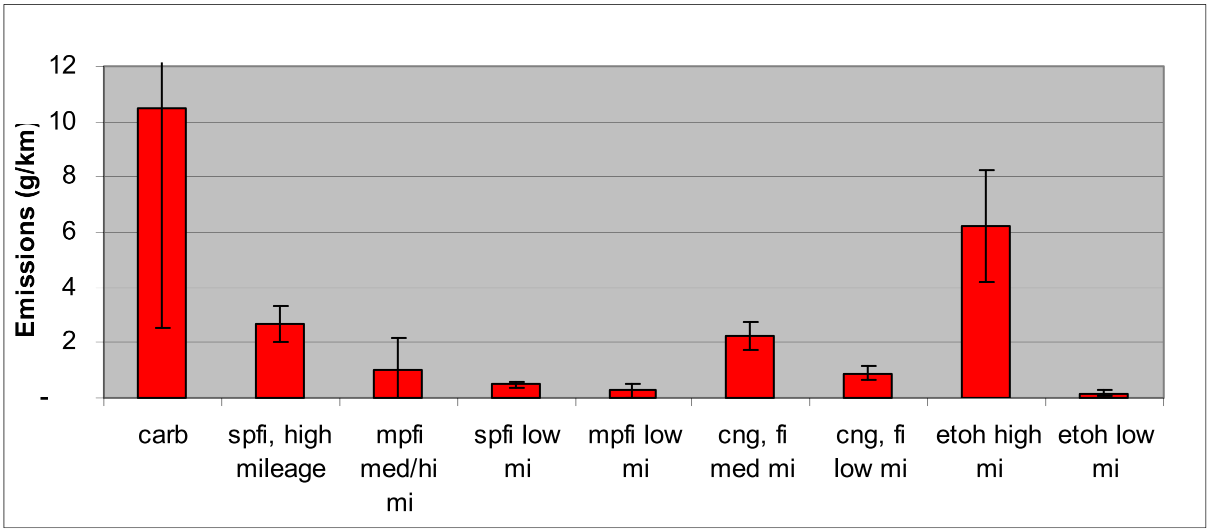


Figure V-11 Comparison of FTP corrected total hydrocarbon emission values for the predominant Sao Paulo vehicle technologies

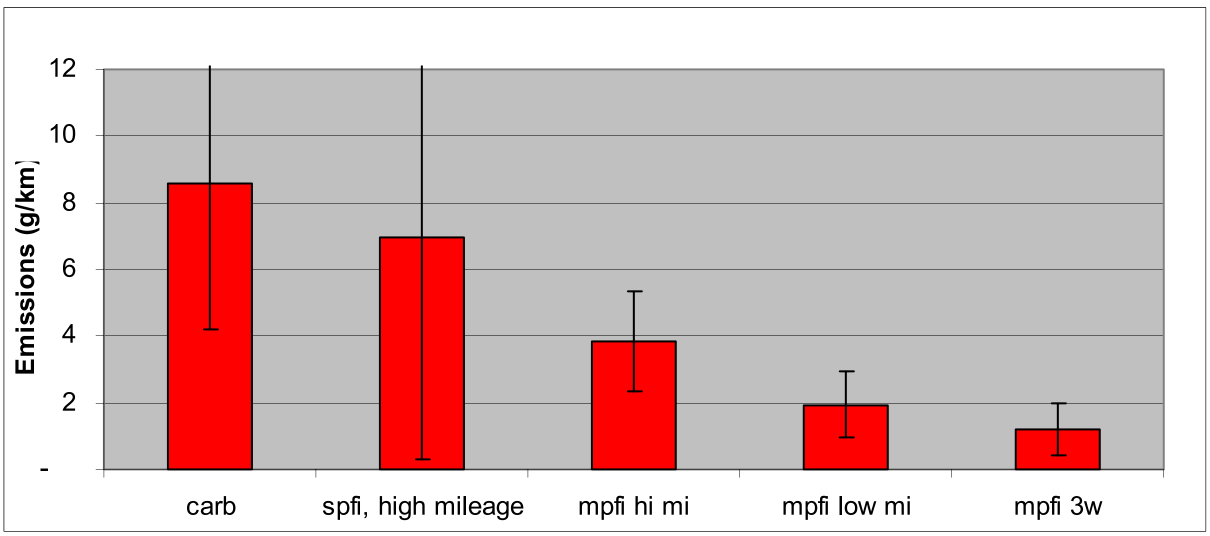


Figure V-12 Comparison of FTP corrected total hydrocarbon emission values for the predominant Nairobi vehicle technologies

In general the emission rates observed from the fleet followed the predicted trend. One standard deviation is shown in the error bars to illustrate the variation in the dataset. Some of this variation is due to mixing IVE classes (i.e. categories 85 and 86 should have similar but different emissions); some is due to the variations within each vehicle class. In general, the variation is reduced for the newer vehicles, which behave more consistently (in terms of emissions) from vehicle to vehicle than the older aged vehicles. For CO2, all emission rates are similar between the classes. This indicates that there is not a clear trend in fuel efficiency between these classes. (There is a trend seen with CO2 and size of vehicle, as expected). For CO, NOx, and THC, the carbureted, non-catalyst vehicles (Categories 4, 5 & 8) generally have the highest emissions.

The older single and multi point fuel injected catalyst vehicles also have high emissions. The lowest emissions are from the newest fuel injected catalyst vehicles. Within the same technology type, there is clear difference between the newer and older aged vehicles, and also between the vehicles with many miles and those with not very many miles. The older model year vehicles with significant use have emissions that are more than twice the emissions of similar technology newer vehicles with low use, and their emissions more closely resemble carbureted vehicles. While the datasets show expected trend in emissions, there is still a large error and more vehicles should be tested to improve the confidence levels.

V.C. Emissions Variations by Model Year within a Technology Class

One observation made in viewing the test results were that emissions varied by model year for several of the technologies, even though they were identical as far as technology class and type. For example, in Mexico City, IVE Class 120 (multipoint fuel injected with 3 way catalysts and low mileage), the vehicles have significantly different emissions depending on which year the vehicle was built. Similar results were observed for IVE Class 121, multipoint fuel injection with 3 way catalyst and medium mileage, and IVE Class 133, heavy weight multipoint fuel injection with 3 way catalysts, exhaust gas recirculation, and medium mileage. The emissions from these 3 classes are combined and shown in Figure V-13 - Figure V-24. Because of this observed variation in emissions, vehicles in class 120 and 121 with model years of less than 2000 were considered as a separate category and vehicles less than model year 1998 for group 133 were placed in a separate category as well. The reason for this variation in emissions is probably due to more stringent regulations set on vehicles beginning around model year 1999. INE reports that the Mexico City standards were tightened for 2002 but that there was considerable pressure placed on manufactures to comply by 2000, which they did. For these classes, a vehicle with the same control technology, age, and use (i.e. medium weight, multipoint fuel injected 3-way catalyst with medium use) built in 1997 would have significantly higher emissions than the same exact vehicle in 2001. While it is not possible to differentiate by the general technology type that the emissions are different, it is likely that the catalyst loading and efficiency were improved to meet the more stringent regulations. Therefore, it is necessary to place these vehicles in different categories since they are essentially a different technology. Sao Paulo also shows a differentiation in several classes by model year, however, Nairobi does not show this trend. In Nairobi, almost all of the vehicles come from Japan. These used Japanese vehicles have consistently been regulated throughout the 1990s. In addition, the leaded fuel in use in Nairobi has likely destroyed all of the vehicle catalysts. Thus, the year to year variation in emissions for Nairobi is more consistent than the other two cities.

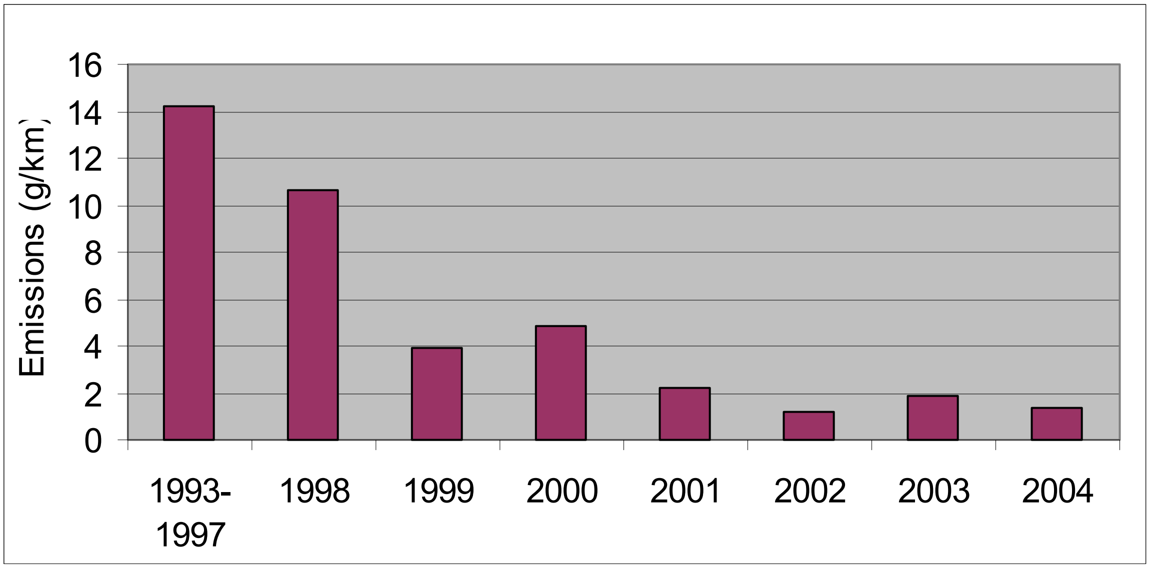


Figure V-13 Mexico City Comparison of carbon monoxide emission values for select IVE Classes by Model Year

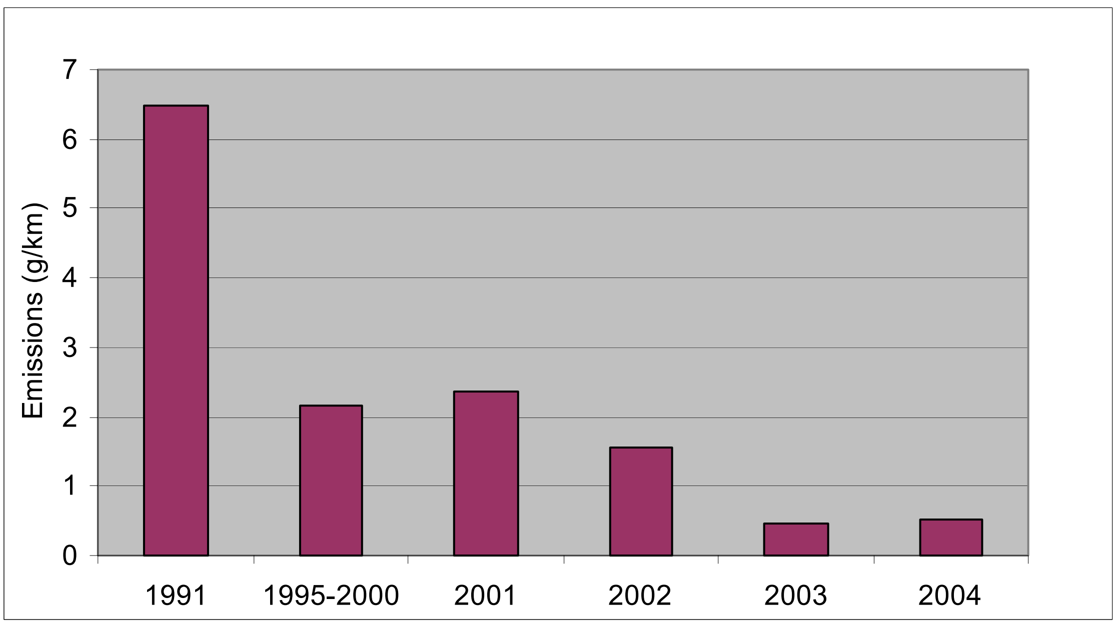


Figure V-14 Sao Paulo Comparison of carbon monoxide emission values for select IVE Classes by Model Year

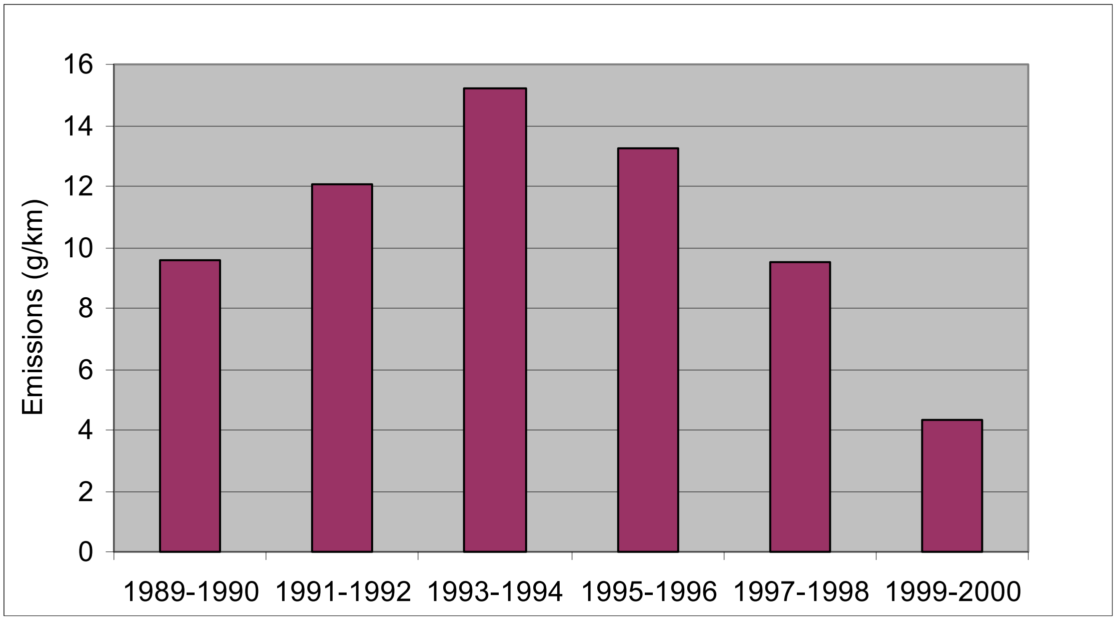


Figure V-15 Nairobi Comparison of carbon monoxide emission values for select IVE Classes by Model Year

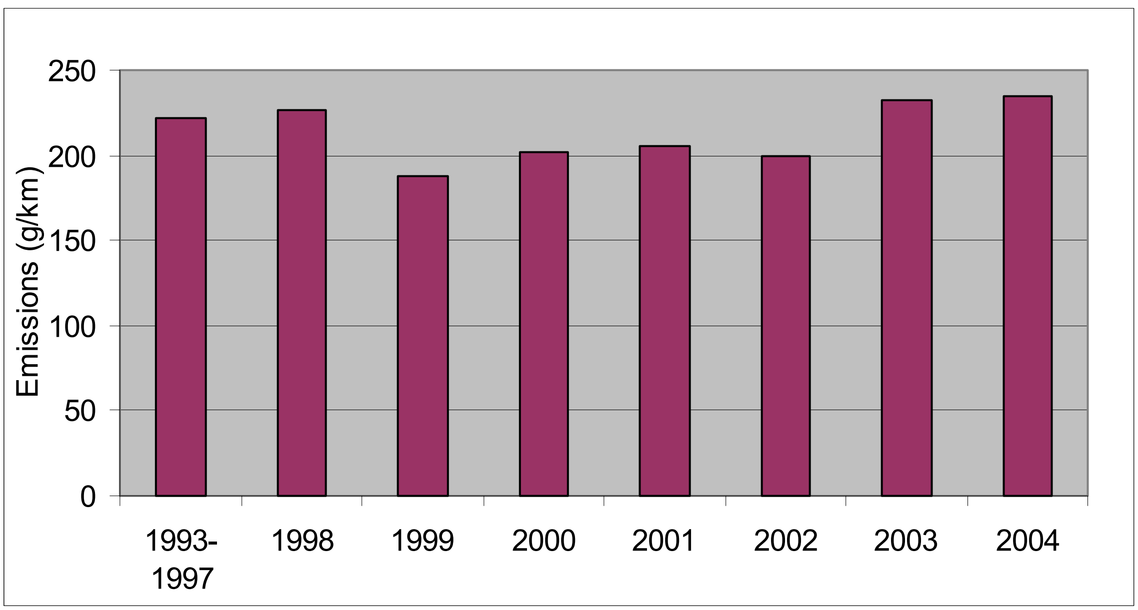


Figure V-16 Mexico City Comparison of carbon dioxide emission values for select IVE Classes by Model Year

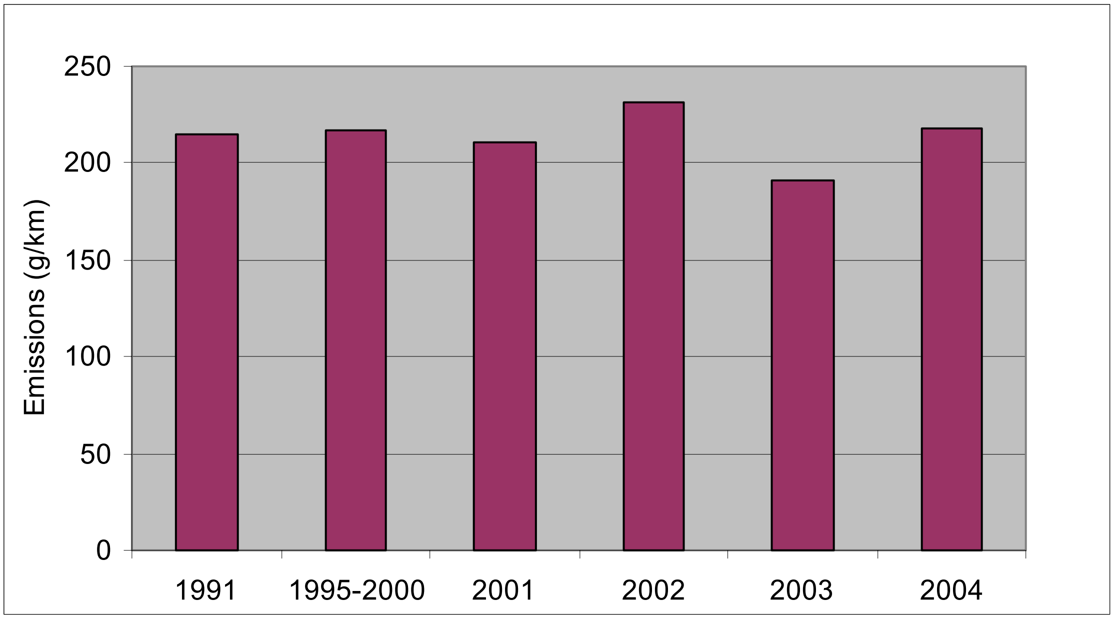


Figure V-17 Sao Paulo Comparison of carbon dioxide emission values for select IVE Classes by Model Year

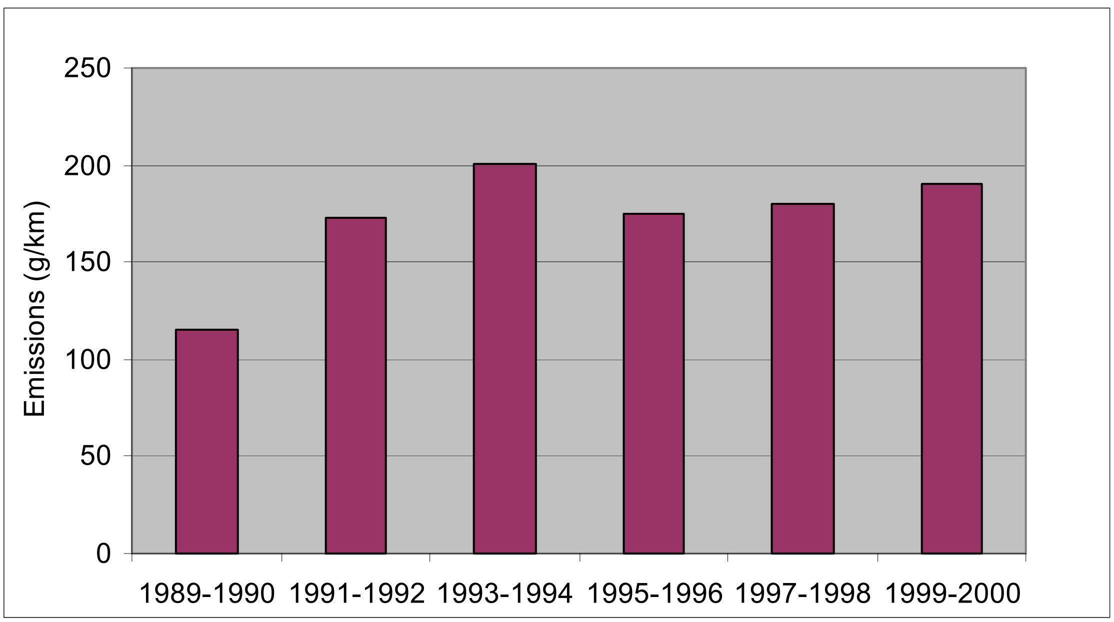


Figure V-18 Nairobi Comparison of carbon dioxide emission values for select IVE Classes by Model Year

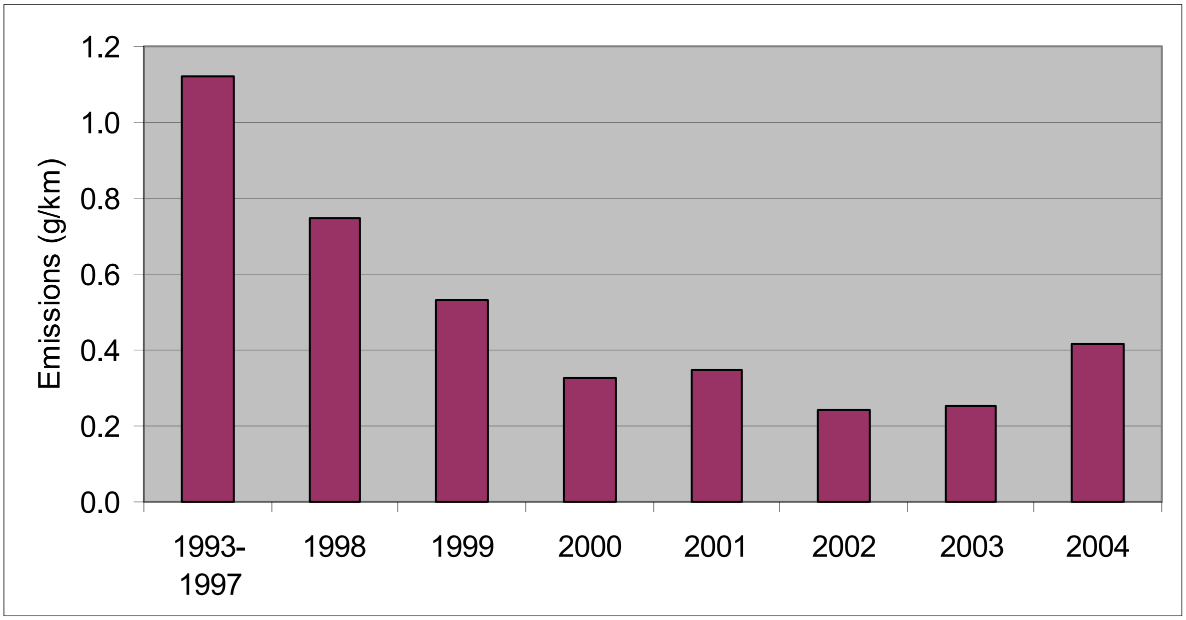


Figure V-19 Mexico City Comparison of nitrogen oxide emission values for select IVE Classes by Model Year

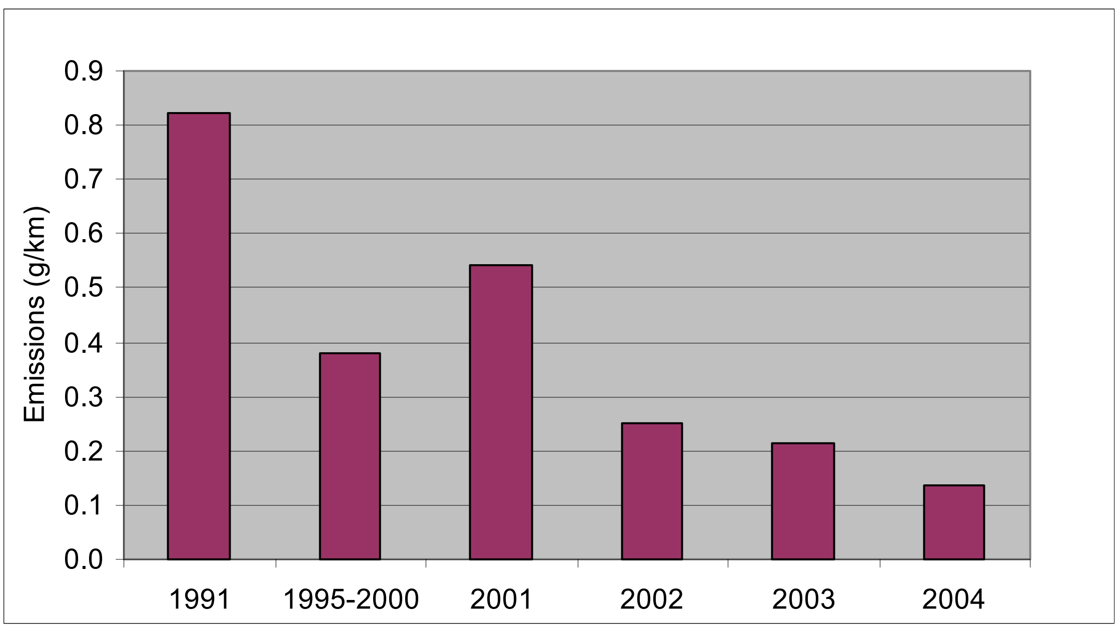


Figure V-20 Sao Paulo Comparison of nitrogen oxide emission values for select IVE Classes by Model Year

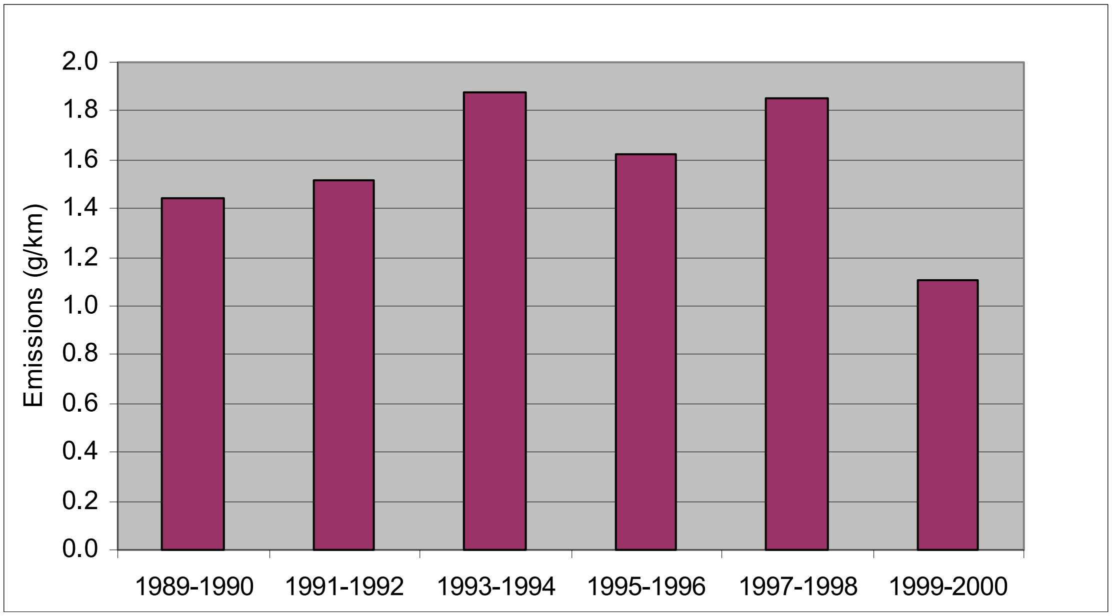


Figure V-21 Nairobi Comparison of nitrogen oxide emission values for select IVE Classes by Model Year

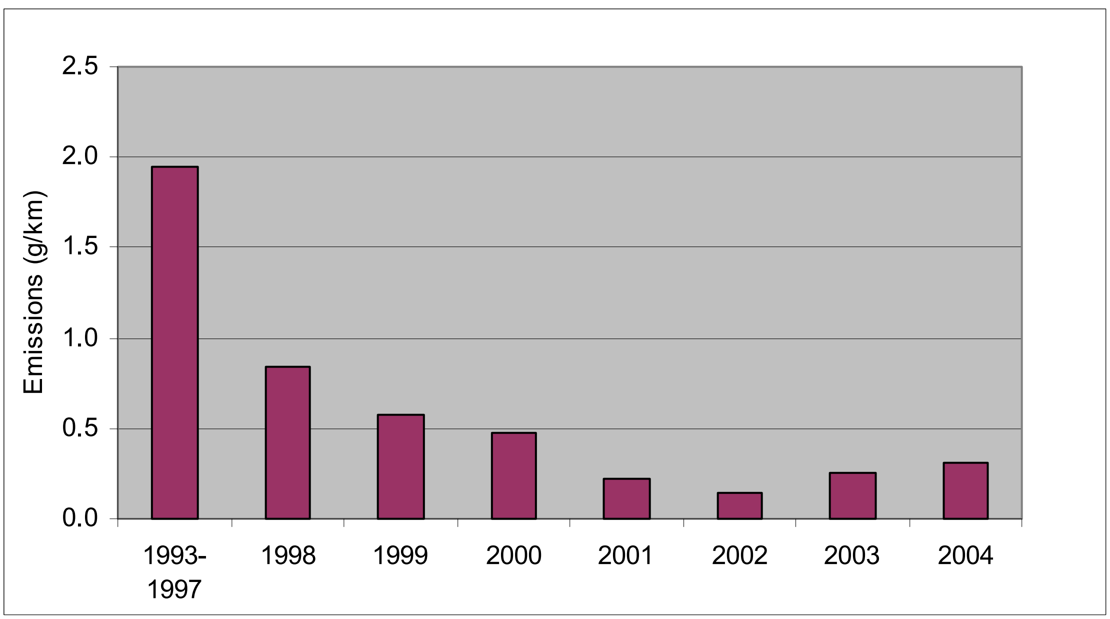


Figure V-22 Mexico City Comparison of total hydrocarbon emission values for select IVE Classes by Model Year

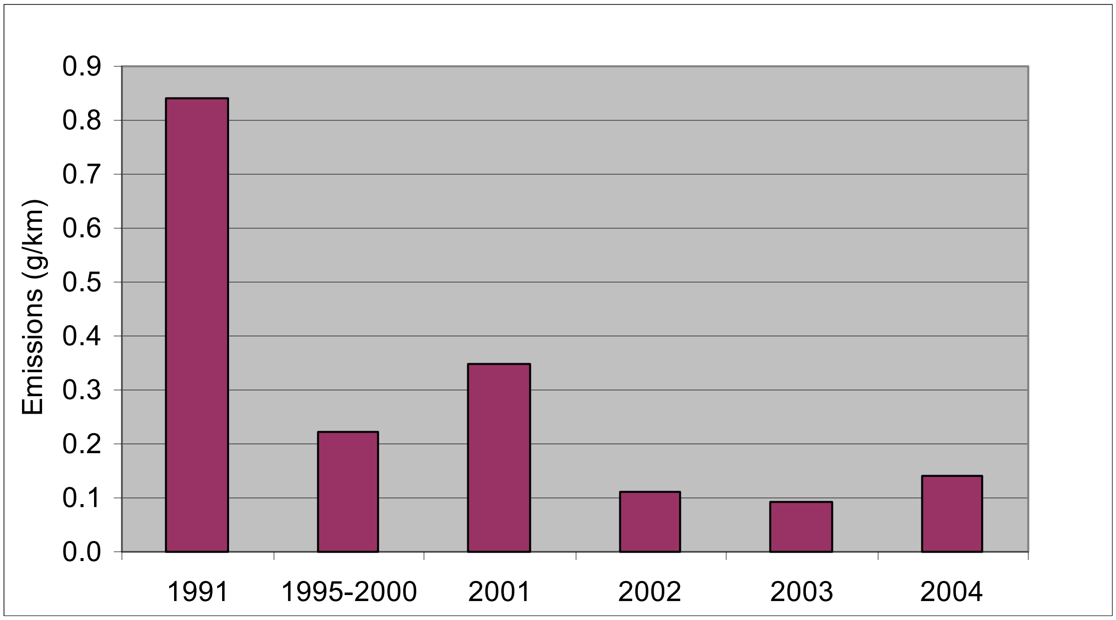


Figure V-23 Sao Paulo Comparison of total hydrocarbon emission values for select IVE Classes by Model Year

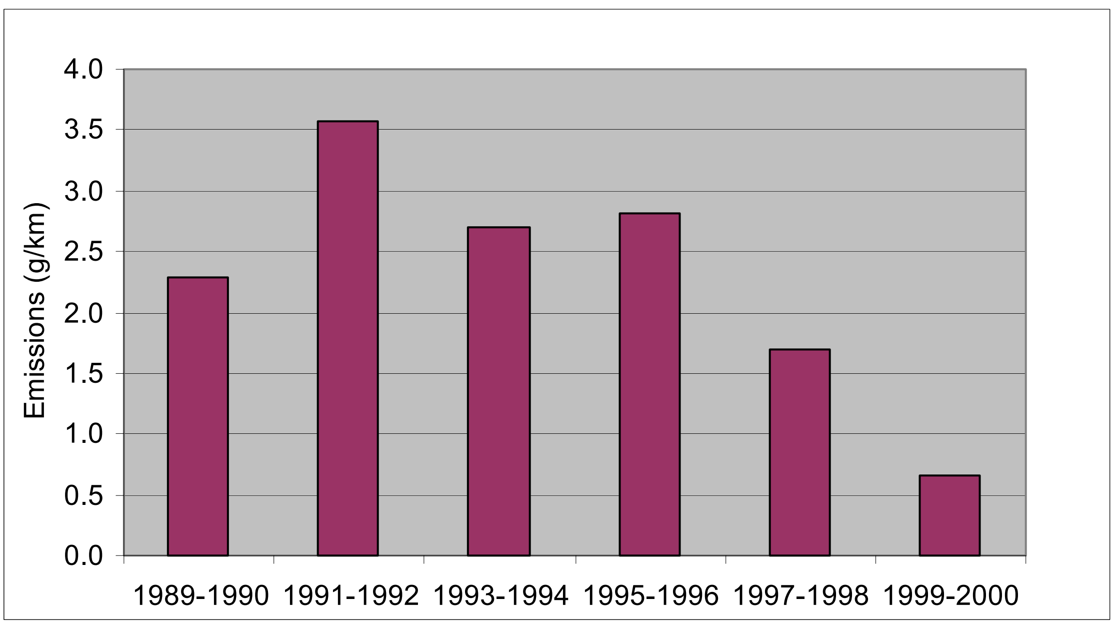


Figure V-24 Nairobi Comparison of total hydrocarbon emission values for select IVE Classes by Model Year

V.D. Comparison between Cities

Figure V-25 summarizes average emissions for all cities and the light duty fleet average emissions when normalized to the LA4 cycle. Overall, these results indicate that the carbureted vehicles pollute the most, followed by single point fuel injection and multipoint fuel injection vehicles, although there is variability between cities, due to technology differences and different mixes of technologies. For all pollutants except CO2, Nairobi has the highest fleet-wide emissions and Sao Paulo has the lowest. This is expected since the Nairobi fleet is largely non-catalyst and the Sao Paulo fleet has a mixture of low emissions alternative fueled technologies. For CO2, it appears the Nairobi fleet has the lowest emissions and the Mexican fleet has the highest. This is also expected from the size of the fleet, where Nairobi does not have any larger passenger vehicles while Mexico city has a significant fraction of larger SUVs and passenger trucks, looking more like the US fleet, reflecting the lower average fuel economy.

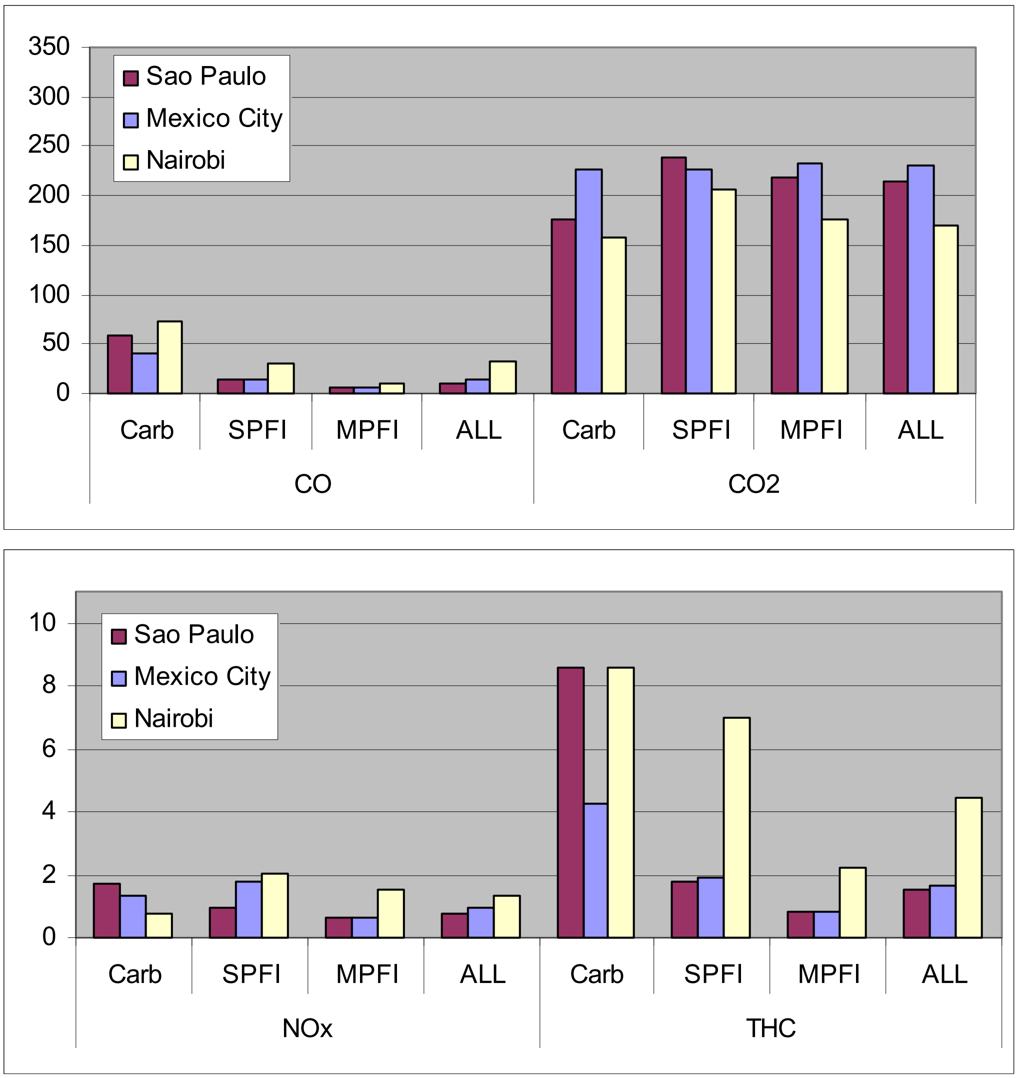


Figure V-25 Comparison of LA-4 Emission Rates in Three Cities

Figure V-26 shows a comparison of the actual measured on-road running emissions for the three cities. As expected, emissions increase from the LA-4 cycle to on-road driving by 20-40% for both Mexico City and Sao Paulo. However, interestingly enough, emissions in Nairobi were lower (except for NOx) during on-road driving than the LA-4 cycle. So when comparing emissions between cities, Nairobi still has the highest emissions, but the difference is not as great as when the vehicles were operating on the same LA4 cycle.

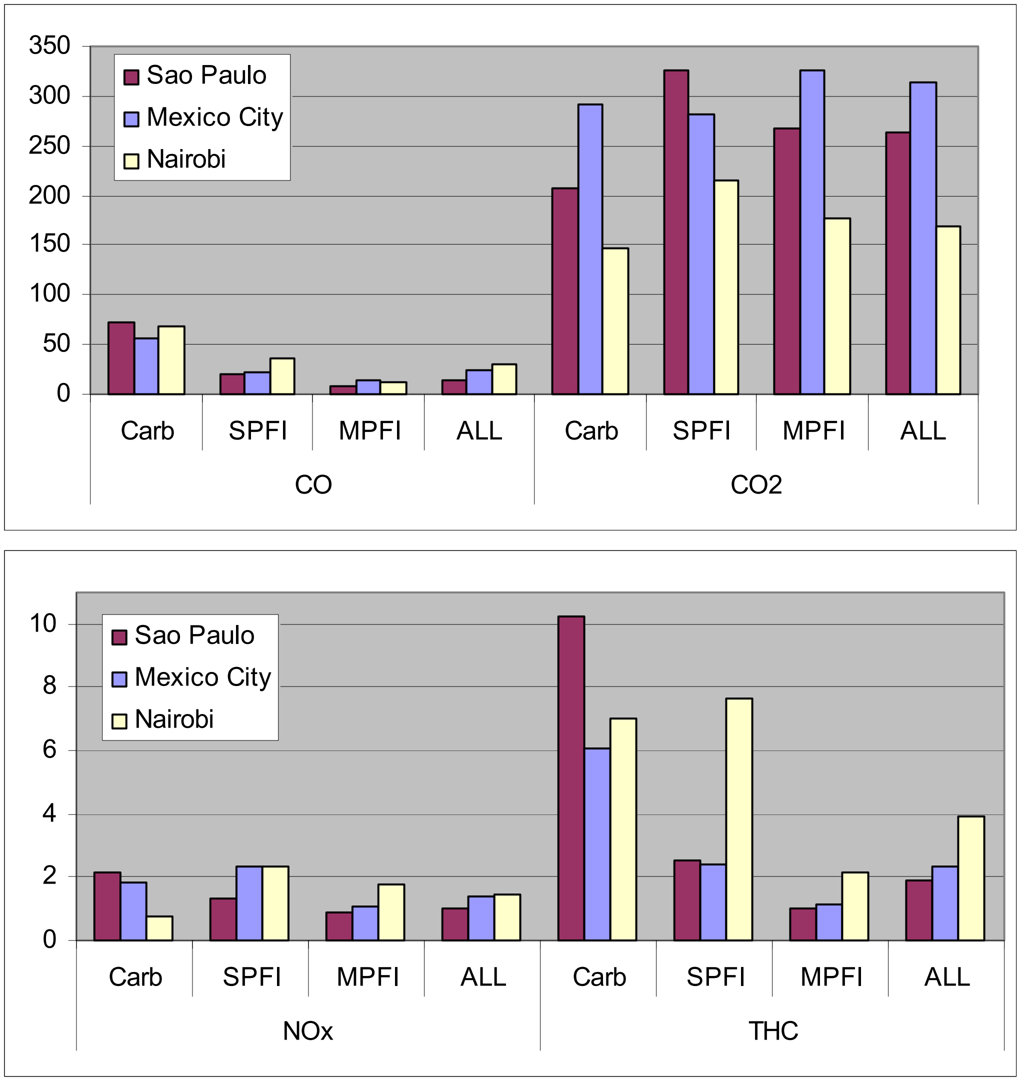


Figure V-26 Comparison of On-Road Running Emission Rates in Three Cities

V.E. Running Emission Corrections to the IVE Model

One of the main purposes of collecting this on-road data in these cities is to improve the current emissions database and the resulting emissions modeling. Currently, emission rates in the IVE model and other models have not had the opportunity to utilize actual emissions data from the local fleet. However, with the 100 emissions tests conducted in this study, current data can be edited to obtain a more realistic estimate of the true on-road emissions. Additional emissions data will be collected in the near future and incorporated into these corrections as well.

The method for correcting for locally specific emissions in the IVE model is simple. The ratio of the measured emissions on the LA4 cycle to the IVE default emissions are input into the model for each technology available. A ratio of 1.0 indicates that the measured and IVE projected values are equal. A value less than 1.0 indicates that the IVE model is predicting values greater than actually measured, and a value greater than 1.0 indicates that the IVE model is under predicting emissions compared to measured emissions. A value different than 1 is expected in most cases, since it is believed that the fleet in other areas is not the same as the fleet used to derive the IVE model (mostly US vehicles). However, a value grossly different than 1 is not usually anticipated since it is believed that similar technologies should have similar emissions, no matter where they are built or used.

Figure V-27- Figure V-29 compares the FTP corrected hot running emissions from the tests with the rates projected by the IVE model for the various technology types for the altitude and temperatures in Mexico City observed during this testing. Because of the variability in the dataset and small sample size of many of the IVE Classes, similar classes were combined and compared with IVE predicted emissions values of the same combination. This method enables a general trend to be observed for the different groups.

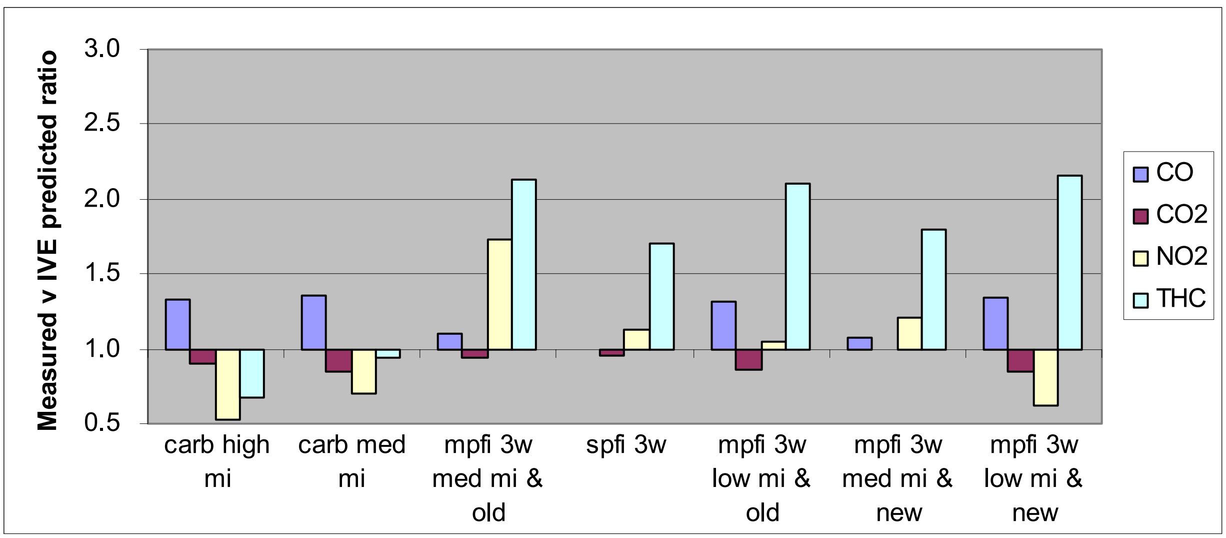
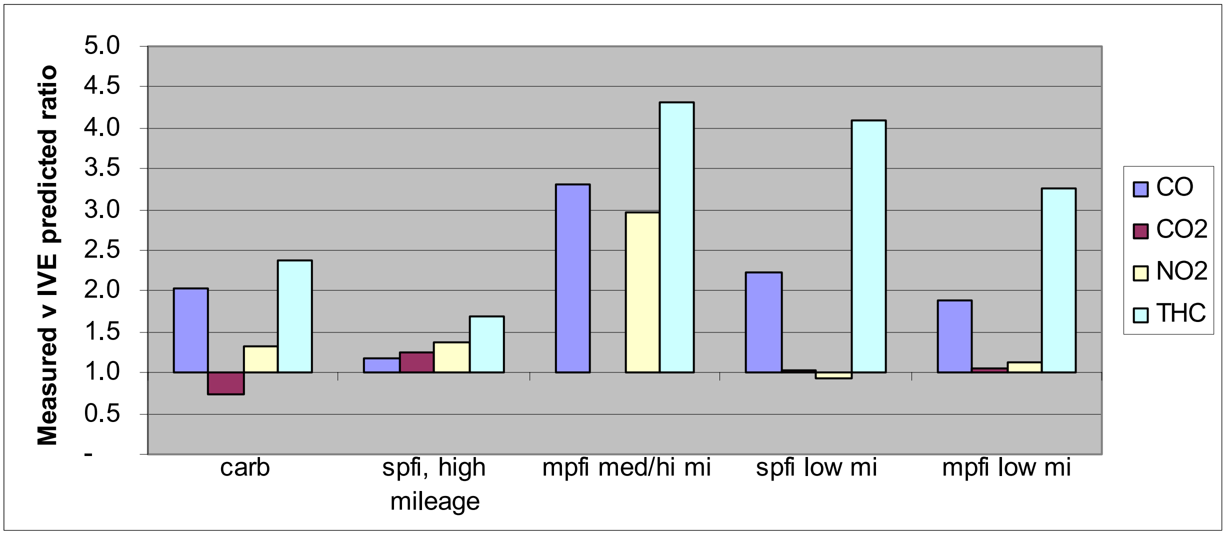


Figure V-27 Mexico City measured running emissions compared to IVE projected emissions for General technology types



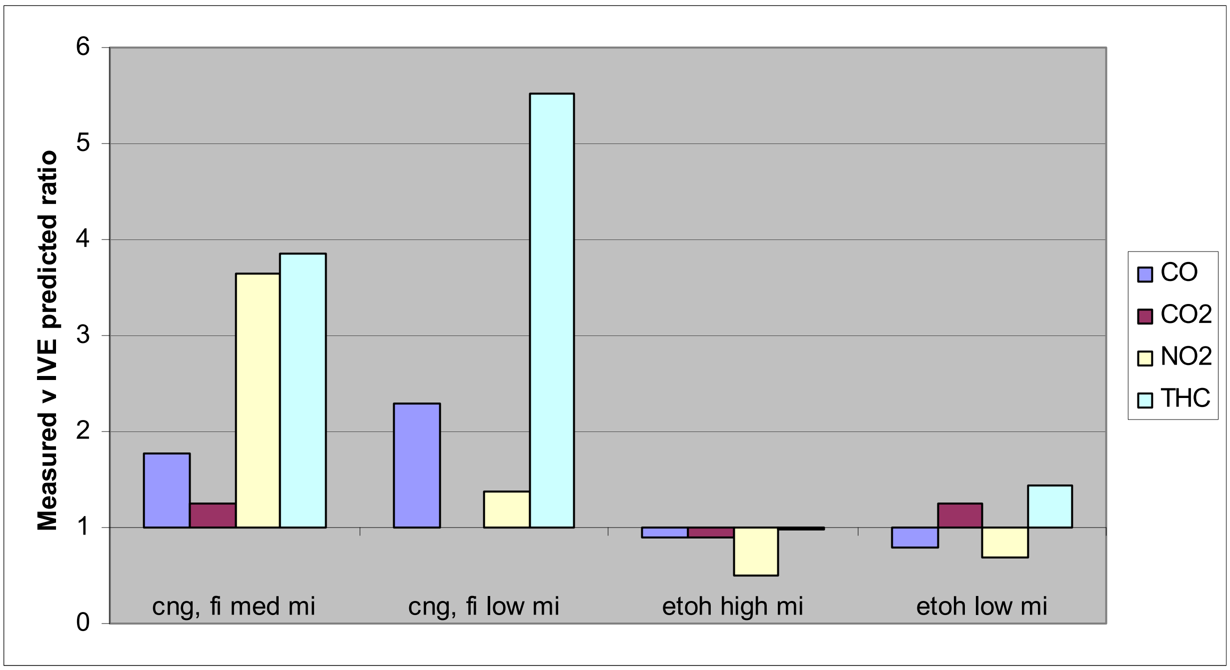


Figure V-28 Sao Paulo measured running emissions compared to IVE projected emissions for general technology types

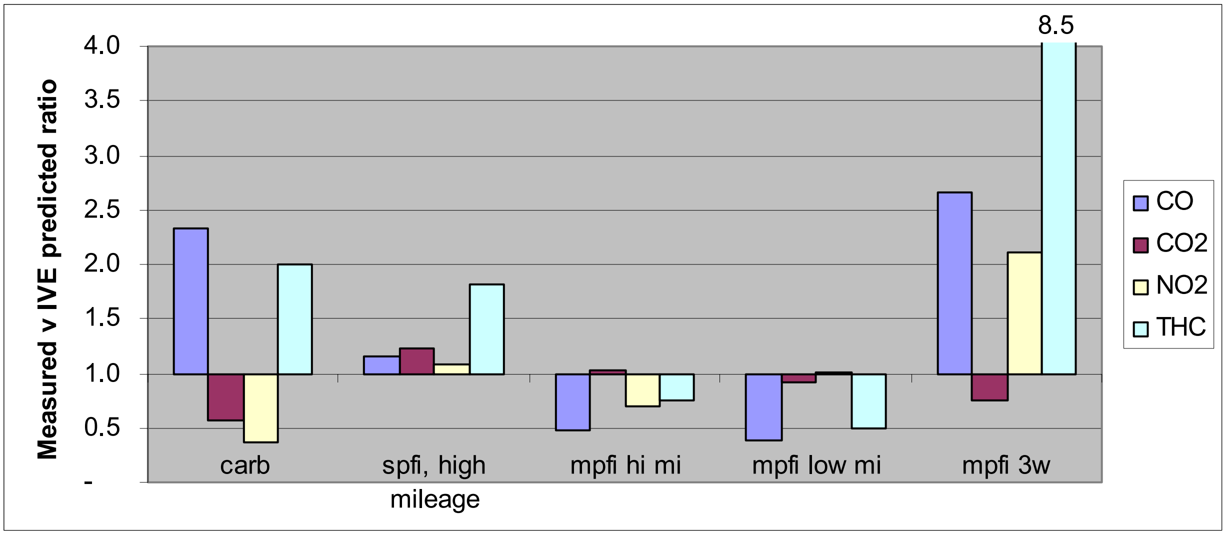


Figure V-29 Nairobi measured running emissions compared to IVE projected emissions for general technology types

For Mexico City, the running CO ratio of measured to IVE predicted values ranges from 1.0 to 1.35. So in general, actual measurements of CO were around 20% higher than predicted from the model. The CO2 emissions values are generally below the IVE predicted values, ranging from 0.85 to 1.0. For the two categories with ratios of 0.85, this may indicate that the IVE values are slightly over predicting fuel efficiency. For NOx, the ratio ranged from 0.5 to 1.7 depending on technology type. The IVE model significantly over predicted NOx emissions for the carbureted vehicles, and the cleanest multipoint vehicles. Finally, the THC emissions were roughly two times higher than predicted for most categories. This may be due to the fact that the vehicles in these cities are operating in a rich mode which increases CO and THC but can decrease NOx. While this data is not from a large sample set, some adjustments to the IVE factors and other groups of similar vehicles are warranted for Mexico City. Additional measurements planned in the near future will clarify whether these trends are still observed with a larger sample set.

In addition to these correction factors, several new categories were developed for Mexico City and Nairobi. These were developed for groups that had two distinct emissions (mainly for varying model years), and therefore it was decided to group them into two separate categories. In this instance, the new base emission rate was created from the measured data and input directly into the user defined categories in the correction factor file. (The base emission rate for a user defined category is 1, so instead of a ratio of IVE to new emissions put into the correction factor file as is done most of the time, the exact emission rate in g/km is input for user defined technologies). These have no comparison to the IVE model, so are not shown as part of the correction factors here. However, the emission rates can be found in the correction factor file in Appendix C.

V.F. Starting Emissions and Corrections to the IVE Model

The estimation of cold start emissions is a very difficult calculation to make. A 10% error in the estimation of hot running emissions to subtract from the observed cold running emissions can result in a 20% error in estimating cold start emissions. Since cold start and hot start emissions tend to be more consistent among vehicles and due to the potential for errors, these emissions were grouped into two categories. These categories are fuel injected vehicles and carbureted vehicles. This is close to saying pre-1992 vehicles and post-1992 vehicles. During the course of this investigation in the three cities tested, it was observed that there were not a large amount of excess emissions due to starts with a 10 minute soak (hot start). Therefore, the hot start was eliminated from the test procedure and is assumed to be the same as predicted by the IVE model calculations. Table V-13- Table V-15 shows the results of the measured cold start emissions, and the IVE modeled values for similar technologies.

Table V-13 Mexico City Measured Start Emissions Compared to IVE Estimated Start Emissions

Pollutant	Technology	Measured Cold Start (g)	IVE Cold Start (g)	IVE CF Cold St
CO	Carb	54	432	0.1
	Fuel Inj	47	71	0.7
CO2	Carb	85	205	0.4
	Fuel Inj	78	180	0.4
NOx	Carb	0.7	8.1	0.1
	Fuel Inj	1.0	1.8	0.6
THC	Carb	5.9	30.2	0.2
	Fuel Inj	4.9	5.6	0.9

Table V-14 Sao Paulo Measured Start Emissions Compared to IVE Estimated Start Emissions

Pollutant	Technology	Measured Cold Start (g)	IVE Cold Start (g)	IVE CF Cold St
CO	Carb	9	347	0.03
	Fuel Inj	21	35	0.6
CO2	Carb	81	188	0.4
	Fuel Inj	57	155	0.4
NOx	Carb	0.6	7.1	0.1
	Fuel Inj	0.7	1.2	0.6
THC	Carb	5.9	24.1	0.2
	Fuel Inj	4.1	2.9	1.4

Table V-15 Nairobi Measured Start Emissions Compared to IVE Estimated Start Emissions

Pollutant	Technology	Measured Cold Start (g)	IVE Cold Start (g)	IVE CF
CO	Carb	4	416	0.01
	Fuel Inj	20	152	0.1

CO2	Carb	21	191	0.1
	Fuel Inj	26	143	0.2
NOx	Carb	0.0	9.0	0.0
	Fuel Inj	-0.1	5.8	0.0
THC	Carb	4.6	29.2	0.2
	Fuel Inj	4.2	10.9	0.4

There is considerable disagreement between the measured start emissions and the IVE estimated values. The errors in the estimation process are not adequate to account for the difference. Therefore, the IVE model start correction factors will be updated to reflect these emissions.

V.G. Revised IVE Model Emissions Estimate

In each of these three cities, previous estimates of vehicular emissions were made using the IVE model. At the time of these estimates, there was no on-road emissions data available in these locations. Only local fleet and activity data were available. Now, with the availability of some light duty vehicle emissions data for VOC, CO, CO2, and NOx, the emissions estimates can be improved. Using the correction factors derived in section V.E and V.F from this dataset, the emissions for the fleets were recalculated. These emissions are believed to be an improvement from the previous emissions estimate which did not use locally specific emissions data at all. However, caution should still be employed because of the uncertainty in these emissions estimates, and also the fact that only light duty passenger vehicles were tested, whereas the emissions are estimated from the entire fleet. As further testing is conducted, the estimates can be improved.

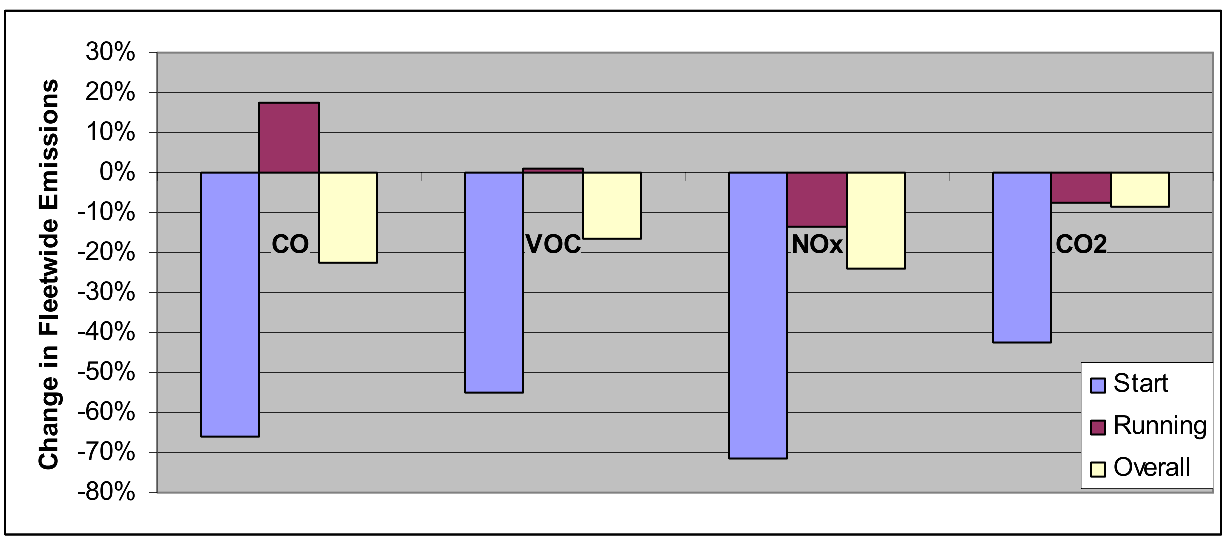


Figure V-30 Change in Original IVE Emissions Estimate for Mexico City Based on Updated IVE Emission Factors for Light Duty Vehicles

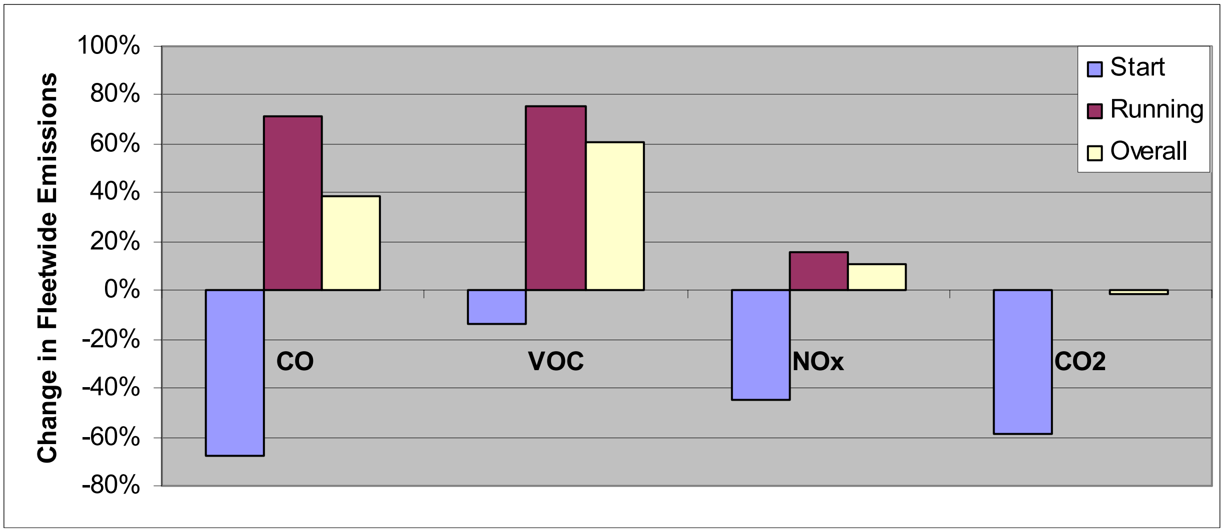


Figure V-31 Change in Original IVE Emissions Estimate for Sao Paulo Based on Updated IVE Emission Factors for Light Duty Vehicles

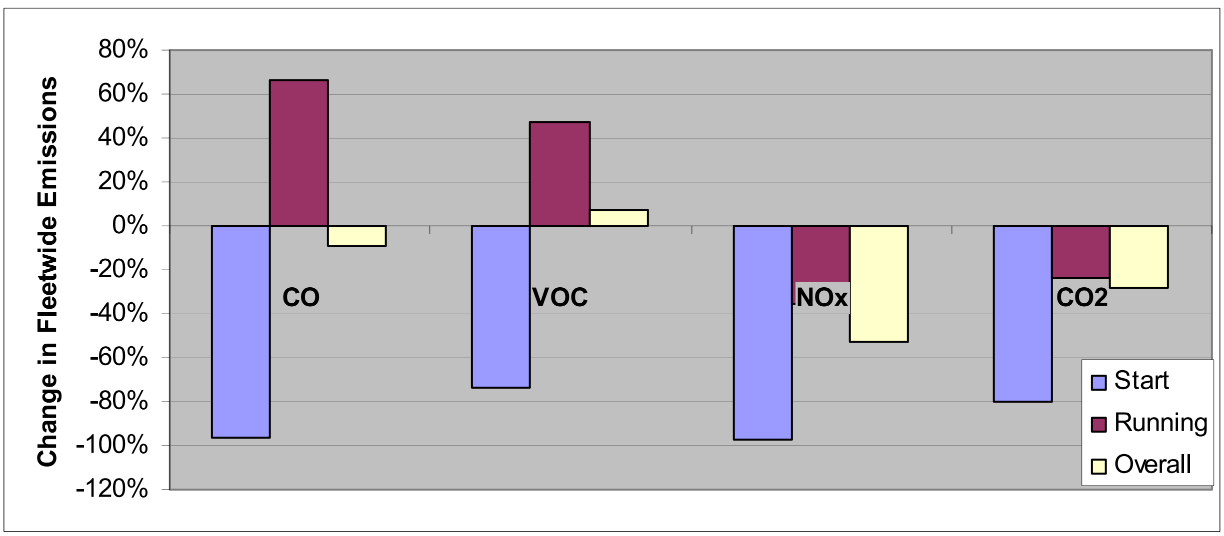


Figure V-32 Change in Original IVE Emissions Estimate for Nairobi Based on Updated IVE Emission Factors for Light Duty Vehicles

Figure V-33 and Figure V-34 show the updated emissions inventory for Mexico and Sao Paulo. (Fleetwide emission predictions were not conducted for Nairobi). In each figure, the overall average tons of pollutant emitted per day from on-road sources is listed along with the percent contribution from each major vehicle class. As can be seen from these figures, the passenger fleet contributed the majority of the CO, NOx, THC, and CO2 emissions, followed by trucks, taxis, and buses in both cities. So, while more accurate passenger fleet emissions data is useful, it is recommended that emissions estimates be conducted on the other vehicle types as well, since they do contribute significantly to the inventory, and the majority of the PM inventory.

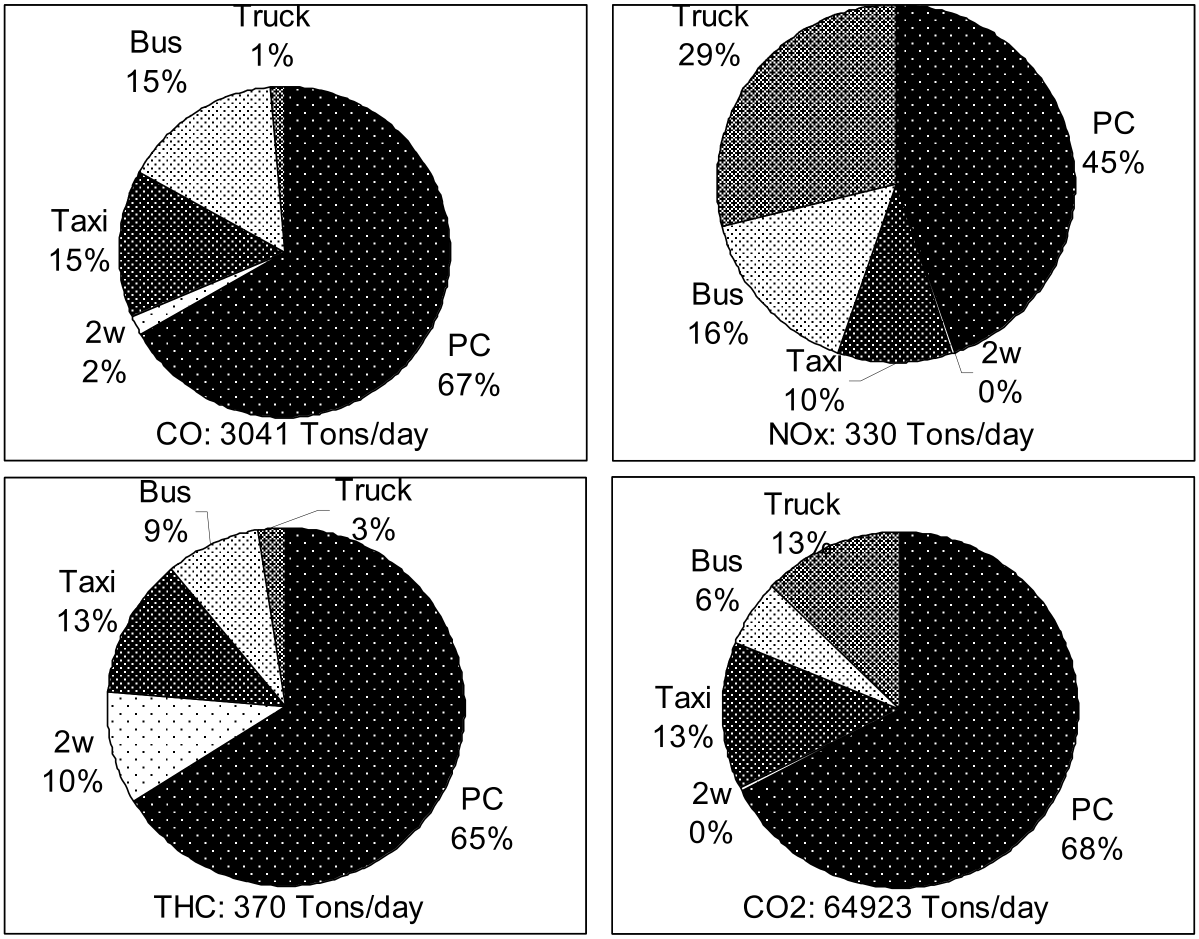


Figure V-33 Estimated Emissions in Mexico City for On-Road Vehicles

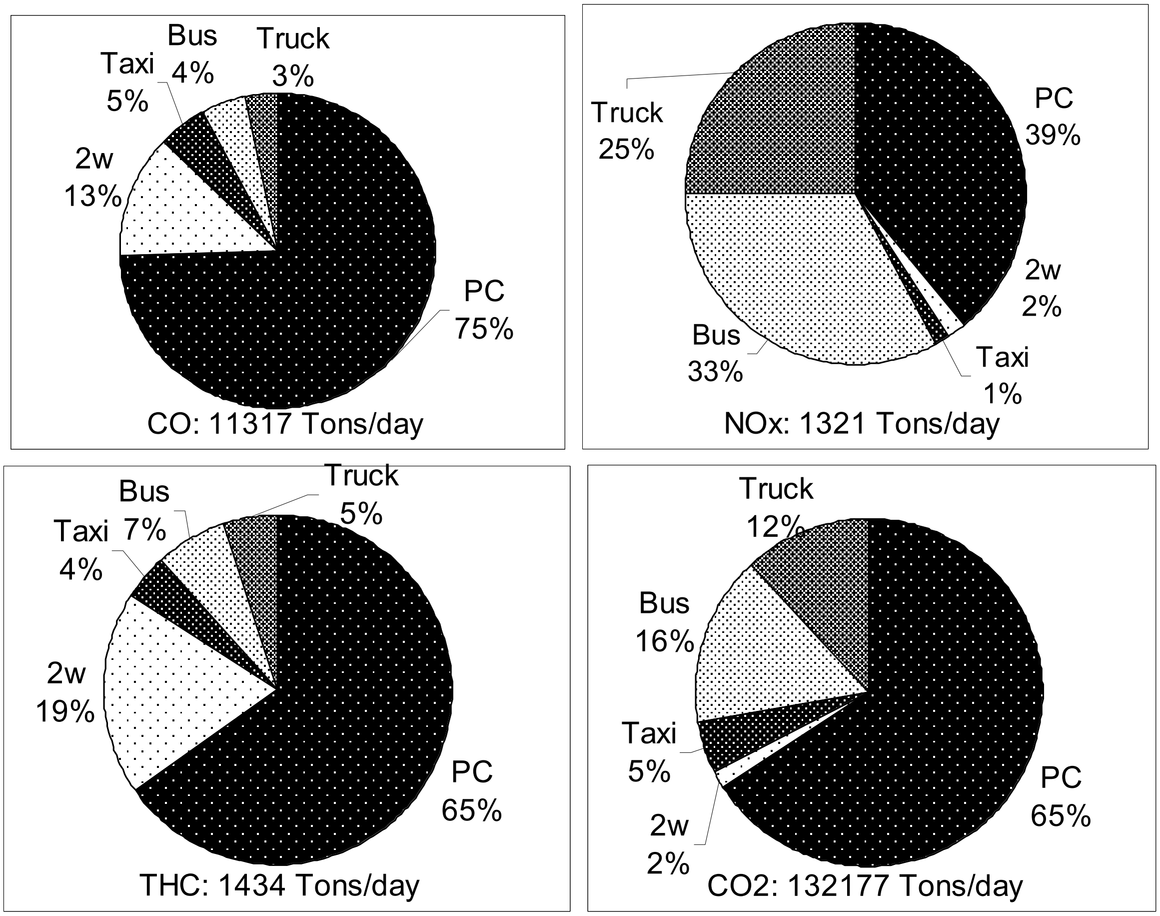


Figure V-34 Estimated Emissions in Sao Paulo for On-Road Vehicles

VI. Summary and Conclusions

On-road tailpipe emissions of CO, THC, NOx, and CO2 were successfully measured from a total of three hundred and twenty-four light duty vehicles in Mexico City, Sao Paulo, and Nairobi. The measurement system used in each city was a Sensors SEMTECH gasoline unit and flowmeter that collected realtime flowrates, vehicle position, and ambient temperature and humidity in addition to the pollutants. Calibration and quality assurance procedures were conducted on a routine basis to ensure accurate data collection. A cold start and roughly 30 minutes of running emissions over a variety of speed and acceleration conditions were collected for each vehicle. It was determined by testing in each city that the hot (10 minute soak) starting emissions were in the noise of the measurement system and therefore were considered to be close to zero.

These data were used to gain an understanding of the light duty passenger vehicle emissions in these areas and to improve model estimates of on-road vehicle emissions in the IVE model. In general, CO, THC, and NOx emissions varied significantly from vehicle to vehicle, and from city to city. Confidence intervals of $\pm$ 20% or greater are common. Due to this variability, it is recommended that additional testing be conducted in each city to improve the estimates. However, even with the large variability, general trends were observed in each fleet and some corrections can be applied to improve the emissions estimates. It must also be mentioned that this study did not include measurements of 2 and 3 wheeled vehicles, buses, or heavy trucks. In areas where these vehicles are an important component of the inventory, it is recommended that emissions testing be conducted on those vehicle types.

On average, the Nairobi passenger fleet has the highest CO, NOx, and THC emissions and the lowest CO2 emissions (Figure VI-1). This is to be expected, since many of the vehicles in Nairobi are imported from Japan and are therefore small engines with higher fuel economy. Additionally, Nairobi uses leaded fuel which has poisoned the catalysts on the vehicles, rendering them ineffective and leading to higher emissions of CO, NOx and THC. Mexico City observed the highest emissions of CO2. This is also consistent with earlier studies showing the Mexican fleet having relatively large engines, similar to the US. Sao Paulo has the lowest fleet emissions of the three cities measured. This is a combination of emissions regulations for newer model year vehicles and the use of alternative fueled vehicles. (However, in some cases, the alternative fueled vehicles polluted more than the gasoline counterpart.)

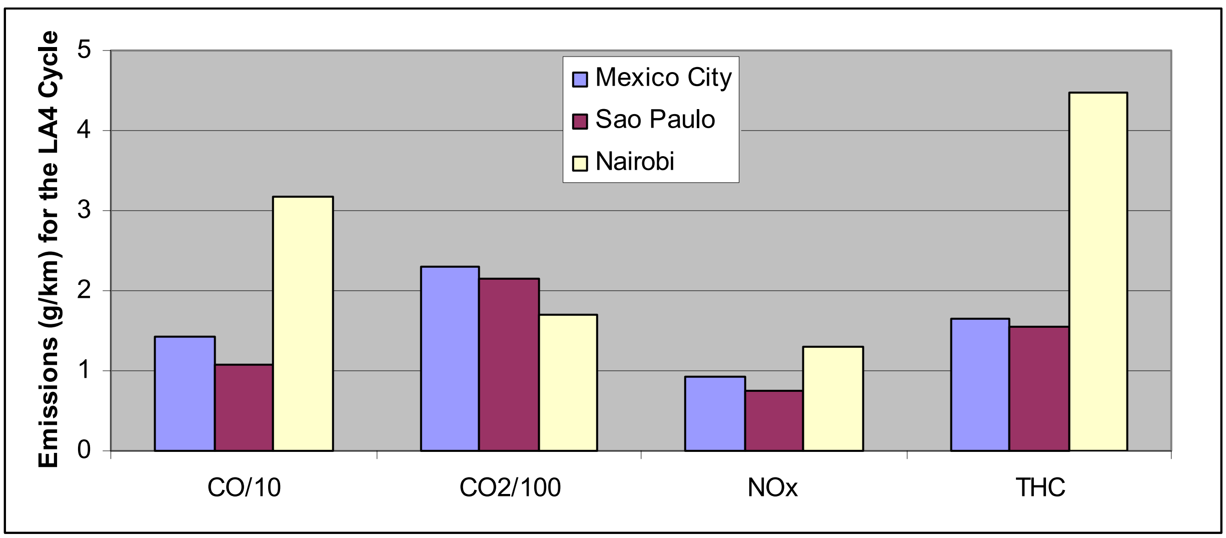


Figure VI-1 Fleet Average Emissions for the LA4 Cycle in Three Cities

One of the premises of the IVE model is that similar technologies will, in general, pollute similarly no matter where they are produced or operated. However, it was anticipated that some variation in emissions exist for same technologies in different cities, and therefore the collection of this data is necessary to update the emissions in each area to reflect these regional differences. The IVE model allows for the application of these locally specific emissions through the use of emission correction factors. There are correction factors allowed for start and running emissions for each technology and each pollutant.

Figure VI-2 shows an example of the running emissions variation from the cities tested and the generic IVE data for two of the most common vehicle classes. Class 5 is carbureted, high mileage non catalyst light duty gasoline vehicles, and Class 120 are multipoint fuel injected vehicles with 3-way catalysts and low mileage. From the figure, it can be seen that there is significant emissions variability between cities, confirming the assumption that the base emissions should be corrected for location.

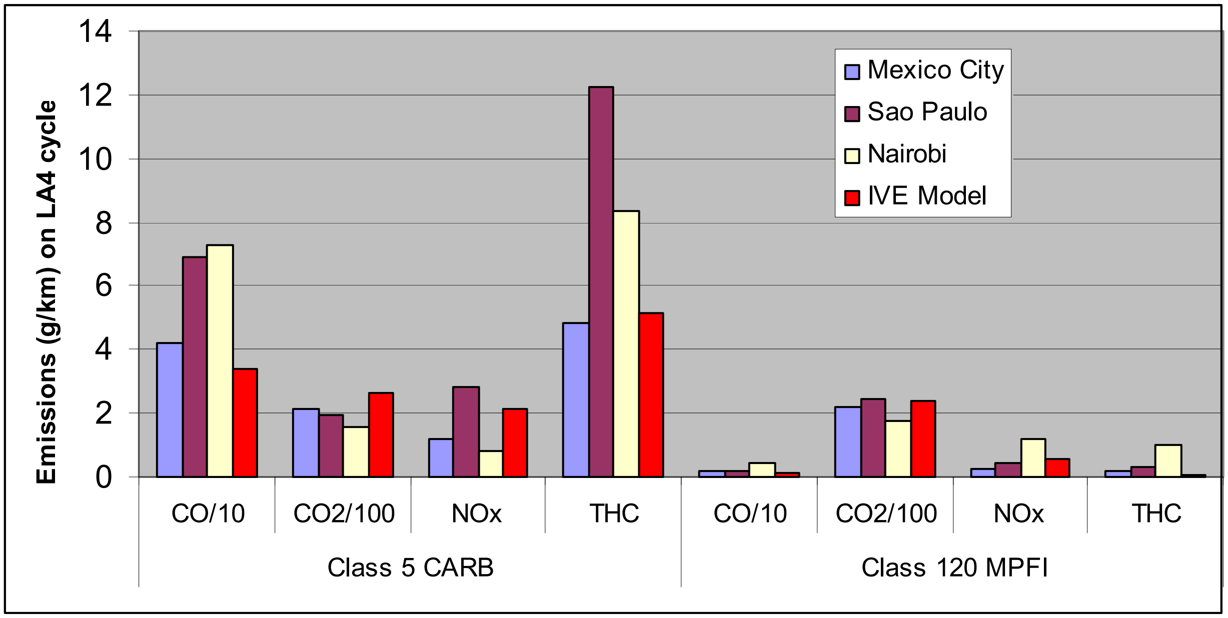


Figure VI-2 Base Running Emission Rates compared between Three Cities for Two Technology Types

The last (red) bar on Figure VI-2 refers to the base running emission rate used in the IVE model, which has been derived from emissions testing on US vehicles. In most cases, this emission rate falls in the mid range of the emissions measured from the various cities. Therefore, in a general sense, it is appropriate to assume that the IVE model emission rates are appropriate 'generic' emission factors to use if local emission data is not available. However, if local emission factors are available, like the three cities here, it is advised that correction factors be applied to account for this variability. If an area does not have any local emissions available to fine tune the emission factors, they can choose a region that is believed to be similar to one with available data. For example, another city in Africa would probably yield more accurate results if they used the Nairobi corrections instead of the IVE model default values alone.

The emissions data collected in each of the cities was analyzed and processed to yield correction factors for general technology classes. In the model, a different correction factor for every technology type and every pollutant is available; however, due to the variability and amount of data collected, the emissions were aggregated across similar groups. This process can be updated as more data is collected within each group. Figure VI-3 shows a summary of the average correction factors applied for four gasoline types, carbureted, single point fuel injected vehicles, older multipoint fuel injection vehicles, and newer multipoint fuel injected vehicles with 3 way catalysts. In reality, more than four sets of correction factors are used but the values have been aggregated here for ease of visual comparison. A complete list of correction factors developed for each city can be found in Appendix C. A correction factor of greater than 1 indicates the emissions in that city are greater than predicted by the default emission factors in the IVE model, and a value of less than one indicates the IVE model default rates are over predicting that vehicle type.

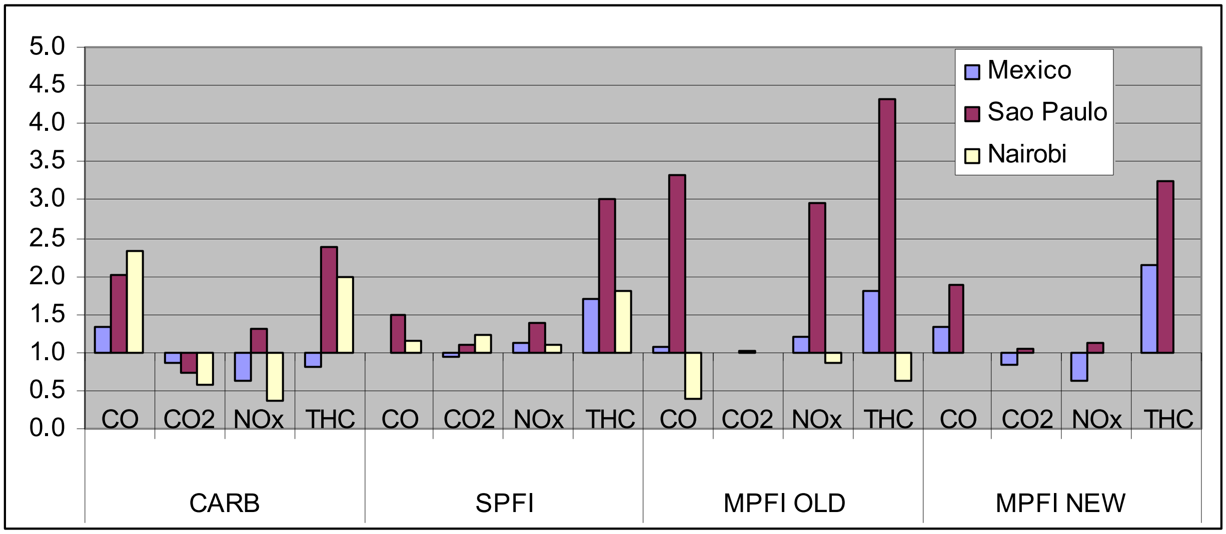


Figure VI-3 Summary of Running Emission Correction Factors In Three Cities

As can bee seen in Figure VI-3, the corrections for running emissions vary widely from city to city and pollutant to pollutant. In general, hydrocarbon emission rates were the most variable and were most often underestimated by the original IVE dataset. The simpler carbureted and the newer multipoint three way catalyst vehicles in general were the least variable and showed the least deviations from the original IVE database. The most deviation is from older multipoint three way catalyst vehicles, where deterioration of some portion of the fleet can make emission rates the most variable. As with THC, CO was underestimated compared to the default IVE data in most cases. CO2 varied the least and compared well with the IVE model, typically with correction factors of between 0.9 and 1.1. The variability of the emission rates illustrates the need for the collection of on-road data from all types of vehicles in each location. Because of the overestimation and underestimation of emission rates in different locations, it is believed that the default IVE running emission rates are a reasonable representation of a 'generic' location and no changes to the default emission rates will be made.

In addition to the collection of on-road running emissions, both cold and hot starting emissions were measured in each city. For all cases, hot start emissions were in the noise of the measurement system and considered to be close to zero. For cold start emissions, it is shown that the generic IVE database overestimates emissions by a factor of 2 to 3 times in most cases (Figure VI-4). (A complete list of starting correction factors developed for each city can be found in Appendix C). From the consistency of the data collected in all three cities, it is recommended that the base emission rates in the IVE model be reduced by a factor of 2.5 for cold start emissions for all pollutants.

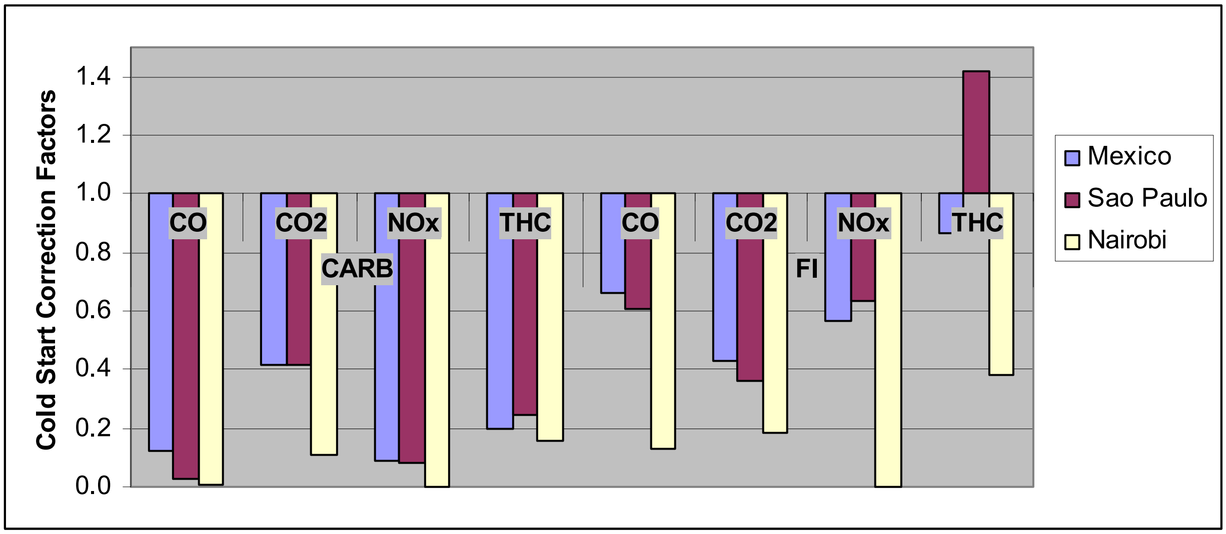


Figure VI-4 Summary of Cold Start Correction Factors in Three Cities

The combination of the over prediction of start emissions and in most cases under prediction of running emissions result in varying changes in the fleetwide emissions estimates for each city (Figure VI-5). When the correction factors were applied to model, along with fleet and activity specific data from each city, the overall emissions were estimated and compared with previous estimates where the generic IVE database was used. For Mexico, overall fleetwide emissions decreased for all pollutants, anywhere from 10% – 25%. For Sao Paulo, all emissions except CO2 increased from between 10% to 60%. And for Nairobi, emissions of CO, NOx, and CO2 decreased 10, 53, and 28% respectively, while VOC emissions increased by a modest 7%. These updated emissions have been incorporated into new emissions estimates and posted on the public ISSRC website for use by persons using the IVE model.

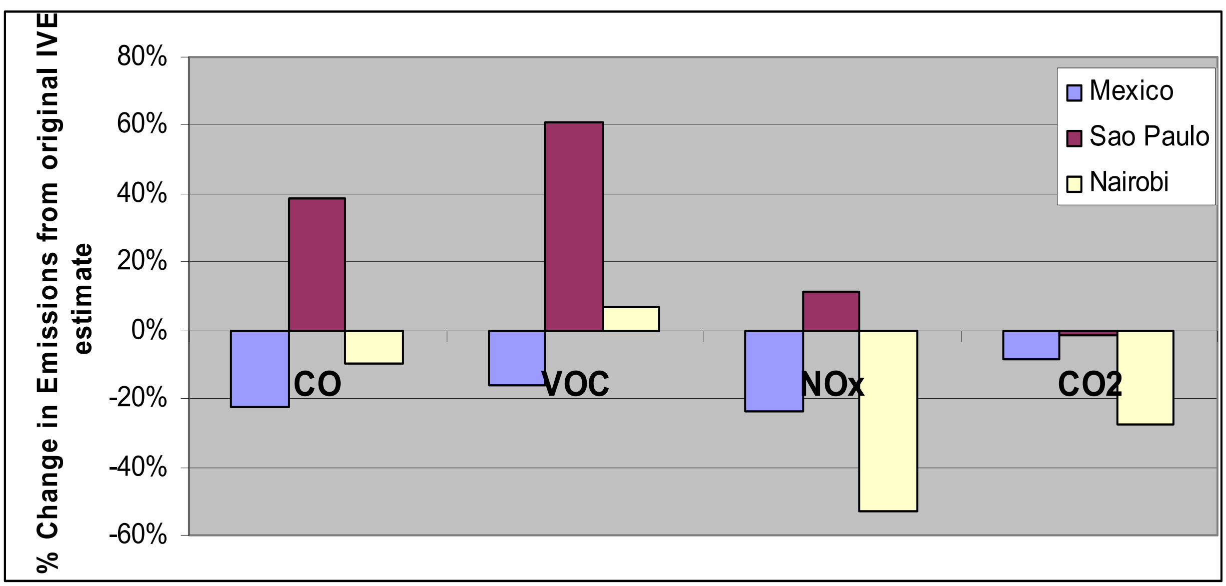


Figure VI-5 Change in On-Road Vehicle Emissions from Original Generic IVE Data set to data with the Incorporation of New Light Duty Emissions Data

While the IVE model original estimates appear to sometimes overestimate and sometimes underestimate real world measured emissions, in general the model shows that it does not have an overall bias and presents a much better estimate of actual on-road emissions than previous estimates were able to. It is believed that the improvement in emissions predictions is due to the combination of the activity measurements and realistic assumptions about deteriorating emissions in the IVE model. Incorporating the emissions data collected in this study will further improve the model's ability to correctly estimate current emissions and provide better tools for the prediction of future scenarios.

To compare with existing inventories used for policy purposes, this study has shown that compared with current Mexico City emissions estimate, mobile sources emit more PM than the current Mexico inventory estimates, and less CO, NOx, and VOCs per distance traveled (Table VI-1). This is a surprising result since simplistic inventory methods tend to underestimate emissions by not accounting for real-world driving effects and deterioration which both increase emissions. In contrast, the exact opposite effect is observed in Sao Paulo. Their 2003 mobile source inventory is higher for PM than updated IVE estimates and lower for CO, VOC, and NOx. It is useful to keep in mind that emissions testing were not locally conducted for PM and the estimates will change once testing is conducted. Also, additional emissions tests are planned for Mexico City and Sao Paulo which will improve the real-world estimate further.

Table VI-1. Percent change in mobile source emissions from Current Regulatory Inventory to IVE updated inventory

Pollutant	Mexico*	Sao Paulo**
PM10	**14%**	**-46%**
CO	**-38%**	**110%**
NOx	**-14%**	**10%**
VOC	**-24%**	**22%**

*Comparison of overall fleet with similar VKT compared with the MCMA 2000 inventory
**Comparison of overall fleet with similar VKT from CETESB 2003 inventory

One other conclusion can be drawn from the data collected in this study. In general, emissions from pre 2000 multi-point fuel injected catalyst passenger vehicles were higher than anticipated throughout the study, and much higher than a similar vehicle with similar mileage built after 2002. Two theories of why this is occurring are: 1. the vehicles built in these locations were not designed to have low emissions prior to 2000, even though they were equipped with multipoint fuel injection and three-way catalysts; and 2. The vehicles were built to lower emission standards, but in the past four years of use have deteriorated significantly and resulted in increased emissions. There is no way to know which of these theories, or a combination of both, have resulted in higher emissions for this vehicle class. The newer post -2002 vehicle seem to be performing much better in all three cities. Only time will tell whether or not these newest vehicles will have significant deterioration over the life of the vehicle.