MEASUREMENT OF AIR POLLUTANT EMISSIONS FROM PUBLIC TRANSPORT BUSES IN THE INSURGENTES CORRIDOR OF MEXICO CITY

FINAL REPORT

JANUARY 2006

PROGRAMA DE INTRODUCCIÓN DE MEDIDAS
AMBIENTALMENTE AMIGABLES EN TRANSPORTE
EN LA ZONA METROPOLITANA DEL VALLE DE MÉXICO

CONTRACT NO. GDF-SMA-GEF-SC-020-04

EF & EE
ENGINE, FUEL, AND EMISSIONS
ENGINEERING, INCORPORATED

AMBIENTALIS
CONSULTORÍA Y PROYECTOS DEL MEDIO AMBIENTE

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EXECUTIVE SUMMARY

Engine, Fuel and Emissions Engineering, Inc. (EF&EE) was contracted by the *Secretaría del Medio Ambiente* (SMA) of the Government of Mexico City to carry out emissions measurements on public transport buses operating in the *Avenida Insurgentes* corridor in Mexico City. This effort was conducted as part of the "Project for Introduction of Climate Friendly Measures in Transport", funded by the Global Environment Fund, and administered by the SMA and the World Bank.

Avenida de los Insurgentes is a major traffic artery which crosses Mexico City from north to south. It is subject to heavy automobile traffic, and to heavy congestion during peak hours. Public transport service in part of the *Insurgentes* corridor is provided by line 3 of the Mexico City Metro system, and by the new "Metrobus" bus rapid transit (BRT) line, which began operation in June, 2005. Until then, *Avenida de los Insurgentes* was served by numerous bus and microbus lines, which have now been re-routed or eliminated.

The main purposes of the work under EF&EE's contract were:

1. to measure the pollutant emissions from a sample of the public transport buses and microbuses that formerly operated on *Avenida Insurgentes*;
2. to measure emissions from the buses used in the new Metrobus line; and
3. to measure the emissions from various advanced and "clean" technology buses that might be considered for future incorporation either into the Metrobus system or the general public transport fleet.

Emission tests were carried out on-board 17 late-model and demonstration buses and four microbuses using the RAVEM ride-along vehicle emission measurement system. Emission testing was carried out in three rounds, generally extending from November, 2004 to October, 2005. Not all of the buses were available for testing in each round.

The buses tested included twelve conventional diesels, two diesel-electric hybrids, and three using compressed natural gas in lean-burn engines. The four microbuses included one using gasoline in a stoichiometric engine, one that had been retrofitted to use LPG, one retrofitted to use CNG, and a dual-fuel vehicle retrofitted to be able to use either CNG or gasoline. Two diesel buses and one diesel-electric hybrid were fitted with diesel particulate filters (DPFs). All of the CNG buses and microbuses were equipped with catalytic converters.

The test route comprised a round-trip along Avenida Insurgentes in Mexico City, from the Indios Verdes Metro station to the Glorieta de Insurgentes traffic circle and return. The total length of the trip was 21.4 kilometers. Testing was undertaken in two driving conditions, corresponding to normal daytime traffic and to operation along a simulated bus corridor free of interfering traffic. Total test times (including idle time at the beginning and end of the routes) were 4500 and 3600 seconds, respectively, corresponding to average speeds of 17.1 and 21.4 kilometers per hour.

The pollutants measured included particulate matter (PM), oxides of nitrogen (NOx), carbon monoxide (CO), carbon dioxide (CO_2), and carbonyls such as formaldehyde, acetaldehyde, and acrolein. Emissions of individual volatile organic compounds (VOC) such as methane, ethane, ethylene, etc. were also measured successfully for some of the tests.

Measured PM emissions from all of the natural gas fueled buses and from the natural gas, dual-fuel, and LPG-fueled microbuses were all extremely low – ranging from 0.01 to 0.04 grams per kilometer. PM emissions from the gasoline microbus were much higher, at 0.16 to 0.22 grams per kilometer. The DPF-equipped diesel hybrid was in the same range as the natural gas buses, emitting 0.03 grams of PM per kilometer, while the two conventional buses equipped with DPFs emitted 0.01 to 0.08 grams of PM per kilometer. Seven of the ten diesel buses without DPFs exhibited relatively low PM emissions, ranging from 0.07 to 0.45 grams per kilometer (with the latter value applying to an 18-meter articulated vehicle). Four of these low-emitting buses had engines certified to the U.S. 1998 emission standard, which is still the limit for new heavy-duty engines in Mexico. One was certified to the EPA 2004 standard, and two to the Euro 3 emissions standard, which is similar to U.S. 1998 in stringency. Two other buses certified to the Euro 3 standard exhibited much higher emission levels 0.55 to 0.68 and 1.55 to 2.08 grams per kilometer, respectively, as did the rehabilitated Phenix bus equipped with a 1991-vintage engine. PM emissions showed a strong correlation with smoke opacity as measured according to SAE J1667.

NOx emissions from the test vehicles ranged from 0.1 to 21.3 grams per kilometer. The natural gas buses and gaseous-fueled microbuses generally exhibited the lowest NOx emissions, while the gasoline microbus exhibited higher NOx. The lowest NOx emissions measured were from the dual-fuel microbus in gasoline mode, but these were accompanied by extremely high emissions of CO.

NOx emissions among the diesel buses varied greatly. The two hybrid buses exhibited respectively the second-lowest and the highest levels of NOx emissions in this group. Most of the buses exhibited much higher ratios of NOx to CO_2 emissions than would be expected, based on the applicable emission standards. Brake-specific NOx emissions from the diesel buses were estimated from the NOx-to-CO_2 ratio, and ranged from 2.1 to 12.1 grams per BHP-hr. Several bus engines purportedly certified to U.S. 1998 or 2004 emission standards exhibited brake-specific NOx emissions 30 to 80 percent above these standards in on-road driving. One Euro 3 bus showed unexpectedly low brake-specific NOx emissions, but also exhibited the highest emissions of particulate matter. This suggests that the fuel injection timing on that vehicle may have been out of adjustment.

CO emissions from the diesel and lean-burn natural gas buses were extremely low – ranging from below detection limits to less than six grams per kilometer. Those from the CNG and LPG microbuses were moderately high at 30 to 40 and about 80 grams per kilometer, respectively. CO emissions from the gasoline microbus and the dual-fuel microbus in gasoline mode were extremely high, ranging from 147 to 362 grams per kilometer. This indicates that the air-fuel mixture in these buses must have been very rich, on average.

The three CNG buses equipped with lean-burn engines emitted 5 to 52 grams of methane per kilometer, about 0.1 to 3.1 grams of ethane, and much lower levels of ethylene and higher-carbon VOC species. In CNG mode, the dual-fuel microbus emitted 0.8 to 4.6 g/km of methane, 0.05 to 0.24 g/km of ethane, and very small amounts of higher NMHC. In gasoline mode, its methane emissions were about 80% lower, but its NMHC emissions increased greatly – averaging two to 3.7 grams per kilometer. VOC emissions from the diesel buses were so low that they could not be distinguished reliably from background VOC levels.

Fuel consumption and CO_2 emissions among the diesel buses varied with the size of the bus, ranging from about 200 grams of fuel per kilometer for a 10-meter light bus to about 500 g/km for the 18 meter articulated vehicle. Mass fuel consumption for the CNG buses was similar to that for diesel buses of the same size. The CNG and LPG microbuses used about 2/3 as much fuel as the diesel and CNG buses. Mass fuel consumption for the gasoline minibus was substantially higher.

Fuel consumption and emissions in regular driving were sometimes higher and sometimes lower than in the simulated bus corridor conditions, depending on the bus and/or driver. The absence of traffic allowed more-aggressive bus drivers to drive faster and accelerate harder, thus increasing fuel consumption. A statistical analysis of the six buses with the most complete data showed a mean reduction in fuel consumption and CO_2 emissions of 10% for three diesel buses combined when operating in the simulated bus corridor conditions compared to regular driving. For three CNG buses, the reduction was 11%. Neither value was statistically significant at the 90% level, however.

Eight of the vehicles tested in this program were also tested on the West Virginia University (WVU) transportable chassis dynamometer system. The WVU MX3 cycle was designed to simulate bus corridor operation, in the same way as our Insurgentes Corredor route, and the average speeds in the two cycles are similar. The MX3 is a more severe cycle, however, with 50 stops per hour compared to 30 in the Insurgentes Corredor route. This would tend to produce higher emissions per kilometer. The two sets of measurements show similar trends, but the RAVEM Insurgentes Corredor data averaged about one-third lower than the WVU MX3 results.

Limited emission testing was also performed on two 1991 model Mercedes buses, one of which had been repowered with an engine meeting current Mexican emissions standards. Emissions of PM, CO, and NOx from the repowered bus were 88 percent, 86 percent, and 59 percent lower, respectively, than those from the bus that had not been repowered. Thus, repowering older buses with modern, emission-controlled engines can achieve large emission reductions. Such repowering is most feasible in rear-engine buses, as front-engine vehicles often lack sufficient space to accommodate the engine accessories.

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1. INTRODUCTION

Engine, Fuel and Emissions Engineering, Inc. (EF&EE) has been contracted by the *Secretaría del Medio Ambiente* (SMA) of the Government of Mexico City to carry out emissions measurements on public transport buses operating in the *Avenida Insurgentes* corridor in Mexico City. This effort is being conducted as part of the “Project for Introduction of Climate Friendly Measures in Transport”, funded by the Global Environment Fund, and administered by the SMA and the World Bank.

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The main purposes of the work under EF&EE’s contract were:

1. to measure the pollutant emissions from a sample of the public transport buses and microbuses that formerly operated on *Avenida Insurgentes*;
2. to measure emissions from the buses used in the new Metrobus line; and
3. to measure the emissions from various advanced and “clean” technology buses that might be considered for future incorporation either into the Metrobus system or the general public transport fleet.

Emission measurements were performed in three rounds of emission testing, extending from November, 2004 to October, 2005. Not all of the buses were available for testing in each round. This final report contains the results from all three rounds of emission testing.

Mass exhaust emissions were measured using Version 3 of the Ride-Along Vehicle Emissions Measurement (RAVEM) system. This system was developed by EF&EE, and RAVEM serial number 002 was purchased by the SMA specifically for use in this project. This was the first commercial sale of a RAVEM system.

The RAVEM system uses proportional partial-flow constant-volume sampling (CVS) to measure particulate matter (PM), oxides of nitrogen (NOx), carbon monoxide (CO), and carbon dioxide (CO_2). DNPH cartridges and integrated bag samples of dilute exhaust gas were also collected for subsequent characterization of carbonyls and speciated VOC emissions, respectively.

During the first round of testing, pollutant emission measurements were conducted on 17 late-model and demonstration buses and four microbuses (23-passenger, front-engine vehicles based on van chassis). Twelve of the buses used diesel fuel, two were diesel-electric hybrids, and three were fueled by compressed natural gas (CNG). Two diesel buses and one diesel-electric hybrid were equipped with diesel particulate filters (DPFs). One microbus operated on gasoline, one had been retrofit to use CNG, one to use liquefied petroleum gas (LPG), and one to use either

CNG or gasoline. All of the microbuses and all of the CNG buses were equipped with catalytic converters. Four of the diesel buses (including both of those equipped with DPFs) and three of the microbuses were owned by public transport organizations serving the *Insurgentes* corridor; the rest were prototypes or demonstration units made available by their manufacturers.

Emissions were measured while operating on one of two specified routes. Both routes traversed the northern segment of *Avenida de los Insurgentes*, between the *Indios Verdes* metro station and the *Glorieta de los Insurgentes* traffic circle, a roundtrip distance of 21 km. The *Insurgentes Norte* route was driven during off-peak hours in the morning, and was designed to reflect normal bus operation under conditions before the opening of the Metrobus line. The *Insurgente*s *Corredor* route was designed to simulate expected traffic conditions in the Metrobus's dedicated bus lane. This route had fewer stops, and was driven during the period from 2:00 AM to 6:00 AM, when traffic was normally light.

Limited emission testing was also performed on two 1991-model RTP buses, one of which had been repowered with an engine meeting current Mexican emission standards. These tests used a different test route, and are reported separately.

2. CHARACTERISTICS OF THE BUSES AND THE TEST ROUTES

2.1 TEST VEHICLES

Emission tests were carried out on-board the 17 buses and four microbuses shown in.Table 1 The buses tested included twelve with conventional diesel drive systems, two diesel-electric hybrids, and three using compressed natural gas in lean-burn engines. All of the buses except the Busscar had automatic transmissions. Two diesel buses and one diesel-electric hybrid were fitted with Johnson-Matthey CRT™ catalytic diesel particulate filters (DPFs). All of the CNG buses were equipped with two-way catalytic converters (2WC).

The four microbuses included one using gasoline in a stoichiometric engine, one that had been retrofitted to use LPG, one retrofitted to use CNG, and a dual-fuel vehicle that could operate on either gasoline or CNG, and was tested on each fuel. The microbuses were originally equipped with three-way catalytic converters (3WC), but we did not verify that these were intact. From the emissions performance of the vehicles, the 3WC on the gasoline-only microbus appears to have been severely degraded.

The two Mercedes/Marco Polo Torinos and the two International buses were taken from the regular RTP transit fleet. The three metrobuses were also in transit service with the new Metrobus bus rapid transit system. Three of the four microbuses were also in regular transit service, while the dual-fuel microbus belonged to ECOMEX, a private company. The other buses tested had been made available by their manufacturers for demonstration purposes.

For testing purposes, staff of the Servicio de Transportes Electricos loaded each of the buses to approximately 70% of their rated passenger loads, using containers of water in place of passengers. EF&EE did not verify that the loading was correct in each case. In some cases – such as the Busscar – data on the rated passenger capacity were not provided to us. In these cases, the “test weight” is shown as “NA” for “not available”.

2.2 DRIVING ROUTES

Exhaust emissions were evaluated under two real driving routes that included the combination of stop-go and cruise-speed driving typically experienced by public transportation in Mexico City. The test routes were located at an altitude of approximately 2250 meters, and the typical barometric pressure was about 785 millibar – 23 percent less than at sea-level. Following is a description of both driving routes.

Table 1: Test vehicles

Bus Manufacturer	Model/ Description	Identifier	Engine		Emission Controls	Fuel	Weight (kg)	
			Model	HP			Test	Gross
Diesel Buses								
Mercedes Benz	RTP No. 12-592	RTP 1	OM 906-LA	230	EPA 1998	D50	12,020	14,000
International	RTP No. 23-995	RTP 2	DT466E	215	EPA 1998	D350	13,994	15,800
Volvo	12 m	Vol 12	D7C	300	Euro 3	D15	14,131	16,000
Scania	18-m Articulated	Sc 18	DC9	300	Euro 3	D50	25,957	29,500
Mercedes Benz	10 m Boxer	MB 10	OM924-LA	NA	EPA 2004	D15	NA	8,063
Mercedes Benz	11.4 m Torino	MB 11	OM924-LA	230	EPA 1998	D15	NA	NA
Mercedes Benz	12.3 m Torino	MB 12	OM926-LA	280	EPA 1998	D50	NA	NA
Diesel Metrobuses								
Scania	18-m Articulated	RTP	DC9	300	EURO 3	D350	25,957	29,500
Volvo	18-m Articulated	CISA	DH12-340	340	EURO 3	D350	25,957	29,500
Phenix	18-m Articulated	Phenix	DDC	NA	NA	D350	NA	NA
Diesel Buses with Additional Emission Controls								
Mercedes Benz	RTP No. 12-569	RTP3	OM 906-LA	230	EPA 98 + DPF	D50	12,020	14,000
International	RTP No. 23-1022	RTP4	DT466E	215	EPA 98 + DPF	D15	13,994	15,800
Gillig/Allison	"Magic Bus" hybrid	Allison	ISB	260	Hybrid + DPF	D15	13,646	15,890
Eletrabus	Hybrid	Eletrabus	OM 904-LA	150	Hybrid + Euro 2	D15	NA	NA
Lean-Burn Natural Gas Buses								
Busscar	Urbanuss Plus	Busscar	B5.9-230G	230	EPA '04 w 2WC	CNG	N/A	15,760
FAW AMI	CA6160	FAW	C8.3G +	280	EPA '04 w 2WC	CNG	13,706	15,500
Anhui Ankai	HFF6110GK5	Ankai	B5.9-230G	230	EPA '04 w 2WC	CNG	14,350	16,000
Microbuses with Gasoline-Type Engines								
Chevrolet	Ruta 3 No. 030473	M-CNG	NA	NA	3WC	LPG	NA	NA
NA	Ruta 2 No. 1133	M-LPG	NA	NA	3WC	CNG	NA	NA
NA	Ruta 2 No. 21403	M-Gsln	NA	NA	3WC	Unlead	NA	NA
Chevrolet	Dual-Fuel Microbus	M-D-Gsln M-D-CNG	NA	270	3WC	Unlead CNG	NA	8,000

NA: Not available D15: Diesel with 15 ppm sulphur, D50: diesel with 50 ppm sulfur
D350: regular Mexico City diesel with a maximum of 350 ppm sulphur
CNG: compressed natural gas, LPG: liquefied petroleum gas, Unlead: unleaded gasoline

2.2.1 Insurgentes Norte Driving Route

The first driving route was designed on a pre-determined, real-life traffic, normal driving bus route served by both, the *Red de Transporte de Pasajeros (RTP)*, and microbuses belonging to *Ruta 2*. Hence, real world exhaust emissions were evaluated. To simulate passenger weight, all vehicles were loaded with water containers to 70% of total passenger weight. The route ran along *Avenida de Los Insurgentes*, a major road going through the middle of Mexico City. *Insurgentes* is divided into *Insurgentes Norte* and *Insurgentes Sur*, and runs through the city from North to South. However, since that route is too long, and traffic is highly variable, testing was limited to the *Insurgentes Norte* segment. This segment runs from *Indios Verdes* (north of the city) to *Glorieta de Los Insurgentes* (relatively close to downtown), and back. This segment varies little in altitude along its length. The roundtrip ride is approximately 4,500 seconds (one hour and 15 minutes) long, including stops. Table 2 and Table 3 show the stops along the route.

Table 2 and Table 3 also show three round trips on the *Insurgentes Norte* route (from G*lorieta de Insurgentes* to *Indios Verdes*) performed on Friday, June 4th, 2004. These trips started at 9:10am, 10:30am, and 12:26pm. From these trips it was concluded that **average bus stops were around 35 seconds**. This data was later confirmed as appropriate by RTP's management. These trips were carried out by Enrique Rivero Borrell, from the Mexico City Government, and Marco Balam from Ambientalis.

The *Insurgentes Norte* route is composed of two relatively well defined sections: a faster section where speeds can be up to 65 km/hr, and a slower business/commercial section, where average speeds are about 17 km/hr. It is estimated that these conditions replicate average transit bus routes in Mexico City.

Table 2: Trip from Glorieta de Insurgentes (downtown) to Indios Verdes (north), following an RTP bus.

START	**9:10AM**		**10:30AM**		**12:26PM**	
From G. Insurgentes to Indios Verdes	**Cumulative time**					
Commercial Section	Min	Sec	Min	Sec	Min	Sec
G. Insurgentes	0	0	0	0	0	0
Londres	2	2	1	12	-	-
Hamburgo (Oxxo)	2	40	1	40	-	-
Reforma (VIPS)	3	50	2	58	2	20
Sullivan II	5	38	4	57	4	6
Antonio Caso	6	13	6	1	5	16
Edison (Dormimundo)	8	5	-	-	-	-
Pte. de Alvarado	9	3	7	22	7	26
H. Ferrocarrileros	9	50	-	-	-	-
Colosio (PRI)	11	2	-	-	-	-
Mosqueta	11	21	9	20	9	39
Faster Section						
Díaz Mirón (Buenavista)	-	-	-	-	10	54
Eligio Ancona	-	-	11	20	-	-
M. González (Eje 2 Nte)	13	0	12	18	12	32
San Simón I	-	-	-	-	-	-
Monum. a la Raza	-	-	-	-	-	-
Gas PEMEX	-	-	14	52	-	-
Metro la Raza	15	44	-	-	15	15
Euzcaro	18	50	17	0	-	-
Montevideo	-	-	18	12	18	19
Indios Verdes	**20**	**38**	**20**	**06**	**20**	**08**

Note: A line (-) in the table means that the bus was not required to make a stop for passengers.

Table 2 shows that travel time was very consistent, on this day, at around 20 to 21 minutes from Glorieta de Insurgentes to Indios Verdes, making it convenient for exhaust emissions testing.

Table 3: Trip from Indios Verdes (north) to Glorieta de Insurgentes (downtown), following an RTP bus.

From I. Verdes to G. Insurgentes	**Cumulative time**					
Faster Section	Min	Sec	Min	Sec	Min	Sec
Paradero Indios Verdes	0	0	0	7	0	0
Metro La Raza	3	55	3		3	25
San Simón	-	-	-	-	-	-
Eulalia Guzmán (Eje 2 Nte)	6	15	5	15	5	43
M. Carpio	-	-	7	23	7	45
Alzate	10	20	8	53	10	10
Commercial Section						
Sor Juana Inés (VIPS)	-	-	10	18	15	6
Amado Nervo (PRI)	-	-	-	-	19	0
San Cosme	14	30	16	48	23	0
Gómez Farías	20	39	21	26	30	0
Antonio Caso	23	30	24	40	32	7
Sullivan	25	30	27	18	-	-
Villalongín (Reforma)	-	-	29	0	-	-
Nápoles	28	52	31	16	38	16
Niza	-	-	33	6	39	58
Glorieta de Insurgentes	**31**	**05**	**34**	**40**	**41**	**29**

Note: A line (-) in the table means that the bus was not required to make a stop for passengers.

Table 3, however, shows more variability on the trip back from *Indios Verdes* to *Glorieta de los Insurgentes*, where each trip lasted from 31 to 42 minutes.

Hence, exhaust emissions were measured on test buses on the *Insurgentes Norte* route, where each test lasted 4,500 seconds (75 minutes). A test of this duration should eliminate some variability due to individual cycles. If any of the measuring test trips were shorter than 4,500 seconds, then the bus would stand at idle until the 4,500 seconds were completed. If a trip was longer than 4,500 seconds, then the emissions measurement was stopped at 4,500 seconds (if not more than 1 to 3 minutes). The difference in either case would come from the bus being at idle in regular traffic.

Hence, the round trip of this route lasted 4,500 seconds, and covered on average 21.4 kilometers. The number and location of bus stops is shown in Table 2 and Table 3.

Figure 1 is a plot showing the typical variation of bus speed vs. time over the Insurgentes Norte route. As the figure shows, results from the Doppler speed sensor and the GPS system agreed very closely. However, the GPS speed trace exhibits occasional "spikes" – sudden changes in measured speed that are not physically realistic. Two such spikes are visible in Figure 1, at about 3500 and 4000 seconds. These are believed to be due to the GPS signal being reflected from buildings or other vehicles along the route. An outlier-detection algorithm was developed and implemented in the RAVEM processing software to eliminate these spikes in the GPS trace.

Emissions testing in this route took place in the morning and early afternoon, between 9:00am to 2:00pm, from Monday to Saturday, as during that time traffic conditions generally did not vary greatly. Later than 2:00pm, however, mid-rush, and rush hours would have made the round-trip timing significantly more variable.

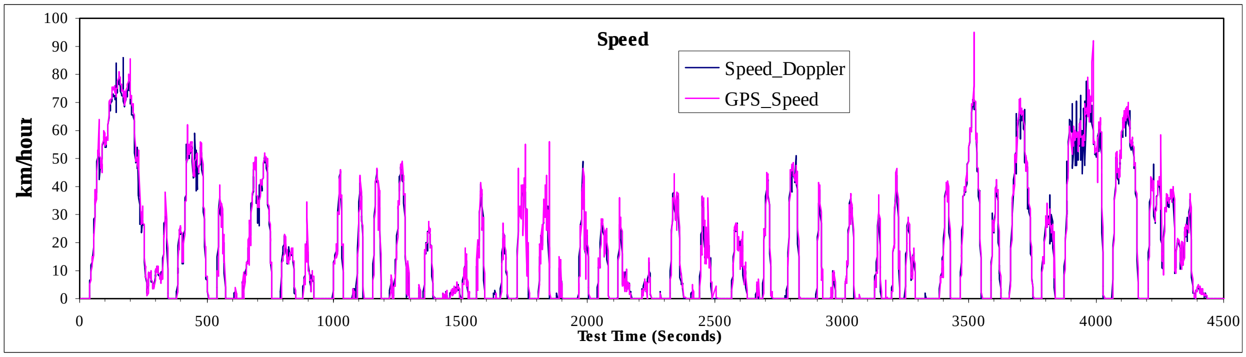


Figure 1: Typical Speed Trace for the *Insurgentes Norte* driving route (fileMX0202, RTP 23-1003).

During the test period, traffic conditions on *Avenida de los Insurgentes* changed considerably due to the construction and implementation of the Metrobus bus rapid transit system. As part of these changes, the operation of buses and microbuses was prohibited (except for the buses of the BRT system), and the lanes formerly used by buses and microbuses to pick up passengers were dedicated to other vehicles instead. With this change in traffic patterns, continued testing according to the Insurgentes Norte route would have created serious traffic disruptions – thus, this route was not used during the second and third rounds of emission testing.

2.2.2 *Insurgentes Corredor* Driving Route

This route was similar to the *Insurgentes Norte* route, except that exhaust emission testing took place during the night (between 2:00 am and 6:00 am) to simulate driving along the single lane corridor recently built for the Metrobus BRT (bus rapid transit system). Also, the bus stops were different from the Insurgentes Norte Route – matching those defined for the new BRT system, as shown in Figure 2.

It is important to mention that operation in the “corridor” (reserved bus lane) had to be simulated, as its construction was not completed until June 2005. Even afterward, buses other than those of the BRT system were not permitted to operate in the bus lane, so that the tests on the remaining buses in the program were carried out at night, and outside of the bus lane. However, emission tests on the three metrobuses were carried out in the bus lane, during the morning rush period, but with ballast rather than passengers aboard.

For the *Insurgentes Corredor* route, the total length of the emission tests was reduced from 4500 to 3600 seconds. With the construction of the single-lane corridor, the effects of traffic congestion on bus travel were greatly reduced, and there were fewer bus stops, so that the total transit time was reduced.

As in the case of the other route, vehicles tested in the *Insurgentes Corredor* route were also loaded with water containers to simulate 70% of maximum passenger capacity.

Figure 2: Bus stops for Corredor Insurgentes Norte Route (from Indios Verdes to Insurgentes, which includes only the 30 roundtrip bus stops in Insurgentes Norte). Source: Mexico City Metrobús.

2.3 DRIVERS

Driving habits have a substantial impact on exhaust emissions. Hence, a single driver for all exhaust emission tests was requested. This, however, was not possible due to working hour restrictions and logistics.

With regard to training of the drivers for adequate driving, they were just told to drive normally. At the beginning of testing, drivers were slightly nervous. However, after the first loop of their respective driving route, they started driving more normally.

With the entry into operation of the metrobus BRT system, traffic conditions during the Insurgentes Corredor route were generally improved during the second and especially the third rounds of emission testing. The drivers also tended to match the pace of the metrobuses, rather than driving as fast as possible between stops as some had during the first testing round. The improved traffic and reduced maximum speed generally led to lower emissions and fuel consumption during these later test rounds.

3. RAVEM SYSTEM CHARACTERISTICS

Emission measurements were performed using Ride-Along Vehicle Emission Measurement (RAVEM) system serial number 002. This system was purchased by the SMA specifically for this project. The RAVEM technology was developed by and patented by EF&EE. The RAVEM system was among the first portable emission measurement systems (PEMS) to be developed, and is presently the only commercially-available PEMS with ability to measure emissions of PM as well as NOx, CO, and CO_2. Optional capabilities – which were employed in this work – also allow the measurement and quantification of individual species of volatile organic compounds (VOC) and carbonyls such as formaldehyde, acetaldehyde, and acrolein.

During the last four years, EF&EE has applied it´s own prototype RAVEM unit to measure pollutant emissions from a wide variety of mobile sources, ranging from natural gas garbage trucks[1] to diesel ferryboats[2]. It has also been applied to the evaluation of emission control systems including selective catalytic reduction (SCR), diesel particulate filters (DPF), diesel oxidation catalysts (DOC) and emulsion fuels.

3.1 PRINCIPLES OF OPERATION

The RAVEM system is described in two published papers[3,4], so its operating principles are summarized only briefly here. As Reference 3 explains in more detail, the RAVEM system is based on proportional *partial-flow* constant volume sampling (CVS) from the vehicle exhaust pipe. The CVS principle is widely used for vehicle emission measurements because the air dilution and total flow arrangements are such that the pollutant *concentration* in the CVS dilution tunnel is proportional to the pollutant *mass flow rate* in the vehicle exhaust. Gaseous pollutant concentrations can be measured readily, as can integrated concentrations of particulate matter. On the other hand, exhaust mass flow rates are difficult and expensive to measure accurately – especially under transient conditions.

The total pollutant mass emissions over a given driving cycle, such as the US Federal Test Procedure, European Transient Cycle, or Mexico City Bus Cycle, are equal to the integral of the pollutant mass flow rate over that cycle. In a CVS system, this integrated value can readily be determined by integrating the concentration measurement alone. The CVS flow rate enters into the calculation as a constant multiplier. The integration of pollutant concentration can be accomplished either numerically or physically. The vehicle exhaust mass flow rate does not enter into the calculation, making it unnecessary to measure.

For gases, the RAVEM system uses both numerical and physical integration. Concentrations of NOx, CO_2, and CO in the dilute exhaust gas are recorded second-by-second during each test. In addition, integrated samples of the dilute exhaust mixture and dilution air are collected in

Tedlar® bags during the test, and analyzed afterward for NOx, CO_2, CO and (optionally) other pollutants.

In CVS sampling for particulate matter, sample integration is accomplished physically -- by passing dilute exhaust mixture through a pre-weighed filter at a constant, controlled flow rate. The weight gain by the filter is then divided by the volume of mixture passed through it to yield the average particulate concentration over the test cycle.

A schematic diagram of the RAVEM system is shown in Figure 3. Except for the isokinetic sampling system at the top of the figure, this diagram closely resembles a conventional single-dilution CVS emission measurement system.

Conventional emission laboratory methods defined by the U.S. EPA[5] and California ARB[6] utilize full-flow CVS, in which the entire exhaust flow is extracted and diluted with air. However, the large amounts of dilution air required make full-flow CVS impractical for portable systems.

The principle of the RAVEM sampling system is as follows: the RAVEM's sampling system extracts and dilutes only a small, constant fraction of the total exhaust flow. The dilution air requirements and dilution tunnel size can thus be reduced to levels compatible with portable operation. As explained in Section 3.2.2, the patented isokinetic proportional sampling system[7]. system continuously adjusts the sample flow rate so that the flow velocity in the sample probe is equal to that of the surrounding exhaust. Since the velocities are equal ("isokinetic"), the ratio of the flow rates in the exhaust pipe and the sample probe is equal to the ratio of their cross-sectional areas.

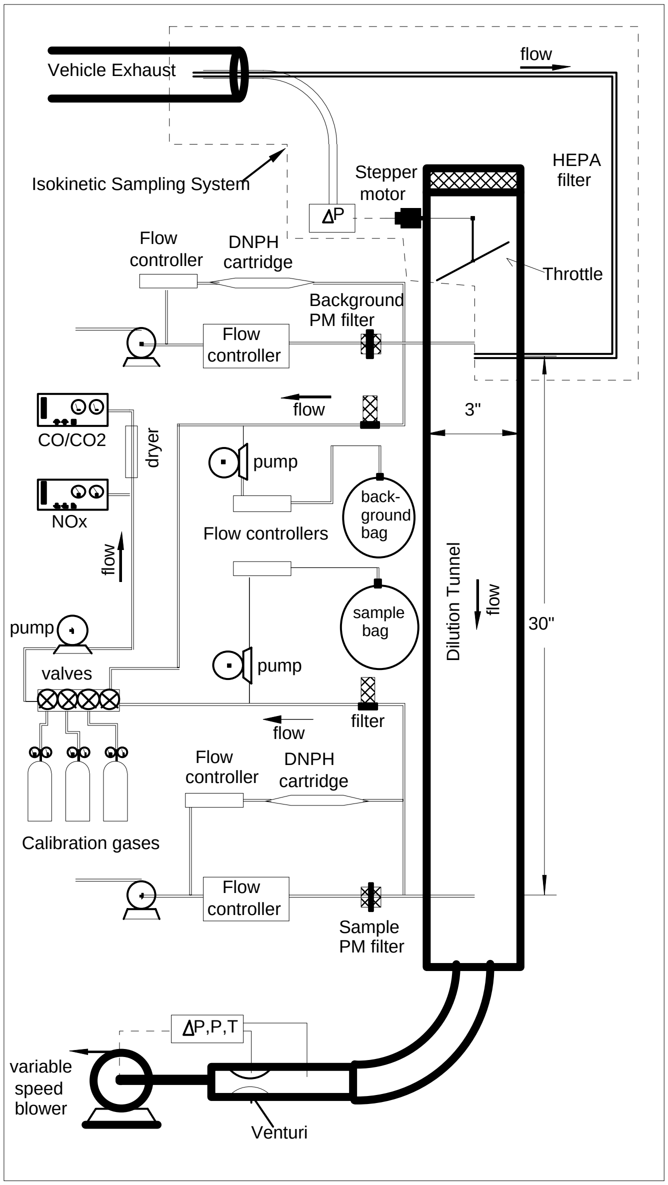


Figure 3: Schematic diagram of the RAVEM system

Pollutant concentration measurements in the RAVEM system follow the methods specified by the U.S. EPA (US CFR Vol 40 Part 86) and ISO standard 8178. The pollutants measured are as follows:

- Oxides of Nitrogen (NOx) by chemilumenescent analysis of the dilute exhaust sample,
- Carbon monoxide (CO) and carbon dioxide (CO_2) by non-dispersive infrared analysis of the dehumidified dilute exhaust sample;
- Particulate matter (PM) by collection particulate matter on pre-weighed filters of Teflon-coated borosilicate glass fiber, followed by post-conditioning and reweighing of the exposed filters.
- Volatile organic compounds (VOC) by gas-chromatographic (GC) analysis of the integrated bag samples, using flame ionization detectors in a method patterned on California Air Resources Board methods 102 and 103.
- Aldehydes and carbonyls by collection in silica-gel cartridges coated with di-nitro phenyl hydrazine (DNPH), followed by elution with acetonitrile and analysis of the eluate by high-pressure liquid chromatography, as specified in U.S. EPA method TO-11a.

Aldehyde measurements and GC analysis to characterize VOC emissions were not employed during the first part of this test program, as these optional capabilities were ordered later than the basic RAVEM system, and were not available at the time that the program began.

3.2 RAVEM SUBSYSTEMS AND OPERATION

The RAVEM system comprises the following key subsystems.

- Miniature constant volume dilution system
- Isokinetic proportional sampling system
- Bag sampling system: a) exhaust sample; b) background air sample
- Gas analyzer system: a) CO/CO_2; b) NO_x
- Particulate sampling system
- Cartridge sampling system (not used in this test program)
- Data processing and handling system
- Auxiliary inputs

Each of these is briefly discussed below.

3.2.1 Miniature Constant-Volume Dilution System

This constitutes the heart of the RAVEM system. As diagrammed in Figure 3, the variable speed blower draws dilute air/exhaust gas mixture out of the dilution tunnel at a constant rate (expressed in standard liters per minute). The flow rate is controlled by a closed-loop system that measures volumetric flow rate via a venturi meter, corrects this to standard conditions of one atmosphere pressure and 20^o C, and then adjusts the blower speed to maintain the flow setpoint. The venturi meter is calibrated against a high-accuracy hot-wire mass flow meter (not shown) in order to compensate for any drift. High accuracy is needed, as any error in the mass flow will result in a proportional error in the final results.

Raw exhaust gas enters the dilution tunnel near the upper end, where it mixes with filtered dilution air. The relative proportions of exhaust gas and dilution air are controlled by the isokinetic sampling system, by means of the throttle in the air inlet.

3.2.2 Isokinetic Proportional Sampling System

The isokinetic sampling system comprises: a) the sampling probe in the exhaust pipe; b) an insulated sample line connecting the sampling probe to the raw gas inlet on the dilution tunnel; and c) the system for controlling the sample flow to maintain isokinetic conditions. The control system uses static pressure taps on the inside and outside surfaces of the probe, connected to a sensitive differential pressure sensor. When this sensor reads zero, the inside and outside pressures are the same. This requires that the velocities inside and outside the sample probe also be equal – i.e. isokinetic. Thus, exhaust gas entering the sampling probe is equal in velocity to that in the main engine exhaust stream ($v_1 = v_2$).

The throttle at the upstream end of the dilution tunnel is connected to a “smart” motor/controller combination. The controller responds to the signal from the differential pressure sensor by changing the throttle position to maintain isokinetic conditions. When the exhaust flow rate increases, the controller closes the throttle somewhat, increasing the pressure drop between the probe and the dilution tunnel, and thus increasing the flow velocity through the probe. When the exhaust flow decreases, the throttle opens, decreasing the pressure drop and the flow velocity in the probe. A fan upstream of the throttle (not shown) extends the possible range of dilution tunnel pressures to include slightly positive as well as negative values (compared to ambient atmospheric pressure).

Since the control system depends on equalizing the static pressures measured inside and outside the probe, leaks or other problems in the pressure taps, pressure lines, or differential pressure sensor can affect the measured pressure difference, and thus the emission results. This was a significant problem during the early part of the measurement campaign. The need to strengthen quality assurance procedures in this area was one of the key lessons drawn from the experience of this project. To aid in detecting this problem, EF&EE developed and retrofit a design change to permit *in situ* leak checks on the differential pressure lines. This modification was installed in the Mexico City RAVEM at the beginning of September, 2005.

3.2.3 Bag Sampling System

The bag sampling system is designed to fill one pair of Tedlar bags for each test. One bag contains an integrated sample of the dilute exhaust from the dilution tunnel, and the other contains an integrated sample of the dilution air. Two choices are available with respect to the Tedlar bags: a pair of internal bags having a usable volume of about 10 liters, or a pair of 60 liter external bags fed through two quick-connect ports on the exterior of the system unit. The system is designed to allow the external bags to be exchanged quickly between tests, so that the bag samples for each test can analyzed off-board – e.g. by gas chromatograph. A pair of manually operated three-way valves selects the internal or external bags.

For each bag, gas is drawn from a sample port in the dilution tunnel, through a filter to a small pump. It then passes through a mass flow controller to the bag selector valve, and thence to the bag. The flow rate to the bags typically ranges from 0.25 to 1.5 standard liters per minute, and is kept constant during each emission test. The flow rate is normally calculated and set automatically, to capture a specified volume of gas over the length of the emission test. It can also be set manually by the RAVEM operator. The volume flowing to the sample bag is added to the total CVS flow in calculating the emission results.

Any leaks in the sample bag will directly affect the bag emission results. A leak check is therefore performed in the process of emptying the sample bags before each test.

During this test program, we found that the mass flow controllers to the sample bags would occasionally malfunction during long tests, allowing the bags to overfill and pop. The cause of this problem has not yet been identified, but software changes to monitor the backpressure in the bag feed lines have made it possible to detect and correct it.

3.2.4 Gas Analyzer System

The gas analyzer system comprises a sample pump, valve manifold, and conventional laboratory-grade heated NOx and ambient-temperature CO/CO_2 analyzers installed in a shock-mounted 19 inch rack inside a protective case. Both analyzers comply with the U.S. EPA’s performance standards for laboratory emission analyzers, which are given 40 CFR 86. The NOx analyzer is a California Analytical Instruments HCLD 400 equipped with an NO to NO_2 converter using activated carbon. The analyzer is maintained at 60^oC, making it unnecessary to dry the sample to avoid condensation Dry, low-pressure compressed air for the ozone generator is supplied by an on-board pump by way of a filter and desiccant cartridge.

The CO/CO_2 analyzer is a California Analytical Instruments model ZRH using non-dispersive infrared (NDIR) analysis. Water vapor interferes with the NDIR measurement, especially for CO, and must be removed from the sample. This is accomplished by passing it through a Nafion™ semi-permeable membrane mass-exchanger. Dry gas for the other side of the mass exchanger is supplied by a small pump circulating air through a desiccant cartridge.

The gas analyzer system valve manifold allows the analyzer sample feed to be drawn from any one of the following sources: the dilute exhaust mixture in the dilution tunnel, the dilution air entering the tunnel (for background measurements), the integrated sample bag, the integrated background bag, zero gas, CO/CO_2 span gas, or NOx span gas. The latter three gases are used for calibration, and are supplied to quick-connect ports on the exterior of the RAVEM system unit. The gases used are certified by the manufacturer (PraxAir) and are traceable to U.S. NIST standards.

During an emission test, gas concentrations in the dilute exhaust are monitored continuously, and recorded about once per second. After the test ends, the analyzers are normally again calibrated prior to analyzing the concentrations in the sample and background bags.

Since the second-by-second pollutant readings can be affected by drift, vibration, and changes in background pollutant concentrations as the vehicle drives, the bag data are normally more accurate, and are generally the ones reported. The second-by-second data are useful for examining the variation in emissions over the driving cycle, and also provide a backup should the bag results be compromised – e.g. by bag failure during a test.

3.2.5 Particulate Sampling System

The particulate sampling system comprises a vacuum pump, two flow controllers, two shutoff valves, and two filter holders: one for the PM sample, and one for the background dilution air. Each filter holder contains two 37 mm filters in series. The filters are composed of Teflon-coated borosilicate glass, and meet U.S. EPA (40 CFR 86.1311-90) and ISO 8178 specifications for diesel PM measurement. At least two sets of filter holders are used, and they are designed to be quickly connected and removed from the sampling system – thus allowing one emission test to go on while the filters from the last test are being exchanged for the filters for the next.

During an emission test, the shutoff valves are opened, and the dilute exhaust gas and dilution air are drawn through their respective filter sets. The filtered gas then passes through the flow controllers to the vacuum pump, where it is exhausted. The flow controllers maintain a constant flow rate (typically 10 to 30 SLPM, depending on the anticipated PM loading) throughout the emission test. Integrated flow volume is recorded during the emission test in order to calculate the particulate mass concentration in the dilute air/exhaust sample and in the background dilution air.

The mass flow controllers were calibrated by the manufacturer before installation in the RAVEM. It is recommended that they be recalibrated annually, but such recalibration was not necessary during this program, as it was only one year in length. The mass flow controllers were checked on several occasions against a Sierra Instruments thermal mass flow meter, and were found to be in agreement.

The filter set exposed to the dilution air provides a “blank” sample for each test, correcting for the effects of changing humidity, atmospheric pressures, and any ambient PM (including condensable species) present in the filtered dilution air. Experience has shown that such corrections can amount to 0.01 to 0.02 grams of PM per BHP-hr. This is important since this amount of PM is of the same order as the total measured PM emissions for the DPF-equipped vehicles in this study.

3.2.6 Cartridge Sampling System

The DNPH cartridge sampling system is similar in design to the PM sampling system described above, comprising two shutoff valves, two holders for SKC 6 mm glass sampling tubes, two flow controllers. Initially, the system included only a single pump, but later each flow controller was given its own pump. The DNPH sampling system differs from the PM sampling system in having much lower designed flow rates (i.e. 0 to 2 liters per minute, rather than 0 to 30), and in drawing from the filtered sample stream that also feeds the Tedlar bags, rather than directly from the dilution tunnel.

To measure the concentration of carbonyls such as formaldehyde, acetaldehyde, and acetone, the cartridge sampler is loaded with two 6 mm glass tubes containing DNPH-impregnated silica gel.

Gas is drawn from the sample and dilution air ports, through filters, and then through the cartridges, where any carbonyls present react with the DNPH and are retained in the cartridge. The cartridges are then removed, placed in a cooler at approximately 4 ^{o}C, and transported to the laboratory, where they are kept in a freezer until analysis by high performance liquid chromatography (HPLC).

The analysis is done by isocratic HPLC, as specified in EPA method TO11a for formaldehyde. This method can also separate and identify most of the other carbonyls having carbon numbers up to four, as well as benzaldehyde. Higher-carbon species such as valeraldehyde, hexaldehyde, and tolualdehydes tend to form broad peaks that overlap with peaks for other, unknown species in the background samples.

3.2.7 Data Processing and Handling System

The data processing and handling system comprises a laptop computer, connected to a National Instruments Fieldpoint system containing 24 analog-to-digital channels, 8 digital-to-analog channels, 36 digital outputs, 8 general-purpose digital inputs, and 4 counter inputs. These include a number of spare inputs and outputs beyond those required by the RAVEM system itself, making it easy to interface auxiliary sensors.

The RAVEM system measures and records numerous data on a second-by-second basis during each emission test, including the raw inputs and calculated concentrations of CO, CO_2, and NOx, the CVS flow rate, throttle position, and differential pressure sensor reading. Calibration data relating the raw inputs and calculated concentrations are also recorded, making it possible to recalculate the second-by-second results using the calibration at the end of the test. Exhaust temperature and up to two auxiliary temperatures are recorded second-by-second; in addition, the temperature, barometric pressure, and humidity are recorded at the beginning of each test. All of these are stored in separate data file for each test, in a compact binary format.

A data file reading utility is supplied with the RAVEM system. This utility can be used to review and correct the data collected for each test, and to add data developed later such as the post-test weights of the particulate filters. This utility can also copy the data to a Microsoft Excel worksheet file. This file is formatted to be “human readable”, and occupies much more space than the compact binary format. Copies of the Excel worksheets for each emission test are given in the CD ROM that accompanies this report, along with summary worksheets that combine the individual test results.

3.2.8 Auxiliary Inputs

Auxiliary inputs to the RAVEM system include a global positioning system (GPS) receiver, a Doppler-radar speed sensor, and an ammeter clamp used to measure the flow of current into and out of the batteries in a hybrid vehicle. The GPS system provides three-dimensional location and velocity data, based on signals from the global positioning network. These are supplied and recorded at a frequency of 1 Hz.

The Doppler speed sensor works by measuring the Doppler shift in a radar signal emitted toward the ground under the vehicle. The result is expressed as a pulse frequency by the sensor. This frequency is translated into velocity by the data processing system and recorded second-by-second during the emission test. The relationship between Doppler shift and vehicle speed varies with the cosine of the angle between the centerline of the sensor and the ground, making it necessary to measure this angle for each bus. This angle varies with bus loading and acceleration, affecting the results. The Doppler sensor was originally requested because of uncertainty about the reliability and accuracy of the GPS data. However, a comparison of the two data sets shows that they agree closely, suggesting that future campaigns could rely on the GPS system alone.

3.3 QUALITY CONTROL MEASURES

RAVEM operating procedures include a number of quality assurance measures. Two key QA procedures are CO_2 recovery tests and fuel consumption checks. The CO_2 recovery check injects CO_2 gas from a cylinder into the dilution tunnel, and compares the CO_2 mass measured to the change in weight of the CO_2 cylinder. This confirms the accuracy of the CVS flow measurement, as well as the gas sampling system and the CO_2 analyzer. As mentioned earlier, CO_2 recovery checks performed prior to the correlation testing with WVU showed a discrepancy of 6 to 8%. The source of this discrepancy was subsequently determined to be leakage through a setscrew hole. Once this hole was plugged, CO_2 recovery checks have shown close agreement between the CO_2 emissions as measured by the RAVEM system and by the change in weight of the gas cylinder.

Fuel consumption checks compare the mass of fuel consumed by the vehicle under test to the fuel consumption calculated from the CO_2 and CO emissions by carbon balance. In addition to the CVS and gas sampling system, this procedure also checks that the isokinetic sampling system is working properly. Table 4 summarizes fuel recovery tests conducted before, during, and after the correlation program with WVU.

Table 4: Fuel Recovery Test Results for the RAVEM

Test File	Test Date/Time	Vehicle	Test Cycle	Calc Fuel	Weighed Fuel	Calc/ Weighed
MX0017	10/30/04 12:55	RTP 23-955*	Modulo 23	1,161	1,317	88.1%
MX0023	10/31/04 19:17	RTP 23-955*	Módulo 23	965	1,305	74.0%
MX0081	11/12/04 21:23	RTP 23-955**	CBD	914	905	101.0%
MX0193	1/7/05 12:34	RTP 23-0992$^+$	Modulo 23 wo Idle	941	1,040	90.5%
MX0194	1/7/05 13:04	RTP 23-0992$^+$	Continuous Idle	1,014	980	103.5%
MX0203	1/10/05 9:35	RTP 23-1003	Insurgentes Norte	7,871	8,196	96.0%
MX0282	2/3/05 2:42	Busscar GNC	Insurgentes Corredor	6,932	6,750	102.7%
MX0288	2/4/05 4:06	FAW GNC Bus	Insurgentes Corredor	10,353	10,000	103.5%
MX0289	2/4/05 5:36	FAW GNC Bus	Insurgentes Corredor	9,229	8,800	104.9%

* Test with defective probe MX01
** Correlation test with WVU
$^+$ Possibly affected by fuel system leak

Additional fuel recovery checks were conducted during September and October, 2005, in the course of a separate emission testing program to evaluate diesel retrofit devices. These tests generally showed fuel recovery percentages between 75 and 85 percent. However, extensive checks of the RAVEM system showed that it was functioning properly. Furthermore, the emission results in the Modulo 23 cycle obtained in the retrofit testing during this time period were consistent with those obtained from the same buses during November 2004 to January 2005. This suggests that the measurement performance of the RAVEM system did not change over the course of the test program. A possible explanation for these conflicting data is that there may have been some leakage, either of fuel or of exhaust. However, the source of this discrepancy has not yet been identified.

3.4 CORRELATION TESTING

To assess the correlation between RAVEM system results and those of a conventional full-flow constant-volume sampling system, a series of correlation tests was carried out between the RAVEM system and the West Virginia University (WVU) transportable chassis dynamometer emission laboratory. The results of that testing were reported in an earlier joint WVU-EF&EE report.[8] The main conclusions of that study were as follows:

- RAVEM mass CO_2 data correlated well with WVU values, but were, on average, 18% lower than the values measured by WVU. On the other hand, the RAVEM data were very close to the single mass fuel consumption measurement carried out during the program. Fuel mass measurements during a number of subsequent on-road emission tests also showed good agreement with the RAVEM results. Further correlation testing is needed to resolve this discrepancy.
- RAVEM mass NO_X also correlated well with WVU, but were, on average, 16% lower than the WVU values. Combined with the CO_2 data, this suggests that the RAVEM was consistently undersampling by about 16-18% compared to the WVU system.
- RAVEM NO_X/CO_2 ratios corresponded reasonably with the WVU ratios.
- RAVEM mass CO data were, on average, 34% of the WVU values. These measurements appear to be affected by water and CO_2 interference at the very low CO concentrations observed in the correlation test program. Measurements at higher CO concentrations (e.g. for gasoline vehicles) would probably show much better agreement.
- For WVU CO values of less than 25 g/cycle, most RAVEM CO values were at or below 0 g/cycle, which is consistent with the hypothesis that these results were affected by different responses to water and CO_2 interference between the two analyzers
- RAVEM mass PM data were, on average, about 57% of the WVU PM values. After factoring out the apparent undersampling compared to the WVU system, the RAVEM PM results were about 30% lower than the filter results obtained by WVU, but very similar in magnitude to those of the WVU TEOM. This difference is likely due to differences in the PM dilution and collection systems between the RAVEM and the WVU system, resulting in different condensation and retention of semivolatile organic compounds. The RAVEM system uses a much higher dilution ratio than the WVU system used in these tests, and this likely resulted in less retention of semivolatile organic species. (In on-road driving, exhaust dilution ratios are even higher than for the RAVEM – thus, the RAVEM results may be more representative of PM formation under on-road conditions).

The discrepancy between the RAVEM and WVU results for gaseous emissions appears to be due to a systematic difference in CVS flow measurements between the two systems, while the difference in PM emissions is likely due both to this and to the difference in dilution ratios. Such a difference is not completely surprising – an interlaboratory comparison between five heavy-duty CVS chassis test facilities[9] (including WVU) found substantially larger lab-to-lab variations in both gaseous and PM measurements among the five facilities tested.

At this point, it not possible to state whether the results of the WVU or RAVEM system are closer to correct, and further correlation testing (with fuel recovery) has been proposed to resolve this issue. For gaseous emissions, the fact that recent fuel recovery tests on the RAVEM have also shown about 75 to 80% fuel recovery suggests that the WVU data are more likely to be correct – in which case the RAVEM data would systematically be about 20% low. With respect to the PM emissions, the much lower dilution ratio used in the WVU CVS system would tend to over-collect the semi-volatile organic PM species, while the RAVEM's higher dilution ratio is more representative of PM formation in the atmosphere.

4. MASS EMISSIONS RESULTS

4.1 PM, NOX, CO, CO_2, AND FUEL CONSUMPTION

The RAVEM results for particulate matter (PM), oxides of nitrogen (NOx), carbon monoxide (CO) and carbon dioxide (CO_2) from the diesel buses tested are summarized in Table 5. Table 6 summarizes the same data for the natural buses tested, and for the microbuses. The mass fuel consumption, calculated by carbon balance, is also shown in these tables. This value was calculated by multiplying the measured CO_2 emissions by 12/44 (the mass fraction of carbon in the CO_2 molecule) and the measured CO emissions by 12/28 (the mass fraction of carbon in the CO molecule), then adding the results to get the total carbon emissions. Carbon emissions in the form of unburned HC were ignored, as this mass is very small compared to the CO_2 and CO emissions. The resulting sum was then divided by the carbon content of the fuel, expressed as a mass fraction. The fuel mass fraction of carbon was taken as 0.867 (corresponding to a fuel composition of $CH_{1.85}$) for diesel fuel and gasoline, 0.76 for natural gas, and 0.82 for LPG. Data on the actual elemental compositions of the fuels used was not available, but these values should be accurate within a few percent.

Figure 4 is a bar chart comparing the PM emissions from the diesel buses, while Figure 6 and Figure 8 compare the NOx emissions and fuel consumption, respectively. Figure 5, Figure 7, and Figure 9 compare the same data for the natural gas buses and microbuses. The error bars in these graphs show the upper and lower bounds of the 90% confidence interval, calculated from the standard deviation of the data from the multiple tests taken at each point. No error bars are shown where the only a single test result was available, as the standard deviation in that case is not defined.

Among the diesel buses tested, the PM and NOx emissions from the DPF-equipped Allison hybrid-electric bus were the lowest – comparable to those from the natural gas buses. The Eletrabus hybrid also showed very low PM emissions, but the highest NOx emissions of any of the buses tested. RTP 3 and RTP 4 – the two DPF-equipped RTP buses – had very low PM emissions as well, and these emissions appeared to decrease further over the course of the demonstration program (this may be due to the filtering effect of ash buildup in the DPF).

Among diesel buses without DPFs, RTP 1 and RTP 2 showed only moderate levels of PM emissions, reflecting their relatively recent vintage and the generally good maintenance of the RTP fleet. PM emissions from the Volvo and Scania metrobuses were significantly higher on a per-kilometer basis, reflecting the higher fuel consumption and work output required by these large articulate buses. The engines in the RTP buses were certified to Mexican emission standards for heavy-duty diesel engines, which are equivalent to the U.S. EPA 1998 standards; while the Volvo and Scania Metrobus engines were certified to the Euro 3 emission standards. The engine in the rehabilitated Phenix metrobus was a 1991-vintage Detroit Diesel two-stroke engine. Data on its emission certification were not available, but it is likely that it met U.S. 1991 emission standards.

Table 5: Regulated emissions and fuel consumption for diesel buses

Vehicle	Test Date	Test Route	No Of Tests	Emissions - g/km								Fuel g/km	
				PM		NOx		CO		CO_2			
				Avg.	σ	Avg.	σ	Avg.	σ	Avg.	σ	Avg.	σ
Diesel Buses													
RTP 1	14-Dec-2004	Norte	3	0.26	0.05	8.6	0.1	2.2	2.4	945	4	298	2
	14-Dec-2004	Corredor	3	0.25	0.01	8.1	0.7	Neg.	2.6	908	97	285	32
	26-May-2005	Corredor	3	0.17	0.01	7.2	0.3	2.4	0.4	816	37	258	12
	29-Sep-2005	Corredor	3	0.19	0.02	6.9	0.4	2.1	1.1	825	25	260	8
RTP 2	6-Dec-2004	Norte	1	0.28	-	16.2	-	1.2	-	1,214	-	382	-
	6-Dec-2004	Corredor	2	0.23	0.02	15.3	1.4	3.9	3.0	1,077	2	341	2
Vol 12	11-Feb-2005	Norte	2	0.68	0.05	12.1	0.9	12.8	0.8	1,007	123	323	39
	11-Feb-2005	Corredor	3	0.63	0.07	11.6	0.4	11.6	1.1	1,031	8	330	3
	13-Jun-2005	Corredor	3	0.55	0.08	9.6	0.4	9.9	0.9	807	30	259	10
	6-Sep-2005	Corredor	2	0.68	0.01	9.4	0.2	11.2	0.4	822	41	264	13
Sc 18	8-Feb-2005	Norte	2	2.08	0.07	7.7	0.1	10.6	2.1	1,684	135	535	41
	8-Feb-2005	Corredor	3	1.55	0.07	7.0	0.3	6.5	2.3	1,685	95	559	72
MB 10	9-Nov-2004	Norte	3	0.13	0.01	5.0	0.3	1.4	0.3	573	199	181	62
	9-Nov-2004	Corredor	2	0.11	0.01	5.8	0.1	1.9	0.2	651	14	206	4
MB 11	24-Jun-2005	Corredor	3	0.07	0.01	8.8	0.3	2.0	0.9	763	59	241	19
	28-Sep-2005	Corredor	3	0.10	0.01	8.0	0.4	1.9	0.4	746	62	236	20
MB 12	16-Dec-2004	Norte	3	0.22	0.01	14.5	0.1	4.1	1.7	1,224	19	387	7
	16-Dec-2004	Corredor	3	0.17	0.05	13.7	0.6	4.5	1.8	1,164	43	368	13
Diesel Metrobuses													
RTP	7-Sep-2005	Corredor	3	0.45	0.08	12.2	0.7	2.5	0.6	1,574	82	497	26
CISA	8-Sep-2005	Corredor	3	0.33	0.02	16.9	1.2	8.1	0.6	1,385	71	440	22
Phenix	9-Sep-2005	Corredor	3	0.97	0.13	10.7	0.3	8.2	1.2	1,558	59	495	19
Diesel Buses with Added Emission Control													
RTP 3	8-Dec-2004	Norte	2	0.06	0.02	8.3	0.6	0.8	0.5	881	27	277	9
	8-Dec-2004	Corredor	3	0.08	0.04	7.6	0.5	1.2	1.0	903	33	285	10
	23-May-2005	Corredor	3	0.06	0.02	6.1	0.7	0.4	0.9	756	86	238	27
	12-Sep-2005	Corredor	3	0.01	0.01	5.4	0.2	1.3	1.8	721	37	228	12
RTP 4	3-Dec-2004	Norte	3	0.07	0.01	14.9	0.6	Neg.	2.2	1,274	34	399	12
	3-Dec-2004	Corredor	3	0.04	0.01	14.7	0.5	0.0	3.3	1,251	57	394	19
Allison	6-Nov-2004	Norte	3	0.03	0.01	7.4	0.4	Neg.	3.6	1,062	120	333	39
	6-Nov-2004	Corredor	3	0.03	0.01	5.8	0.4	Neg.	3.1	1,203	94	378	28
Eletrabus	28-Sep-2005	Corredor	3	0.05	0.00	21.3	0.2	3.0	1.1	946	4	299	1

Among the new diesel buses under test, the MB 10 and MB 11 showed the lowest NOx and PM emissions. The MB10 is reportedly certified to U.S. 2004 standards, while the MB 11 is certified to U.S. 1998. NOx emissions from the Euro 3 certified Volvo and Scania buses were also low, but the PM emissions from the Volvo and Scania buses in the demonstration program were much higher than those of the other buses tested. The difference in PM emissions between vehicle SC 18 and the RTP metrobus is especially notable. Both vehicles were 18-meter articulated buses, made by Scania, and reportedly equipped with Scania DC9, 300 HP Euro 3 engines. Thus, the more than three-fold difference in their PM emissions suggests that the demonstration bus may not have been operating properly, or may not have been properly adjusted for Mexico City's altitude. However, an e-mail communication from the Scania representative[10] stated that the bus was calibrated for an altitude up to 3000 meters. In the case of the Volvo bus, the local representative indicated that the engine had not been adjusted for Mexico City, and that – in addition – there had been a problem with the turbocharger for much of the time that the bus was in demonstration.

Table 6: Regulated emissions and fuel economy for natural gas buses and microbuses

Vehicle	Test Date	Test Route	No Of Tests	Emissions - g/km								Fuel g/km	
				PM		NOx		CO		CO_2			
				Avg.	σ	Avg.	σ	Avg.	σ	Avg.	σ	Avg.	σ
Natural Gas Buses													
Busscar	3-Feb-2005	Norte	3	0.04	0.03	5.6	0.2	0.0	0.0	1,087	20	390	7
	3-Feb-2005	Corredor	2	0.00	0.01	4.4	0.9	0.2	0.3	945	158	339	57
	8-Jun-2005	Corredor	3	0.01	0.03	6.4	0.4	Neg.	0.4	913	7	328	3
	3-Oct-2005	Corredor	3	0.01	0.01	5.7	0.4	0.0	0.1	768	65	276	23
FAW	4-Feb-2005	Norte	3	0.03	0.02	8.3	0.3	Neg.	0.8	1,100	58	395	21
	4-Feb-2005	Corredor	2	0.02	0.00	9.9	1.9	5.1	8.3	1,261	28	455	5
	27-Jun-2005	Corredor	3	0.03	0.04	14.4	0.7	0.6	1.0	1,184	38	425	14
	4-Oct-2005	Corredor	3	0.03	0.01	6.7	0.9	Neg.	2.3	1,021	34	365	14
Ankai	5-Feb-2005	Norte	3	0.02	0.01	6.1	0.2	0.6	0.7	1,051	31	378	11
	5-Feb-2005	Corredor	3	0.02	0.00	4.8	0.3	0.4	0.1	924	32	332	11
	5-Oct-2005	Corredor	3	0.02	0.00	3.9	0.9	Neg.	0.3	842	84	302	30
Microbuses													
M-LPG	24-Feb-2005	Norte	1	0.02	-	3.3	-	82.1	-	605	-	244	-
	24-Feb-2005	Corredor	2	0.02	0.01	4.6	0.2	79.5	0.4	759	11	294	3
	11-Nov-2005	Montevid	1	na	-	3.6	-	55.7	-	431	-	173	-
M-CNG	9-Mar-2005	Norte	2	0.01	0.01	4.8	0.0	30.1	6.3	530	27	207	13
	9-Mar-2005	Corredor	1	0.01	-	3.9	-	40.1	-	479	-	195	-
M-D-CNG	3-Jun-2005	Corredor	3	0.01	0.01	2.7	0.2	Neg.	0.4	527	10	189	4
	7-Oct-2005	Corredor	1	0.00	-	7.2	-	4.1	-	587	-	213	-
M-D-Gsln	6-Jun-2005	Corredor	3	0.01	0.00	0.3	0.0	147.8	11.0	661	42	281	12
	6-Oct-2005	Corredor	2	0.01	0.00	0.1	0.0	235.0	17.7	646	39	319	21
M-Gsln	10-Mar-2005	Norte	1	0.22	-	9.6	-	362.4	-	1,177	-	549	-
	10-Mar-2005	Corredor	2	0.16	0.03	8.9	0.3	250.2	44.1	915	70	412	44

CO emissions from all of the diesel and lean-burn natural gas buses were relatively low – in most cases, at or below the detection limits for the RAVEM system. In a number of cases, the measured CO concentration was slightly below background levels, resulting in a negative emission value. These negative values are indicated as "neg." in the table, and should be interpreted as zero values or "below detection limit". Among the diesel buses, the highest CO emissions measured were from vehicles Vol 12 and Sc 18, which also exhibited the highest PM emissions. An association between high CO and high PM emissions in diesel vehicles has also been observed in other studies[11].

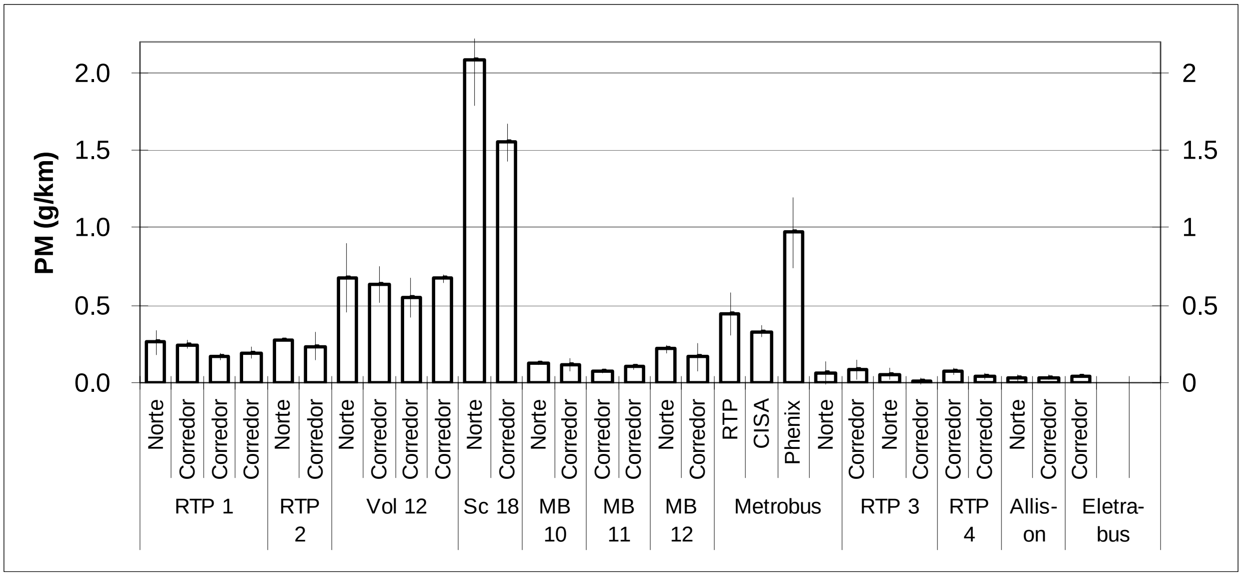


Figure 4: Bar chart of PM emissions from diesel buses

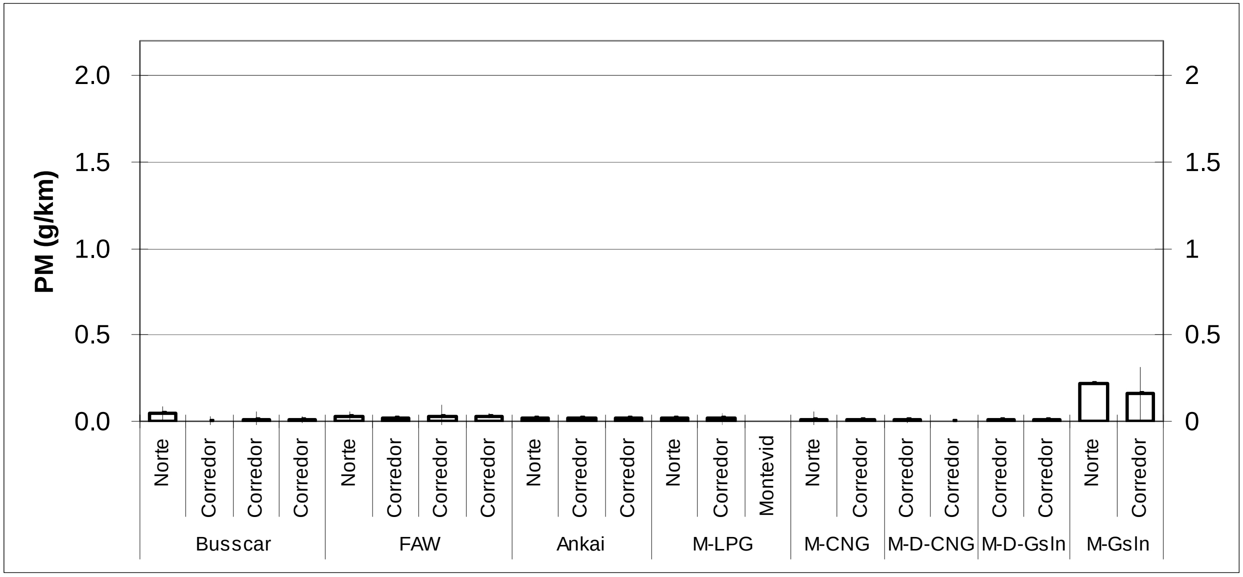


Figure 5: Bar chart of PM emissions from natural gas buses and microbuses

Measured PM and NOx emissions from all of the natural gas fueled buses, from the natural gas fueled microbus, and from the first test of the LPG-fueled microbus were very low, as might be expected. Except under very rich conditions, the combustion process in these engines does not form particulate matter, so that the PM emissions are limited to small amounts of lubricating oil. Surprisingly, however, the gasoline microbus did exhibit substantial PM mass emissions. Possible sources of this PM are excess of lubricating oil in the exhaust (due to worn-out piston rings or valve seals), and/or soot formation during combustion under very rich conditions. This vehicle also showed very high CO emissions, indicating that a substantial amount of rich combustion occurred during the test. The second test of the LPG-fueled microbus also showed significant PM emissions. However, the PM was present in small balls of black soot, and we concluded that this was most likely a sampling artifact, and that it had come from the walls of the sampler rather than actual emissions from the vehicle.

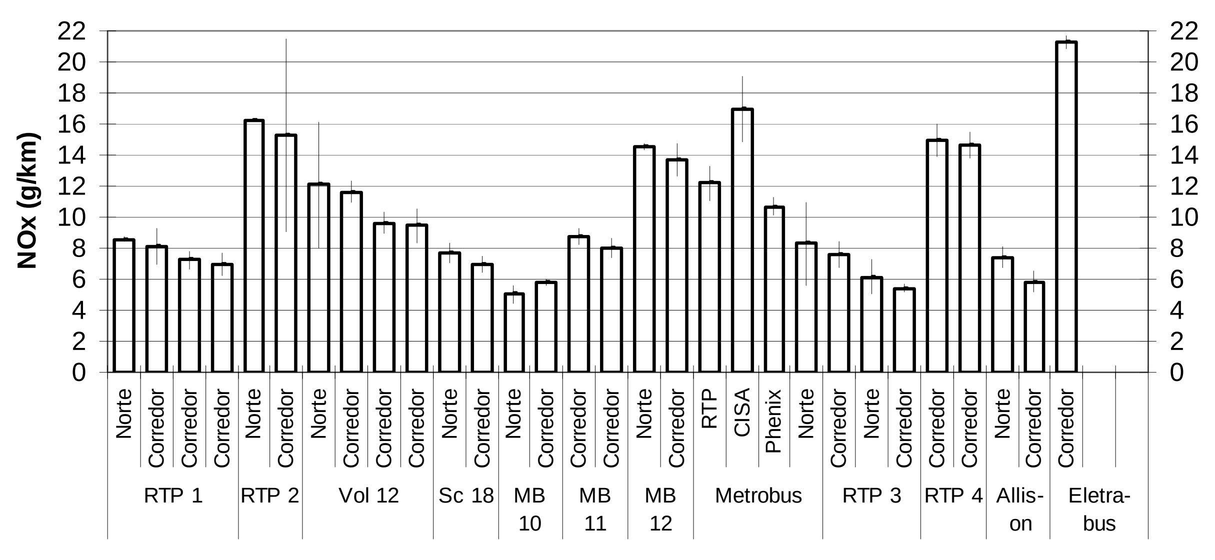


Figure 6: Bar chart of NOx emissions from diesel buses

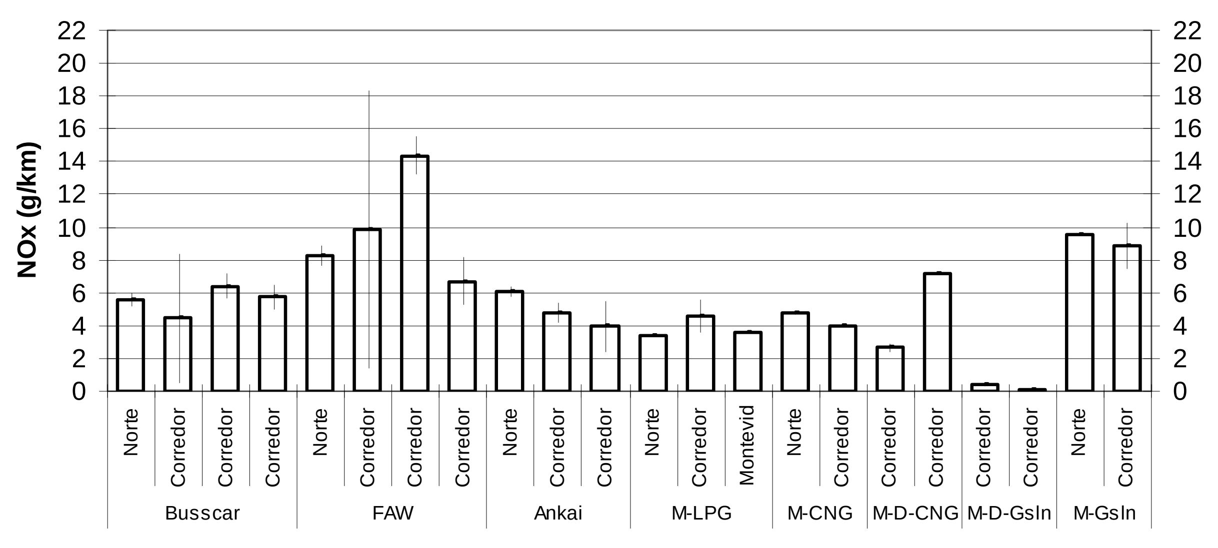


Figure 7: Bar chart of NOx emissions from natural gas buses and microbuses

In gasoline mode, the dual-fuel microbus showed by far the lowest NOx emissions of any of the vehicles tested – 0.1 to 0.3 g/km. These very low NOx emissions are attributable to the use of a three-way catalyst with an overall rich air-fuel ratio, as indicated by the high CO emissions produced in the same mode. In CNG mode, the air-fuel ratio was evidently lean, since CO emissions are nearly zero, but NOx emissions are many times higher. When tested on June 3, this vehicle had just undergone a tune-up, so that air-fuel ratios and the tradeoffs between NOx and CO emissions were optimized to the degree possible. When retested in October, it is clear that the air-fuel ratios had drifted further from the optimal levels.

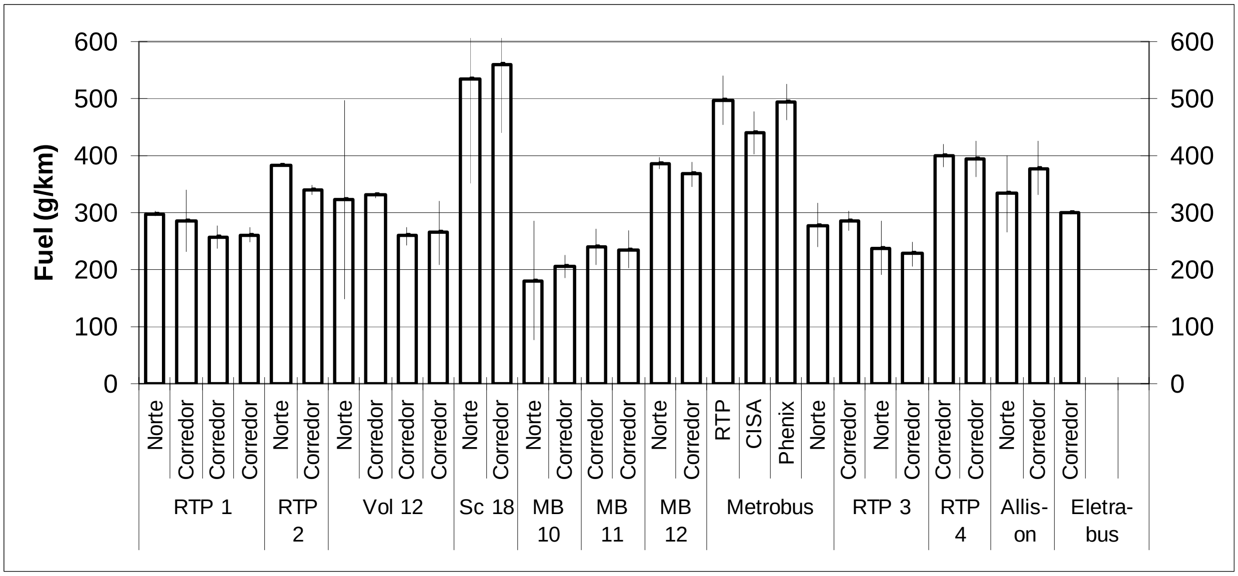


Figure 8: Bar chart of fuel consumption by diesel buses

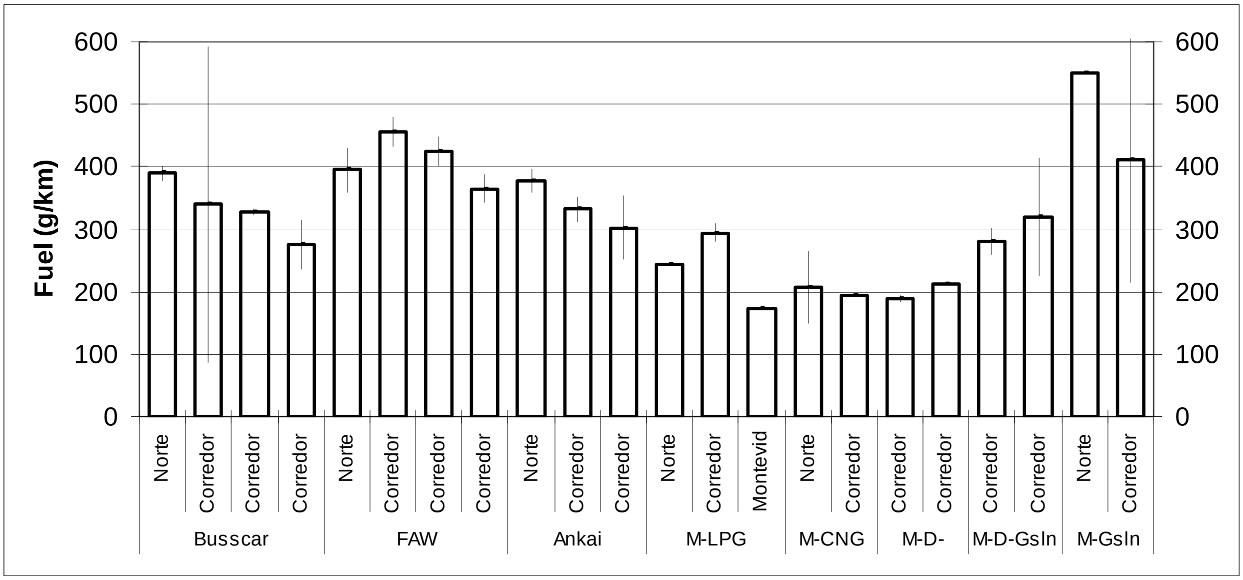


Figure 9: Bar chart of fuel consumption by natural gas buses and microbuses

The other gasoline microbus tested exhibited high levels of both NOx and CO emissions, as well as particulate matter – indicating that the three-way catalyst was no longer performing effectively. The microbuses using CNG and LPG fuel exhibited intermediate levels of CO and NOx emissions. With either CNG or LPG fuel, the combination of an effective three-way catalyst and a good closed-loop air-fuel ratio control system is capable of achieving much lower levels of both NOx and CO than measured from these vehicles.

Comparing the emission results from the *Insurgentes Norte* and *Insurgentes Corredor* driving routes, it can be seen that PM emissions are nearly always lower in the Corredor route, due to the reduction in stop-and-go driving. Fuel consumption and NOx emissions were frequently as high or higher in the Corredor as in the Norte routes during the first round of testing, but were generally lower in the second and third rounds. During the first test round, many of the drivers took advantage of the absence of traffic to increase their driving speed during the Corredor tests, resulting in an increase of fuel consumption. This tendency was restrained during the second and third rounds, when the drivers were able to compare their speed to that of the metrobuses moving in the adjacent BRT corridor.

Table 7: Change in emissions due to simulated bus corridor operation

Vehicle	Test Route	No of Tests	Emissions - g/km								Fuel g/km	
			PM		NOx		CO		CO_2			
			Avg.	+/-*	Avg.	+/-	Avg.	+/-	Avg.	+/-	Avg.	+/-
Diesel Buses												
RTP 1	Norte	3	0.26	0.08	8.6	0.2	2.2	4.0	945	6	298	4
	Corredor	9	0.20	0.02	7.4	0.4	1.4	1.2	849	43	268	14
Vol 12	Norte	2	0.68	0.22	12.1	4.0	12.8	3.6	1007	551	323	175
	Corredor	8	0.61	0.05	10.3	0.7	10.9	0.7	895	77	287	25
RTP 3	Norte	2	0.06	0.07	8.3	2.7	0.8	2.2	881	120	277	39
	Corredor	9	0.05	0.02	6.4	0.7	1.0	0.7	793	60	250	19
Avg. Diesel Reduction			18%	49%	17%	14%	10%	126%	10%	13%	10%	13%
Natural Gas Buses												
Busscar	Norte	3	0.04	0.04	5.6	0.4	0.0	0.0	1087	33	390	12
	Corredor	8	0.01	0.01	5.7	0.6	Neg	0.2	867	72	311	26
FAW	Norte	3	0.03	0.03	8.3	0.6	Neg	1.3	1100	97	395	35
	Corredor	8	0.03	0.01	10.4	2.5	0.8	3.0	1142	73	410	27
Ankai	Norte	3	0.02	0.01	6.1	0.3	0.6	1.2	1051	52	378	19
	Corredor	8	0.02	0.00	4.4	0.5	0.1	0.2	883	48	317	17
Avg. CNG Reduction			30%	124%	0%	24%	234%	475%	11%	11%	11%	11%

* 90% confidence interval. Shaded data are significantly different at the 90% confidence level

To assess the effect of the bus corridor, we carried out a statistical analysis of the emission results. So that the results were not dominated by the more aggressive driving during the first round of tests, we limited the analysis to those buses for which we had Insurgentes Corredor data during all three test rounds. This limited the dataset to three diesel and three natural gas buses. The results are shown in Table 7. Three of the six buses showed statistically significant reductions in fuel consumption and CO_2 emissions. The mean reduction was 10% for the three diesel buses combined, and 11% for the three CNG buses. Neither value was statistically significant at the 90% level, however.

The NOx emissions from the conventional diesel buses tested in this program showed surprising variation from manufacturer to manufacturer, given that all were purportedly designed and calibrated to meet U.S. EPA 1998, U.S. EPA 2004, or Euro 3 emission standards. These standards limit NOx emissions to 4.0, 2.4, and 3.7 g/BHP-hr, respectively.

For diesel vehicles, on-road emissions in grams per BHP-hr can be estimated fairly accurately by dividing fuel consumption per kilometer by average brake-specific fuel consumption. Since engine-specific BSFC data were not available for these buses, we assumed a typical BSFC value of 170 grams per BHP-hr. This should be within 10% of actual in-use BSFC for most commercial diesel engines. The results of this calculation are shown in Table 8.

As Table 8 shows, on-road NOx emissions from the RTP 2 and RTP 4 – the two International buses – were equivalent to about 6.3 to 7.6 grams per BHP-hr, compared to an emission standard of 4.0 grams per BHP-hr. For the 12 meter Volvo, and for the Volvo metrobus, on-road NOx emissions were around 6.0 to 6.5 g/BHP-hr. For the Mercedes buses, NOx emissions ranged from around 4.7 to 6.4 grams per BHP-hr. NOx emissions from MB 10 were no lower than those for RTP 1, RTP 3, and MB 11 – the three Mercedes buses certified to U.S. 1998 standards. On the other hand, on-road NOx emissions from the Allison bus were generally consistent with its claimed emissions certification levels. NOx emissions from the Scania metrobus were close to the Euro 3 emission limit, the Scania demonstration bus were well below Euro 3 levels. The latter fact suggests that the injection timing on the Scania demonstration bus may have been too retarded, which could account for its excessive PM emissions.

The large differences between on-road NOx levels and the NOx levels reported for certification purposes are likely the result of differences in calibration strategies (in particular, the responses to altitude and to transient operations) between engine manufacturers. In some cases, the differences are so large as to potentially warrant investigation as “defeat devices”.

Since the buses tested are designed to carry different numbers of passengers, it is appropriate to consider the emissions and fuel consumption per passenger-kilometer in comparing their performance. Table 9 shows these data for the diesel buses, while Table 10 shows them for the natural gas buses and the microbuses. These tables also show the number of passengers estimated for each bus. Since the emission tests were conducted with a simulated load equal to 70% of the rated passenger capacity, we calculated the emissions per passenger-kilometer on the same basis.

Table 8: Diesel bus emissions in grams per (estimated) BHP-hr

Vehicle	Test Date	Test Route	No Of Tests	Emissions – g/BHP-hr							
				PM		NOx		CO		CO$_2$	
				Avg.	σ	Avg.	σ	Avg.	σ	Avg.	σ
Diesel Buses											
RTP 1	14-Dec-2004	Norte	3	0.15	0.03	4.9	0.1	1.2	1.4	539	2
	14-Dec-2004	Corredor	3	0.15	0.01	4.8	0.4	Neg.	1.6	541	58
	26-May-2005	Corredor	3	0.11	0.01	4.8	0.2	1.6	0.3	538	25
	29-Sep-2005	Corredor	3	0.12	0.01	4.5	0.3	1.4	0.7	538	16
RTP 2	6-Dec-2004	Norte	1	0.12	-	7.2	-	0.5	-	540	-
	6-Dec-2004	Corredor	2	0.12	0.01	7.6	0.7	2.0	1.5	537	1
Vol 12	11-Feb-2005	Norte	2	0.36	0.03	6.3	0.5	6.7	0.4	530	65
	11-Feb-2005	Corredor	3	0.33	0.04	6.0	0.2	6.0	0.6	531	4
	13-Jun-2005	Corredor	3	0.36	0.05	6.3	0.3	6.5	0.6	530	20
	6-Sep-2005	Corredor	2	0.43	0.00	6.1	0.2	7.2	0.2	528	26
Sc 18	8-Feb-2005	Norte	2	0.66	0.02	2.4	0.0	3.4	0.7	535	43
	8-Feb-2005	Corredor	3	0.47	0.02	2.1	0.1	2.0	0.7	512	29
MB 10	9-Nov-2004	Norte	3	0.12	0.01	4.7	0.3	1.3	0.3	538	187
	9-Nov-2004	Corredor	2	0.09	0.01	4.8	0.0	1.6	0.1	538	11
MB 11	24-Jun-2005	Corredor	3	0.05	0.00	6.2	0.2	1.4	0.7	538	42
	28-Sep-2005	Corredor	3	0.07	0.01	5.8	0.3	1.3	0.3	538	45
MB 12	16-Dec-2004	Norte	3	0.10	0.01	6.4	0.1	1.8	0.7	538	8
	16-Dec-2004	Corredor	3	0.08	0.02	6.3	0.3	2.1	0.8	537	20
Diesel Metrobuses											
RTP	7-Sep-2005	Corredor	3	0.15	0.03	4.2	0.2	0.8	0.2	538	28
CISA	8-Sep-2005	Corredor	3	0.13	0.01	6.5	0.5	3.1	0.2	535	27
Phenix	9-Sep-2005	Corredor	3	0.33	0.05	3.7	0.1	2.8	0.4	535	20
Diesel Buses with Added Emission Control											
RTP 3	8-Dec-2004	Norte	2	0.04	0.01	5.1	0.4	0.5	0.3	540	16
	8-Dec-2004	Corredor	3	0.05	0.02	4.5	0.3	0.7	0.6	539	20
	23-May-2005	Corredor	3	0.04	0.02	4.4	0.5	0.3	0.6	540	62
	12-Sep-2005	Corredor	3	0.01	0.01	4.1	0.1	1.0	1.3	539	28
RTP 4	3-Dec-2004	Norte	3	0.03	0.01	6.4	0.3	Neg.	1.0	543	15
	3-Dec-2004	Corredor	3	0.02	0.01	6.3	0.2	0.0	1.4	540	24
Allison	6-Nov-2004	Norte	3	0.01	0.01	3.8	0.2	Neg.	1.8	542	61
	6-Nov-2004	Corredor	3	0.02	0.00	2.6	0.2	Neg.	1.4	541	42
Eletrabus	28-Sep-2005	Corredor	3	0.03	0.00	12.1	0.1	1.7	0.6	538	2

Table 9: Diesel bus emissions per passenger-kilometer

			No	Pass-	mg/passenger-km						g/pas-km			
	Test	Test	of	engers/	PM		NOx		CO		CO_2		Fuel	
Vehicle	Date	Route	Tests	Bus	Avg.	σ	Avg.	σ	Avg.	σ	Avg.	σ	Avg.	Σ
Diesel Buses														
RTP 1	14-Dec-2004	Norte	3	85	4.4	0.8	144	2	36	40	15.9	0.1	5.0	0.0
	14-Dec-2004	Corredor	3		4.1	0.2	136	12	-6	44	15.3	1.6	4.8	0.5
	26-May-2005	Corredor	3		2.9	0.2	122	6	40	7	13.7	0.6	4.3	0.2
	29-Sep-2005	Corredor	3		3.2	0.4	116	8	36	18	13.9	0.4	4.4	0.1
RTP 2	6-Dec-2004	Norte	1	85	4.7	-	272	-	20	-	20.4	-	6.4	-
	6-Dec-2004	Corredor	2		3.9	0.3	257	23	66	50	18.1	0.0	5.7	0.0
Vol 12	11-Feb-2005	Norte	2	90	10.7	0.8	191	14	203	13	16.0	2.0	5.1	0.6
	11-Feb-2005	Corredor	3		10.1	1.1	184	7	184	18	16.4	0.1	5.2	0.0
	13-Jun-2005	Corredor	3		8.7	1.2	152	6	158	15	12.8	0.5	4.1	0.2
	6-Sep-2005	Corredor	2		10.7	0.1	150	4	178	6	13.0	0.7	4.2	0.2
Sc 18	8-Feb-2005	Norte	2	160	18.6	0.6	68	1	94	19	15.0	1.2	4.8	0.4
	8-Feb-2005	Corredor	3		13.8	0.6	62	3	58	21	15.0	0.9	5.0	0.6
MB 10	9-Nov-2004	Norte	3	80	2.3	0.1	89	6	26	6	10.2	3.6	3.2	1.1
	9-Nov-2004	Corredor	2		2.0	0.2	103	1	34	3	11.6	0.2	3.7	0.1
MB 11	24-Jun-2005	Corredor	3	85	1.2	0.1	147	5	34	16	12.8	1.0	4.0	0.3
	28-Sep-2005	Corredor	3		1.7	0.2	135	6	31	7	12.5	1.0	4.0	0.3
MB 12	16-Dec-2004	Norte	3	90	3.5	0.2	230	2	64	27	19.4	0.3	6.1	0.1
	16-Dec-2004	Corredor	3		2.7	0.8	217	10	71	29	18.5	0.7	5.8	0.2
Diesel Metrobuses														
RTP	7-Sep-2005	Corredor	3	160	4.0	0.7	109	6	22	6	14.1	0.7	4.4	0.2
CISA	8-Sep-2005	Corredor	3	160	3.0	0.2	151	11	72	5	12.4	0.6	3.9	0.2
Phenix	9-Sep-2005	Corredor	3	160	8.7	1.2	95	3	73	11	13.9	0.5	4.4	0.2
Diesel Buses with Added Emission Control														
RTP 3	8-Dec-2004	Norte	2	85	1.1	0.3	139	10	14	8	14.8	0.5	4.7	0.1
	8-Dec-2004	Corredor	3		1.4	0.7	128	8	21	17	15.2	0.6	4.8	0.2
	23-May-2005	Corredor	3		1.0	0.4	103	11	7	15	12.7	1.5	4.0	0.5
	12-Sep-2005	Corredor	3		0.2	0.2	91	3	22	30	12.1	0.6	3.8	0.2
RTP 4	3-Dec-2004	Norte	3	85	1.2	0.2	251	10	Neg.	38	21.4	0.6	6.7	0.2
	3-Dec-2004	Corredor	3		0.7	0.2	246	9	0	56	21.0	1.0	6.6	0.3
Allison	6-Nov-2004	Norte	3	110	0.4	0.2	96	5	Neg.	46	13.8	1.6	4.3	0.5
	6-Nov-2004	Corredor	3		0.4	0.1	76	5	Neg.	41	15.6	1.2	4.9	0.4
Eletrabus	28-Sep-2005	Corredor	3	85	0.8	0.1	357	4	50	19	15.9	0.1	5.0	0.0

Table 10: Emissions per passenger-kilometer for natural gas buses and microbuses

Vehicle	Test Date	Test Route	No of Tests	Pass-engers/ Bus	mg/passenger-km						g/pas-km			
					PM		NOx		CO		CO_2		Fuel	
					Avg.	σ	Avg.	σ	Avg.	σ	Avg.	σ	Avg.	Σ
Natural Gas Buses														
Busscar	3-Feb-2005	Norte	3	85	0.7	0.4	93	4	1	0	18.3	0.3	6.6	0.1
	3-Feb-2005	Corredor	2		0.1	0.1	75	15	4	5	15.9	2.7	5.7	1.0
	8-Jun-2005	Corredor	3		0.2	0.4	107	7	Neg.	6	15.4	0.1	5.5	0.0
	3-Oct-2005	Corredor	3		0.2	0.2	96	7	1	1	12.9	1.1	4.6	0.4
FAW	4-Feb-2005	Norte	3	120	0.3	0.2	98	4	Neg.	10	13.1	0.7	4.7	0.3
	4-Feb-2005	Corredor	2		0.2	0.0	117	22	60	99	15.0	0.3	5.4	0.1
	27-Jun-2005	Corredor	3		0.4	0.4	171	8	7	12	14.1	0.5	5.1	0.2
	4-Oct-2005	Corredor	3		0.4	0.1	80	10	Neg.	27	12.2	0.4	4.3	0.2
Ankai	5-Feb-2005	Norte	3	85	0.3	0.1	102	3	11	12	17.7	0.5	6.3	0.2
	5-Feb-2005	Corredor	3		0.3	0.1	80	6	6	1	15.5	0.5	5.6	0.2
	5-Oct-2005	Corredor	3		0.3	0.1	66	15	Neg.	5	14.2	1.4	5.1	0.5
Microbuses														
M-LPG	24-Feb-2005	Norte	1	35	0.7	-	137	-	3351	-	24.7	-	10.0	-
	24-Feb-2005	Corredor	2		0.7	0.3	186	9	3245	14	31.0	0.4	12.0	0.1
	11-Nov-2005	Montev	1		na	-	147	-	2275	-	17.6	-	7.0	-
M-CNG	9-Mar-2005	Norte	2	35	0.4	0.5	196	1	1227	257	21.6	1.1	8.4	0.5
	9-Mar-2005	Corredor	1		0.4	-	161	-	1637	-	19.6	-	7.9	-
M-D-CNG	3-Jun-2005	Corredor	3	35	0.2	0.3	108	7	Neg.	16	21.5	0.4	7.7	0.1
	7-Oct-2005	Corredor	1		0.1	-	294	-	166	-	24.0	-	8.7	-
M-D-Gsln	6-Jun-2005	Corredor	3	35	0.2	0.1	14	1	6031	447	27.0	1.7	11.5	0.5
	6-Oct-2005	Corredor	2		0.3	0.1	4	1	9593	723	26.4	1.6	13.0	0.9
M-Gsln	10-Mar-2005	Norte	1	35	8.9	-	390	-	14791	-	48.0	-	22.4	-
	10-Mar-2005	Corredor	2		6.5	1.4	362	12	10214	1799	37.4	2.9	16.8	1.8

4.2 EFFECTS OF REPOWERING A 1991 BUS

At the request of SMA, the project carried out limited tests on two 1991 Mercedes buses in the RTP transit fleet. One of these buses, labeled RTP 5 in the table below, was equipped with the original 1991 model engine. Mexican emission standards in 1991 were effectively Euro Zero. The second bus (RTP 6) had been repowered with a Mercedes OM-366-LA engine meeting current Mexican emission standards, which are equivalent to EPA 1998. Instead of the Insurgentes routes, these buses were tested using a shorter, low-speed test cycle called the RTP-23, which is designed to simulate transit bus operation in the central city. The test results are summarized in Table 11. As this table shows, the effects of repowering were dramatic – PM emissions from the repowered bus were reduce by 88 percent, NOx emissions by 59 percent, and CO emissions by 86 percent, while fuel economy was equal between the two buses. This shows that repowering with modern, emission-controlled engines holds great promise for reducing pollutant emissions from older buses.

Table 11: Emissions and fuel consumption for a 1991 bus and a repowered 1991 bus

Vehicle	Test Date	Test Route	No Tests	Emissions – g/km				Fuel g/km
				PM	NOx	CO	CO_2	
RTP-5	30-Jun-2005	RTP-23	3	2.25	24.3	31.9	1,186	389
RTP-6	29-Jun-2005	RTP-23	3	0.27	10.0	4.5	1,233	390

4.3 CARBONYLS

Equipment for measurement of carbonyls and VOCs was purchased later than the remainder of the RAVEM system, and was not available for use until the first round of testing on most of the diesel buses was already complete. The first round tests on the natural gas buses and microbuses were delayed until this equipment was available, as these data were considered much more important for the gaseous fuels. Thus, carbonyl measurements are available for the buses using gaseous fuels, and for the diesel buses tested in the second round. The carbonyl measurements are summarized in Table 12 and

Table 13. As these tables show, measured carbonyl emissions were generally low, and exhibited great test-to-test variability. This variability is largely due to the “noise” created by high background concentrations, which were generally of the same order as the concentrations in the samples.

The principal environmental concern with respect to carbonyl emissions was for the buses equipped with lean-burn natural gas engines, since these can produce significant amounts of formaldehyde. However, the data in Table 12 show that the catalytic converters installed on these buses were effective in controlling their carbonyl emissions. The highest emissions of formaldehyde were found in the microbuses and in the Volvo 12 diesel bus. The Volvo bus also exhibited higher-than-usual emissions of several other aldehyde species.

Table 12: Carbonyl emissions

				Aldehyde Emissions - g/km							
				Formald.		**Acetald.**		**Acetone + Acr.**		**Propionald.**	
Vehicle	**Date**	**Test Route**	**No Tests**	**Avg.**	**σ**	**Avg.**	**σ**	**Avg.**	**σ**	**Avg.**	**σ**
Diesel Buses											
RTP 1	26-May-2005	Corredor	3	0.015	0.009	0.013	0.030	0.021	0.008	0.008	0.013
	29-Sep-2005	Corredor	3	0.005	0.002	neg.	0.007	neg.	0.010	0.004	0.005
Vol 12	11-Feb-2005	Norte	3	0.055	0.027	0.034	0.039	0.015	0.027	0.021	0.020
	11-Feb-2005	Corredor	2	0.041	0.027	0.101	0.006	0.075	0.107	0.051	0.072
	13-Jun-2005	Corredor	1	0.049	-	0.108	-	neg.	-	0.052	-
	8-Oct-2005	Corredor	2	0.001	0.005	neg.	0.009	0.006	0.007	0.001	0.06
Sc 18	8-Feb-2005	Norte	3	0.011	0.010	0.016	0.016	0.027	0.018	0.002	0.025
	8-Feb-2005	Corredor	3	0.017	0.014	0.006	0.018	0.012	0.031	0.023	0.025
MB 11	24-Jun-2005	Corredor	3	0.011	0.004	0.017	0.008	0.028	0.037	0.009	0.036
	28-Sep-2005	Corredor	3	0.010	0.002	neg.	0.002	0.000	0.012	0.004	0.002
RTP 3	23-May-2005	Corredor	3	0.015	0.005	0.000	0.016	0.006	0.017	0.023	0.011
	12-Sep-2005	Corredor	3	0.024	0.018	neg.	0.010	0.003	0.007	0.004	0.012
Eletrabus	28-Sep-2005	Corredor	3	0.004	0.003	neg.	0.003	neg.	0.007	neg.	0.007
Diesel Metrobuses											
RTP	7-Sep-2005	Corredor	3	0.004	0.002	0.007	0.009	0.004	0.011	0.005	0.012
CISA	8-Sep-2005	Corredor	3	0.004	0.004	0.005	0.012	0.007	0.011	0.007	0.010
Phenix	9-Sep-2005	Corredor	3	0.015	0.008	0.002	0.019	0.005	0.004	neg.	0.006
Natural Gas Buses											
Busscar	3-Feb-2005	Norte	1	0.033	-	0.057	-	0.002	-	0.015	-
	8-Jun-2005	Corredor	3	0.017	0.011	0.033	0.026	0.023	0.015	0.005	0.036
	3-Oct-2005	Corredor	0	0.005	0.002	0.002	0.002	0.003	0.005	neg.	0.005
FAW	4-Feb-2005	Norte	3	0.021	0.029	0.038	0.028	0.025	0.048	0.014	0.014
	4-Feb-2005	Corredor	2	0.036	0.006	0.058	0.011	0.017	0.003	0.001	0.014
	27-Jun-2005	Corredor	2	0.024	0.018	0.026	0.037	0.028	0.003	0.009	0.013
	4-Oct-2005	Corredor	3	0.012	0.001	0.007	0.010	neg.	0.006	neg.	0.000
ANKAI	5-Feb-2005	Norte	3	0.022	0.003	0.040	0.015	0.016	0.035	0.022	0.039
	5-Feb-2005	Corredor	3	0.018	0.012	0.025	0.004	0.035	0.015	0.046	0.022
	5-Oct-2005	Corredor	2	0.008	0.009	neg.	0.001	0.007	0.012	0.010	0.013
Microbuses											
M-LPG	24-Feb-2005	Norte	1	0.066	-	0.023	-	0.013	-	0.014	-
	24-Feb-2005	Corredor	2	0.071	0.020	0.028	0.018	0.009	0.012	0.006	0.002
	11-Nov-2005	Montevid	1	0.007	-	0.008	-	0.003	-	0.002	-
M-CNG	9-Mar-2005	Norte	2	0.050	0.030	0.002	0.003	0.004	0.006	0.000	0.000
	9-Mar-2005	Corredor	1	0.017	-	neg.	-	0.002	-	neg.	-
M-Gsln	10-Mar-2005	Norte	1	0.049	-	0.024	-	0.000	-	0.044	-
	10-Mar-2005	Corredor	2	0.068	0.089	0.022	0.008	0.025	0.036	0.003	0.004
M-D-CNG	3-Jun-2005	Corredor	2	0.010	0.001	0.009	0.040	0.019	0.007	neg.	0.005
	7-Oct-2005	Corredor	1	neg.	-	0.006	-	0.000	-	0.000	-
M-D-Gsln	6-Jun-2005	Corredor	3	0.004	0.004	0.005	0.012	0.008	0.007	0.002	0.004
	6-Oct-2005	Corredor	2	0.001	0.001	0.001	0.003	0.005	0.001	0.001	0.003

Table 13: Carbonyl emission (concluded)

				Aldehyde Emissions - g/km					
		Test	No	Crotonald.		Butyrald.		Benzald.	
Vehicle	Date	Route	Tests	Avg.	σ	Avg.	σ	Avg.	σ
Diesel Buses									
RTP 1	26-May-2005	Corredor	3	0.023	0.017	0.011	0.048	0.022	0.012
	29-Sep-2005	Corredor	3	neg.	0.005	0.002	0.002	neg.	0.012
Vol 12	11-Feb-2005	Norte	3	0.042	0.072	neg.	0.132	neg.	0.067
	11-Feb-2005	Corredor	2	0.139	0.141	0.137	0.005	neg.	0.200
	13-Jun-2005	Corredor	1	0.048	-	0.078	-	0.050	-
	8-Oct-2005	Corredor	2	0.003	0.000	0.009	0.002	0.001	0.007
Sc 18	8-Feb-2005	Norte	3	0.033	0.029	0.038	0.101	0.092	0.056
	8-Feb-2005	Corredor	3	0.013	0.011	0.010	0.030	0.048	0.054
MB 11	24-Jun-2005	Corredor	3	0.040	0.034	0.009	0.001	0.019	0.020
	28-Sep-2005	Corredor	3	neg.	0.002	0.003	0.006	0.006	0.009
RTP 3	23-May-2005	Corredor	3	0.007	0.010	neg.	0.014	neg.	0.015
	12-Sep-2005	Corredor	3	0.006	0.008	0.001	0.016	0.009	0.017
Eletrabus	28-Sep-2005	Corredor	3	neg.	0.020	0.001	0.005	0.007	0.015
Diesel Metrobuses									
RTP	7-Sep-2005	Corredor	3	0.004	0.006	0.002	0.004	0.011	0.021
CISA	8-Sep-2005	Corredor	3	0.012	0.011	neg.	0.003	0.006	0.008
Phenix	9-Sep-2005	Corredor	3	0.004	0.004	0.009	0.006	neg.	0.005
Natural Gas Buses									
Busscar	3-Feb-2005	Norte	1	0.017	-	0.001	-	neg.	-
	8-Jun-2005	Corredor	3	0.010	0.020	0.018	0.010	0.028	0.034
	3-Oct-2005	Corredor	3	0.003	0.006	0.009	0.000	neg.	0.018
FAW	4-Feb-2005	Norte	3	0.030	0.040	0.022	0.029	0.042	0.027
	4-Feb-2005	Corredor	2	0.012	0.005	0.005	0.000	0.005	0.007
	27-Jun-2005	Corredor	2	neg.	0.008	0.029	0.017	0.033	0.000
	4-Oct-2005	Corredor	3	neg.	0.012	neg.	0.007	0.008	0.007
ANKAI	5-Feb-2005	Norte	3	0.029	0.019	0.052	0.019	0.045	0.033
	5-Feb-2005	Corredor	3	0.005	0.030	0.032	0.021	neg.	0.012
	5-Oct-2005	Corredor	2	0.006	0.009	neg.	0.003	0.004	0.001
Microbuses									
M-LPG	24-Feb-2005	Norte	1	0.010	-	0.005	-	0.004	-
	24-Feb-2005	Corredor	2	0.013	0.019	0.000	0.002	0.013	0.015
	11-Nov-2005	Montevid	1	0.003	-	0.008	-	0.005	-
M-CNG	9-Mar-2005	Norte	2	0.005	0.007	neg.	0.009	neg.	0.001
	9-Mar-2005	Corredor	1	0.000	-	neg.	-	0.013	-
M-Gsln	10-Mar-2005	Norte	1	0.017	-	0.028	-	0.028	-
	10-Mar-2005	Corredor	2	0.007	0.009	0.002	0.002	0.007	0.008
M-D-CNG	3-Jun-2005	Corredor	2	0.009	0.007	0.011	0.002	0.036	0.002
	7-Oct-2005	Corredor	1	neg.	-	neg.	-	neg.	-
M-D-Gsln	6-Jun-2005	Corredor	3	0.003	0.005	0.005	0.010	0.010	0.007
	6-Oct-2005	Corredor	2	0.000	0.002	0.002	0.001	0.004	0.001

4.4 SPECIATED VOC EMISSIONS

As mentioned earlier, equipment for measurement of carbonyls and VOCs was purchased later than the remainder of the RAVEM system, and was not available for use until first-round testing had already been carried out on most of the diesel buses. Operator error also resulted in invalid data for a substantial number of GC analyses undertaken during the first and second campaigns, and for the Metrobus tests taken at the beginning of the third round. Unfortunately, this was not discovered until the Tedlar bags containing the samples in question had been purged. Thus, most of the valid data on VOC were collected in the third round of testing. The valid VOC speciation data are summarized in Table 14, Table 15, and Table 16.

Table 14: Speciated VOC emissions

				VOC Emissions - g/km									
				Methane		**Ethane**		**Ethylene**		**Propane**		**Propylene**	
Vehicle	**Test Date**	**Test Route**	**No Tests**	**Avg.**	**σ**	**Avg.**	**σ**	**Avg.**	**σ**	**Avg.**	**σ**	**Avg.**	**σ**
Diesel Buses													
RTP 1	30-Sep-05	Corredor	3	0.06	0.14	0.001	0.002	0.005	0.006	0.000	0.002	0.002	0.002
RTP 5	30-Jun-05	Norte	2	0.33	0.05	0.009	0.001	0.213	0.016	0.000	0.002	0.043	0.002
RTP 6	29-Jun-05	Corredor	2	0.05	0.04	0.001	0.000	0.029	0.000	0.004	0.007	0.007	0.000
Vol 12	11-Feb-05	Norte	2	neg.	0.03	0.000	0.000	0.027	0.002	0.000	0.000	0.006	0.000
	11-Feb-05	Corredor	2	0.37	0.37	0.003	0.003	0.040	0.040	0.009	0.009	0.010	0.010
	13-Jun-05	Corredor	1	neg.	-	0.000	-	0.016	-	0.000	-	0.005	-
MB 11	28-Sep-05	Corredor	2	0.03	0.01	0.000	0.000	0.010	0.002	neg.	0.000	0.002	0.000
Eletrabus	28-Sep-05	Corredor	2	0.33	0.05	0.009	0.001	0.213	0.016	0.000	0.002	0.043	0.002
CNG Buses													
Busscar	03-Feb-05	Norte	3	10.02	0.31	0.390	0.013	0.029	0.009	0.013	0.005	0.002	0.002
	03-Feb-05	Corredor	2	5.16	5.23	0.107	0.138	0.012	0.001	0.014	0.040	0.000	0.003
	08-Jun-05	Corredor	2	24.19	33.47	2.432	1.045	0.024	0.007	0.086	0.011	neg.	0.000
	03-Oct-05	Corredor	3	4.36	3.51	0.267	0.207	0.007	0.004	0.010	0.007	0.001	0.001
FAW	04-Feb-05	Norte	3	10.57	5.97	0.328	0.171	0.004	0.016	neg.	0.016	neg.	0.002
	27-Jun-05	Corredor	2	11.08	6.21	0.371	0.325	0.011	0.011	0.014	0.003	0.000	0.001
	04-Oct-05	Corredor	2	51.93	2.38	3.122	0.193	0.178	0.013	0.136	0.019	0.004	0.003
ANKAI	05-Oct-05	Corredor	2	8.25	5.11	0.462	0.356	0.022	0.012	0.015	0.012	0.001	0.001
Microbuses													
M-LPG	11-Nov-05	Montevid	1	0.25	-	0.071	-	0.240	-	2.772	-	0.170	-
	11-Nov-05	RTP-23	1	0.34	-	0.085	-	0.323	-	2.931	-	0.189	-
M-D-CNG	06-Jun-05	Corredor	2	0.80	0.52	0.050	0.028	0.002	0.000	0.002	0.002	neg.	0.001
	07-Oct-05	Corredor	1	4.60	-	0.237	-	0.043	-	0.009	-	0.008	-
M-D-Gsln	03-Jun-05	Corredor	2	0.13	0.32	0.026	0.019	0.125	0.124	neg.	0.007	0.026	0.047
	06-Oct-05	Corredor	2	0.65	0.70	0.037	0.035	0.329	0.297	0.007	0.009	0.084	0.072

As Table 14 shows, the natural gas buses show relatively high emissions of methane – an important greenhouse gas, but one that exhibits virtually no activity for urban ozone formation. For these buses, the methane emissions ranged from five to 50 grams per kilometer. Ethane, another low-reactivity VOC, accounted for the bulk of the remaining VOC emissions. More-reactive species such as ethylene, propylene, etc. were present only at very low concentrations, which were difficult to distinguish from background levels. Emissions of both methane and non-methane VOC from the FAW bus were much higher in the second and third campaigns than in the first campaign. This could be due to a change in engine calibration and/or fuel composition, resulting in occasional misfiring or incomplete combustion. This is a common occurrence with lean-burn natural gas engines.

Table 15: Speciated VOC emissions (continued)

				VOC Emissions - g/km									
	Test	Test	No	I-Butane		N-butane		Acetylene		Butenes		Pentanes	
Vehicle	Date	Route	Tests	Avg.	σ	Avg.	σ	Avg.	σ	Avg.	σ	Avg.	σ
Diesel Buses													
RTP 1	30-Sep-05	Corredor	3	0.00	0.00	neg.	0.001	0.001	0.005	0.001	0.001	neg.	0.001
RTP 5	30-Jun-05	Norte	2	neg.	0.00	neg.	0.000	0.105	0.015	0.013	0.000	neg.	0.006
RTP 6	29-Jun-05	Corredor	2	0.00	0.00	0.001	0.001	0.007	0.010	0.002	0.001	neg.	0.004
Vol 12	11-Feb-05	Norte	2	0.00	0.00	neg.	0.000	0.000	0.000	0.003	0.001	0.000	0.000
	11-Feb-05	Corredor	2	0.00	0.00	0.003	0.003	0.000	0.000	0.009	0.009	0.003	0.003
	13-Jun-05	Corredor	1	neg.	-	0.000	-	0.000	-	0.003	-	0.000	-
MB 11	28-Sep-05	Corredor	2	neg.	0.00	0.000	0.000	0.006	0.001	0.001	0.001	neg.	0.000
Eletrabus	28-Sep-05	Corredor	2	neg.	0.00	neg.	0.000	0.105	0.015	0.013	0.000	neg.	0.006
CNG Buses													
Busscar	03-Feb-05	Norte	3	0.00	0.00	0.002	0.002	0.000	0.000	0.001	0.001	0.001	0.002
	03-Feb-05	Corredor	2	neg.	0.00	0.004	0.014	0.018	0.005	neg.	0.000	neg.	0.009
	08-Jun-05	Corredor	2	0.01	0.00	0.012	0.006	0.000	0.000	0.000	0.000	neg.	0.011
	03-Oct-05	Corredor	3	0.00	0.00	0.001	0.001	0.003	0.000	0.000	0.001	0.000	0.000
FAW	04-Feb-05	Norte	3	neg.	0.00	neg.	0.004	neg.	0.020	neg.	0.001	neg.	0.018
	27-Jun-05	Corredor	2	0.00	0.00	neg.	0.003	0.000	0.000	0.000	0.000	0.001	0.001
	04-Oct-05	Corredor	2	0.01	0.00	0.010	0.003	0.000	0.000	neg.	0.000	0.002	0.002
ANKAI	05-Oct-05	Corredor	2	0.00	0.00	neg.	0.006	neg.	0.001	neg.	0.001	neg.	0.007
Microbuses													
M-LPG	11-Nov-05	Montevid	1	0.31	-	0.991	-	0.199	-	0.073	-	0.005	-
	11-Nov-05	RTP-23	1	0.33	-	1.035	-	0.300	-	0.070	-	0.000	-
M-D-CNG	06-Jun-05	Corredor	2	0.00	0.00	0.001	0.002	neg.	0.035	neg.	0.002	0.001	0.023
	07-Oct-05	Corredor	1	0.00	-	0.001	-	0.000	-	0.005	-	0.002	-
M-D-Gsln	03-Jun-05	Corredor	2	0.08	0.11	0.029	0.035	0.644	0.901	0.372	0.354	neg.	0.064
	06-Oct-05	Corredor	2	0.00	0.00	0.020	0.019	0.013	0.011	0.162	0.171	0.043	0.037

Emissions of VOC from all of the diesel buses were extremely low, making them difficult to distinguish from background levels. The highest non-methane VOC emissions were measured from the dual-fuel gasoline bus. In addition to relatively high levels of reactive ethylene, butanes, pentenes and "other" hydrocarbons, this vehicles exhibited the highest emissions of 1,3 butadiene – a significant carcinogen. This is consistent with the common observation that gasoline engines tend to have much higher non-methane HC emissions than either diesels or natural gas engines.

Table 16: Speciated VOC emissions (concluded)

Vehicle	Test Date	Test Route	No Tests	VOC Emissions - g/km							
				1,3 Butadiene		Pentenes		Other HC		Total NMHC	
				Avg.	σ	Avg.	σ	Avg.	σ	Avg.	σ
Diesel Buses											
RTP 1	30-Sep-05	Corredor	3	0.00	0.00	0.000	0.000	neg.	0.058	0.001	0.045
RTP 5	30-Jun-05	Norte	2	0.01	0.00	0.002	0.000	0.083	0.031	0.472	0.063
RTP 6	29-Jun-05	Corredor	2	0.00	0.00	0.000	0.000	neg.	0.114	neg.	0.121
Vol 12	11-Feb-05	Norte	2	0.00	0.00	0.000	0.000	0.043	0.055	0.080	0.052
	11-Feb-05	Corredor	2	0.00	0.00	0.002	0.002	neg.	neg.	0.029	0.029
	13-Jun-05	Corredor	1	0.00	-	0.000	-	0.026	-	0.051	-
MB 11	28-Sep-05	Corredor	2	0.00	0.00	0.000	0.000	neg.	0.032	0.006	0.028
Eletrabus	28-Sep-05	Corredor	2	0.01	0.00	0.002	0.000	0.083	0.031	0.472	0.063
CNG Buses											
Busscar	03-Feb-05	Norte	3	0.00	0.00	0.000	0.000	0.007	0.007	0.447	0.037
	03-Feb-05	Corredor	2	0.00	0.00	0.000	0.000	neg.	0.015	0.145	0.056
	08-Jun-05	Corredor	2	0.00	0.00	neg.	0.001	neg.	0.480	2.220	0.565
	03-Oct-05	Corredor	3	0.00	0.00	0.000	0.000	0.021	0.025	0.311	0.243
FAW	04-Feb-05	Norte	3	0.00	0.00	0.000	0.000	neg.	0.011	0.301	0.248
	27-Jun-05	Corredor	2	0.00	0.00	0.000	0.000	0.003	0.000	0.401	0.339
	04-Oct-05	Corredor	2	0.00	0.00	0.000	0.000	0.006	0.001	3.469	0.234
ANKAI	05-Oct-05	Corredor	2	0.00	0.00	neg.	0.001	neg.	0.200	0.335	0.166
Microbuses											
M-LPG	11-Nov-05	Montevid	1	0.00	-	0.006	-	0.004	-	0.000	-
	11-Nov-05	RTP-23	1	0.00	-	0.001	-	neg.	-	neg.	-
M-D-CNG	06-Jun-05	Corredor	2	neg.	0.00	neg.	0.036	neg.	0.314	neg.	0.334
	07-Oct-05	Corredor	1	0.00	-	0.001	-	0.105	-	0.411	-
M-D-Gsln	03-Jun-05	Corredor	2	0.02	0.01	0.097	0.114	2.316	2.662	3.680	4.208
	06-Oct-05	Corredor	2	0.02	0.01	0.030	0.024	1.233	0.866	1.980	1.559

4.5 COMPARISON TO WEST VIRGINIA UNIVERSITY DATA

Eight of the vehicles tested in this program were also tested on the West Virginia University (WVU) transportable chassis dynamometer system[12]. WVU tested the buses on four driving cycles, of which three were specifically developed to reflect bus operation in Mexico City. The WVU MX3 cycle was designed to simulate bus corridor operation, in the same way as our Insurgentes Corredor route, while the MX1 and MX2 cycles reflected low-speed urban and high-speed highway driving, respectively. The final cycle used in the WVU testing was the European Transient Cycle (ETC).

Although the MX3 cycle is designed to simulate bus corridor operation, it is substantially more severe than the Insurgentes Corredor driving route that we used. Although the average speed of the two cycles is similar, the MX3 cycle contains 14 stop/accelerate sequences in 1000 seconds (equal to 50 per hour), compared to only 30 stops in the Insurgentes Corredor driving route.

The results of the WVU MX3 data and our Insurgentes Corredor data are compared in Table 17, and plotted against each other in Figure 10. Except for PM, the two sets of measurements show similar trends, but the RAVEM Insurgentes Corredor data average about one-third lower than the MX3 results, which is consistent with the greater severity of the MX3 cycle.

The PM trends are complicated by large differences in the PM measurements for vehicles MB 10 and Sc 18. For MB 10, the RAVEM PM measurements are much lower than the WVU data, while the reverse is true in the case of Sc 18. The RAVEM measurements on vehicle Sc 18 were taken February 8, 2005, and the high PM emissions observed then were hypothesized to be due to engine malfunction. Thus, it is not surprising that the WVU measurements in November, 2004 were substantially lower. RAVEM measurements on vehicle Sc 18 were also taken in November 2004, in parallel with the WVU system, and averaged 0.41 g/km of PM.

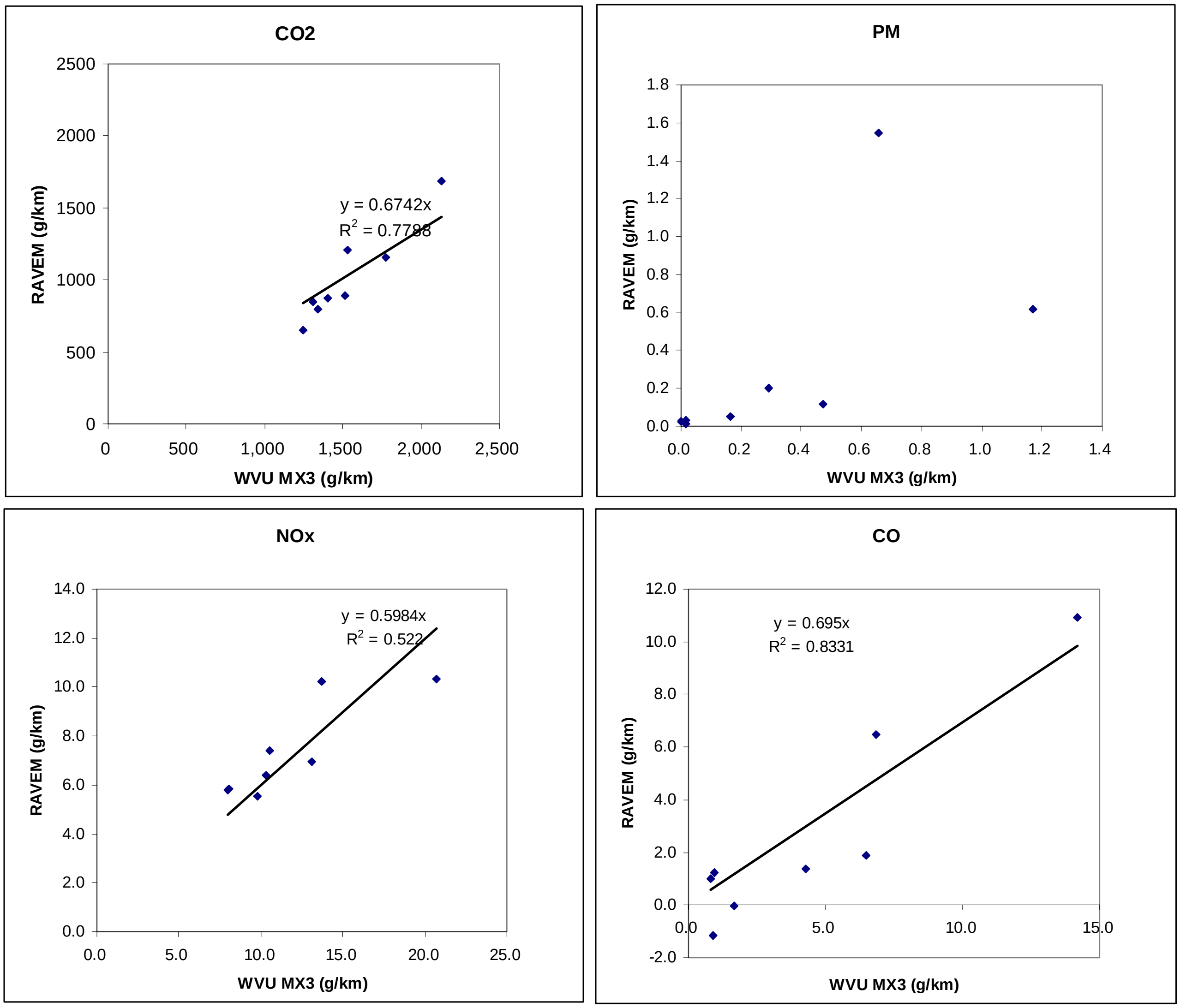
In the case of MB 10, the WVU and RAVEM measurements were taken on consecutive days, so it is unlikely that the difference is due to a change in the mechanical condition of the engine. Instead, it appears that MB 10's PM emissions may have been either highly variable or very sensitive to the driving cycle. In the ETC cycle, WVU measured PM emissions from MB10 at only 0.09 gram per kilometer, which is one-fifth of the level measured for the MX3 cycle, and similar to the PM emissions measured by the RAVEM.

Table 17: RAVEM Insurgentes Corredor measurements compared to WVU MX3 results

	PM (g/km)		NOx (g/km)		CO (g/km)	
	RAVEM	WVU	RAVEM	WVU	RAVEM	WVU
RTP 1	0.20	0.29	7.42	10.5	1.39	4.3
Vol 12	0.62	1.17	10.21	13.7	10.91	14.2
Sc 18	1.55	0.66	6.95	13.1	6.46	6.8
MB 10	0.11	0.47	5.79	8.0	1.88	6.5
RTP	0.05	0.16	6.39	10.3	1.00	0.8
Allison	0.03	0.02	5.82	8.0	Neg.	0.9
Busscar	0.01	0.02	5.52	9.8	Neg.	1.6
FAW	0.03	0.00	10.32	20.7	1.25	0.9

	CO2 (g/km)		THC (g/km)	
	RAVEM	WVU	RAVEM	WVU
RTP 1	849	1,306	0.06	0.15
Vol 12	887	1,514	0.03	0.18
SC 18	1,685	2,128	na	0.07
MB 10	651	1,245	na	0.02
RTP 3	793	1,338	na	na
Allison	1,203	1,527	na	na
Busscar	876	1,402	5.30	8.41
FAW	1,155	1,777	11.08	3.50

Figure 10: RAVEM Insurgentes Corredor measurements vs. WVU MX3 results



5. ADDITIONAL MEASUREMENTS: NOISE AND SMOKE OPACITY

In addition to mass pollutant emissions in the exhaust, the Scope of Work for this project also called for the measurement of noise emissions and smoke opacity. This chapter documents the measurement procedures and the results of these measurements.

5.1 NOISE

5.1.1 Measurement Procedure

Noise emission measurements were carried out in accordance with NOM-080-ECOL-1994 and ISO 5130. This procedure calls for the sound level meter or microphone to be placed at a height equal to that of the exhaust pipe outlet, 0.5 m away from the outlet, and at a 45^{o} angle ($\pm 10^{o}$) from the direction of the exhaust gas flow. The engine is then accelerated three times to governor speed, and the peak noise level during the acceleration is recorded. The test result is the average of the minimum and maximum noise levels during the test. The corresponding noise standard established by NOM-080-ECOL-1994 is 95 dB(a).

5.1.2 Results

The results of these measurements are summarized in Table 18. Only one vehicle – the Ankai – exceeded the noise standard. Buses RTP3 and Vol 12 were noticeably quieter than the rest of the vehicles tested, which clustered in a fairly narrow band around 90 dB(A).

Table 18: Noise emission measurement results

Bus	Fuel	Test Date	Noise Measurement dB(A)			
			1	2	3	Avg.
RTP 3	D 50	23-May	84.2	86.1	86.2	85.2
RTP 2	D 350	23-May	91.0	91.2	90.8	91.1
RTP 4	D 350	23-May	94.9	93.5	92.8	94.2
MB 11	D 15	16-Apr	89.3	87.3	90.3	89.8
Ankai	CNG	16-Apr	104.2	103.8	102.3	103.3
FAW	CNG	16-Apr	92.5	88.3	89.3	90.9
Busscar	CNG	16-Apr	87.9	87.5	87.0	87.7
MB 12	D 50	16-Apr	84.6	88.0	95.2	89.9
Vol 12	D 15	16-Apr	82.5	82.2	82.2	82.4
CISA	D 350	8-Sep	88.8	89.2	88.9	89.0
Phoenix Metrobús	D 350	9-Sep	91.3	94.5	93.1	92.9
Mexican Standard	**NOM-080-ECOL-1994**					**95**

5.2 SMOKE OPACITY

5.2.1 Measurement Procedure

Smoke testing was carried out in accordance with SAE Recommended Practice J1667.

> *"Prior to each snap-idle cycle, the vehicle's engine shall be at normal low idle. From this position, the operator shall as rapidly as possible move the throttle to the wide open position. The operator shall hold the throttle at a wide open position until the engine has reached its maximum governed speed and an additional one to four seconds has elapsed. After this period, the throttle shall be fully released, and the engine allowed to return to normal idle. The engine shall be allowed to remain at idle for at least 5 seconds prior to the next snap cycle in the test sequence. This allows the engine's turbocharger (if equipped) to decelerate to its normal speed at engine idle, and helps to maintain repeatability between snap-idle cycles".*

The result of the SAE J1667 test procedure is the average of three successive snap accelerations. For the test to be valid, the difference between the highest and the lowest value must be no more than 5% opacity – otherwise additional snap accelerations are performed until a sequence of three meets the criterion.

All of the smoke tests were performed with a Wager 2500 smoke opacity meter, using the partial-flow sensing head. This head has a path length of 5 inches, or 12.7 centimeters.

5.2.2 Results

The smoke test results are summarized in Table 19. The table shows both the smoke opacity (measured over the five inch path length) and the corresponding smoke density or “K” value in the Beer-Lambert law. The latter is preferred as a basis for regulations, since it is independent of path length. As the table shows, all of the buses would have complied with the ECE R24 snap acceleration smoke limit of 2.5 m^{-1}.

Also shown in the table are the PM emissions in grams per BHP-hr measured for each bus over the Insurgentes Norte test route. The relationship between smoke density K and mass PM emissions is plotted in Figure 11. As the figure shows, for this group of buses, high smoke opacity in the snap acceleration test is usually associated with high in-use PM emissions, and vice-versa. The snap acceleration test may be a better predictor of in-use emissions for buses than for other vehicles, since bus operation is dominated by stop-start operation.

Table 19: Results of SAE J1667 smoke opacity testing

Vehicle	Date	% Opacity	"K" m-1	PM g/BHP-hr
Allison	11-Nov-04	0.5	0.04	0.02
RTP 4	3-Dec-04	0.4	0.03	0.03
RTP 3	8-Dec-04	2.1	0.17	0.04
RTP 1	14-Dec-04	7.8	0.64	0.15
MB 10	16-Dec-04	4.3	0.35	0.12
SC 18	8-Feb-05	21.0	1.86	0.66
Vol 12	11-Feb-05	22.0	1.96	0.36
Eletrabus	20-Oct-05	2.8	0.22	0.03
RTP 2	3-Dec-05	5.9	0.48	0.12
CISA Metrobus	3-Dec-05	22.0	1.96	0.13
Fenix Metrobus	3-Dec-05	23.8	2.14	0.33

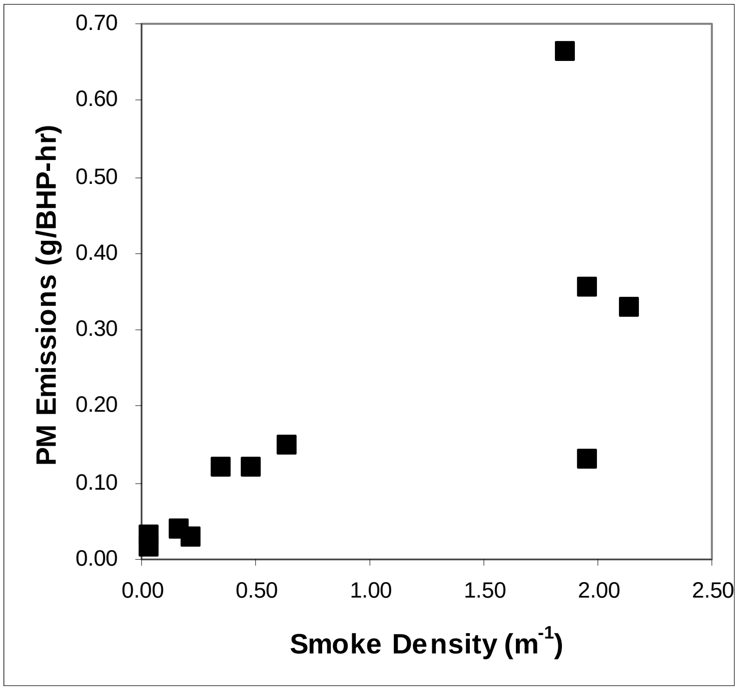


Figure 11: Brake-specific PM emissions vs. smoke density

6. CONCLUSIONS

Emission tests were carried out on-board 17 late-model and demonstration buses and four microbuses using the RAVEM ride-along vehicle emission measurement system. The buses tested included twelve conventional diesels, two diesel-electric hybrids, and three using compressed natural gas in lean-burn engines. The four microbuses included one using gasoline in a stoichiometric engine, one that had been retrofitted to use LPG, one retrofitted to use CNG, and a dual-fuel vehicle retrofitted to be able to use either CNG or gasoline. Two diesel buses and one diesel-electric hybrid were fitted with diesel particulate filters (DPFs). All of the CNG buses and microbuses were equipped with catalytic converters.

The test route comprised a round-trip along Avenida Insurgentes in Mexico City, from the Indios Verdes metro station to the Glorieta de Insurgentes traffic circle and return. The total length of the trip was 21.4 kilometers. Testing was undertaken in two driving conditions, corresponding to normal daytime traffic and to operation along a simulated bus corridor free of interfering traffic. Total test times (including idle time at the beginning and end of the routes) were 3600 and 4500 seconds, respectively, corresponding to average speeds of 17.1 and 21.4 kilometers per hour.

The pollutants measured included particulate matter (PM), oxides of nitrogen (NOx), carbon monoxide (CO), carbon dioxide (CO_2), and carbonyls such as formaldehyde, acetaldehyde, and acrolein. Emissions of individual volatile organic compounds (VOC) such as methane, ethane, ethylene, etc. were also measured successfully for some of the tests.

Measured PM emissions from all of the natural gas fueled buses and from the natural gas, dual-fuel, and LPG-fueled microbuses were all extremely low – ranging from 0.01 to 0.04 grams per kilometer. PM emissions from the gasoline microbus were much higher, at 0.16 to 0.22 grams per kilometer. The DPF-equipped diesel hybrid was in the same range as the natural gas buses, emitting 0.03 grams of PM per kilometer, while the two conventional buses equipped with DPFs emitted 0.01 to 0.08 grams of PM per kilometer. Five of the ten diesel buses without DPFs exhibited relatively low PM emissions, ranging from 0.07 to 0.28 grams per kilometer. Four of these buses were certified using the U.S. EPA transient test procedure, the certification status of the fifth was not available at the time of this writing. Two buses certified to the steady-state Euro 3 test procedure exhibited much higher emission levels 0.55 to 0.68 and 1.54 to 2.07 grams per kilometer, respectively. PM emissions showed a strong correlation with smoke opacity as measured according to SAE J1667.

NOx emissions from the test vehicles ranged from 0.1 to 21.3 grams per kilometer. The natural gas buses and gaseous-fueled microbuses generally exhibited the lowest NOx emissions, while the gasoline microbus exhibited higher NOx. The lowest NOx emissions measured were from the dual-fuel microbus in gasoline mode, but these were accompanied by extremely high emissions of CO.

NOx emissions among the diesel buses varied greatly. The two hybrid buses exhibited respectively the second-lowest and the highest levels of NOx emissions in this group. Since Most of the buses exhibited much higher NOx emissions than expected, based on the applicable emission standards. Brake-specific NOx emissions were estimated from fuel consumption, and ranged from 2.1 to 12.1 grams per BHP-hr. Several bus engines purportedly certified to U.S. 1998 or 2004 emission standards exhibited brake-specific NOx emissions 30 to 80 percent above these standards in on-road driving. One bus showed unexpectedly low brake-specific NOx emissions, but also exhibited the highest emissions of particulate matter. This suggests that the fuel injection timing may have been out of adjustment.

CO emissions from the diesel and lean-burn natural gas buses were extremely low – ranging from small negative values to less than six grams per kilometer. Those from the CNG and LPG microbuses were moderately high at 30 to 40 and about 80 grams per kilometer, respectively. CO emissions from the gasoline microbus and the dual-fuel microbus in gasoline mode were extremely high, ranging from 147 to 362 grams per kilometer.

The three CNG buses equipped with lean-burn engines emitted 5 to 52 grams of methane per kilometer, about 0.1 to 3.1 grams of ethane, and much lower levels of ethylene and higher-carbon VOC species. In CNG mode, the dual-fuel microbus emitted 0.8 to 4.6 g/km of methane, 0.05 to .24 g/km of ethane, and very small amounts of higher NMHC. In gasoline mode, its methane emissions were about 80% lower, but its NMHC emissions increased greatly – averaging two to 3.7 grams per kilometer. VOC emissions from the diesel buses were so low that they could not be distinguished reliably from background VOC levels.

Fuel consumption and CO_2 emissions among the diesel buses varied with the size of the bus, ranging from about 200 grams of fuel per kilometer for a 10-meter light bus to about 500 g/km for the 18 meter articulated vehicle. Mass fuel consumption for the CNG buses was similar to that for diesel buses of the same size. The CNG and LPG microbuses used about 2/3 as much fuel as the diesel and CNG buses. Mass fuel consumption for the gasoline minibus was substantially higher.

Fuel consumption and emissions in regular driving were sometimes higher and sometimes lower than in the simulated bus corridor conditions, depending on the bus and/or driver. The absence of traffic allowed more-aggressive bus drivers to drive faster and accelerate harder, thus increasing fuel consumption. A statistical analysis of the six buses with the most complete data showed a mean reduction in fuel consumption and CO_2 emissions of 10% for three diesel buses combined when operating in the simulated bus corridor conditions compared to regular driving. For three CNG buses, the reduction was 11%. Neither value was statistically significant at the 90% level, however.

Eight of the vehicles tested in this program were also tested on the West Virginia University (WVU) transportable chassis dynamometer system. The WVU MX3 cycle was designed to simulate bus corridor operation, in the same way as our Insurgentes Corredor route, and the average speeds in the two cycles are similar. The MX3 is a more severe cycle, however, with 50 stops per hour compared to 30 in the Insurgentes Corredor route. This would tend to produce higher emissions per kilometer. The two sets of measurements show similar trends, but the RAVEM Insurgentes Corredor data averaged about one-third lower than the WVU MX3 results.

Limited emission testing was also performed on two 1991 model Mercedes buses, one of which had been repowered with an engine meeting current Mexican emissions standards. Emissions of PM, CO, and NOx from the repowered bus were 88 percent, 86 percent, and 59 percent lower, respectively, than those from the bus that had not been repowered. Thus, repowering older buses with modern, emission-controlled engines can achieve large emission reductions. Such repowering is most feasible in rear-engine buses, as front-engine vehicles often lack sufficient space to accommodate the engine accessories.

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