A Tunnel Study to Characterize $PM_{2.5}$ Emissions from Light-Duty Vehicles in Monterrey, Mexico

Yasmany Mancilla, Alejandro E. Araizaga and Alberto Mendoza
Department of Chemical Engineering, Tecnológico de Monterrey
Ave. Eugenio Garza Sada 2501, Monterrey, Nuevo León, 64849 México
a00800372@itesm.mx

ABSTRACT

One of the main sources of air pollution in the Monterrey Metropolitan Area (MMA), Mexico is vehicle exhausts. In this study, emission factors for $PM_{2.5}$ and CO_2 from mobile sources operating under real world conditions were determined using as experimental setup the Loma Larga Tunnel (LLT). This tunnel is 532 meters-long and has an average slope of 3.5%. Two sampling stations were located inside the tunnel, one at the entrance and another at the middle of the tunnel. At each station, low-volume devices were deployed to collect 2.5 hour-average $PM_{2.5}$ samples, while for CO_2, real-time measurements were taken. In addition, continuous temperature, pressure and wind intensity were also registered at each sampling point. From the samples collected, $PM_{2.5}$ mass emission factors were estimated, as well as chemical profiles for 38 metals (Na to Pb), cations (Na^+, K^+, NH_4^+), anions (Cl^-, NO_3^-, SO_4^{2-}), organic carbon (OC) and elemental carbon (EC). During the sampling periods conducted for this study a fleet of 108,569 vehicles crossed the tunnel with average speeds that ranged from 43 km/h to 76 km/h. Average emission rates of 17.5±5.7 mg/veh-km and 145±94 mg/L for $PM_{2.5}$ were obtained. CO_2 emission rates uphill (188±22 g/veh-km and 2,012±20 g/L) were greater than downhill (152±22 g/veh-km and 2,045±219 g/L). Vehicular $PM_{2.5}$ emissions were dominated mainly by OC and EC, these species represented 55.2 ± 2.8% and 16.3 ± 1.6% of the total emitted mass. The OC/EC ratio was 2.85±0.79 and 1.19±0.65 for heavy traffic and moderate traffic conditions, respectively.

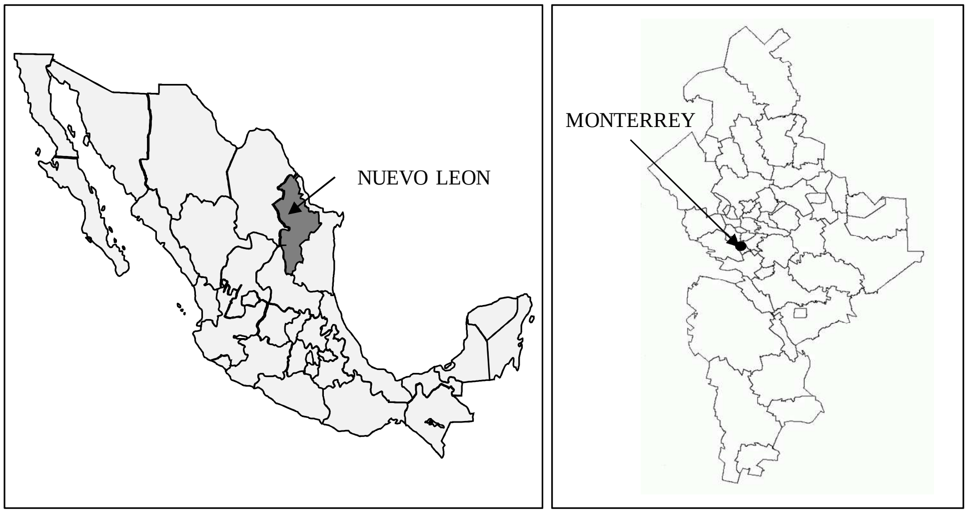
INTRODUCTION

One of the most important environmental problems that urban areas face is that associated to air quality deterioration. Pollutants such as CO, CO_2, NOx ($NOx=NO+NO_2$), volatile organic compounds (VOCs), SOx ($SOx = SO_2 + SO_3$) and particulate matter are some species of interest due to their environmental and health impacts. In Mexican urban centers, such as Mexico City or the Monterrey Metropolitan Area (MMA), one of the major contributors to the gaseous emissions released to the atmosphere are mobile sources. For example, it has been estimated that in Mexico City 80% of the air pollution has its origin in the emissions from mobile sources.[1] Equally, in the MMA, the third largest urban center in the country, one of the main air pollution sources is the exhaust from motor vehicles. On average, mobile sources represent the largest contributor of emissions to the air by anthropogenic sources in the country.

Of the pollutants emitted by mobile sources, fine particles ($PM_{2.5}$, particulate matter with aerodynamic diameter under 2.5 μm) have a major impact on health as well as on climate and visibility.[2] In addition, some studies have determined that in the US, on average, 38% of the observed $PM_{2.5}$ emissions come from vehicular combustion and that 74% of these are produced from gasoline-powered light-duty vehicles.[3] Given the high contribution of vehicle emissions in urban centers, it is relevant to characterize these emissions. Even more, given that each region will have its own characteristic vehicular fleet and corresponding conditions that influence vehicular emissions (transportation infrastructure, fuel, pavement conditions, climate, etc.), it is important to conduct local studies to obtain local emission factors (EFs) and profiles. From the different techniques available to perform such emission studies, tunnel studies have proven to be a robust method when the objective is to obtain fleet-average EFs under real-world conditions, including those for $PM_{2.5}$ emissions.[4-8] This method is based on performing a mass balance over a control volume delimited by monitoring stations deployed inside the tunnel. These stations are usually located at the entrance and exit of a tunnel in which pollutants concentration, as well as other parameters such as vehicle speed, fleet count, wind speed, temperature and pressure, are measured. Here, the difference in pollutants concentration between the "inlet" and "outlet" points is assumed to be the emitted mass from mobile sources that traversed the tunnel during each sampling period. Also, other techniques such remote sensing, dynamometer tests and chasing laboratory can be used in order to estimate EFs.

In Mexico, it is common to use EFs and data from the USEPA to estimate emission inventories for different sources. However, this information is inherent to the US conditions and activity patterns. Therefore, the purpose of this study was to conduct a monitoring campaign to gather local emission data of a typical vehicle fleet of the MMA.

Figure 1. Localization of the MMA at the national and state level.

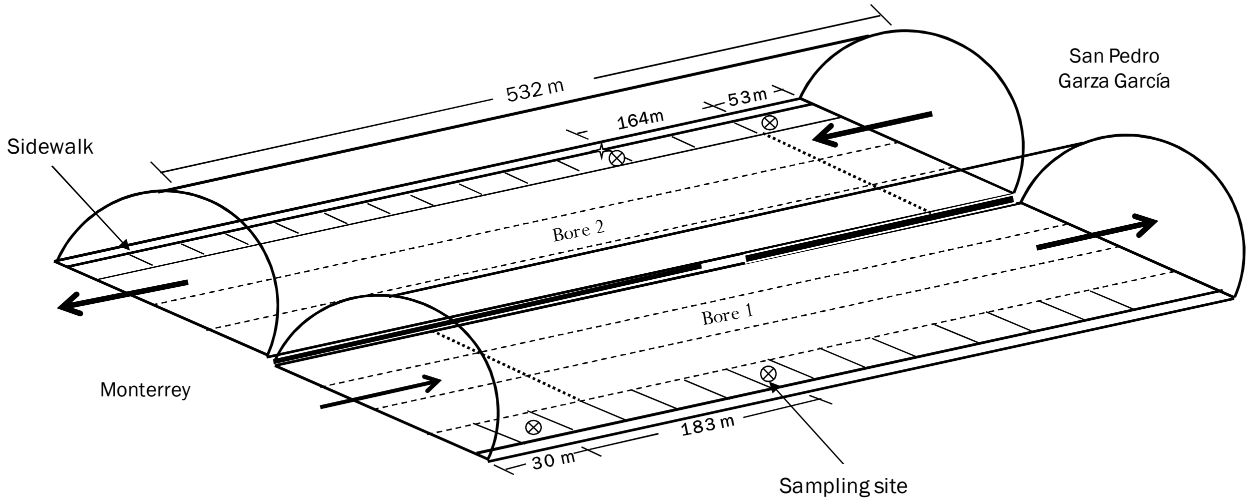


METHODOLOGY

Site and sampling description. The Loma Larga Tunnel (LLT) is a two-bore urban tunnel located to the south of the MMA (Figure 2). This complex is one of the main roadways that connect the municipalities of Monterrey and San Pedro Garza Garcia. The tunnel is 532 meters long, with no internal curves. The two bores are almost completely independent; there is a small interconnection near the middle of the tunnel that connects both bores. Bore 1 (Monterrey to San Pedro Garza Garcia direction, southbound) has a positive slope of 3.5% (uphill) and Bore 2 (San Pedro Garza Garcia to Monterrey direction, northbound) has a negative slope with the same value (downhill). The diameter and cross-sectional area of each bore are 17 m and 113.5 m^2, respectively. The ventilation system of the tunnel is achieved from the vehicle flow (piston effect) that traverses it. There are jet-fans positioned along the ceilings of each bore. However, the jet fans were not operational during the sampling periods of this study. Experiments were conducted separately in each bore, where instruments were set-up on the sidewalks.

The monitoring campaign consisted of six non-consecutive days during June of 2009. The schedule comprised 12 sampling periods, each lasting 2.5 hours. Two sampling periods were carried out per day, one for heavy traffic and another for moderate traffic conditions. The length and time of the sampling periods were chosen to ensure that enough material was collected for chemical analysis, based on previous visits to the TLL. During each sampling period, two sampling stations were located inside a bore of the tunnel, one referred as the "inlet" station and the other as the "outlet" station. In each station, equipment to determine CO_2 levels, wind speed, temperature and pressure were deployed along with devices for collecting $PM_{2.5}$ samples. In accordance to other studies,[6,8] the first station (the "inlet" station) was located 30 m from the actual tunnel entrance in Bore 1 (uphill condition), while it was located 53 m from the entrance of Bore 2 (downhill condition). The second station was positioned in the middle of the tunnel, just before the interconnection to avoid mass loss by the exchange of air trough it (Figure 2). The distances among stations were 183 m and 164 m, for Bore 1 and Bore 2, respectively.

Figure 2. Experimental set-up at the LLT.



$PM_{2.5}$ samples were collected using low-volume filter-based instruments (MiniVol^{TM}, Airmetrics). These devices consist of an ambient air suction pump that can operate at volumetric flow rates up to 10 L/min. After suction, the air goes through a filter in which particulate matter is collected. These units can be used for sampling TSP, PM_{10}, $PM_{2.5}$ and non reactive gases. The sampling system included: a fine-particle size-selective inlet ($PM_{2.5}$ cut-off), 47 mm filter holder and the proper filter, flow control valve and programming control panel. Four MiniVol^{TM} air samplers were deployed during each sampling period, two at each monitoring station. The samples were taken at a height of 2 m from the sidewalk level. Teflon and quartz air sampling filters (one in each device at both sampling sites) were used for taking the $PM_{2.5}$ samples simultaneously at the entrance and exit of the tunnel. Flow rates of 7.4 and 5.5 L/min were drawn through the devices for quartz and Teflon filters, respectively. Before each run, the MiniVols were calibrated using the local temperature and pressure inside the tunnel, and new filters were placed. The loaded filters were stored inside a cooler chilled with blue ice to keep them fresh and avoid evaporation losses of the sampled material while they were delivered to the laboratory for their chemical analysis.

To determine CO_2 concentrations, a multifunctional TESTO 435 instrument was used. This device uses an IAQ (Indoor Air Quality) probe and is equiped with a sensor that measures and records CO_2 levels in a range of 0 to 9,999 ppmv. In addition, the TESTO 435 device was used to measure pressure, temperature and relative humidity levels at each sampling point. Values of the measured variables were recorded every minute during the 2.5 hours that each sampling period lasted. Wind speed was measured using a TESTO 425 device, a thermal anemometer that consists of a handling telescopic probe integrated with a sensor that measures parameters like wind speed (up to 20 m/s) and temperature (–20 ^{o}C to +70 ^{o}C). In this study, an average wind speed and volumetric air flow were obtained for each sampling period. The probes were positioned at a height of 1.5 m the sidewalk floor and 1.5 m distance from the wall.

A vehicle count carried out on June 2007[9] by the *Consejo Estatal de Transporte y Vialidad del Estado de Nuevo de León* (CETyV; Nuevo Leon State Council for Transportation and Highway Administration) shows that vehicles that travel across the tunnel, in both directions, are mainly dominated by gasoline-powered light duty vehicles. The vehicular fleet was characterized (speed, count and classification) using video-recording cameras positioned inside the tunnel.

Chemical analysis. In this study, as mentioned previously, Teflon and quartz filters were used to collect $PM_{2.5}$ samples. Teflon filters were used to determine the amount of collected mass by gravimetric analysis and level of 38 metals (Na to Pb) by X-ray fluorescence (IO-3.3 USEPA method). Ion chromatography analysis was used on quartz filters to determine cations (Na^+, K^+, NH_4^+), anions (Cl^-, NO_3^-, SO_4^{2-}). Organic carbon (OC) and elemental carbon (EC) was determined by thermal-optical-transmittance (5040 NIOSH method). All laboratory analyses were conducted by Chester LabNet (Tigard, OR).

Emission Factors. An emission factor (EF) is defined as the mass of a specific pollutant emitted to the atmosphere associated to the activity of a given source (e.g., distance traveled by a mobile source). In tunnel studies, EFs can be determined by performing a mass balance inside the tunnel; the main assumption is that the concentration difference between sampling points located at the boundaries of an imaginary control volume inside the tunnel represents the mass emitted of any pollutant *k* from vehicle emissions.[10] Thus, the average emission factor for pollutant *k* (E_k), in terms of mass emitted per distance traveled per vehicle, can be estimated from:

Equation (1) $$EF_k = \frac{\left(C_{k,e}V - C_{k,i}V_i\right)}{N \cdot L}$$

where

C_k = concentration of pollutant k (e.g. mg/m^3)
V = air volumetric flow
N = number of vehicles that traverse the tunnel during each sampling period
L = distance between sampling points

In equation 1, subindices *e* and i in the C_k terms represent the exit and inlet concentrations, respectively.

A carbon mass balance can also be used to estimate EFs in terms of mass emitted per volume of fuel burned (E_k') from.[11]

Equation (2) $$E_k' = \left(\frac{\Delta C_k}{\Delta C_{CO2} + \Delta C_{CO} + \Delta C_{TNMOC}}\right) \cdot \rho_g w_c$$

where

ΔC_k = concentration difference of species k between the sampling points
ΔC_{CO2} = concentration difference for CO_2
ΔC_{CO} = concentration difference for CO
ΔC_{TNMOC} = carbon-equivalent concentration difference for TNMOC
ρ_g = gasoline density (740 g/L)[1]
w_c = mass fraction of carbon in the gasoline (0.84, assuming C_8H_{18} as the average molecular composition of gasoline). The average molecular weight of TNMOC was assumed at 92 g/gmol.

RESULTS

Sampled vehicular fleet and overall EFs. The 2.5 hour-averaged micrometeorological conditions inside the LLT and traffic counts are provided in Table 1. The average wind speeds for heavy and moderate traffic were 2.02 m/s and 2.27 m/s, respectively. A total of 108,569 vehicles traveled across the tunnel during the study, of which gasoline-powered vehicles represented 97% of the total fleet and the remaining were heavy diesel trucks (1.87%), motorcycles (0.65%), and diesel buses (0.48%). 54% of all the sampled vehicles were identified during the morning rush hours in Bore 1 (06:45–09:15) and evening rush hours in Bore 2 (17:45–20:15), whereas the complementary 46% were identified during the other two monitoring periods: 09:45–12:15 in Bore 1 and 10:45–13:15 in Bore 2. The average vehicle speeds for heavy and moderate traffic were 48±3 km/h and 59±13 km/h, respectively.

Table 1. Monitoring conditions in the LLT Study.

Period	Date	Time	Traffic Density	Traffic Number		*Ws*[a]		*Vs*[b]	
				B1[c]	B2[d]	B1	B2	B1	B2
1	June 22	6:45-9:15	H[f]	7739		2.01		43.4	
2	June 22	10:45-13:15	M[g]	7725		2.18		47.3	
3	June 23	6:45-9:15	H	9893		1.87		51.3	
4	June 23	10:45-13:15	M	9235		2.62		71.7	
5	June 24	6:45-9:15	H	9320		2.04		46.2	
6	June 24	10:45-13:15	M	9234		2.75		42.0	
7	June 25	9:45-12:15	M		7837		2.12		76.0
8	June 25	17:45-20:15	H		10380		1.58		51.9
9	June 29	9:45-12:15	M		7613		1.72		56.6
10	June 29	16:45-19:15	H		10766		2.48		47.8
11	June 30	9:45-12:15	M		8169		2.23		62.6
12	June 30	16:45-19:15	H		10658		2.15		49.2
Ave[e]				8858	9237	2.25	2.05	50.3	57.3

[a] *Ws*: Wind speed (m/s). [b] *Vs*: Vehicle speed (km/h). [c] Bore 1. [d] Bore 2. [e] Average. [f] Heavy and [g] moderate traffic density.

A total of 12 concentration profiles for CO_2 were obtained, one for each sampling period, inside the LLT. Figure 3a illustrates the expected behavior, in which the inlet concentrations were higher than outlet concentrations. However, in some sampling periods, a concentration cross-over occurred as a result of traffic jams; that can be observed in Figure 3b. When this last occurred, the data was not useful for further analysis and thus was discarded. The average estimated CO_2 EFs were 188±22 g/veh-km and 152±22 g/veh-km for uphill and downhill conditions, respectively. A comparison of these EFs with those obtained in other studies is shown in Table 2; here the LLT CO_2 EFs in terms of g/veh-km are in range of magnitude, while those in terms of g/L are slightly lower. The effect of roadway grade on CO_2 emissions is notorious: EFs (g/veh-km) uphill are 1.3 times higher than EFs downhill. This increment can be caused by a constant acceleration experienced by the vehicles when they move uphill, which entails a larger fuel consumption and, therefore, higher emission rates. Even though the average EFs estimated for CO_2 appear to be different, an ANOVA demonstrated that the EFs were independent of the bore and the sampling period, probably due to the limited number of sampling periods. With the results obtained for CO_2, an average fuel consumption of 12.1±1.9 km/L was estimated.

Figure 3. Examples of CO_2 time series: a) Bore 1, June 22, 2009; b) Bore 2, June 29, 2009.

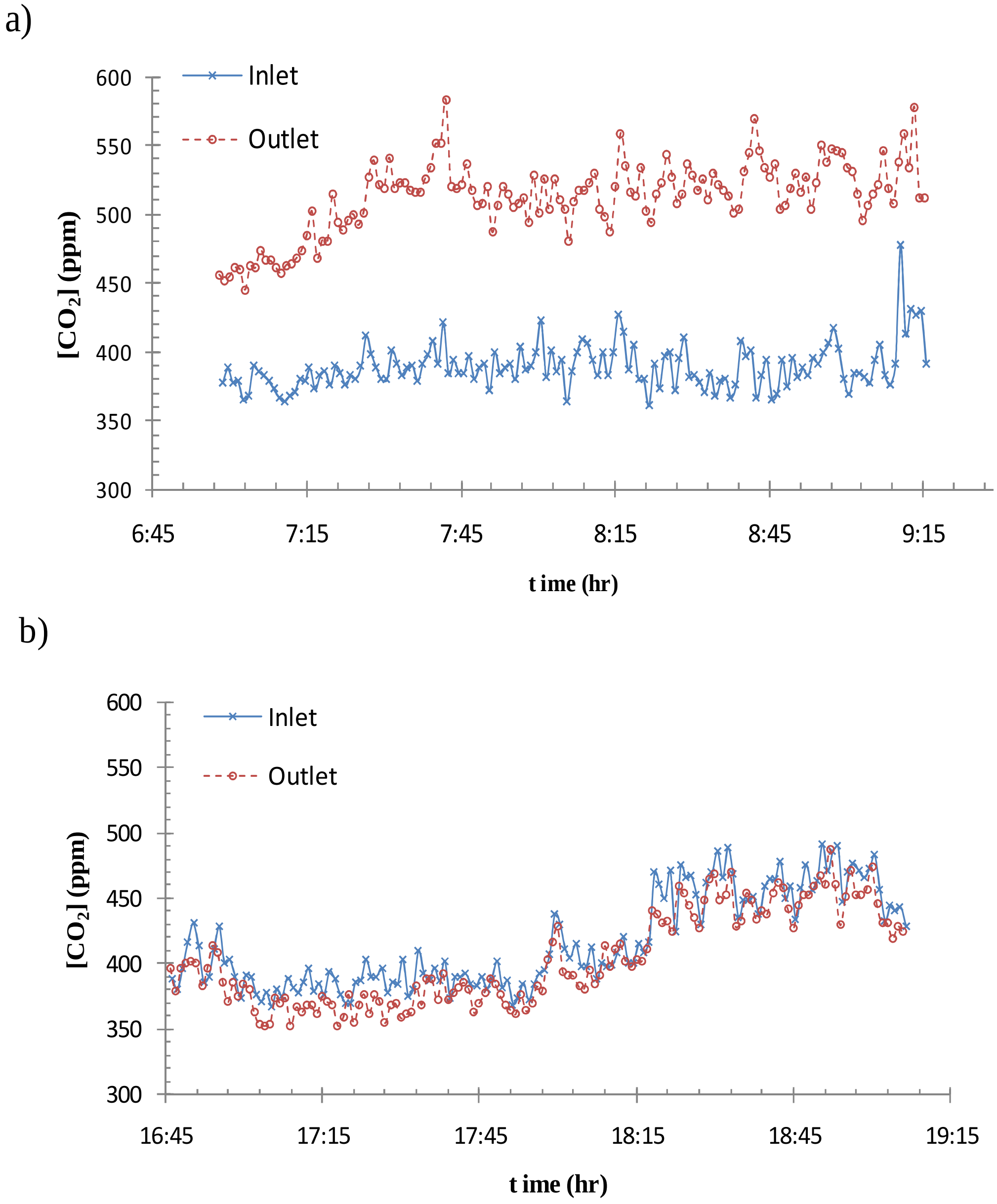


Table 2. CO_2 EFs comparison between the LLT and other tunnel studies.

Tunnel	LD[a] (%)	Total Vehicles	V_s (km/h)	Grade	EF (g /veh-km)	(g/L)
LLT (this study)	97	108,569	48-59	3.50 %	188±22	2012
				–3.50 %	152±22	2045
Tuscarora[10]	82	5,928	88-96	0.0 %	144±22	2217
The Fort McHenry[10]	90	26,665	60-85	3.30 %	230±20	2199
				–1.80 %	147±6	2211
Gelizinis Vilkas[6]	90	1,800	60	0.0 %	147±11	

[a] LD: Contribution of light-duty vehicles to the total sampled fleet.

Figure 4 presents 2.5-hour $PM_{2.5}$ average concentrations for the entire sampling campaign. It can be observed that concentration cross-over also occurred in some $PM_{2.5}$ samples, which were also discarded for further analysis. Average $PM_{2.5}$ EFs uphill were 13.3±6.3 mg/veh-km and 160±77 mg/L, whereas downhill EFs were 21.7±9.5 mg/veh-km and 130±173 mg/L. EFs were corrected by dust resuspension considering that silicon (Si) is one of the key markers for fugitive dust[12] and field blanks. $PM_{2.5}$ emissions were higher downhill than uphill traffic probably because vehicles moving downhill tend to emit additional $PM_{2.5}$ from brake wear.[13] A comparison of $PM_{2.5}$ EFs with other tunnel studies is shown in Table 3, it can be observed that the LLT EFs are the lowest, probably because the sampled fleet is composed heavily of gasoline vehicles (diesel trucks tend to emit larger amounts of $PM_{2.5}$). In addition, results from a parallel study indicates that the fleet appears to be rather well maintained and of recent model year.[14]

Figure 4. $PM_{2.5}$ concentrations for the entire sampling campaign.

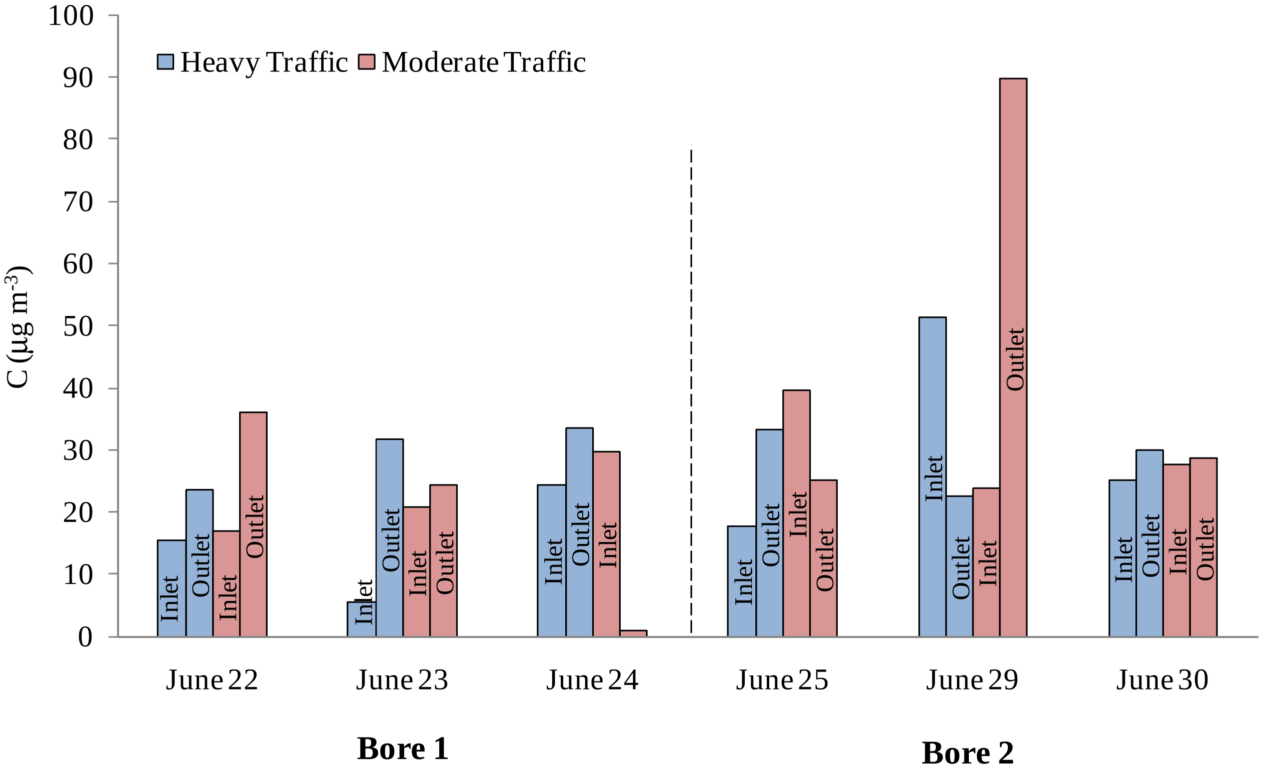


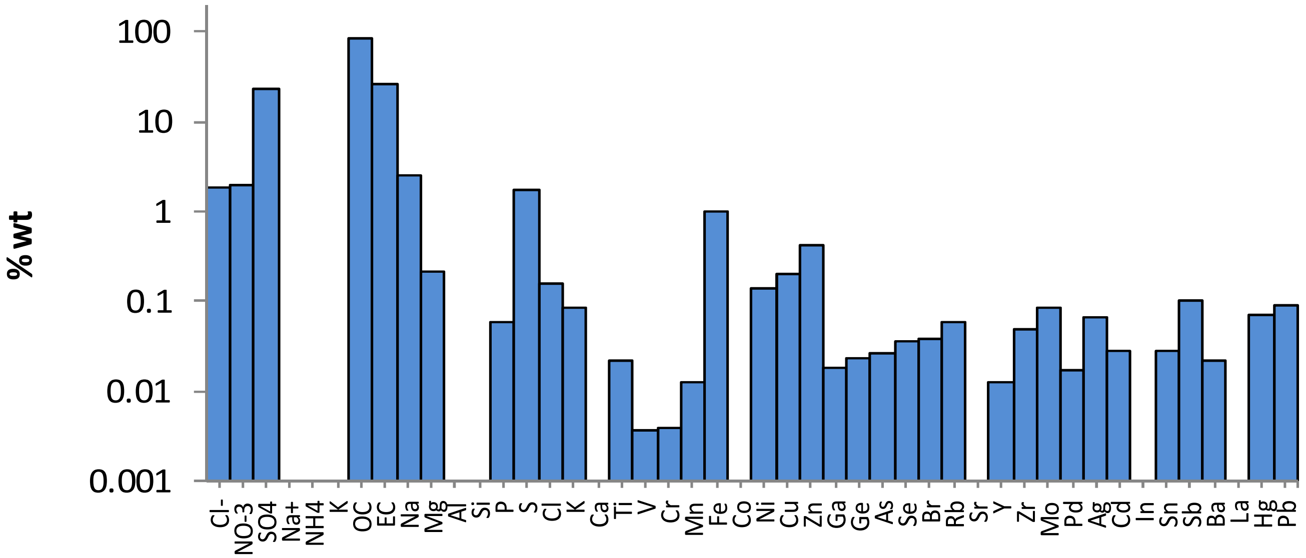
Table 3. $PM_{2.5}$ EFs comparison between the LLT and other tunnel studies (mg/veh-km).

LLT	Caldecott[4] (San Francisco)		Shing Mung[8] (Hong Kong)		Wolloongabba[15] (Brisbane)	Sepulveda[5] (Los Angeles)	Söderleds[7] (Stockholm)	Kilborn/ Howell[16] (Milwaukee)
LD	HD[b]	LD	(HD, LD)	DV	DV	(HD, LD)	(HD, LD)	LD
17.5±5.7[a]	430±79	85±6	131±37	257±31	267±207	52±27	67±5	33.4±5.3

[a] Average between uphill and downhill EFs. [b] HD: Heavy Duty.

Chemical Profiles. Figure 5 represents an average chemical profile of the $PM_{2.5}$ emitted inside the LLT. The species that contribute the most to the total $PM_{2.5}$ (weight percent) were: OC (55.2%), EC (16.3%) and sulfate (SO_4^{2-}; 15.3%). Table 4 shows different $PM_{2.5}$ profiles obtained for different traffic densities and bores in the LLT. The average EFs (mg/veh-km) of the main emitted species were: OC 12.61±8.36, EC 5.69±5.06, SO_4^{2-} 1.15±2.84, Fe 0.51±0.18, Cu 0.05±0.04 and Sb 0.06±0.13. Table 5 presents an EFs comparison of the main species with those obtained in other tunnel studies. Here, we can observe that EFs obtained in the LLT for Fe are up to 5 times lower, for OC they are 13% to 20% lower, while for EC EFs are up to 5 times lower. Fe, Cu and Sb are markers of brake linings and their EFs were two times higher in Bore 2 (downhill) than in Bore 1 (uphill). For example, Sb EFs (mg/veh-km) were 0.09±0.16 in Bore 2 and 0.04±0.10 in Bore 1. This supports the reasoning, mentioned previously, that brake wear contributed to downhill emissions.

Figure 5. Average chemical speciation of $PM_{2.5}$ emitted inside the LLT.



Finally, the OC/EC ratio is a characteristic tracer of anthropogenic sources where fuel combustion occurs. Thus, this ratio can give information on the source of the measured OC; i.e., it could be from primary (vehicles) or secondary sources.[12] An OC/EC ratio with values between 1 and 3 gives indication of a high probability that the OC and EC emissions come exclusively from mobile sources. In this study, average OC/EC values of 2.85±0.79 (R^2=0.71) and 1.19±0.65 (R^2=0.94) was obtained for heavy and moderate traffic conditions, respectively. The OC/EC ratio is lower in moderate traffic because vehicles move at higher speeds, which causes more efficient fuel consumption and therefore less OC emissions.

Table 4. LLT $PM_{2.5}$ profiles (%Wt)[a].

Specie	LLTHI1	LLTHO1	LLTMI1	LLTMO1	LLTHI2	LLTHO2	LLTMI2	LLTMO2
Cl^-	9.059±0.724	1.881±0.726	2.278±0.970	1.653±0.135	0.000±0.817	0.000±1.014	1.250±0.732	1.178±0.244
NO^-_3	4.660±0.317	1.978±0.728	8.756±0.621	2.932±0.236	2.484±0.171	3.136±0.214	6.131±0.426	4.160±0.344
SO4	32.261±2.257	23.646±1.641	40.015±2.717	19.303±1.638	23.421±1.536	30.185±1.966	30.436±1.964	20.547±1.440
Na^+	173.859±11.739	100.490±6.549	115.349±7.472	69.427±5.555	50.940±3.360	71.969±4.938	77.518±5.343	40.637±3.024
NH^+_4	0.000±2.342	0.000±1.315	0.000±1.616	0.000±1.068	0.000±0.817	0.000±1.014	0.647±0.951	0.785±0.545
K	1.401±2.047	0.000±1.315	0.000±1.616	0.000±1.068	0.000±0.817	0.000±1.014	0.000±1.101	0.000±0.765
OC	67.700±8.671	82.986±7.488	62.563±6.818	46.802±5.458	34.836±3.642	52.686±5.008	55.348±5.345	38.385±3.853
EC	16.140±6.190	26.544±4.243	11.273±4.274	16.575±3.390	8.019±2.269	12.198±2.878	9.455±2.965	9.722±2.218
Na	2.766±1.140	2.500±0.948	3.113±0.885	1.697±0.777	3.360±1.025	2.320±1.011	3.230±1.070	2.693±0.788
Mg	0.033±0.212	0.220±0.231	0.614±0.251	0.113±0.153	0.367±0.262	0.000±0.149	0.124±0.237	0.232±0.198
Al	0.000±0.185	0.000±0.105	0.000±0.121	0.000±0.086	0.000±0.11	0.000±0.135	0.000±0.153	0.000±0.113
Si	0.000±0.158	0.000±0.100	0.000±0.105	0.000±0.080	0.000±0.092	0.000±0.127	0.000±0.150	0.000±0.129
P	0.007±0.035	0.059±0.021	0.016±0.025	0.041±0.017	0.018±0.022	0.019±0.026	0.014±0.028	0.019±0.021
S	2.264±0.211	1.760±0.159	3.073±0.249	1.267±0.135	3.377±0.243	4.287±0.304	3.918±0.302	2.786±0.242
Cl	0.251±0.065	0.157±0.035	0.040±0.041	0.011±0.027	0.017±0.034	0.012±0.040	0.050±0.044	0.021±0.031
K	0.132±0.048	0.086±0.028	0.144±0.035	0.056±0.025	0.036±0.024	0.015±0.030	0.116±0.040	0.105±0.034
Ca	0.000±0.592	0.000±0.381	0.000±0.396	0.000±0.301	0.000±0.205	0.000±0.294	0.000±0.343	0.000±0.299
Ti	0.030±0.014	0.023±0.008	0.039±0.010	0.023±0.007	0.029±0.009	0.082±0.013	0.055±0.013	0.078±0.011
V	0.000±0.013	0.004±0.006	0.013±0.009	0.005±0.006	0.022±0.008	0.042±0.010	0.003±0.011	0.010±0.007
Cr	0.000±0.014	0.004±0.008	0.000±0.010	0.000±0.007	0.007±0.009	0.012±0.010	0.004±0.011	0.010±0.008
Mn	0.004±0.022	0.013±0.012	0.000±0.016	0.019±0.010	0.016±0.014	0.004±0.016	0.018±0.018	0.009±0.012
Fe	0.690±0.097	0.995±0.103	0.987±0.100	0.851±0.090	1.202±0.100	2.640±0.209	1.568±0.138	2.280±0.192
Co	0.005±0.047	0.000±0.026	0.000±0.032	0.000±0.023	0.000±0.028	0.063±0.037	0.000±0.037	0.016±0.029
Ni	0.039±0.045	0.142±0.030	0.082±0.032	0.039±0.022	0.039±0.027	0.071±0.032	0.037±0.035	0.026±0.025
Cu	0.261±0.046	0.204±0.027	0.268±0.035	0.131±0.023	0.212±0.029	0.316±0.037	0.263±0.038	0.206±0.028
Zn	0.045±0.055	0.421±0.227	0.113±0.040	0.053±0.026	0.074±0.033	0.144±0.042	0.181±0.046	0.126±0.033
Ga	0.025±0.030	0.018±0.017	0.033±0.022	0.007±0.014	0.020±0.018	0.013±0.022	0.016±0.024	0.019±0.016
Ge	0.044±0.035	0.024±0.019	0.045±0.023	0.009±0.016	0.038±0.018	0.018±0.023	0.015±0.026	0.036±0.017
As	0.044±0.038	0.027±0.021	0.097±0.021	0.025±0.016	0.039±0.022	0.020±0.028	0.021±0.029	0.052±0.020
Se	0.048±0.032	0.037±0.017	0.040±0.023	0.012±0.015	0.031±0.019	0.025±0.022	0.011±0.024	0.024±0.018
Br	0.101±0.025	0.037±0.014	0.048±0.018	0.011±0.011	0.025±0.014	0.018±0.017	0.021±0.019	0.030±0.013
Rb	0.003±0.032	0.058±0.017	0.017±0.021	0.045±0.015	0.032±0.019	0.040±0.022	0.039±0.024	0.038±0.017
Sr	0.046±0.036	0.000±0.019	0.029±0.025	0.032±0.017	0.027±0.021	0.000±0.025	0.036±0.028	0.037±0.019
Y	0.189±0.043	0.012±0.022	0.063±0.030	0.013±0.019	0.027±0.024	0.046±0.029	0.041±0.033	0.039±0.022
Zr	0.146±0.049	0.050±0.027	0.096±0.035	0.060±0.022	0.095±0.029	0.097±0.034	0.158±0.038	0.071±0.026
Mo	0.220±0.072	0.084±0.038	0.085±0.049	0.034±0.032	0.062±0.042	0.000±0.049	0.053±0.054	0.025±0.037
Pd	0.122±0.114	0.017±0.062	0.008±0.079	0.076±0.054	0.000±0.068	0.048±0.082	0.075±0.089	0.003±0.062
Ag	0.165±0.108	0.067±0.060	0.144±0.076	0.030±0.049	0.046±0.065	0.072±0.078	0.147±0.084	0.027±0.058
Cd	0.129±0.103	0.028±0.057	0.058±0.072	0.045±0.048	0.043±0.062	0.191±0.078	0.049±0.080	0.046±0.056
In	0.000±0.107	0.000±0.059	0.018±0.075	0.023±0.049	0.021±0.064	0.009±0.078	0.000±0.085	0.002±0.060
Sn	0.119±0.131	0.027±0.073	0.202±0.096	0.035±0.061	0.156±0.082	0.157±0.100	0.141±0.106	0.084±0.074
Sb	0.222±0.153	0.102±0.084	0.089±0.109	0.103±0.072	0.182±0.094	0.273±0.112	0.087±0.123	0.235±0.087
Ba	0.000±0.049	0.022±0.026	0.000±0.033	0.014±0.023	0.008±0.030	0.082±0.037	0.022±0.039	0.057±0.029
La	0.005±0.030	0.000±0.017	0.009±0.021	0.000±0.014	0.000±0.019	0.014±0.023	0.000±0.024	0.000±0.018
Hg	0.151±0.072	0.071±0.038	0.039±0.051	0.044±0.032	0.033±0.040	0.037±0.048	0.112±0.054	0.017±0.040
Pb	0.109±0.066	0.091±0.036	0.044±0.046	0.029±0.030	0.061±0.039	0.083±0.046	0.114±0.051	0.072±0.036
Sum	139.638±11.439	144.393±9.084	134.552±8.936	92.218±6.863	78.483±4.909	109.475±6.46	114.006±6.754	84.305±4.88

[a] LLT: Loma Larga Tunnel, H: Heavy Traffic, M: Moderate Traffic, I: Inlet, O: Outlet, 1: Bore 1, 2: Bore 2. For example, LLTHI1: Loma Larga Tunnel, Heavy Traffic, Intlet, Bore 1.

Table 5. EFs for different species contained in the $PM_{2.5}$ for several tunnel studies (mg/veh-km).

	LLT			Los Angeles[5]	Denver[17]	Los Angeles[18]	Vienna[19]	Vilnius[6]
Species	Bore 1	Bore 2	Average					
Na	0.3903±0.9688	1.6136±2.1803	1.0019±1.5745	0.30±1.17	0.200	0.0200		
Mg	0.1020±0.2009	0.1247±0.3549	0.1134±0.2779	0.26±0.29	0.170	0.0500		
Al	0.0000±0.1303	0±0.1944	0±0.1623	0.22±0.15	0.080	0.0300		
Si	0.0000±0.1168	0±0.1929	0±0.1549	0.56±0.12	1.260	0.4800		
P	0.0269±0.0252	0.0136±0.0348	0.0202±0.03	0.09±0.15	0.110	0.1700		
S	0.1603±0.1882	0.0505±0.1945	0.1054±0.1914	0.32±0.56	1.330	0.4000		
Cl	0.0389±0.0472	0.0239±0.0639	0.0314±0.0556	0.32±0.18	0.240	0.1800		
K	0.0131±0.0334	0.0194±0.053	0.0162±0.0432	0.08±0.07	0.020	0.0200		
Ca	0.0000±0.4429	0±0.4427	0±0.4428	0.30±0.07	0.190	0.2600		
Ti	0.0039±0.0107	0.0332±0.0176	0.0186±0.0142	0.09±0.50	0.002	0.0002		
V	0.0014±0.0079	0.0073±0.013	0.0044±0.0105	0.05±0.21	0.002	0.0003	0.0010±0.0007	
Cr	0.0013±0.0101	0.0058±0.014	0.0035±0.012	0.02±0.05	0.010	0.0030		
Mn	0.0094±0.0152	0.0019±0.0196	0.0056±0.0174	0.02±0.03	0.004	0.0020		0.020±0.006
Fe	0.2903±0.1054	0.7262±0.2438	0.5082±0.1746	2.79±0.29	0.720	0.4600		
Co	0.0000±0.0313	0.0239±0.0495	0.012±0.0404	0.00±0.10	0.000			
Ni	0.0463±0.0311	0.0297±0.0434	0.038±0.0372	0.01±0.02	0.010	0.0100	0.0018±0.0021	
Cu	0.0287±0.0298	0.065±0.0583	0.0469±0.0441	0.17±0.02	0.020	0.0100	0.0302±0.0202	0.061±0.009
Zn	0.1370±0.1074	0.0222±0.058	0.0796±0.0827	0.14±0.02	0.170	0.3400	0.0342±0.0299	0.092±0.026
Ga	0.0045±0.0165	0.0156±0.0248	0.01±0.0206	0.01±0.04				
Ge	0.0118±0.0239	0.0162±0.0325	0.014±0.0282					
As	0.0193±0.0244	0.0212±0.0401	0.0202±0.0323	0.00±0.05				
Se	0.0096±0.0235	0.0155±0.0302	0.0126±0.0268	0.00±0.02				
Br	0.0090±0.0204	0.0099±0.0203	0.0095±0.0203	0.01±0.02	0.020	0.0010		
Rb	0.0285±0.0216	0.0113±0.0298	0.0199±0.0257	0.00±0.02				
Sr	0.0087±0.0250	0.0157±0.0341	0.0122±0.0295	0.02±0.02				
Y	0.0292±0.0445	0.0292±0.0445	0.0292±0.0445	0.00±0.03				
Zr	0.0116±0.0351	0.0153±0.0469	0.0134±0.041	0.01±0.03				
Mo	0.0624±0.0432	0.0188±0.0762	0.0406±0.0597	0.01±0.06	0.000	0.0010		
Pd	0.0358±0.0803	0.0225±0.1173	0.0292±0.0988	0.02±0.18	0.010	0.0003		
Ag	0.0107±0.0774	0.0238±0.1004	0.0172±0.0889	0.04±0.20				
Cd	0.0318±0.0906	0.071±0.1005	0.0514±0.0955	0.02±0.22	0.010	0.0000		
In	0.0048±0.0736	0.0005±0.1107	0.0026±0.0921					
Sn	0.0009±0.0715	0.0593±0.1109	0.0301±0.0912	0.10±0.31	0.010	0.0010		
Sb	0.0398±0.1000	0.0883±0.1605	0.0641±0.1303	0.15±0.37	0.010	0.0020		
Ba	0.0100±0.0334	0.0399±0.0516	0.025±0.0425	0.36±1.37	0.160	0.0400		0.102±0.008
La	0.0000±0.0220	0.0046±0.0314	0.0023±0.0267	0.00±1.83	0.040	0.0100		
Hg	0.0218±0.0467	0.0127±0.0655	0.0173±0.0561	0.01±0.05				
Pb	0.0323±0.0476	0.0209±0.0605	0.0266±0.0541	0.03±0.06	0.100	0.0200	0.0095±0.0067	0.035±0.006
Cl-	0.9997±0.8886	0.2375±1.3701	0.6186±1.1294	0.67±0.99				
NO-3	0.3926±0.2267	0.2727±0.7594	0.3326±0.493	3.27±1.17				
SO42-	1.4603±1.8556	0.8476±3.8138	1.154±2.8347	1.77±2.06			2.3000±0.8000	
Na+	5.7322±7.7912	2.1999±6.5501	3.9661±7.1707	0.35±0.16				
NH4+	0.0000±1.6037	0.0737±1.5135	0.0368±1.5586	1.61±1.06			1.2000±0.4000	
K+	0.0000±1.6566	0±1.829	0±1.7428	0.10±0.08				
OC	17.706±8.3563	7.5118±8.361	12.6089±8.3586	19.27±8.46			12.2000±7.9612	
EC	8.8581±5.0205	2.5155±5.096	5.6868±5.0583	25.50±4.98			27.5000±4.300	
TC	26.5843±11.4763	10.424±11.2027	18.5041±11.3395	44.26±11.26			39.7000±6.7000	

CONCLUSIONS

It is important for any region to have real-world data to establish confident air quality management strategies. The aim of this study was to estimate EFs of a typical gasoline-powered light duty vehicle fleet of the MMA (Mexico) by using a tunnel technique that allowed sampling a large number of vehicles. For the sampled fleet, the estimated EFs (mg/veh-km) for CO_2 were higher than those reported in other tunnel studies, while for $PM_{2.5}$ the values tended to be lower. The effect of the tunnel grade can be relevant; uphill EFs for CO_2 were higher than downhill, while for $PM_{2.5}$ downhill

EFs were higher than uphill. As expected, $PM_{2.5}$ emissions were mainly composed of OC and EC. The results showed a high correlation between OC and EC species, whereas the OC/EC ratio gave indication that the $PM_{2.5}$ emissions came preferentially from mobile sources. This is the first study that has used the tunnel methodology for estimating EFs from mobile sources in the MMA. The results obtained are in good agreement with those obtained in other tunnel studies and can be complementary to those obtained by other techniques such as chassis dynamometer tests to derive a better emissions inventory for the MMA. In addition, the $PM_{2.5}$ chemical profiles obtained can be used as local source profiles in receptor model studies, such as the ones that use the Chemical Mass Balance (CMB) receptor model, in order to obtain more realistic source contributions to receptor concentrations.

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KEYWORDS

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