2010

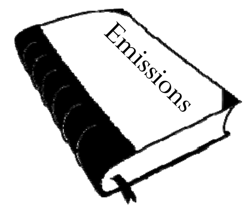
A Tunnel Study to Characterize $PM_{2.5}$ Emissions from Light-Duty Vehicles in Monterrey, Mexico

Yasmany Mancilla, Alejandro E. Araizaga and Alberto Mendoza
Department of Chemical Engineering, Tecnológico de Monterrey

Air Pollution and PM

- In Mexico City:

80% of air pollution



2000 Inventory

80% $PM_{2.5}$

- In other studies:
  - 38% of the $PM_{2.5}$ emissions come from vehicles, and
  - 74% of these are emitted from gasoline-powered LD vehicles.

- Fine Particulate Matter:

Exhaust

Brake Wear

Dust Resuspension

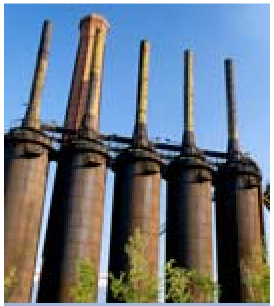
$PM_{2.5}$

Health

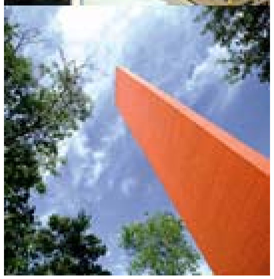
Climate

Visibility

Monterrey Metropolitan Area (MMA)







- 3.8 million inhabitants in 2005
- Territory of 573 km^2
- The third largest urban center

What is the aim of this tunnel study?

High Contribution of vehicle emissions

↓

Conduct local studies

↓

OBJECTIVE:

Emission Factors and Chemical Profiles

Measurement techniques

NOT DEFINED STANDARD PROTOCOL

LOW COST

FLEET-AVERAGE RESULTS

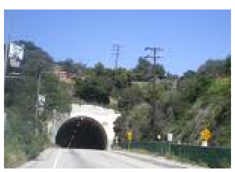
LARGE SAMPLES

LIMITED SAMPLING CONDITIONS CONTROL

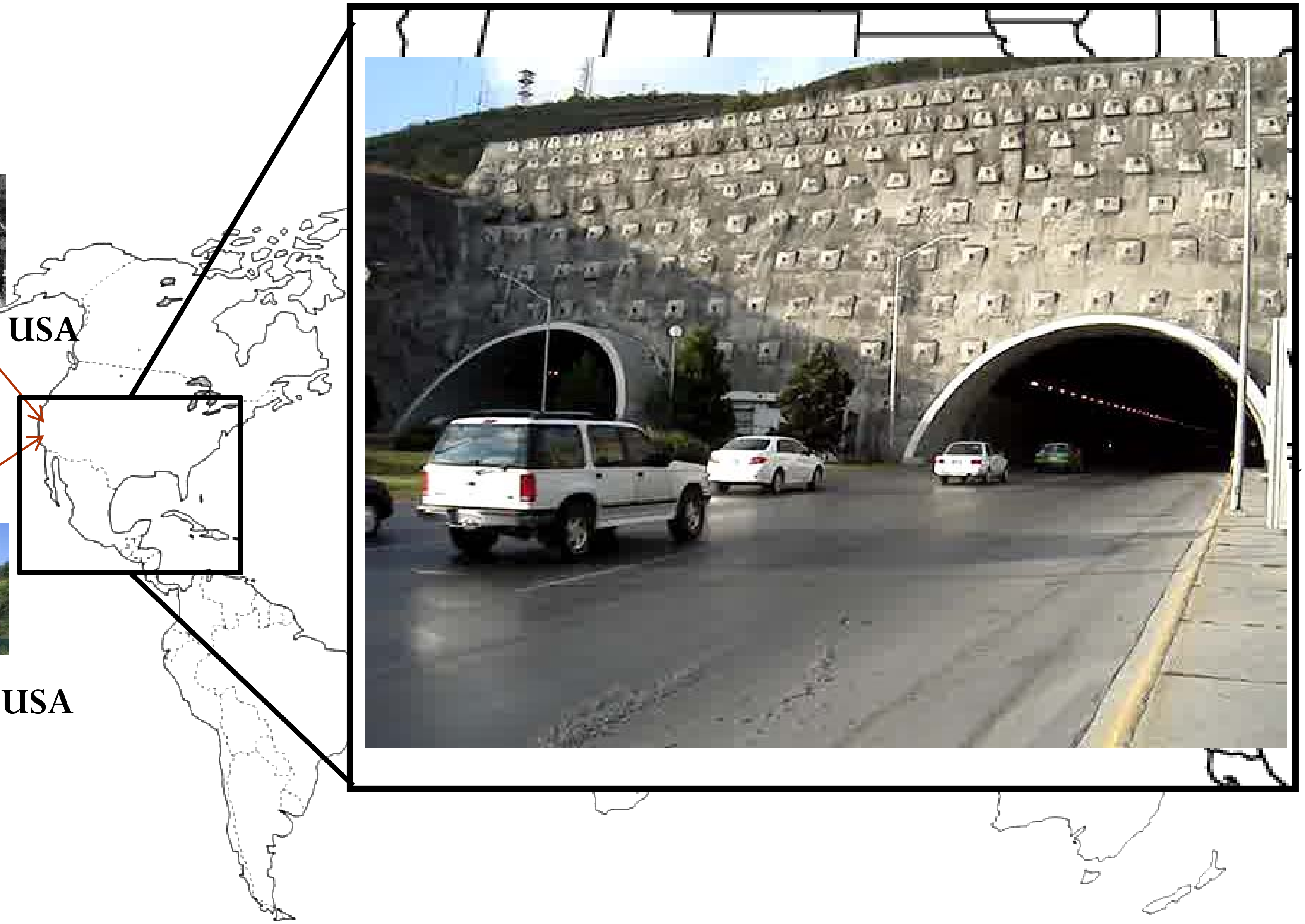
TUNNEL STUDY

$PM_{2.5}$ Tunnel studies around the world

San Francisco, USA



Los Angeles, USA



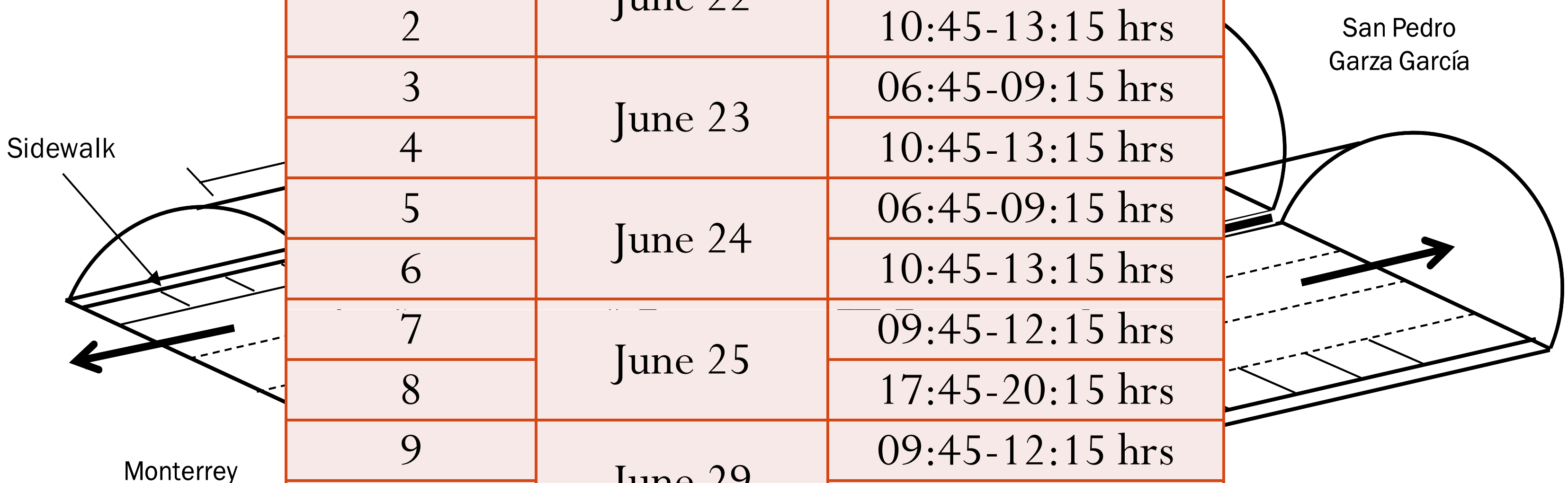
The Loma Larga Tunnel (LLT)

Cross-sectional Area of 113.5 m^2

±3.5% slope

2.5 h sampling periods

Period	Date	Time
1	June 22	06:45-09:15 hrs
2		10:45-13:15 hrs
3	June 23	06:45-09:15 hrs
4		10:45-13:15 hrs
5	June 24	06:45-09:15 hrs
6		10:45-13:15 hrs
7	June 25	09:45-12:15 hrs
8		17:45-20:15 hrs
9	June 29	09:45-12:15 hrs
10		16:45-19:15 hrs
11	June 30	09:45-12:15 hrs
12		16:45-19:15 hrs



Six non-consecutive days campaign (Summer 2009)

Materials and Devices

MiniVol Air Sampler

- 7.4 LPM for quartz filters
- 5.5 LPM for teflon filters

Filters

- Quartz: Cations, anions, OC and EC
- Teflon: Gravimetric analysis and 38 metals (XFR)

Testo 435 device

- Concentration of CO_2, pressure, temperature and %RH

Testo 425 device

- Thermal Anemometer

Devices on site

Emission Factor Estimation

EF: mass emitted per distance traveled per vehicle

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

Where:

- C_k = **Concentration of pollutant *k* at the exit, *e*, and inlet, *i*, sampling points.**
- V = **Air volumetric flow.**
- N = **Total number of vehicles that traverse during the sampling period.**
- L = **Distance between two sampling stations.**

More about EFs…

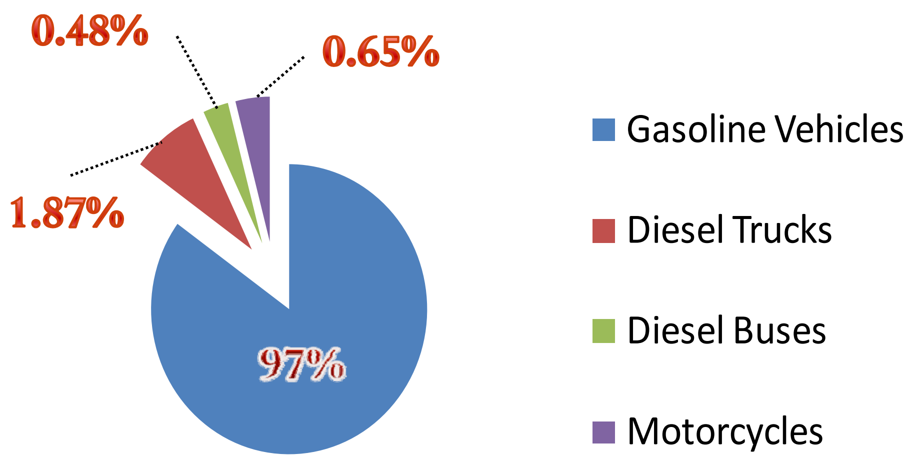
EF: mass emitted per volume of fuel burned

$$E'_k = \left(\frac{\Delta C_k}{\Delta C_{CO_2} + \Delta C_{CO} + \Delta C_{TNMOC}} \right) \cdot \rho_g w_c$$

Where:

- ΔC_k = Concentration difference of the species k between the two sampling points.
- ΔC_{CO2}, ΔC_{CO} and ΔC_{TNMOC} = Carbon-equivalent concentration differences for CO_2, CO and Total Non-Methane Organic Compounds.
- w_c = Carbon mass fraction in the fuel (0.84, assuming C_8H_{18}).
- ρ_g = Density of gasoline (740 g/L).

Experimental Field Conditions

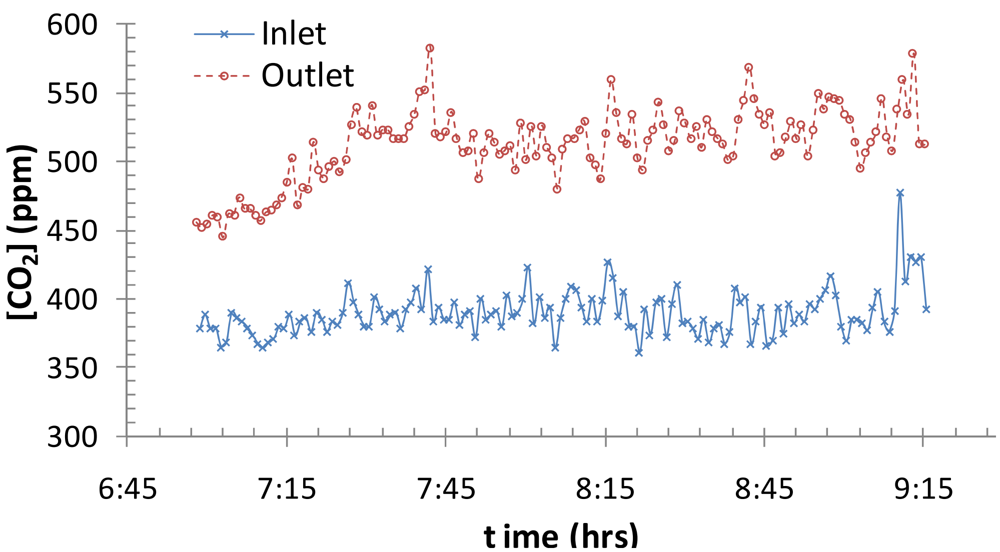


- Total of 108,569 vehicles
- 97% were gasoline-powered vehicles

- Average wind speeds inside the tunnel were 2.02 m/s and 2.27 m/s for heavy and moderate traffic.

- Average vehicle speeds were 48 km/h and 59 km/h for heavy and moderate traffic.

CO_2 Concentrations

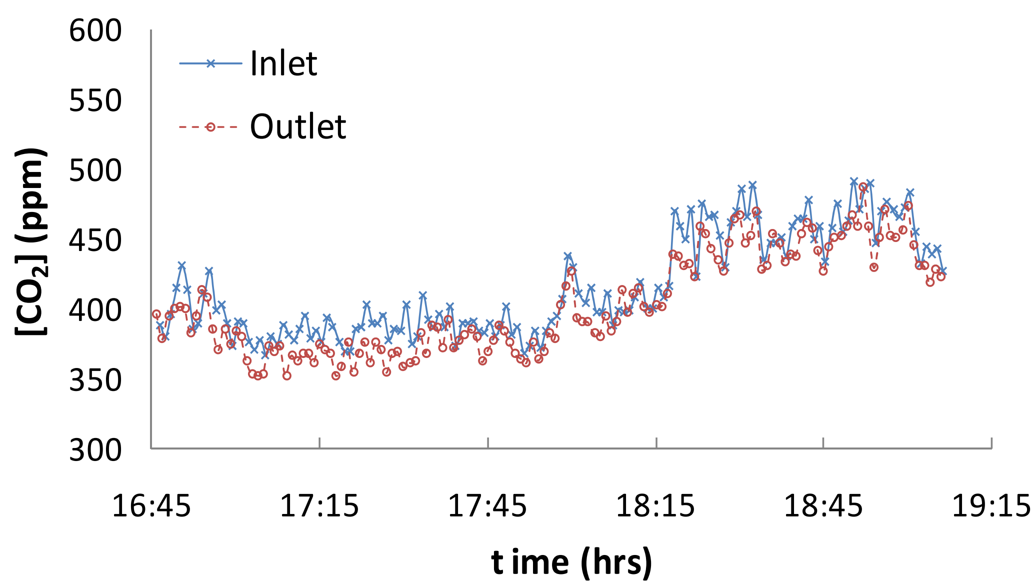


- June 22, Bore 1
- Expected behavior:

Outlet > Inlet

- June 29, Bore 2
- Concentration cross-over:

Outlet < Inlet



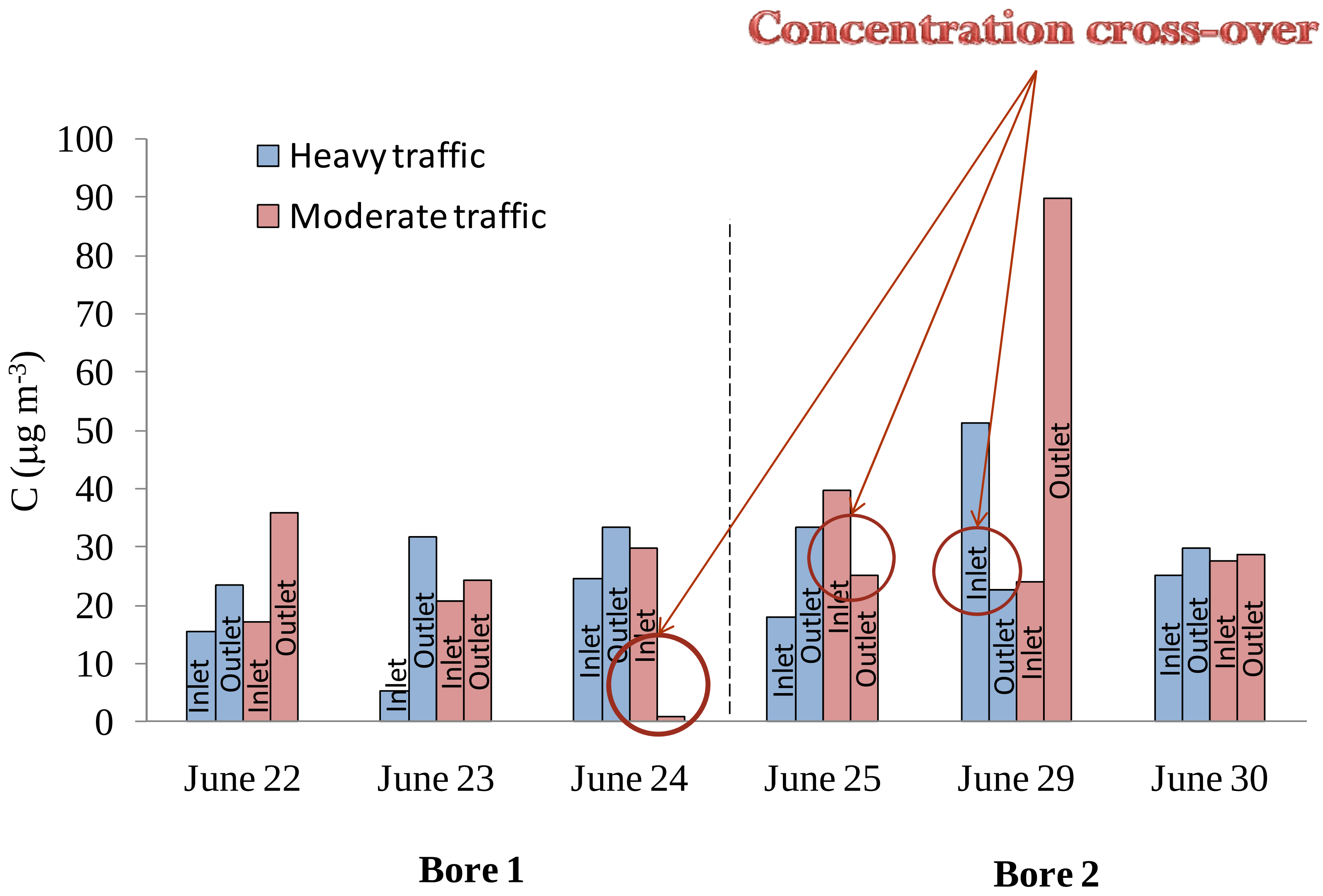
CO_2 EFs

❖CO_2 EFs comparison.

Tunnel	LD[a] (%)	Total Vehicles	V_s (km/h)	Grade	EF (g /veh-km)	EF (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	

Average Fuel Economy= 12.1±1.9 km/L

$PM_{2.5}$ Concentrations



$PM_{2.5}$ EFs

Bore	EF	
	mg/veh-km	mg/L
Monterrey-San Pedro (Uphill)	13.3 ± 6.3	160 ± 77
San Pedro-Monterrey (Downhill)	21.7 ± 9.5	130 ± 173

- $PM_{2.5}$ emissions in Bore 1 (uphill) $\leq$ in Bore 2 (downhill)
- Vehicles downhill tend to emit $PM_{2.5}$ from brake wear

E.g. *Sb* EFs (mg/veh-km) were 0.04 in Bore 1 and 0.09 in Bore 2

- These EFs were corrected by dust resuspension

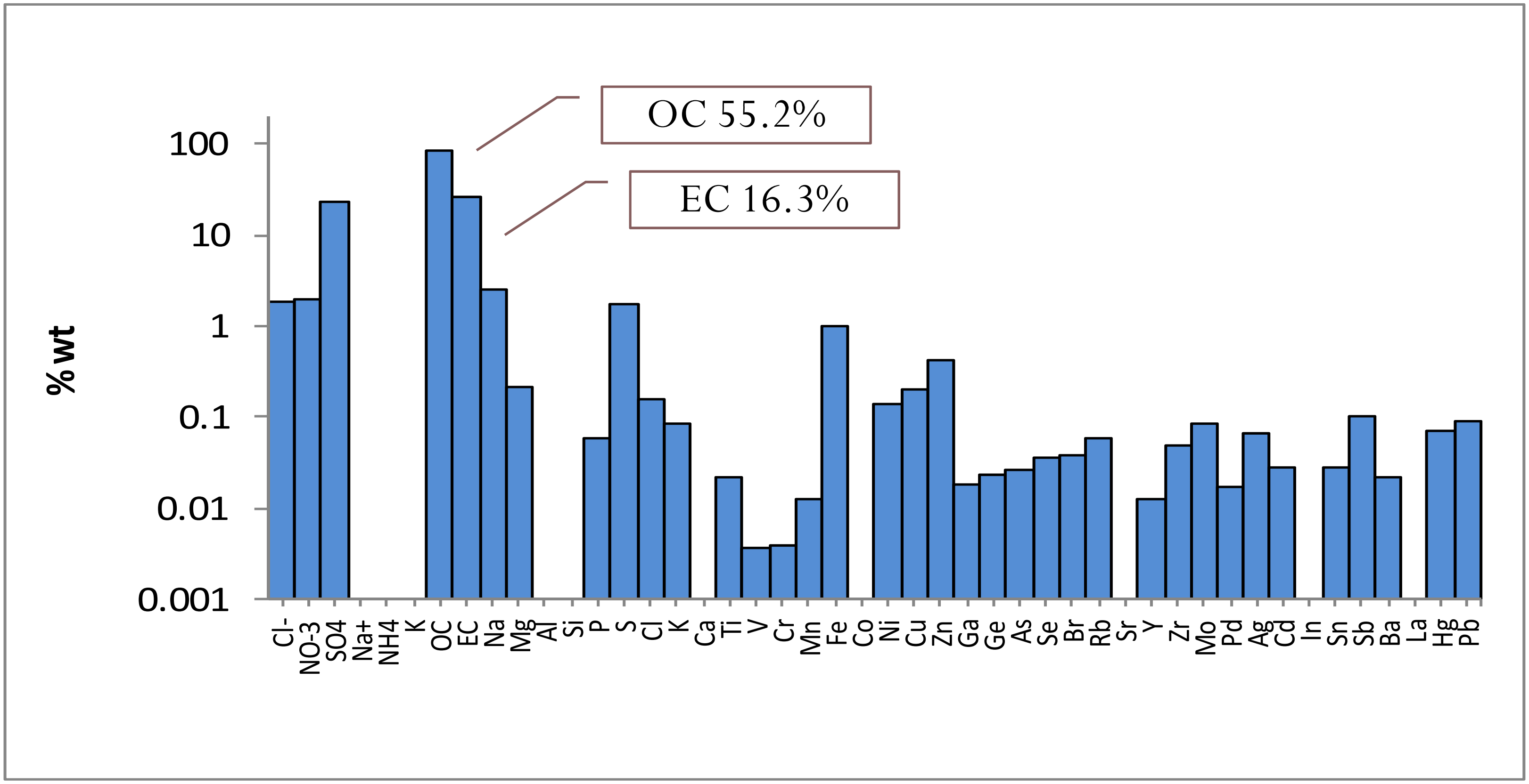
$PM_{2.5}$ EFs

- Comparison between the LLT and other tunnel studies (mg/veh-km).

LLT	Caldecott[4] (San Francisco)		Shing Mung[8] (Hong Kong)		Wolloon-gabba[15] (Brisbane)	Sepulveda[5] (Los Angeles)	Söderleds[7] (Stockholm)	Kilborn/ Howell[16] (Milwau-kee)
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

Chemical Profile

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



Average OC/EC: 2.85±0.79 and 1.19±0.65 for heavy and moderate traffic.

Specie	TLLAE1	TLLAS1	TLLME1	TLLMS1	TLLAE2	TLLAS2	TLLME2	TLLMS2
Cl^-	9.0593 ± 0.7242	1.8807 ± 0.7258	2.2777 ± 0.9699	1.6533 ± 0.1354	0.0000 ± 0.8166	0.0000 ± 1.0145	1.2499 ± 0.7318	1.1778 ± 0.2439
NO^{-3}	4.6604 ± 0.3166	1.9778 ± 0.7280	8.7559 ± 0.6207	2.9323 ± 0.2363	2.4844 ± 0.1709	3.1359 ± 0.2137	6.1310 ± 0.4259	4.1599 ± 0.3436
SO_4^{2-}	32.2606 ± 2.2567	23.6461 ± 1.6411	40.0155 ± 2.7166	19.3032 ± 1.6384	23.4213 ± 1.5359	30.1850 ± 1.9660	30.4358 ± 1.9636	20.5469 ± 1.4400
NH_4^+	0.0000 ± 2.3421	0.0000 ± 1.3150	0.0000 ± 1.6160	0.0000 ± 1.0680	0.0000 ± 0.8166	0.0000 ± 1.0145	0.6471 ± 0.9514	0.7847 ± 0.5454
K^+	1.4012 ± 2.0470	0.0000 ± 1.3150	0.0000 ± 1.6161	0.0000 ± 1.0680	0.0000 ± 0.8166	0.0000 ± 1.0145	0.0000 ± 1.1010	0.0000 ± 0.7648
OC	67.7000 ± 8.6714	82.9863 ± 7.4879	62.5632 ± 6.8183	46.8022 ± 5.4575	34.8361 ± 3.6420	52.6864 ± 5.0078	55.3482 ± 5.3454	38.3850 ± 3.8529
EC	16.1403 ± 6.1903	26.5438 ± 4.2426	11.2726 ± 4.2742	16.5755 ± 3.3898	8.0188 ± 2.2686	12.1984 ± 2.8776	9.4552 ± 2.9651	9.7221 ± 2.2185
Na	2.7664 ± 1.1400	2.4998 ± 0.9475	3.1131 ± 0.8852	1.6973 ± 0.7771	3.3600 ± 1.0250	2.3198 ± 1.0114	3.2301 ± 1.0701	2.6927 ± 0.7878
Mg	0.0331 ± 0.2122	0.2202 ± 0.2309	0.6142 ± 0.2513	0.1133 ± 0.1528	0.3675 ± 0.2620	0.0000 ± 0.1488	0.1239 ± 0.2368	0.2316 ± 0.1981
Al	0.0000 ± 0.1852	0.0000 ± 0.1051	0.0000 ± 0.1210	0.0000 ± 0.0864	0.0000 ± 0.1098	0.0000 ± 0.1354	0.0000 ± 0.1526	0.0000 ± 0.1130
Si	0.0000 ± 0.1579	0.0000 ± 0.0999	0.0000 ± 0.1054	0.0000 ± 0.0797	0.0000 ± 0.0925	0.0000 ± 0.1265	0.0000 ± 0.1501	0.0000 ± 0.1289
P	0.0073 ± 0.0348	0.0588 ± 0.0211	0.0165 ± 0.0250	0.0414 ± 0.0174	0.0183 ± 0.0221	0.0193 ± 0.0261	0.0138 ± 0.0282	0.0192 ± 0.0206
S	2.2639 ± 0.2114	1.7602 ± 0.1588	3.0733 ± 0.2495	1.2670 ± 0.1346	3.3767 ± 0.2433	4.2871 ± 0.3037	3.9178 ± 0.3022	2.7859 ± 0.2419
Cl	0.2511 ± 0.0651	0.1568 ± 0.0347	0.0402 ± 0.0407	0.0107 ± 0.0266	0.0169 ± 0.0336	0.0123 ± 0.0397	0.0496 ± 0.0444	0.0214 ± 0.0310
K	0.1318 ± 0.0483	0.0860 ± 0.0280	0.1445 ± 0.0345	0.0556 ± 0.0246	0.0361 ± 0.0243	0.0153 ± 0.0303	0.1159 ± 0.0399	0.1052 ± 0.0339
Ca	0.0000 ± 0.5919	0.0000 ± 0.3807	0.0000 ± 0.3958	0.0000 ± 0.3008	0.0000 ± 0.2047	0.0000 ± 0.2942	0.0000 ± 0.3433	0.0000 ± 0.2992
Ti	0.0302 ± 0.0141	0.0225 ± 0.0081	0.0386 ± 0.0099	0.0226 ± 0.0072	0.0291 ± 0.0086	0.0816 ± 0.0125	0.0547 ± 0.0127	0.0777 ± 0.0114
V	0.0000 ± 0.0132	0.0037 ± 0.0065	0.0129 ± 0.0087	0.0047 ± 0.0061	0.0217 ± 0.0081	0.0420 ± 0.0101	0.0027 ± 0.0106	0.0100 ± 0.0074
Cr	0.0000 ± 0.0142	0.0039 ± 0.0079	0.0000 ± 0.0104	0.0000 ± 0.0065	0.0069 ± 0.0095	0.0116 ± 0.0104	0.0044 ± 0.0112	0.0105 ± 0.0081
Mn	0.0036 ± 0.0222	0.0126 ± 0.0121	0.0000 ± 0.0158	0.0187 ± 0.0098	0.0159 ± 0.0136	0.0040 ± 0.0157	0.0185 ± 0.0177	0.0092 ± 0.0118
Fe	0.6896 ± 0.0971	0.9947 ± 0.1026	0.9865 ± 0.1000	0.8509 ± 0.0896	1.2022 ± 0.1001	2.6402 ± 0.2094	1.5680 ± 0.1383	2.2797 ± 0.1924
Co	0.0050 ± 0.0473	0.0000 ± 0.0261	0.0000 ± 0.0325	0.0000 ± 0.0229	0.0000 ± 0.0280	0.0629 ± 0.0368	0.0000 ± 0.0367	0.0155 ± 0.0287
Ni	0.0393 ± 0.0455	0.1424 ± 0.0296	0.0825 ± 0.0320	0.0393 ± 0.0216	0.0388 ± 0.0269	0.0707 ± 0.0322	0.0369 ± 0.0352	0.0256 ± 0.0251
Cu	0.2613 ± 0.0462	0.2037 ± 0.0272	0.2684 ± 0.0353	0.1308 ± 0.0227	0.2120 ± 0.0295	0.3156 ± 0.0374	0.2626 ± 0.0378	0.2059 ± 0.0278
Zn	0.0451 ± 0.0546	0.4212 ± 0.2274	0.1128 ± 0.0405	0.0526 ± 0.0263	0.0743 ± 0.0329	0.1438 ± 0.0420	0.1814 ± 0.0464	0.1261 ± 0.0331
Ga	0.0253 ± 0.0302	0.0183 ± 0.0169	0.0328 ± 0.0224	0.0067 ± 0.0141	0.0203 ± 0.0181	0.0134 ± 0.0215	0.0159 ± 0.0239	0.0190 ± 0.0163
Ge	0.0439 ± 0.0345	0.0238 ± 0.0188	0.0451 ± 0.0228	0.0094 ± 0.0157	0.0380 ± 0.0182	0.0183 ± 0.0233	0.0154 ± 0.0265	0.0364 ± 0.0168
As	0.0440 ± 0.0385	0.0266 ± 0.0211	0.0973 ± 0.0215	0.0250 ± 0.0159	0.0388 ± 0.0217	0.0203 ± 0.0275	0.0209 ± 0.0291	0.0525 ± 0.0198
Se	0.0477 ± 0.0323	0.0368 ± 0.0171	0.0398 ± 0.0227	0.0123 ± 0.0145	0.0315 ± 0.0191	0.0245 ± 0.0221	0.0110 ± 0.0239	0.0235 ± 0.0177
Br	0.1008 ± 0.0255	0.0375 ± 0.0141	0.0480 ± 0.0178	0.0108 ± 0.0109	0.0246 ± 0.0143	0.0177 ± 0.0169	0.0210 ± 0.0185	0.0301 ± 0.0134
Rb	0.0034 ± 0.0318	0.0578 ± 0.0173	0.0174 ± 0.0214	0.0451 ± 0.0149	0.0321 ± 0.0190	0.0398 ± 0.0222	0.0387 ± 0.0240	0.0381 ± 0.0170
Sr	0.0458 ± 0.0356	0.0000 ± 0.0193	0.0292 ± 0.0250	0.0316 ± 0.0167	0.0269 ± 0.0210	0.0000 ± 0.0247	0.0361 ± 0.0283	0.0366 ± 0.0194
Y	0.1887 ± 0.0430	0.0123 ± 0.0222	0.0628 ± 0.0298	0.0134 ± 0.0194	0.0268 ± 0.0244	0.0456 ± 0.0287	0.0410 ± 0.0325	0.0393 ± 0.0222
Zr	0.1464 ± 0.0492	0.0496 ± 0.0266	0.0959 ± 0.0349	0.0601 ± 0.0222	0.0951 ± 0.0294	0.0967 ± 0.0336	0.1578 ± 0.0378	0.0707 ± 0.0260
Mo	0.2202 ± 0.0719	0.0840 ± 0.0378	0.0848 ± 0.0493	0.0338 ± 0.0315	0.0617 ± 0.0418	0.0000 ± 0.0486	0.0535 ± 0.0543	0.0251 ± 0.0375
Pd	0.1222 ± 0.1137	0.0167 ± 0.0620	0.0075 ± 0.0791	0.0763 ± 0.0537	0.0000 ± 0.0684	0.0479 ± 0.0818	0.0746 ± 0.0887	0.0028 ± 0.0625
Ag	0.1652 ± 0.1079	0.0667 ± 0.0596	0.1441 ± 0.0758	0.0299 ± 0.0488	0.0464 ± 0.0645	0.0717 ± 0.0780	0.1473 ± 0.0844	0.0272 ± 0.0583
Cd	0.1291 ± 0.1028	0.0279 ± 0.0567	0.0583 ± 0.0717	0.0453 ± 0.0484	0.0428 ± 0.0617	0.1913 ± 0.0776	0.0486 ± 0.0796	0.0456 ± 0.0561
In	0.0000 ± 0.1072	0.0000 ± 0.0592	0.0184 ± 0.0749	0.0232 ± 0.0491	0.0205 ± 0.0642	0.0092 ± 0.0779	0.0000 ± 0.0852	0.0019 ± 0.0597
Sn	0.1194 ± 0.1308	0.0273 ± 0.0731	0.2019 ± 0.0957	0.0345 ± 0.0608	0.1561 ± 0.0819	0.1574 ± 0.0995	0.1411 ± 0.1060	0.0837 ± 0.0744
Sb	0.2224 ± 0.1533	0.1019 ± 0.0837	0.0890 ± 0.1087	0.1031 ± 0.0722	0.1817 ± 0.0941	0.2730 ± 0.1123	0.0872 ± 0.1227	0.2348 ± 0.0873
Ba	0.0000 ± 0.0486	0.0221 ± 0.0264	0.0000 ± 0.0335	0.0136 ± 0.0229	0.0084 ± 0.0305	0.0823 ± 0.0373	0.0223 ± 0.0394	0.0568 ± 0.0290
La	0.0049 ± 0.0302	0.0000 ± 0.0169	0.0086 ± 0.0213	0.0000 ± 0.0145	0.0000 ± 0.0186	0.0137 ± 0.0228	0.0000 ± 0.0239	0.0000 ± 0.0176
Hg	0.1508 ± 0.0724	0.0709 ± 0.0380	0.0395 ± 0.0509	0.0440 ± 0.0318	0.0335 ± 0.0402	0.0375 ± 0.0484	0.1122 ± 0.0543	0.0172 ± 0.0400
Pb	0.1088 ± 0.0655	0.0909 ± 0.0360	0.0438 ± 0.0459	0.0287 ± 0.0296	0.0608 ± 0.0387	0.0832 ± 0.0457	0.1139 ± 0.0511	0.0718 ± 0.0358
Sum	139.6384 ± 11.4389	144.3926 ± 9.0841	134.5525 ± 8.9362	92.2182 ± 6.8631	78.4832 ± 4.9091	109.4755 ± 6.4599	114.0057 ± 6.7538	84.3054 ± 4.8802

Conclusions…

- To have a real-world data.
- EFs of a typical vehicle fleet of the MMA
- Tunnel technique → more confident results
- First tunnel study in MMA
- $PM_{2.5}$ EFs tended to be lower
- $PM_{2.5}$ profiles can be used in receptor models (e.g. CMB)
- $PM_{2.5}$ emissions were mainly composed of OC and EC
- OC/EC → primary sources

Acknowledgements

- Grant from the Mexican National Council for Science and Technology (CONACYT)

- Additional funding was provided by the Research Chair in Air Pollution Engineering (Tecnológico de Monterrey).

- Alejandro Araizaga received additional support (scholarship) through the Mexican Institute of Chemical Engineers (IMIQ) and Yasmany Mancilla through CONACYT.

- The support from the municipality of Monterrey during the field campaign conducted in this study.

THANK YOU!

Alberto Mendoza

mendoza.alberto@itesm.mx

TECNOLÓGICO DE MONTERREY

Departamento de Ingeniería Química

DEPARTMENT OF CHEMICAL ENGINEERING