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A NEW DATABASE OF ON-ROAD VEHICLE EMISSION FACTORS FOR COLOMBIA: A CASE STUDY OF BOGOTA

UNA NUEVA BASE DE DATOS PARA FACTORES DE EMISIÓN DE FUENTES MÓVILES EN COLOMBIA: UN CASO DE ESTUDIO PARA BOGOTÁ

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ABSTRACT

Mobile sources contribute directly or indirectly with most of the atmospheric emissions in Colombian cities. Quantification of mobile source emissions rely on emission factors (EF) and vehicle activity. However, EF for vehicles in the country have not evolved at the same time as fleet renovation and fuel composition changes in the last few years. In fact, estimated EF before 2010 may not reflect the reduction of sulfur content in diesel and the renovation and deterioration of passenger vehicles; therefore, emission levels may be over or under estimated. To account for these changes, we have implemented the MOVES model in Bogota and obtained a new database of on-road vehicle emission factors. For this purpose, local information of activity rates, speed profiles, vehicle population distribution and age, meteorology and fuel composition was used. Emissions were estimated with these new set of EF and compared with previous inventories. We observed large reductions in SO_2 (-87%), CO (-65%) and VOC (-62%) emissions from mobiles sources and lower reductions in NOx (-20%). Other pollutants such as $PM_{2.5}$ (+15%) and CO_2 (+28%) reported increases. This paper includes a new database of on-road vehicle emission factors for Bogota, which can be applied in other Colombian cities in the absence of local data.

RESUMEN

Las fuentes móviles emiten directa o indirectamente la mayor cantidad de contaminantes a la atmósfera en Colombia. La construcción de inventarios de emisiones de fuentes móviles requiere de factores de emisión (FE) e información de actividad vehicular. Sin embargo, los FE en el país no han sido ajustados adecuadamente a las nuevas condiciones de calidad de combustible y renovación del parque vehicular que ha ocurrido en los últimos años. En efecto, los FE estimados con anterioridad al año 2010 no reflejan la reducción del azufre en el combustible diésel ni la renovación o deterioro del parque vehicular. Con el fin de tener en cuenta éstos cambios se ha implementado en Bogotá el modelo MOVES, con el cual se ha obtenido una nueva base de datos de factores de emisión. El modelo requiere información local sobre actividad vehicular, distribución y edad del parque, perfiles de velocidad, meteorología y características del combustible. Los FE estimados con MOVES fueron comparados con los existentes a nivel local y se construyó un nuevo inventario. Se observa una reducción considerable en las emisiones de SO_2 (-87%), CO (-65%) y VOC (-62%) y una reducción menor en las emisiones de NOx (-20%). En el caso de $PM_{2.5}$ (+15%) y CO_2 (+28%) se registró un leve aumento. Este manuscrito pone a disposición del lector una nueva base de datos de FE para fuentes móviles en Bogotá, que podrían aplicarse en otras ciudades colombianas en ausencia de información local.

KEYWORDS / PALABRAS CLAVE

Emission Factors | Fuel composition | MOVES
Vehicle technology | Emission inventory.
Factores de emisión | Calidad de combustible
Modelo MOVES | Tecnología vehicular | Inventario emisiones.

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1 INTRODUCTION

Air pollution is a major problem worldwide and responsible for a large number of premature deaths and respiratory diseases [1]-[4]. Different policies have been established around the world to improve air quality, such as the use of cleaner fuels, better emission control technologies, alternative fuels for industry and mobile sources, among others [5]. In order to improve air quality in different countries, many agencies, industries and governments work together to create the partnership for clean fuels and vehicles [6],[7].

Bogota has established different policies and projects to mitigate and abate its air pollution problem, especially by organizing and improving its public transportation system. This is possible given the fuel quality available in Colombia since 2010 (50ppm of sulfur in diesel and 270ppm in gasoline) [8]. The city is also working in the implementation of emission control devices for mobile and point sources. To account for emission reductions in mobile sources, it is necessary to keep a reliable database of emission factors.

During the last decade, local studies have estimated emissions from mobile and point sources using emission factors (EF) from international references or obtained from emission models. For example, the International Vehicle Emission (IVE) model has been used to produce emission factors for Bogota [9],[10] and Cali [11]. In 2008, Bogota´s Environmental Agency (SDA) developed a ten-year air pollution abatement plan (PDDAB) [12], where emission factors from IVE were used. Additionally, local studies have measured exhaust emissions from a sample of vehicles and calculated EFs for the city [13],[14].

Emission factors (EF) for mobile sources have not evolved at the same time as fleet renovation and fuel composition changes in the country in recent years. For example, in 2008 the sulfur content in diesel was substantially reduced from 1,000 to 500 ppm and subsequently to 50 ppm in 2010 [15]. Emission factors found in the PDDAB were designed prior to 2009 and do not reflect any change in sulfur fuel composition. Similarly, emission factors for passenger vehicles in the PDDAB do not consider vehicle age and effects from renovation and deterioration on emission levels.

MOVES is the state-of-the-art model designed by the US-EPA to estimate EFs or inventories in project or county areas using local data [16]. MOVES has the capability to estimate the change in EF related to fuel reformulation, fleet age and composition, and local meteorology [17],[18]. This capability was the reason to choose MOVES for this project.

2. EXPERIMENTAL DEVELOPMENT

The MOVES model uses local information to estimate emissions and EF from mobile sources. We used the MOVES 2014a-20151201 version of the model. MOVES was executed in county mode and the input database included only local information: vehicle age (30 years from 1984-2014), number and activity (average kilometers traveled – activity factor (AF)), meteorology, fuel composition, road types and speed profiles. AF information was obtained from the local environmental agency [12]. The original vehicular database was processed to remove outliers. The vehicle activity was estimated using the total km travelled per vehicle and the vehicle age. Finally, the AF is the average of all vehicle activity reported by category. The bus rapid transit (BRT) was reported directly by Transmilenio S.A. Equation 1 summarizes the validation process.

$$AF_i = \frac{\sum_1^i \frac{TD}{VA}}{N_i} \qquad (1)$$

VA:Vehicle age (years)
TD: Travelled Distance (km)
AF_i: Activity factor vehicle i (km/year)
N_i: number of vehicles i

Vehicle number was taken from the Colombian vehicle database (RUNT) [19]. RUNT comprises every vehicle registration made in the country by municipality. This information was validated by the local environmental agency considering vehicle age, condition and registration place. The database was modified removing vehicles older than 50 years (not allowed to ride in Bogota), incomplete registrations and off-road machinery. Then the vehicles were aggregated per model year, fuel type and vehicle category (Table 1).

Fuel formulation was obtained from national regulations on fuel composition [15] and meteorological data (temperature and relative humidity) were obtained from the Bogota´s Air Quality Monitoring Network (RMCAB). Vehicle speed profiles were built from local traffic records in different corridors, which include only three vehicle categories: public transport (buses), private transport (taxis) and passenger vehicles [20]. Therefore, speed profiles for other vehicle types were assumed for the existing records, i.e., truck speed profiles from buses and motorcycle speed profiles form passenger vehicles. This assumption considers that short-haul trucks and buses ride on the same roads and have similar vehicular weight. Furthermore, motorcycles and commercial trucks used the same roads as passenger vehicles and are subjected to the same speed limits.

Once MOVES databases were built, a sensibility analysis was conducted to assess the impact of three input parameters in emission factors: i) meteorological variables: two months were selected, one of high temperature and one of low temperature; ii) fuel composition: 15 scenarios were used to estimate the effect of sulfur content, aromatic content, Reid vapor pressure (RVP) and distillation curves T50 and T90 changing a variable per model run; iii) emission generation processes: running exhaust, evaporation, fuel venting and running crankcase were evaluated for two vehicle categories (passenger vehicles and transit buses). This sensibility analysis was conducted to optimize model execution times and define fuel quality properties influencing emissions. Sensitivity analysis using biofuels (ethanol in gasoline and biodiesel) were out of the scope of this work, but local studies can be found anywhere else [21].

For MOVES application in Bogota, a standardization process was conducted between the US fleet and the local fleet based on vehicle characteristics such as passenger capacity, vehicle weight, engine

Table 1. Vehicle number and activity factors for Bogota. In Fuel D: Diesel, P: Petrol, VNG: Vehicle Natural Gas. Adapted from (SDA - Secretaría Distrital de Ambiente, 2015)

Category	Local Category	Fuel	Vehicle Number	FA (km/year)	Category	Local Category	Fuel	Vehicle Number	FA (km/year)
Public Bus	BN1	D	2,019	67,268	Truck	C6	VNG	6,868	22,300
Public Bus	BN3	D	608	67,268	Truck	C7	VNG	1,189	22,300
Public Bus	BN4	D	1,099	67,268	Public Bus	BE1	D	7,241	15,000
Public Bus	P1	D	428	67,290	Public Bus	BE2	P	191	15,000
Public Bus	P3	D	28	67,290	Public Bus	BE3	VNG	23	15,000
Public Bus	P4	D	1,360	67,290	Public Bus	BTE1	D	2,287	15,000
BRT	ART1	D	1,125	82,486	Public Bus	BTE2	P	299	15,000
BRT	ART3	D	203	82,486	Public Bus	BTE3	VNG	188	15,000
BRT	ART4	D	116	82,486	Public Bus	MBTE1	D	8,722	15,000
BRT	BART1	D	41	82,486	Public Bus	MBTE2	P	6,615	15,000
BRT	BART2	D	265	82,486	Public Bus	MBTE3	VNG	7,829	15,000
Public Bus	MB	D	712	69,000	Motorcycles	M1	P	5,541	15,000
Public Bus	B1	D	456	93,000	Motorcycles	M2	P	143,412	17,483
Public Bus	B3	D	394	93,000	Motorcycles	M3	P	278,609	17,483
Public Bus	B4	D	140	93,000	Taxis	T1	P	18,423	73,000
Public Bus	MB	D	4,000	69,000	Taxis	T2	VNG	33,713	73,000
Public Bus	B	D	750	93,000	Passenger vehicles	VP1	P	389,780	16,520
Passenger Truck	CC1	P	10,486	24,200	Passenger vehicles	VP2	P	389,780	16,520
Passenger Truck	CC2	P	7,950	24,200	Passenger vehicles	VP3	P	76,751	10,440
Passenger Truck	CC3	P	134	24,200	Passenger vehicles	VP4	P	76,751	10,440
Passenger Truck	CC4	VNG	2,253	17,800	Passenger vehicles	VP5	VNG	16,073	18,800
Passenger Truck	CC5	D	3,012	19,600	Light Com Truck	CC1	P	322,284	12,670
Passenger Truck	CC6	D	8,644	19,600	Light Com Truck	CC2	P	25,852	10,715
Truck	C1	D	3,172	29,000	Light Com Truck	CC3	P	25,852	10,715
Truck	C2	D	2,433	29,000	Light Com Truck	CC4	VNG	6,287	12,670
Truck	C3	D	42,368	29,000	Light Com Truck	CC5	D	18,953	12,670
Truck	C4	P	12,371	20,500	Light Com Truck	CC6	D	30,476	12,670
Truck	C5	P	4,455	20,500					

power and emission standard associated with emission control technologies. First, comparing vehicle size, activity and engine power between Bogota fleet and US fleet, six vehicle categories were selected to run MOVES. Once the vehicle categories were selected, it was necessary to standardize the vehicle age between MOVES and Bogota's fleet. Emission control systems are directly related to vehicle age in MOVES. Table A1 in the Annexes was built to ease future analysis in the city after comparing the emission standards between environmental agencies and the composition of the local fleet in Bogota.

Finally, MOVES was run with the local database and EFs were estimated for $PM_{2.5}$, PM_{10}, CO, SO_2, CO_2, NOx and VOC species. We used the Fuel Type and Model Year function to aggregate EFs per category, fuel type and model year of the previous 30 years to the baseline scenario (1984-2014) (Figure 1). The emission inventory was estimated outside of the MOVES model with local data.

EMISSION INVENTORY

Emission inventories for mobile sources in Bogota were built using local EFs available from the Environmental Authority. We estimated the inventory using EFs from MOVES and applying Equation 2.

$$Eij = EFij * AFi * Ni \tag{2}$$

E_{ij}: Annual Emission of vehicle i and pollutant j (g/year)

EF_{ij}: Emission factor for vehicle i and pollutant j (g/km) from MOVES

AF_i: Activity factor vehicle i (km/year)

N_i: number of vehicles i

As previously mentioned, EFij were estimated using MOVES and are available in the Annexes. Activity factors and number of vehicles were obtained from the local environmental agency as mentioned before.

3. RESULTS ANALYSIS

BACKGROUND INFORMATION

In order to run MOVES, a vehicle type equivalence analysis was necessary. Bogota has a mixed vehicle fleet between US, European and Asian brands. An equivalence between Bogota´s fleet and the US (used in the MOVES model) was performed: we compared vehicle weight and control emission technology to standardize vehicle categories, including motorcycles. A major difference in the bus fleet was found: US buses in MOVES (transit, intercity and school) are significantly larger than buses in Bogota, especially those outside the bus rapid transit (BRT) system. Most of the public transport fleet are small buses with engine power from 150 to 170 HP and capacity of 45 to 50 passengers [22],[23], in comparison with US buses typically 220 HP and with passenger capacity of 75 [24]. A

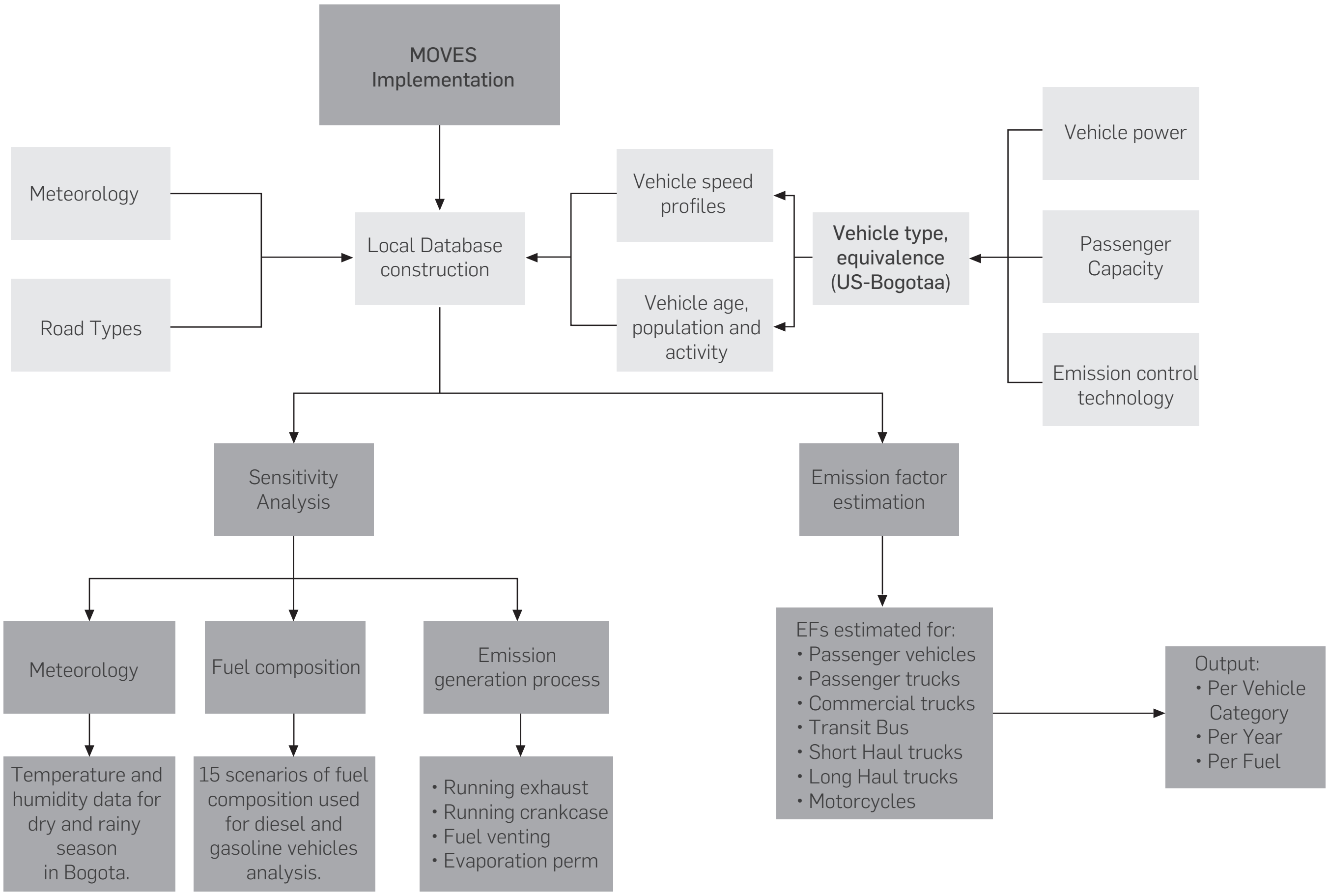

Figure 1. Summary process of MOVES implementation.

similar problem exists with motorcycles and heavy-duty trucks. Motorcycle in US have an average engine power of 100 to 150 HP, while in Colombia the average power ranges between 65 HP and 100 HP. Therefore, MOVES outcomes may overestimate EFs for buses, heavy trucks and motorcycles in Bogota.

Trucks in Bogota were standardized with single unit short-haul trucks in MOVES, considering short distances travelled in the city. For such standardization, an equivalence between US [25],[26] and European [26],[27] emission standards was conducted, given that buses and trucks in Bogota, at large, have European engines, Nevertheless, the equivalence between Colombian and US heavy-duty vehicles represents a major challenge and explains, partially, uncertainty in the results. Once control devices were matched to US technology standards, the application of MOVES was possible (see **Table A1** Annexes).

In Summary, selected fleet categories to run MOVES in Bogota are shown in **Table 2**.

For vehicle speed profiles, the MOVES speed bin profile was determined using a frequency distribution with the local monitor's data. Each bin represents a speed range in MOVES (**Table 3**). Profiles for passenger vehicles and public transport account for over 70% of vehicle behavior on speed bins 3, 4 and 5. Thus, the average speed

Table 2. Selected categories in MOVES. Passenger vehicles and taxis definition [28],Transit bus, Passenger trucks and heavy vehicles definition [29], GVWR: gross vehicle weight rating

MOVES Category	BOGOTA category	Description
Passenger vehicles (PV)	Passenger vehicles	Cars with GVWR < 3.8 ton
Passenger Truck (PT)	Minivans, pickups, SUV	Minivans, pickups, SUV and other vehicles with 2 or 4 axis used for personal transportation
Motorcycles (M2 and M4)	Motorcycles (100 HP to 150HP)	Motorcycles (100 HP to 150HP)
Taxis (T)	Passenger vehicles	Cars with GVWR < 3.8 ton
Transit bus (TB)	Public buses and BRT	Buses commonly used for public transit (200 to 250 HP).
Light commercial truck (CT)	Minivans, pickups, SUV	Minivans, pickups, SUV´s and other vehicles with 2 or 4 axis used for commercial transportation.
Single unit short haul truck (SHT)	Small Trucks	Small Trucks with rides shorter than 200 miles per day

in Bogota is 28 km/h for passenger vehicles and 23 km/h for public transport vehicles, which is a relatively low speed for an urban center given the traffic congestion at almost any time. In fact, Bogota is ranked as the 5th most congested city in the world [30].

Table 3. Vehicle speed profile (fractions) for Bogota

Speed BIN	Average speed [Km/h]	Vehicle Category		
		Passenger vehicles	Public Transportation (bus)	Taxis and other private vehicles
1	4	0	0	0
2	8	0.02	0.028	0.012
3	16	0.219	0.330	0.152
4	24	0.330	0.403	0.299
5	32	0.222	0.188	0.25
6	40	0.124	0.043	0.158
7	48	0.044	0.007	0.068
8	56	0.017	0	0.029
9	64	0.017	0	0.023
10	72	0.005	0	0.009
11 - 16	> 80	0	0	0

Data source: SDM [20].

SENSITIVITY ANALYSIS

The first sensitivity analysis was aimed at assessing the impact of meteorology and time of the day on EF estimates. The impact of temperature and relative humidity was negligible (less than 5%). Pollutants such as SO_2, PM_{10} and $PM_{2.5}$ did not show any changes; this is related to small differences in temperature in the city along the day. On the other hand, CO and VOC pollutants show increases in early and late hours and a decrease at noon. The increases in early and late hours are related to temperature, as lower temperatures decrease the catalytic efficiency [31]. On the contrary, NOx emissions tend to increase with higher temperatures [32],[33]. The greatest temperature change is 6°C, showing ±3% change in EF and this could be considered negligible for the city, considering that Bogota has no seasons and temperature and relative humidity are mostly constant over the year, expecting negligible variations month by month. Therefore, we decided to use one hour (12pm) and one month (February) to estimate EFs for the city.

The second sensitivity analysis was to assess fuel composition. Comparing 15 fuel composition scenarios, it was found that changing sulfur content in gasoline fuel (**Table 4**) generates the biggest changes in EFs while changing fuel distillation parameters (T50 and T90) affects VOC and CO EFs but other pollutants less than 2%. A lower sulfur content decrease SO_2 emissions and improves combustion reducing simultaneously VOC, CO, NOx and PM [34]. Increasing the temperature of T50 and T90 decreases CO emissions but also increases VOC emissions [35]. Finally, decreasing aromatic content in the fuel reduces the CO, NOx and VOC EFs. On the other hand, diesel EFs are mainly affected by changes in sulfur content and cetane index (**Table 5**). When sulfur content is reduced, SO_2 and PM emission factors decrease and when the cetane index is increased, the PM, CO and VOC are reduced due to better combustion conditions [35]-[37]. MOVES is not sensitive to other changes in the diesel formulation, but when more than one parameter is changed at a time, MOVES estimates a combined effect between those parameters.

The third sensitive analysis was focused on assessing the emission process contribution to EF. Four processes were used for the evaluation: running exhaust (RE), evaporation permeability (EP), fuel venting (FE) and running crankcase (RC) (**Table 6**). RE are the main source of emission with 98% contribution for most of pollutants except for VOC, which have a 90% contribution. EP and RC emission was found to be negligible for all pollutants. FV contributes with 9% of VOC emission for passenger vehicles and had no contribution in Transit buses. Only RE EFs were selected to be applied on emission inventories.

Table 4. Sensitivity analysis of gasoline quality parameters on Emission Factor changes

Pollutant	Aromatics (base 20%)			Sulphur (base 50 ppm)			RVP (base 13psi)			T50 (base 84°C)			T90 (base 137 °C)		
	Arom 10%	Arom 15%	Arom 30%	S 15pm	S 30pm	S 270pm	RVP 7,5	RVP 10	RVP 15	T50 (68)	T50 (74)	T50 (89)	T90 (114)	T90 (122)	T90 (145)
Pollutant	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
CO	↓	↓	↑	↓↓	↓	↑↑	↓↓↓	↓↓	↑↑↑	±0	±0	±0	↑	↑	↑
NOx	↓	±0	↑	↓	↓	↑	↓	↓	↑	±0	±0	±0	±0	↑	±0
SO_2	0	0	0	↓↓↓↓	↓↓↓	↑↑↑↑	0	0	0	0	0	0	0	0	0
VOC	±0	±0	±0	↓	↓	↑	↓	↓	↑	↓	↓	↑	↑	↑↑	±0
PM_{10}	0	0	0	±0	±0	±0	0	0	0	0	0	0	0	0	0
$PM_{2.5}$	0	0	0	±0	±0	±0	0	0	0	0	0	0	0	0	0

(0: no change, ±0: -2% to 2%, ↓-↑: 2% to 10%, ↓↓-↑↑: 10% to 20%, ↓↓↓-↑↑↑: 20% to 40%, ↓↓↓↓- ↑↑↑↑: >40

Table 5. Sensitivity analysis of diesel quality parameters on Emission Factor changes

Scenario	Sulfur ppm (base 50 ppm)			Cetane index (base 43)
	S 15 ppm	S 30 ppm	S100 ppm	48
Pollutant	%	%	%	%
CO	0	0	0	-0
NOx	0	0	0	-0
SO_2	↓↓↓↓	↓↓↓↓	↑↑↑↑	0
VOC	0	0	0	-0
PM_{10}	↓	↓	↓	↓
$PM_{2.5}$	↓	↓	↓	↓

(0: no change, ±0: -2% to 2%, ↓-↑: 2% to 10%, ↓↓-↑↑: 10% to 20%, ↓↓↓-↑↑↑: 20% to 40%, ↓↓↓↓- ↑↑↑↑: >40%)

Table 6. Contribution of Emission Factors per emission generation processes.

Process	% EF contribution					
	CO	NO_x	SO_2	VOC	$PM_{2.5}$	CO_2
R.E	98%	98%	98%	90%	98%	98%
E.P	NA	NA	NA	<1%	NA	NA
F.V	NA	NA	NA	8%	NA	NA
R.C	<2%	<2%	<2%	<2%	<2%	<2%

(R.E: Running exhaust, E.P: Evaporation permeability, F.V: Fuel venting in gasoline vehicles, R.C: Running crankcase)

ESTIMATING LOCAL EFs

A weighted average was applied to the EFs obtained from MOVES by vehicle category, vehicle model year and fuel consumed (Figure 1). A database with weighted averaged EFs is available in Table A2 in Annexes. Comparing the newer vehicle technology with the previous one, the SO_2 EFs changes are negligible when the fuel composition is not changed, so the model estimates the SO_2 EFs with the average fuel consumption and the sulfur content in fuel, i.e., 50 ppm for diesel and 270 ppm for gasoline. For CO, NOx and VOC pollutants, the newer technologies present greater reductions related to new emission control technologies and improvements in the combustion process [26],[35],[38]. The reduction of CO and NOx emissions is consistent with the application of the life-cycle assessment LCA model in Bogotá [39]. Finally, the PM emission factors show the largest changes comparing old vs new vehicles. The model reflects improvements in emission controls applied in recent decades, especially on diesel vehicles.

Estimated EFs from MOVES were compared with previous EFs used by the local environmental agency (SDA) named hereafter LOCAL. This comparison was made by each vehicle type performing standardization between the US and Bogota´s fleet (see Table A1 Annexes). The largest change in EFs was in SO_2 and diesel vehicles (Table 7 and Table 8). In all vehicle categories, SO_2 EFs were significantly reduced from local to MOVES estimates. This is explained by the reduction in sulfur content in fuels during the last years.

The CO and NOx EFs decrease in the gasoline fleet except for the two-stroke motorcycles. Reduction in emission of pollutants for passenger vehicles and pick-up trucks are explained by the fleet renovation that the city has experimented in recent years, especially in private vehicles. The increased emissions from motorcycles is caused by the difference in size and power between US and Colombia's motorcycles. VOC EFs decrease for all the categories due to more rigourous VOC controls implemented in the newer fleet. The inclusion of all models of passenger vehicles in MOVES, even the oldest ones, caused the EFs to be greater than those in the local database.

Table 7. Emission factors obtained from MOVES for gasoline vehicles. PV: Passenger vehicle, M2: 2-stroke engine motorcycle, M4: 4-stroke engine motorcycle, PT: Passenger trucks.

Category	Process	EFs g/km				
		CO	NO_x	SO_2	VOC	$PM_{2.5}$
PV	Local	7	0.7	0.34	0.9	0.003
	MOVES	2.85	0.1	0.06	0.02	0.004
	%	-59%	-86%	-82%	-98%	+33%
M2	Local	23	0.1	0.06	18.3	0.22
	MOVES	24.49	0.57	0.05	4.14	0.03
	%	+6%	+470%	-17%	-77%	-86%
M4	Local	38	0.8	0.11	2.6	0.01
	MOVES	16.41	0.56	0.05	1.39	0.022
	%	-57%	-30%	-55%	-47%	+175%
PT	Local	10	1	0.25	0.7	0.003
	MOVES	4.24	0.34	0.08	0.15	0.006
	%	-58%	-66%	-68%	-79%	+100%

Source for Local EFs: SDA [12]

In diesel vehicles, NOx EFs for passenger trucks (PT), short-haul trucks (SHT) and transit buses (TB) estimated with MOVES are larger than EFs from the local database. This is especially significant for TB with an increase of 155% due to larger size and power of buses in the US in comparison to Colombia. VOC EFs are reduced for all categories explained to stricter evaporative emission controls implemented in recent years. There is a decrease in EFs for PM 2.5 for PT and commercial trucks (CT) and an increase for SHT and TB. The increase can be explained by SHT and TB being of larger size and power in the US, while the decrease in PT and CT is due to emission control and newer fleet.

Table 8. Emission factors obtained from MOVES for diesel vehicles. PT: Passenger trucks, SHT: short-haul trucks, CT commercial trucks, TB: Transit Bus.

Category	Source	EFs g/km				
		CO	NO_x	SO_2	VOC	$PM_{2.5}$
PT	Local	1	1	0.56	0.8	0.097
	MOVES	2.12	1.4	0.02	0.28	0.07
	%	+112%	+44%	-96%	-65%	-28%
SHT	Local	4	13.1	0.75	1.9	0.8
	MOVES	5.37	21.6	0.03	1.84	0.95
	%	+34%	+65%	-96%	-3%	+19%
CT	Local	3	9	0.61	1.2	0.3
	MOVES	6.01	4.1	0.02	1.04	0.22
	%	+100%	-54%	-97%	-13%	-27%
TB	Local	11	7.9	0.56	2.5	0.3
	MOVES	6.75	20.1	0.03	1.51	0.41
	%	-39%	+155%	-95%	-40%	+37%

Source for Local EFs: SDA [12]

EMISSION INVENTORY RESULTS

Using the new dataset of EFs in 2014 cause the mobile source emission inventory to differ from the 2012 version (Table 9). There is an increase in PM (+15%) and CO_2 (+28%) emissions due to the growth of the vehicle fleet, and the changes in the $PM_{2.5}$ emission factors for passenger vehicles, including old models in the MOVES model. The increase in the number of motorcycles also affect PM emissions because EFs for four-stroke motorcycles are 175% larger than those in the old database. The contribution of motorcycles to PM emissions in 2014 is 10% to the total PM from mobile sources. There may be some overestimation of emissions for motorcycles, but given the poor maintenance of this fleet, addedto road conditions in the city, emissions can be actually greater. In fact, other studies in Bogota have found motorcycle $PM_{2.5}$ emissions well above emission from all other vehicle categories [39].

The largest reduction in mobile source emissions was for SO_2 (-87%), which is explained by the reduction in sulfur content in diesel. CO and VOC emissions were reduced by 65 and 62% respectively due to fleet renovation in passenger cars and stricter VOC emission control in new cars. NOx emission has a marginal reduction of 20% due to reduction in EFs for commercial trucks and passenger cars. Although the vehicle fleet changes have an impact over emission in 2012 and 2014, the main changes are related to changes in EF, as shown in equation 1; emission depends on both factors but the vehicle fleet grew 8% [41] and changes in EF range from 6% to 155%, making a more significant difference in the emission inventory.

Table 9. Comparison of emission using local database EFs (2012) and MOVES EFs (2014)

Pollutant	Emissions (tons/yr)		
	2012*	2014	% change
CO_2	10 458 221	13 438 647	+28%
CO	866 445	300 969	-65%
NOx	66 540	53 313	-20%
VOC	91 885	34 906	-62%
$PM_{2.5}$	1 163	1 340	+15%
SO_2	14 109	1 860	-87%

*source: SDA[40]

CONCLUSIONS

The motor vehicle emission model MOVES was implemented in Bogota with the best information available and an equivalence between vehicle categories in the US and Colombia. However, it is recognized that vehicles in the US are larger in size and power compared to the Colombian fleet, especially in the case of motorcycles, trucks and buses.

New emission factors estimated with MOVES consider changes in fuel composition and fleet turnover that might not be reflected in EFs prior to 2008. Databases to input in MOVES also consider old passenger cars that were not previously accounted for, which have high emission rates.

EFs estimated with MOVES reflected the changes in sulfur content in fuels in past years. SO_2 emissions reduced significantly using this new set of EFs in comparison with local databases. The emission inventory and the changes in emissions that reflect MOVES with new vehicle technologies show that the best option to reduce emissions is to improve fuel quality and vehicle technology as a combined strategy.

Older vehicles combination with new fuels doesn't make a great difference in emission factors, except in SO_2; as it had been stated by environmental agencies, it is necessary to implement fuel improvement with new vehicle technologies in order to achieve a better cost efficient emission reduction strategy.

A sensitivity analysis was performed with MOVES to explore the impact of different variables (temperature, sulfur content, aromatics content, RVP, distillation curves and emission process) in EFs. We found that temperature and humidity do not have a significant impact on EF as in Bogota there are no seasons. As regards gasoline, the most important variable is its sulfur content, which affects mostly SO_2, but also the CO, VOC, NOx and PM EFs. Furthermore, distillation curves and physical properties have an important effect on CO and VOC.

On the other hand, in diesel, the cetane index and sulfur content generate the most important changes in EFs. Increasing cetane index reduces PM emissions. Decreasing sulfur reduces SO_2 and PM emissions.

MOVES could be implemented in other Colombian cities using a methodology similar to that described herein. The official Colombian database of vehicles, as well as local speed profiles and activity factors, provide an easy mechanism to compare and generate local and regional emission factors.

It should be noted that the EF must always be carefully used depending on each particular application; as a theoretical approach grouping several variables, results may differ from real life emissions. Researchers are encouraged to analyze whether a particular EF suits a given requirement. The authors consider EF a dynamic topic subject to refining and improvement as information becomes available.

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ANNEXES

Table A1 with the comparison of vehicle technologies in Bogota, United states and European Union by vehicle type and model year and NOx and PM emission standard for heavy vehicles standardized between United states and European Union

The first column presents the model year of the vehicle, the second and third one present the dominant passenger vehicle technology in Bogota and US for that specific year. The fourth, fifth and sixth columns present the dominant heavy vehicle technology in Bogota Europe and US for that specific year for PM control. The last two columns represent the differences between environmental agencies in US and Europe, where EPA was focused on PM control before the EEA. On the other hand, in the early 90s, EEA had a strong regulation concerning gas emissions. When using this table, select the technology of the vehicle by model, and then associate it to a model year, which will be the model year used in MOVES.

Table A1. Comparison of emission comparing the emission standards between environmental agencies and the composition of the local fleet in Bogota

<table>
<tr><th>Vehicle type</th><th colspan="2">Light Vehicles</th><th colspan="5">Heavy vehicles</th></tr>
<tr><th rowspan="2">Model Year</th><th rowspan="2">Bogota</th><th rowspan="2">US</th><th rowspan="2">Bogota</th><th rowspan="2">EU</th><th rowspan="2">US</th><th colspan="2">US emission standard standardized to European standards</th></tr>
<tr><th>Gases</th><th>PM</th></tr>
<tr><td>1984</td><td rowspan="13">TIER 0</td><td rowspan="11">TIER 0</td><td rowspan="24">PRE</td><td rowspan="8">PRE</td><td rowspan="10">Without standard (prior 1994)</td><td rowspan="13">PRE</td><td rowspan="10">PRE</td></tr>
<tr><td>1985</td></tr>
<tr><td>1986</td></tr>
<tr><td>1987</td></tr>
<tr><td>1988</td></tr>
<tr><td>1989</td></tr>
<tr><td>1990</td></tr>
<tr><td>1991</td></tr>
<tr><td>1992</td><td rowspan="6">EURO 1</td></tr>
<tr><td>1993</td></tr>
<tr><td>1994</td><td rowspan="2">Standard 1 (1994)</td><td rowspan="2">EURO 2</td></tr>
<tr><td>1995</td><td rowspan="5">TIER 1</td></tr>
<tr><td>1996</td><td rowspan="2">Standard 2 (1996)</td><td rowspan="3">EURO 3</td></tr>
<tr><td>1997</td><td rowspan="4">TIER 1</td><td rowspan="2">EURO 2</td></tr>
<tr><td>1998</td><td rowspan="2">EURO 2</td><td rowspan="6">Standard 3 (1998)</td></tr>
<tr><td>1999</td><td rowspan="6">EURO 3</td><td rowspan="8">EURO 4</td></tr>
<tr><td>2000</td><td rowspan="6">TIER 1 NLEV</td><td rowspan="5">EURO 3</td></tr>
<tr><td>2001</td><td rowspan="8">TIER 1 NLEV</td></tr>
<tr><td>2002</td></tr>
<tr><td>2003</td></tr>
<tr><td>2004</td><td rowspan="3">Standard 4 (2004)</td></tr>
<tr><td>2005</td><td rowspan="3">EURO 4</td><td rowspan="2">EURO 4</td></tr>
<tr><td>2006</td><td rowspan="9">TIER 2</td></tr>
<tr><td>2007</td><td rowspan="3">Standard 5 (2007)</td><td rowspan="8">EURO 5</td><td rowspan="8">EURO 5</td></tr>
<tr><td>2008</td><td rowspan="6">EURO 2</td><td rowspan="7">EURO 5</td></tr>
<tr><td>2009</td><td rowspan="6">TIER 2</td></tr>
<tr><td>2010</td><td rowspan="5">Standard 6 (2010)</td></tr>
<tr><td>2011</td></tr>
<tr><td>2012</td></tr>
<tr><td>2013</td></tr>
<tr><td>2014</td><td>EURO 2, 4 Y 5</td></tr>
</table>

Table A2 with EFs for all pollutants and all vehicle categories. Fuel G: gasoline, D: diesel, PT: Passenger trucks, SHT: Short haul trucks, CT commercial trucks, SB: small buses, TB: Transit Bus, PV: Passenger vehicle, M2: 2-stroke engine motorcycle, M4: 4-stroke engine motorcycle.

Table A2.Database with weighted averaged EFs

			FE g/km						
Vehicle type	Fuel	Tech	PM2.5	PM10	VOC	CO	NO_X	SO_2	CO_2
M2 and M4	G	M2	0.031	0.035	4.142	24.486	0.571	0.047	261.651
		M2	0.022	0.025	1.836	20.230	0.576	0.049	275.387
		M4	0.022	0.025	1.392	16.414	0.560	0.049	275.387
PC	G	TIER0	0.049	0.056	2.377	21.419	2.157	0.065	363.172
		TIER1	0.023	0.025	1.099	9.235	1.484	0.062	344.389
		TIER1NLEV	0.014	0.016	0.338	6.714	0.770	0.063	349.047
		TIER2F1	0.004	0.005	0.029	3.974	0.149	0.062	347.610
		TIER2F2	0.003	0.003	0.006	1.265	0.039	0.057	319.744
		TIER/NLEV	0.004	0.005	0.029	3.974	0.149	0.062	347.610
	D	TIER0	0.023	0.025	1.299	17.286	1.721	0.010	347.797
		TIER1	0.010	0.011	0.511	7.025	1.096	0.011	385.290
		TIER1NLEV	0.006	0.006	0.162	4.036	0.509	0.011	385.290
		TIER2F1	0.005	0.005	0.015	1.924	0.083	0.011	386.005
		TIER2F2	0.004	0.004	0.003	0.629	0.022	0.009	330.760
PT	G	TIER0	0.054	0.061	5.119	45.766	3.774	0.082	456.955
		TIER1	0.019	0.021	2.383	18.271	2.489	0.081	450.693
		TIER1NLEV	0.016	0.018	0.690	11.214	1.259	0.086	479.540
		TIER2F1	0.006	0.006	0.066	4.479	0.249	0.084	466.915
		TIER2F2	0.003	0.004	0.007	1.336	0.049	0.068	381.292
		TIER/NLEV	0.006	0.007	0.152	4.239	0.339	0.077	429.387
	D	TIER0	0.124	0.134	2.528	31.183	4.040	0.013	427.892
		TIER1	0.266	0.289	1.322	11.824	3.913	0.015	511.555
		TIER1NLEV	0.176	0.192	0.884	6.326	3.403	0.018	623.321
		TIER2F1	0.100	0.109	0.308	2.152	1.747	0.019	667.431
		TIER2F2	0.014	0.015	0.027	0.457	0.451	0.016	600.589
		TIER/NLEV	0.074	0.081	0.282	2.121	1.444	0.018	628.351
CT	G	TIER0	0.056	0.064	5.079	44.009	3.741	0.082	455.256
		TIER1	0.019	0.022	2.477	18.980	2.489	0.081	448.957
		TIER1NLEV	0.016	0.018	0.764	11.563	1.349	0.086	477.611
		TIER2F1	0.006	0.007	0.114	5.006	0.343	0.084	465.857
		TIER2F2	0.003	0.004	0.008	1.437	0.055	0.069	385.198
	D	TIER0	0.310	0.337	2.137	21.560	5.543	0.013	430.655
		TIER1	0.477	0.519	1.328	9.425	5.187	0.015	509.828
		TIER1NLEV	0.221	0.241	1.036	6.012	4.175	0.018	620.297
		TIER2F1	0.085	0.092	0.262	2.194	1.461	0.018	653.695
		TIER2F2	0.012	0.014	0.023	0.502	0.377	0.015	561.781
TB	G	PRE	0.125	0.142	7.763	73.903	5.712	0.164	912.129
		EURO2	0.035	0.040	5.696	97.398	5.224	0.164	912.129
		EURO3	0.031	0.035	5.272	70.932	4.596	0.164	912.129
		EURO4	0.010	0.012	2.862	24.356	3.429	0.164	912.129
		EURO5	0.007	0.008	0.664	6.213	1.175	0.164	912.072
	D	PRE	0.653	0.709	1.509	6.753	24.826	0.027	925.326
		EURO2	0.409	0.445	1.509	6.753	20.140	0.027	925.326
		EURO3	0.275	0.299	1.510	6.753	18.022	0.027	925.326
		EURO4	0.227	0.247	1.269	4.740	10.446	0.027	925.326
		EURO5	0.021	0.023	0.058	0.318	1.937	0.025	921.769
SHT	G	PRE	0.122	0.138	7.979	69.403	6.742	0.179	998.949
		EURO2	0.031	0.035	6.443	93.187	6.117	0.179	998.949
		EURO3	0.020	0.023	5.869	71.250	5.348	0.179	998.949
		EURO4	0.009	0.010	3.296	34.702	3.886	0.179	998.949
		EURO5	0.005	0.006	0.702	9.336	1.345	0.179	997.734
	D	PRE	0.946	1.028	1.844	5.372	21.672	0.035	1177.982
		EURO2	1.067	1.160	2.020	5.318	17.471	0.035	1177.982
		EURO3	0.868	0.943	2.020	5.318	16.724	0.035	1177.982
		EURO4	0.413	0.449	1.740	4.367	8.325	0.035	1177.982
		EURO5	0.021	0.023	0.092	0.485	2.076	0.032	1171.941