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Influence of driving patterns on vehicle emissions: A case study for Latin American cities

Robinsson A. Rodríguez, Edgar A. Virguez, Paula A. Rodríguez, Eduardo Behrentz *

Centre for Studies on Urban and Regional Sustainability, Universidad de Los Andes, Bogotá, Colombia

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ABSTRACT

On-board real-time emission experiments were conducted on 78 light-duty vehicles in Bogota. Direct emissions of carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x) and hydrocarbons (HC) were measured. The relationship between such emissions and vehicle specific power (VSP) was established. The experimental matrix included both gasoline-powered and retrofit dual fuel (gasoline–natural gas) vehicles. The results confirm that VSP is an appropriate metric to obtain correlations between driving patterns and air pollutant emissions. Ninety-five percent of the time vehicles in Bogota operate in a VSP between -15.2 and 17.7 kW ton^{-1}, and 50% of the time they operate between -2.9 and 1.2 kW ton^{-1}, representing low engine-load and near-idling conditions, respectively. When engines are subjected to higher loads, pollutant emissions increase significantly. This demonstrates the relevance of reviewing smog check programs and command-and-control measures in Latin America, which are widely based on static (i.e., idling) emissions testing. The effect of different driving patterns on the city's emissions inventory was determined using VSP and numerical simulations. For example, improving vehicle flow and reducing sudden and frequent accelerations could curb annual emissions in Bogota by up to 12% for CO_2, 13% for CO and HC, and 24% for NO_x. This also represents possible fuel consumption savings of between 35 and 85 million gallons per year and total potential economic benefits of up to 1400 million dollars per year.

Introduction

Bogota (Colombia's capital and largest city) is among the most important cities in Latin America, with more than 7.5 million inhabitants in an urban area of approximately 400 km^2. Its light-duty vehicle fleet is comprised of approximately 1.5 million vehicles, with an average usage greater than 15 years (Ministerio de Transporte, 2005; Moreno, 2011). Fifty percent of the city's highway network is improperly maintained (Larson and Ericcson, 2009). Such conditions may be observed in other comparable Latin American cities.

Previous studies have shown the significance of mobile sources in the city's emissions inventory. The first documented emissions inventory for criteria pollutants in Bogota was developed during 2006 using the IVE methodology (Giraldo, 2006) and an inverse modeling technique (Zarate, 2007) Subsequently, a complete emissions inventory was developed in 2009, where the contribution of mobile sources was estimated to be 4,800,000 tons year^{-1} of carbon dioxide (CO_2);

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* Corresponding author.
E-mail address: ebehrent@uniandes.edu.co (E. Behrentz).

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450,000 tons year^{-1} of carbon monoxide (CO); 60,000 tons year^{-1} of hydrocarbons (HC); 30,000 tons year^{-1} of nitrogen oxide (NO_x); and 1100 tons year^{-1} of inhalable particulate matter (PM_{10}) (Behrentz, 2009a; Behrentz et al., 2010).

Peer-reviewed studies conducted around the world have tested several metrics to predict vehicle emissions based on speed and acceleration (André and Hammarström, 2000; André and Rapone, 2009; Hung et al., 2005; Popp et al., 1998), however the inclusion of physical variables like the vehicles mass, the drag coefficient and the route slope have shown to increase the statistical representativeness of the regression models. Following this rationale, vehicle specific power (VSP) approach presents an advantage to such methodologies by effectively relating instantaneous pollutant emissions with the energy used by the vehicle. Also it provides some advantages over traditional metrics used, by presenting a one dimensional metric with a direct physical interpretation that could be calculate from roadside masurements (Lee and Frey, 2012; Liu and Barth, 2012; Schifter et al., 2008; Tolvett, 2009; Yu et al., 2009; Zhai et al., 2008).

By generating reliable information of real time emissions of air pollutants that can be linked to the vehicle operation, the VSP concept can be used to evaluate the effect of modified driving behavior on emissions (Ericcson, 1999, 2001; Huai et al., 2003; Kean et al., 2003; Larson and Ericcson, 2009). By producing a methodology in which the marginal change in vehicles operation can be linked to an instantaneous change in the emission of and air pollutant, the behavioral pattern during real traffic conditions can be addressed. For instance, the implementation of eco-driving (i.e., better driving practices aimed at reducing emissions) has been shown to successfully curb CO_2 emissions in several countries in Asia and Europe (Barkenbus, 2010; EPA, 2011; Zarkadoula et al., 2007; Rolim et al., 2014; Zhang et al., 2014).

The objective of the present study was to document the relationship between driving patterns and vehicle emissions in real-world traffic conditions in Bogota as a case study of a major Latin American city.

Vehicle specific power

As described above, vehicle emissions are dependent upon driving conditions, as the latter have a direct influence on the engine load. Instantaneous pollutant emissions vary as a function of vehicle size and weight, engine and emissions control technology, road conditions and slope (Wyatta et al., 2014), speed, acceleration and environmental conditions, such as temperature and atmospheric pressure (Frey et al., 2006; Yaoa et al., 2013).

In such a context, real-time emission results obtained from on-board measurements become particularly useful when combined with the VSP concept to establish a link between emission and driving behavior for different vehicle categories. The capability of estimating vehicle emissions for various fleets and driving patterns represents a decision-making tool for local environmental and transportation agencies.

VSP (see Eq. (1)) represents the energy used by an internal combustion engine to move a vehicle. It is equal to the product of a vehicle's speed and equivalent acceleration, which includes the effect of the road's slope and friction (Frey et al., 2008; Prati et al., 2014). VSP also considers aerodynamic drag, which is proportional to the speed's third power (Hucho, 1998)

$$\mathrm{VSP} = v \cdot (a \cdot (1 + \varepsilon_i) + g \cdot \mathrm{grade} + g \cdot C_R) + \frac{1}{2}\rho_a \frac{C_D \cdot A}{m} \cdot (v + v_u)^2 \cdot v \tag{1}$$

v: vehicle speed (m sec^{-1}),
a: vehicle acceleration (m sec^{-2}),
ε_i: mass factor (dimensionless),
g: gravitational acceleration (9.8 m sec^{-2}),
grade: vertical rise/slope length,
C_R: coefficient of rolling resistance (dimensionless),
ρ_a: ambient air density (1.2 kg m^{-3} at 20 °C),
C_D: drag coefficient (dimensionless),
A: frontal area of the vehicle (m^2),
m: vehicle mass (kg),
v_u: wind speed (assumed negligible in this study) (m sec^{-1}).

The gear in which vehicles operate has an impact on the mass factor (ε_i). For the first gear, the mass factor is equal to 0.25; for the second gear, the mass factor is equal to 0.15; for the third gear, the mass factor is equal to 0.10; and for the fourth gear, the mass factor is equal to 0.075 (Hucho, 1998). In the present study, the vehicle is assumed to be in third gear most of the time (on average) and, consequently, $\varepsilon_i = 0.10$ and the first component of Eq. (1) may be simplified as ($1.1 \cdot a$). Similarly, ($g \cdot C_R$) may be replaced by 0.132 as a result of multiplying the gravity acceleration by 0.0135 (the C_R value for paved roads according to Bosch (2007)). In addition, the final component of the equation $\left(\frac{1}{2}\rho_a \frac{C_D \cdot A}{m} \cdot (v + v_u)^2 \cdot v\right)$ may be replaced by $0.000302 \cdot v^3$. Jimenez (1999) assumes such a component to be 0.0005 (a value representative of different vehicle loads). Similarly, the physical properties of the vehicle, such as the frontal area and the vehicle's weight, have an influence on the vehicle's emissions and fuel consumption (Oh et al., 2014). The drag coefficient varies between 0.15 and 0.50, depending on the exterior design and frontal area of the vehicle. In the case of the research presented here, such a value is the result of using $C_D = 0.3$, $A = 2$ m^2 and a vehicle mass of 1200 kg as representative values for Bogota's vehicle fleet. All of these values

Table 1
Energy range distribution.

Energy range (bin)	VSP (kW ton^{-1})	
	Lower limit	Higher limit
0	−80.0	−44.0
1	−44.0	−39.9
2	−39.9	−35.8
3	−35.8	−31.7
4	−31.7	−27.6
5	−27.6	−23.4
6	−23.4	−19.3
7	−19.3	−15.2
8	−15.2	−11.1
9	−11.1	−7.0
10	−7.0	−2.9
11	−2.9	1.2
12	1.2	5.3
13	5.3	9.4
14	9.4	13.6
15	13.6	17.7
16	17.7	21.8
17	21.8	25.9
18	25.9	30.0
19	30.0	1,000

Table 2
Energy bins according to engine stress.

Bin distribution	Engine stress (dimensionless)	
	Lower limit	Higher limit
0–19	−1.6	3.1
20–39	3.1	7.8
40–59	7.8	12.6

were estimated for Bogota's in-use fleet and are consistent with the parameters established by Bosch (2007). Eq. (2) shows the VSP expression used in this research.

$$\mathrm{VSP} = v \cdot (1.1 \cdot a + K_1 \cdot \mathrm{grade}\,(\%) + K_2) + K_3 \cdot v^3 \tag{2}$$

$a = (\mathrm{m\ sec}^{-2})$,
$v = (\mathrm{m\ sec}^{-1})$,
$K_1 = 9.81\ \mathrm{m\ sec}^{-2}$,
$K_2 = 0.132\ \mathrm{m\ sec}^{-2}$,
$K_3 = 0.000302\ \mathrm{m}^{-1}$.

Driving cycle and engine stress

A driving cycle is defined as the time-velocity sequence aimed at representing real-world driving conditions (Tong et al., 1999). It is obtained from information that is deemed to be statistically representative for a particular urban area (Osses and Rojas, 2003). Using the available driving cycle information and the energy demand associated with it (using the VSP equation), we can establish the amount of time a vehicle stays in a particular VSP bin (SCSS, 2010).

Engine stress (STR) is a measure of the engine load during road operation for short periods of time (IVE, 2008). Following the model presented by the IVE project (Davis et al., 2005), this study used 20 energy bins (see Table 1) for three engine stress modes (see Table 2) to describe the studied driving cycles (EPA, 2002).

The energetic bins linked to negative VSP values (bins 0–10) represent situations in which the vehicle is decelerating or going downhill. Bin 11 represents near-idling conditions. Higher bins are related to conditions in which significant energy is demanded from the engine, such as the case when drivers accelerate after a stoplight.

Methodology

This research consists of two phases. First, we conducted a complex field campaign to determine on-board real-time emissions from Bogota's in-use vehicle fleet. Second, we used numeric simulations to generate different scenarios for the city's emissions inventory based on its driving conditions.

Emissions Measurements

The field campaign was conducted following the methodology described by Behrentz (2009a, 2009b) and Behrentz et al. (2010). This corresponds to the procedure designed and standardized by the IVE project, (Davis et al., 2005) which has been used in more than a dozen cities around the world.

Selection of routes and test vehicles

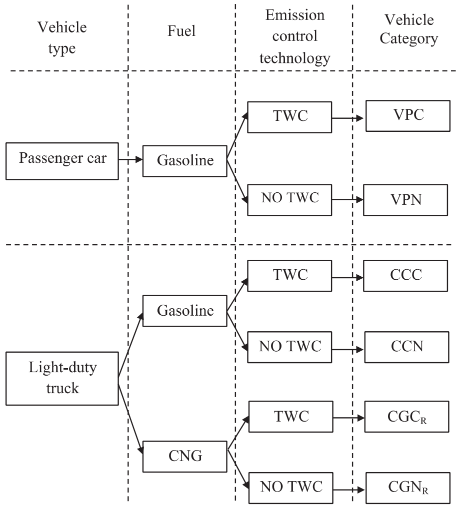
Test vehicles were procured from Bogota's in-use light-duty fleet (see Fig. 1) and classified into six categories according to vehicle type (passenger car vs. light-duty truck), emissions control technology (presence of three-way catalytic converter – TWC) and type of fuel powering their engines (either gasoline or compressed natural gas – CNG). All of the vehicles were inspected by a professional mechanic to ensure that proper technical and safety conditions were observed for the tests.

The emission experiments were conducted on a 10-km urban circuit starting within the city's central-east industrial zone, as shown in Fig. 2. The test route involved a wide variety of traffic conditions and roadway types, ranging from semi-residential streets with little traffic to heavily congested multi-lane primary highways. The test vehicles were operated by two professional drivers.

Direct tailpipe undiluted emission measurements were conducted in 78 vehicles (127 experiments, counting the duplicates), including 64 gasoline-powered engines and 14 gasoline-CNG retrofit vehicles (see Table 3). The latter correspond to original gasoline engines that had been retrofitted to operate as dual fuel motors (either CNG or gasoline). All of the vehicles were cold-start tested with an engine rest period of at least 12 hours before the emission experiments started. This was done to properly document the entire spectrum of emissions. Fig. 3 presents an example of the emissions behavior during one of the tests that were conducted, linking these values to a vehicle's speed.

Instrumentation

The experimental setup included a SEMTECH-G (Sensors, Inc.) to measure the real-time exhaust concentrations of CO, CO_2, HC, and NO_x. This instrument is equipped with a flame ionization detector (for HC detection), a non-dispersive ultraviolet sensor (NO_x detection) and a dispersive infrared analyzer (CO and CO_2 detection). A SEMTECH-EFM was used to determine the real-time exhaust flow rates. A GD30L MMC (Laipactech) high-precision GPS was used to record the real-time location to determine the speed and acceleration of the vehicles. Humidity and temperature were registered using commercially available electronic sensors.



VPC = Passenger car + Gasoline + TWC.
VPN = Passenger car + Gasoline + No TWC.
CCC = Light-duty truck + Gasoline + TWC.
CCN = Light-duty truck + Gasoline + No TWC.
CGC_R = Light-duty truck + Natural gas + TWC (retrofit dual fuel vehicles).
CGN_R = Light-duty truck + Natural gas + No TWC (retrofit dual fuel vehicles).
CNG = Compressed natural gas.
Note: Light-duty truck includes sport utility vehicles.

Fig. 1. Vehicles categories used in this study.

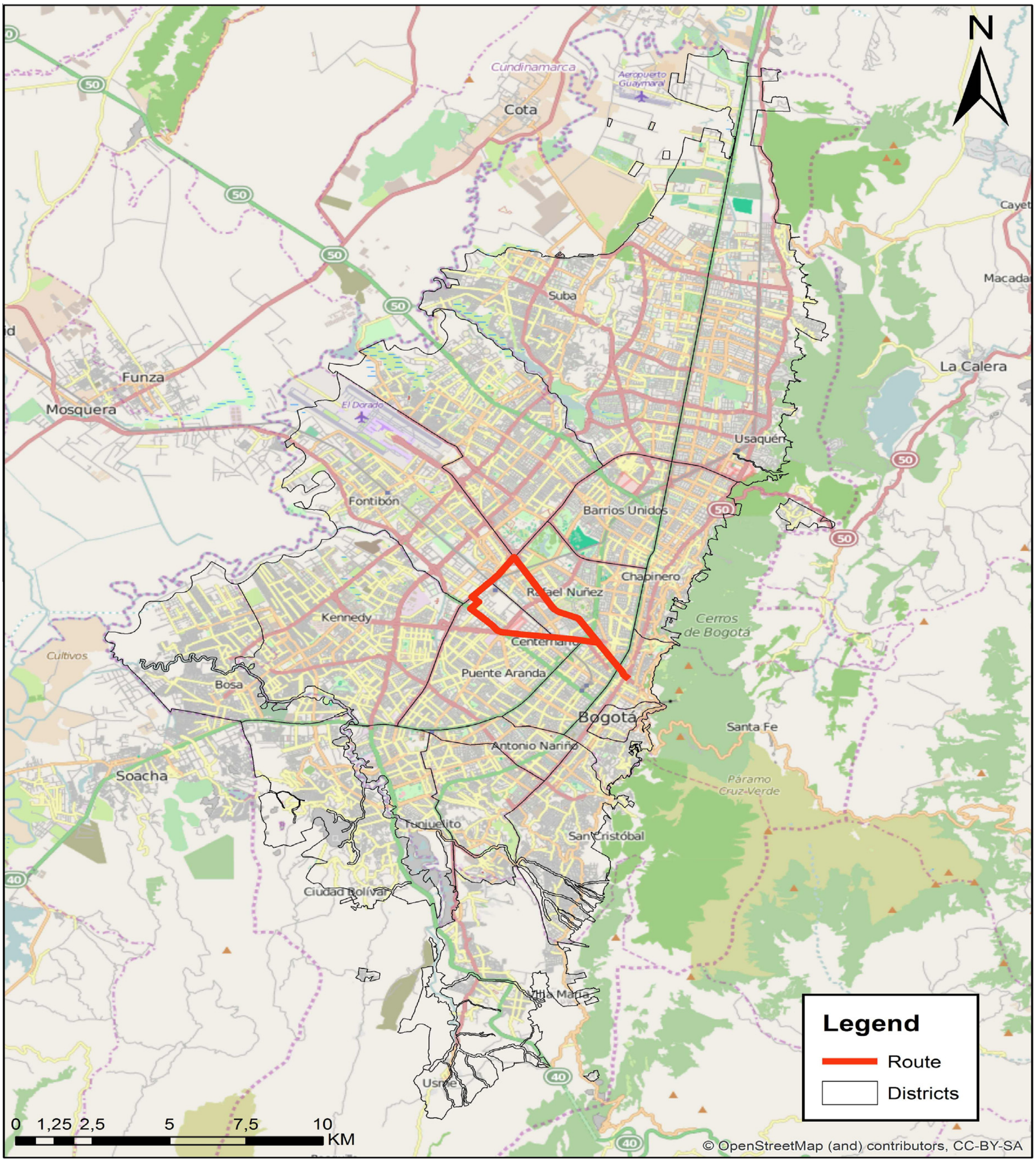


Fig. 2. Urban circuit used in the study.

Data analysis and scenarios simulation

The first step after validating the data gathered during the field campaign was to compute the second-by-second VSP (see Eq. (2)). The time alignment between the VSP and emission data was also necessary given the different sensors' response-time.

The next step was to determine the equation that described the relationship between VSP and emissions (see Table 4) as well as, using the Anderson–Darling test, the probability density function (PDF) for the emission data linked to each one of the VSP bins. Based on the PDF and using Crystal Ball Software, we computed Montecarlo Simulations (IPCC, 2000) to generate random emission values for each VSP bin. The overall emissions PDF was determined as a weighted average according to the time spent by the vehicles in each bin as a consequence of the city's driving cycle.

Table 3
Test vehicles.

Vehicle	Make	Line	Model year	Engine displacement (cm^3)	Odometer readings (km)	Fuel	Type
1	Chevrolet	Rodeo	2000	3,200	68,000	CNG$_R$	LDT
2	Mazda	B 22	2007	2,200	13,000	CNG$_R$	LDT
3	Mazda	B 2600	2007	2,600	11,500	CNG$_R$	LDT
4	Ford	F 150	1994	5,000	165,000	CNG$_R$	LDT
5	Mazda	B-2200	2007	2,200	12,500	CNG$_R$	LDT
6	Mazda	B-22DC3	2007	2,200	8,000	CNG$_R$	LDT
7	Ford	F 150	1997	5,000	132,000	CNG$_R$	LDT
8	Ford	F 150	1998	5,000	226,000	CNG$_R$	LDT
9	Toyota	Land Cruiser	1998	4,500	97,000	CNG$_R$	LDT
10	Chevrolet	Custum	1971	3,100	339,500	CNG$_R$	LDT
11	Ford	Bronco LT	1995	5,000	276,000	CNG$_R$	LDT
12	Ford	Explorer	1997	4,000	132,000	CNG$_R$	LDT
13	Ford	Explorer	1998	4,000	168,500	CNG$_R$	LDT
14	Jeep	Cherokee	1997	4,000	114,000	CNG$_R$	LDT
15	Chevrolet	Grand Vitara	2003	2,000	66,000	Gasoline	LDT
16	Chevrolet	LUV	1997	2,300	72,000	Gasoline	LDT
17	Chevrolet	LUV	1996	1,600	72,000	Gasoline	LDT
18	Datsun	Capacete	1980	1,800	N.A.	Gasoline	LDT
19	Ford	F 150	1996	5,000	174,000	Gasoline	LDT
20	Chevrolet	LUV	1994	2,300	305,000	Gasoline	LDT
21	Toyota	Hilux	1996	2,400	1,800	Gasoline	LDT
22	Mazda	B-22DC9	2003	2,200	43,500	Gasoline	LDT
23	Chevrolet	Grand Vitara	2006	2,000	24,000	Gasoline	LDT
24	Jeep	Grand Cherokee	1998	5,200	148,000	Gasoline	LDT
25	Nissan	Patrol	1999	4,500	107,000	Gasoline	LDT
26	Chevrolet	Trooper	1995	2,600	138,000	Gasoline	LDT
27	Chevrolet	Blazer	1996	4,500	117,000	Gasoline	LDT
28	Jeep	Cherokee	1993	4,000	286,000	Gasoline	LDT
29	Chevrolet	Vitara	2003	1,600	65,000	Gasoline	LDT
30	Kia	Carens LX	2007	2,000	13,000	Gasoline	LDT
31	Mitsubishi	Montero	1993	2,400	197,000	Gasoline	LDT
32	Nissan	Patrol	1982	2,300	N.A.	Gasoline	LDT
33	Chevrolet	Trooper	1990	2,400	349,000	Gasoline	LDT
34	Lada	Niva	1981	1,600	180,000	Gasoline	LDT
35	Chevrolet	Trooper	1988	2,400	304,000	Gasoline	LDT
36	Ford	Bronco	1980	5,000	87,000	Gasoline	LDT
37	Daihatsu	Rocky	1991	2,000	155,600	Gasoline	LDT
38	Chevrolet	Blazer	1996	2,400	100,000	Gasoline	LDT
39	Chevrolet	Trooper	1991	2,500	181,000	Gasoline	LDT
40	Renault	Scenic	2002	1,600	66,000	Gasoline	Passenger Car
41	Subaru	Legacy	1993	2,200	179,000	Gasoline	Passenger Car
42	Renault	Symbol	2003	1,400	71,000	Gasoline	Passenger Car
43	Chevrolet	Alto	2001	1,000	78,500	Gasoline	Passenger Car
44	Renault	Twingo	2003	1,300	43,000	Gasoline	Passenger Car
45	Nissan	Sentra	1995	1,600	38,000	Gasoline	Passenger Car
46	Honda	Accord	1982	1,600	274,000	Gasoline	Passenger Car
47	Renault	Mégane	2000	1,600	216,000	Gasoline	Passenger Car
48	Chevrolet	Sprint	1996	1,000	89,000	Gasoline	Passenger Car
49	Renault	Twingo	2003	1,300	76,000	Gasoline	Passenger Car
50	Renault	19	1996	1,800	143,000	Gasoline	Passenger Car
51	Hyundai	Accent	1996	1,500	167,000	Gasoline	Passenger Car
52	Mazda	626 L	1988	1,800	272,000	Gasoline	Passenger Car
53	Renault	21	1989	2,000	202,000	Gasoline	Passenger Car
54	Chevrolet	Swift	1994	1,300	25,500	Gasoline	Passenger Car
55	Mazda	3	2006	1,600	9,000	Gasoline	Passenger Car
56	Chevrolet	Swift	1996	1,300	125,500	Gasoline	Passenger Car
57	Mazda	626	1984	1,800	200,000	Gasoline	Passenger Car
58	Citroën	Xsara	1998	1,800	90,500	Gasoline	Passenger Car
59	Chevrolet	Epica	2005	2,000	32,800	Gasoline	Passenger Car
60	Volkswagen	Jetta	2007	2,000	1,000	Gasoline	Passenger Car
61	Mazda	323	1985	1,300	62,500	Gasoline	Passenger Car
62	Chevrolet	Alto	2000	1,000	97,000	Gasoline	Passenger Car
63	Renault	Mégane	2002	1,400	86,000	Gasoline	Passenger Car
64	Subaru	Leone	1991	1,800	273,000	Gasoline	Passenger Car
65	Mercedes	Benz 190E	1984	1,900	242,000	Gasoline	Passenger Car
66	Mazda	323	1989	1,500	179,500	Gasoline	Passenger Car
67	Renault	9	1988	1,400	N.A.	Gasoline	Passenger Car
68	Renault	Symbol	2006	1,400	23,000	Gasoline	Passenger Car

(*continued on next page*)

Table 3 (*continued*)

Vehicle	Make	Line	Model year	Engine displacement (cm^3)	Odometer readings (km)	Fuel	Type
69	Volkswagen	Jetta	2005	2,000	28,500	Gasoline	Passenger Car
70	Mazda	Allegro	2003	1,300	91,000	Gasoline	Passenger Car
71	Datsun	120 Y	1981	1,200	167,500	Gasoline	Passenger Car
72	Dacia	1410	1987	1,400	N.A.	Gasoline	Passenger Car
73	Renault	9 Brio	1993	1,300	102,000	Gasoline	Passenger Car
74	Peugeot	206 Midnight	2007	1,600	3,500	Gasoline	Passenger Car
75	Hyundai	Accent	1998	1,500	165,000	Gasoline	Passenger Car
76	Renault	Mégane	2006	1,600	14,500	Gasoline	Passenger Car
77	Chevrolet	Zafira	2002	2,000	70,500	Gasoline	Passenger Car
78	Mazda	626	1998	2,000	216,000	Gasoline	Passenger Car

N.A.: Not available information. CNG$_R$: Compressed natural gas (used in retrofit dual fuel vehicles). LDT = Light-duty trucks (includes sport utility vehicles – SUV).

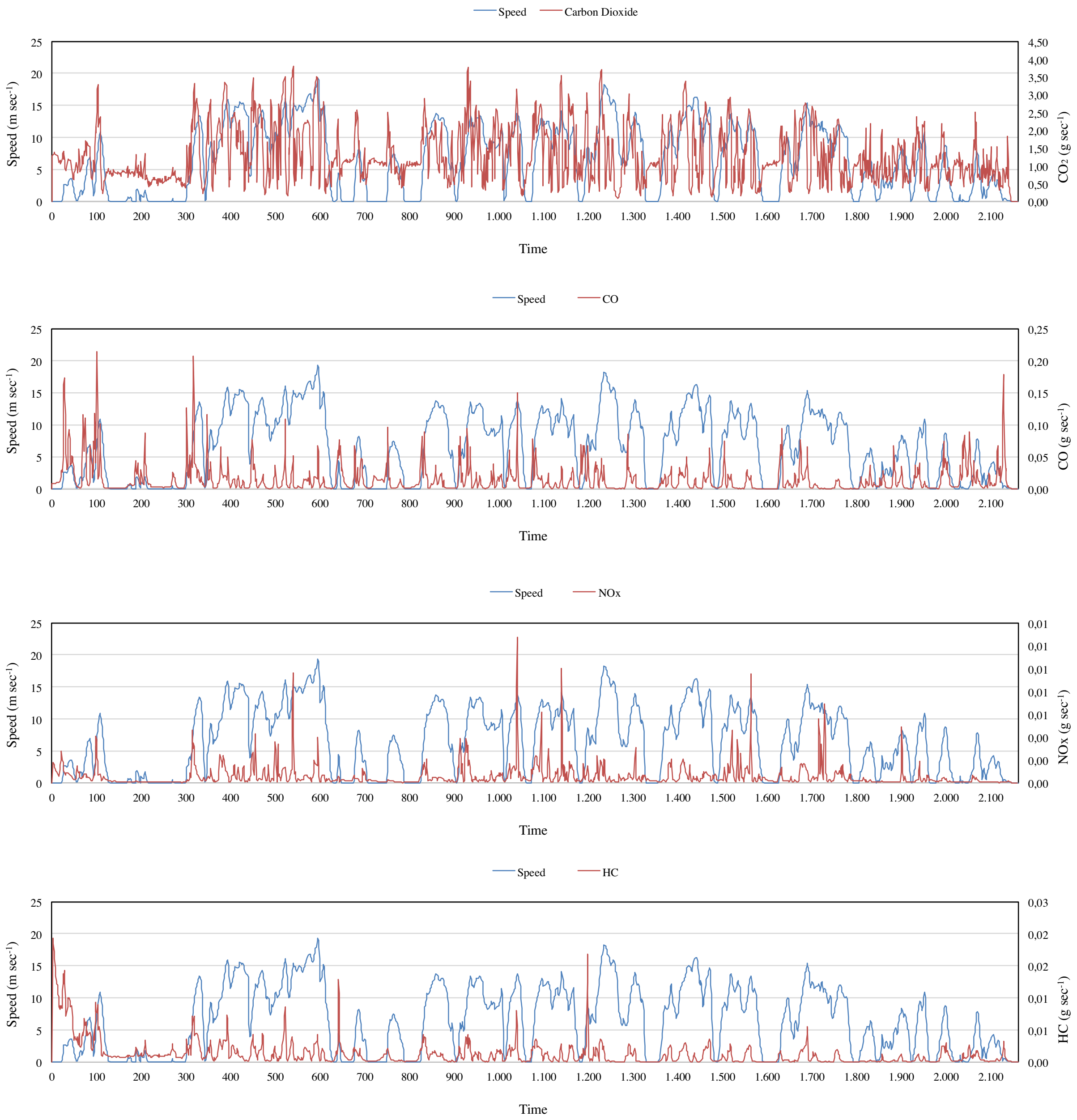


Fig. 3. Example of emissions behavior during a test.

Table 4
Relationship between emissions (y) and VSP (x).

VPC	CO_2	$y = 0.0907x^2 - 1.4941x + 6.7588$	$R^2 = 0.99$
	NO_x	$y = 0.0006x^2 - 0.0103x + 0.0474$	$R^2 = 0.98$
	CO	$y = 0.0015x^2 - 0,0255x + 0,1317$	$R^2 = 0.97$
	HC	$y = 0.0002x^2 - 0.00025x + 0.0103$	$R^2 = 0.99$
VPN	CO_2	$y = 0.0449x^2 - 0.5412x + 2.1415$	$R^2 = 0.97$
	NO_x	$y = 0.0019x^2 - 0.0356x + 0.1692$	$R^2 = 0.99$
	CO	$y = 0.0155x^2 - 0.2539x + 1.2215$	$R^2 = 0.98$
	HC	$y = 0.0009x^2 - 0.0107x + 0.0477$	$R^2 = 0.92$
CCC	CO_2	$y = 0.1545x^2 - 2.5898x + 11.83$	$R^2 = 0.98$
	NO_x	$y = 0.0009x^2 - 0.0166x + 0.0754$	$R^2 = 0.99$
	CO	$y = 0.0096x^2 - 0.1705x + 0.7821$	$R^2 = 0.99$
	HC	$y = 0.0002x^2 - 0.0025x + 0.0103$	$R^2 = 0.99$
CCN	CO_2	$y = 0.1194x^2 - 1.9787x + 9.3871$	$R^2 = 0.99$
	NO_x	$y = 0.0039x^2 - 0.0727x + 0.3403$	$R^2 = 0.99$
	CO	$y = 0.0219x^2 - 0.3647x + 1.7299$	$R^2 = 0.96$
	HC	$y = 0.0029x^2 - 0.0502x + 0.241$	$R^2 = 0.96$
CGC_R	CO_2	$y = 0.1428x^2 - 2.4811x + 11.924$	$R^2 = 0.97$
	NO_x	$y = 0.002x^2 - 0.0358x + 0.1579$	$R^2 = 0.93$
	CO	$y = 0.0132x^2 - 0.2545x + 1.314$	$R^2 = 0.98$
	HC	$y = 0.004x^2 - 0.0769x + 0.3992$	$R^2 = 0.91$
CGN_R	CO_2	$y = 0.1252x^2 - 2.0382x + 9.5593$	$R^2 = 0.98$
	NO_x	$y = 0.0037x^2 - 0.066x + 0.2909$	$R^2 = 0.97$
	CO	$y = 0.0223x^2 - 0.441x + 2.2585$	$R^2 = 0.97$
	HC	$y = 0.0016x^2 - 0.0274x + 0.1278$	$R^2 = 0.99$

VPC = Passenger car + Gasoline + TWC.
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CCC = Light-duty truck + Gasoline + TWC.
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CGC_R = Light-duty truck + Natural gas + TWC (retrofit dual fuel vehicles).
CGN_R = Light-duty truck + Natural gas + No TWC (retrofit dual fuel vehicles).
Note: Light-duty truck includes sport utility vehicles.

The final step was to compare the emissions resulting from Bogota's driving cycle with those linked to other cycles deemed to be less aggressive. The UDDS/LA4 (U.S. dynamometer urban cycle), FTP, LA92/UC (unified California cycle), European NEDC and Japan 10–15 (see Fig. 4 and EPA, 2011) are driving cycles with less accelerations and softer braking compared to Bogota's. Based on the differences discovered, we estimated the potential economic benefits resulting from changes in Bogota's driving patterns in terms of reduced pollutant emissions and fuel costs.

Potential economic benefits

To quantify the potential economic benefits from air pollution reduction, we used data from Bogota's air quality implementation plan (Behrentz et al., 2010), which included cost-effectiveness analyses for different measures aimed at controlling criteria pollutant emissions by evaluating the mortality and morbidity costs associated with exposing the human population to criteria pollutants. According to this study, the most cost-effective strategy to reduce mobile-source related CO, HC, and NO_x emissions in Bogota is installing TWC devices in all gasoline-powered vehicles that are suitable for such technology (currently between 25–30% of the vehicle fleet lacks any form of emissions control equipment).

Installing TWC devices in all of the gasoline-powered vehicles would reduce vehicle emissions at a per-ton rate of US $4,000, $50,000, and $80,000 for CO, NO_x, and HC, respectively. These values were used as reference points to estimate the marginal cost of effectively reducing air pollution in Bogota. Considering that the strategy above is the most cost-effective strategy for curbing emissions, the value of the potential economic benefit presented in this study should be understood to be the lower limit.

In our economic analysis, we used these figures to estimate the savings that could be attained if alternative measures that were not included in the official air quality plan, such as eco-driving, were to be implemented, achieving equivalent emission reductions at the same price.

The reference for the CO_2 economic analysis was the European Climate Exchange (European Environmental Agency, 2014) and NASDAQ OMX Commodities Europe (NASDAQ, 2014). According to these sources, the average market value for 1,000 kg of CO_2 was US $10 in April 2014. Fuel consumption was estimated using the Computer Program to Calculate Emissions from Road Transport (COPERT 4, 2009). The average fuel cost in Bogotá was assumed to be US $4.5 per gallon (MME, 2014). The exchange rate for all of the calculations in this study was COL$ 1,942 for each US dollar.

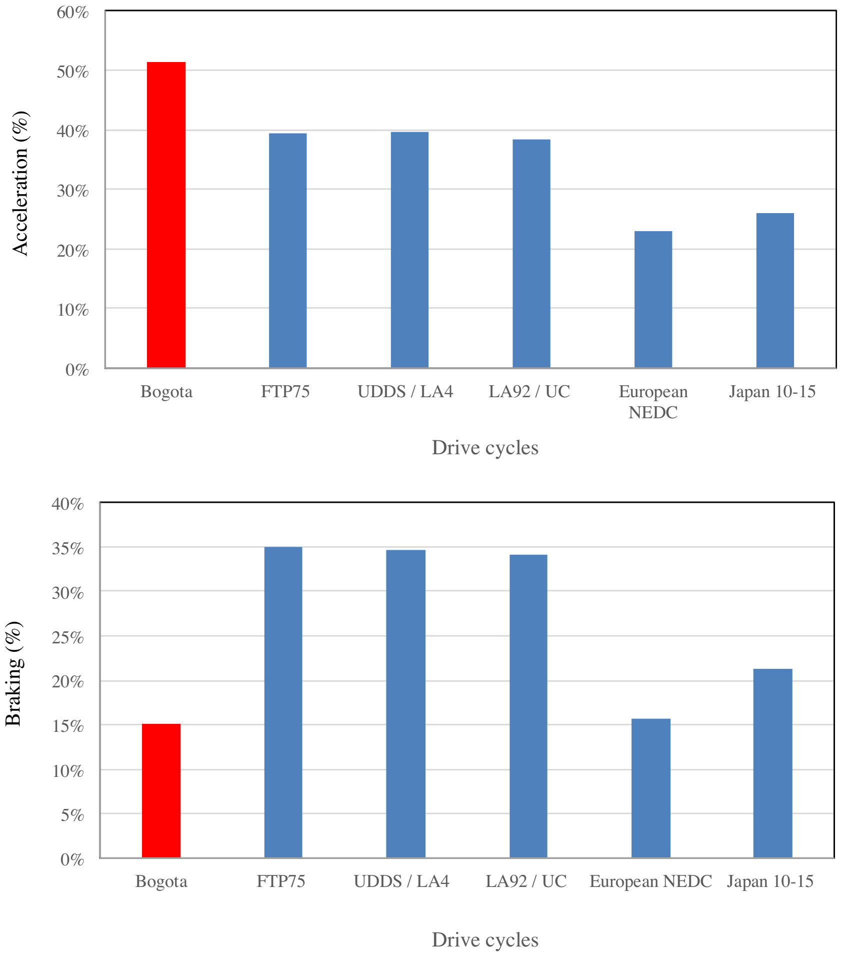


Fig. 4. Characteristics of the drive cycles considered in this study.

Results and discussion

Fig. 5 shows the real-time results for a test conducted in a TWC-equipped gasoline-powered light-duty truck (CCC vehicle category – see Fig. 1). Similar patterns were observed for most of the test vehicles, which demonstrates the advantage of using VSP as a proxy for emissions instead of methodologies exclusively based on speed or acceleration. In this particular case, the correlation between CO_2 emissions and VSP was significantly higher ($r^2 = 0.81$) than that for speed ($r^2 = 0.31$) and acceleration ($r^2 = 0.47$).

Fig. 6 shows the relationship between the VSP bins (after being clustered) and the emissions of CO, HC, and NO_x for all of the test vehicles in the CCC category (see Fig. 1). Table 4 shows the same information for all of the pollutants and all of the vehicle categories in the study. The Pearson Square Correlation (r^2) was above 0.90 in all cases.

Our results show that vehicles in Bogota operate 98% of the time between VSP bins 8 and 15 (i.e., VSP between -15.2 and 17.7 kW ton^{-1}). Such values reflect the driving conditions in the city, which are characterized by heavy traffic, low speeds, and numerous stops. Fifty percent of the time the fleet operates within VSP bin 11 (VSP between 2.9 and 1.2 kW ton^{-1}) and 12% of the time under conditions linked to even lower energy demand.

VSP bin 11 is hereby defined as the emissions activating bin. When the test vehicles were driven under engine loads above that bin (i.e., VSP above 1.2 kW ton^{-1}), the exhaust emissions increased significantly (see Figs. 7 and 8). The opposite was observed for lower VSP bins, including those linked to negative VSP values, which represent unused potential energy (i.e., driving downhill). Incorporating vehicle technologies that are capable of using such potential energy, such as hybrid vehicles, appears to be of particular interest in a city like Bogota.

Figs. 7 and 8 also show that the emissions activation phenomenon occurring at VSP bin 11 is particularly significant for larger engine vehicles (i.e., light-duty trucks compared to passenger cars) as well as those lacking emission control technologies. This suggests that alternative emissions reduction programs, such as eco-driving, could be prioritized for

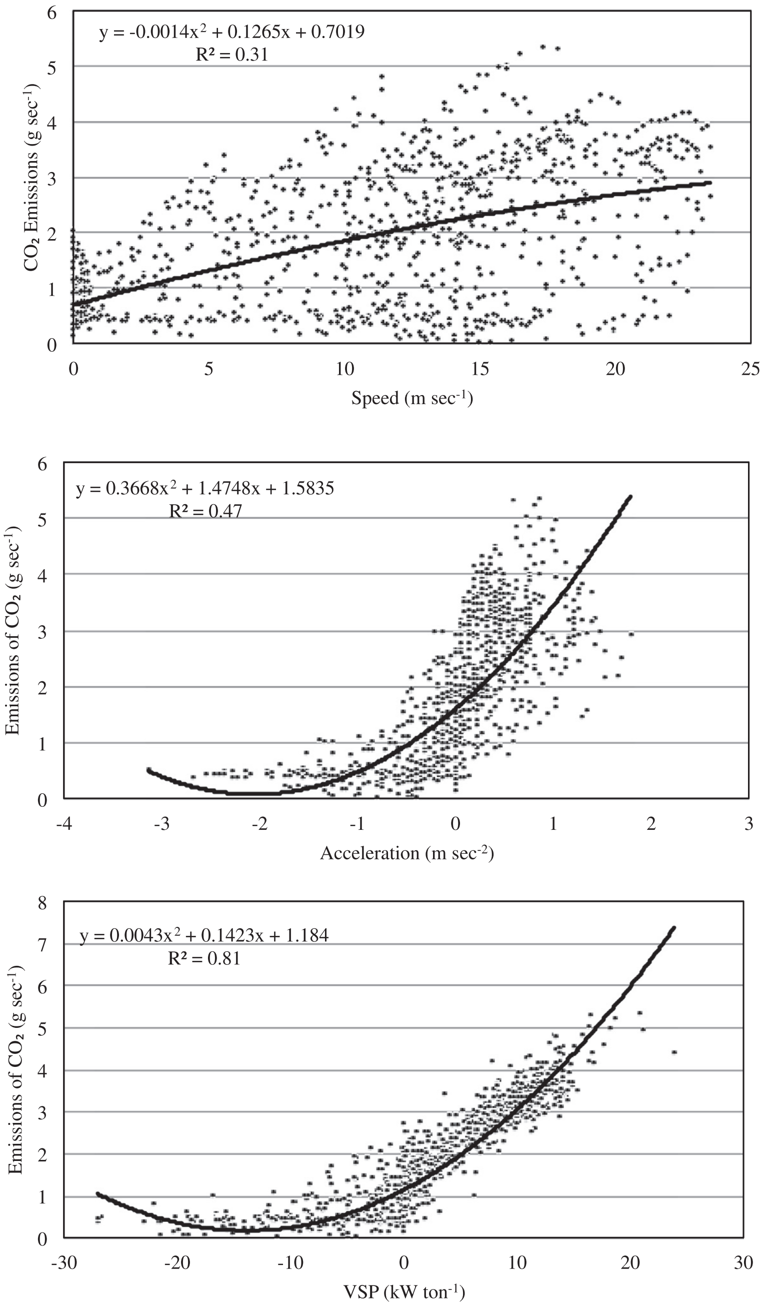


Fig. 5. Relationship between VSP and emissions, speed and acceleration. Results for a single test conducted in a TWC-equipped gasoline-powered light-duty truck.

implementation in the vehicle categories that are responsible for a larger proportion of the mobile source emissions inventory. It also reaffirms the importance of existing emission control technologies.

Fig. 9 shows the emission reductions that could be achieved if driving patterns in Bogota were characterized by smoother vehicle flows with fewer stops and less aggressive accelerations. Under such conditions, compared to the current situation, CO emissions could potentially be reduced by 5–13%, NO_X emissions by 7–24%, HC emissions by 5–13%, and CO_2 emissions by 5–12%.

As stated previously, decreasing the environmental concentration of criteria pollutants generates economic benefits associated with public health savings. Table 5 summarizes the annual potential economic benefits attained from the emissions reductions above: between US $75 and 200 million for CO, between US $95 and 320 million for NO_x, and between US $200 and 500 million for HC. CO_2 emissions reductions could generate between US $4 and 9 million in the global carbon market.

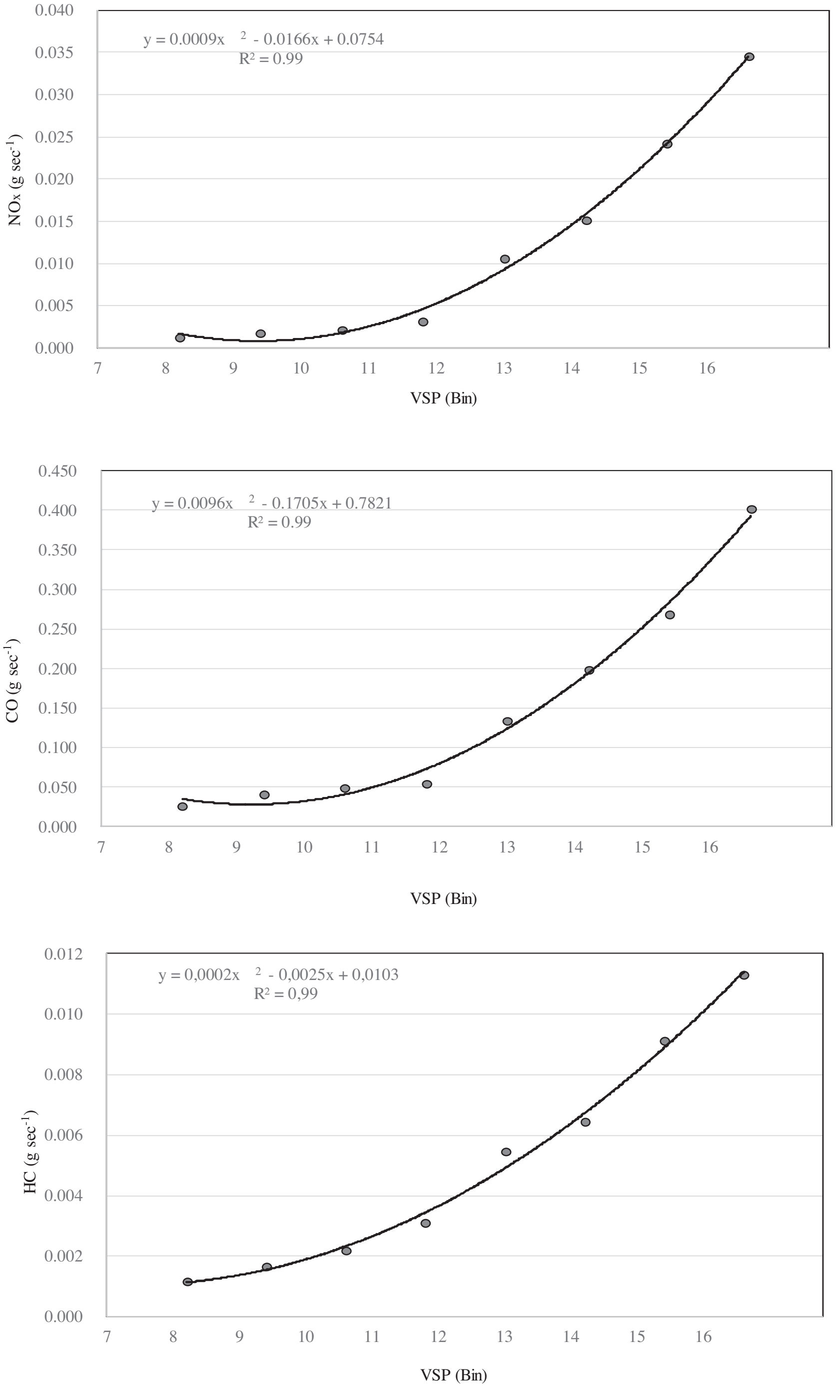
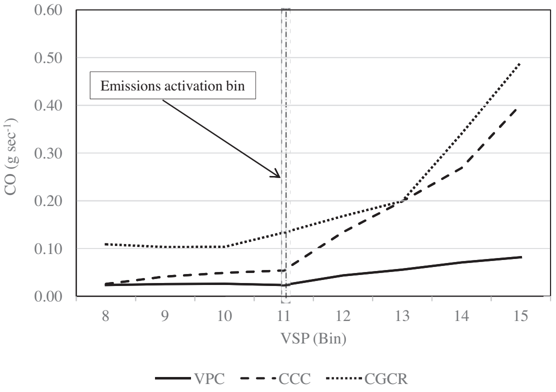


Fig. 6. Relationship between pollutant emissions and VSP bins. Results for all vehicles in the CCC category.

In addition, the potential annual fuel savings could amount to 85 million gallons, representing as much as US $380 million (see Table 6). In total, improving the driving conditions in Bogota could potentially save the city's economy between US $600 and 1,400 million per year.

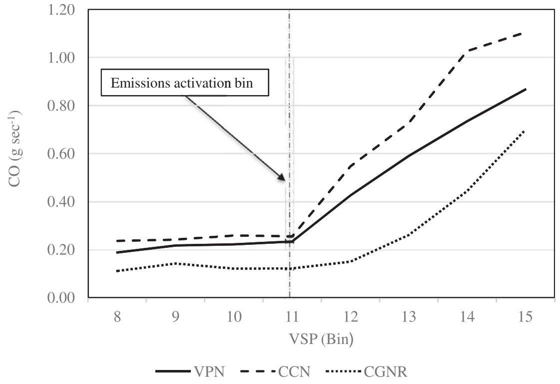
The implication of promoting good driving practices in cities with a high traffic and slow speeds, generating low VSP values and a high level of energy dissipation, like Bogota can be deemed as relevant. It seems highly appropriate to implement technologies with hybrids engines as well as alternatives policies related to discouraging the continuous acceleration during driving in conjunction with the promotion of educational campaigns aimed to training drivers in good driving practices.



VPC = Passenger car + Gasoline + TWC.
CCC = Light-duty truck + Gasoline + TWC.
CGC_R = Light-duty truck + Natural gas + TWC (retrofit dual fuel Vehicles).

Note: Light-duty truck includes sport utility vehicles.

Fig. 7. CO emissions from vehicles equipped with catalytic converter.



VPN = Passenger car + Gasoline + No TWC.
CCN = Light-duty truck + Gasoline + No TWC.
CGN_R = Light-duty truck + Natural gas + No TWC (retrofit dual fuel vehicles)

Note: Light-duty truck includes sport utility vehicles.

Fig. 8. CO emissions from vehicles equipped with no catalytic converter.

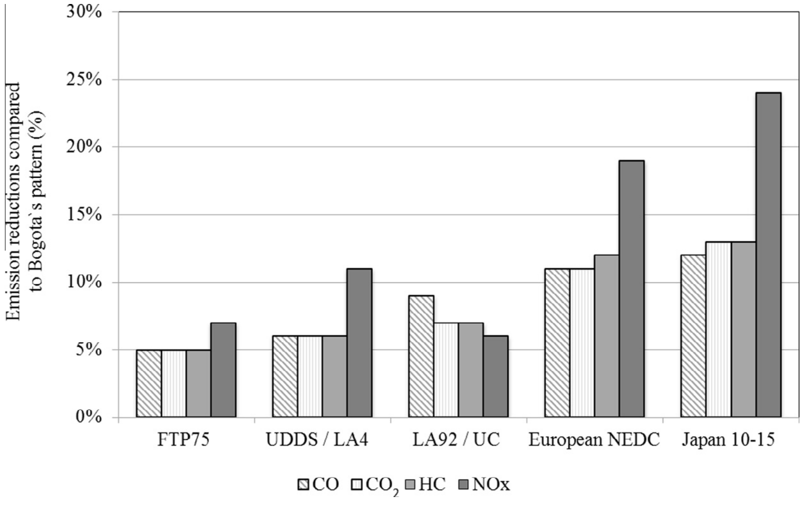


Fig. 9. Emission reductions when compared to Bogota's driving conditions.

Table 5
Economic benefits linked to emission reductions.

Cycle	CO		NO_x		HC		CO_2	
	Reduction ($g \times 10^9$)	Savings[a]	Reduction ($g \times 10^9$)	Savings[a]	Reduction ($g \times 10^9$)	Savings[a]	Reduction ($g \times 10^9$)	Potential savings[b]
FTP75	20	$75	2	$95	3	$210	220	$4
UDDS/LA4	27	$100	3	$140	3	$255	270	$4
LA92/UC	33	$120	2	$110	5	$410	420	$7
European NEDC	50	$185	5	$245	7	$500	510	$8
Japan 10–15	54	$200	7	$320	7	$500	550	$9

[a] Annual money savings (USD × 10^6).
[b] Potential value in the global carbon (USD × 10^6).

Table 6
Fuel savings when compared to Bogota's driving patterns.

Drive cycle	Fuel savings[a]	Savings[b]
FTP75	35	$150
UDDS/LA4	40	$190
LA92/UC	65	$290
European NEDC	80	$360
Japan 10–15	85	$380

[a] Annual fuel savings (gal × 10^6).
[b] Cost reductions linked to fuel savings (USD × 10^6).

The results of implementing these strategies will produce a modification in the driving cycle generating fuel saving as and diminishing the emission of air pollutant as described before. As an example of an effectively implementation of this type, the case of European countries like Greece and Sweden can be analyzed where favorable results were presented (Hucho, 1998; Larson and Ericcson, 2009; Zarkadoula et al., 2007).

Conclusions and recommendations

The results confirm that VSP is a valuable concept to estimate mobile source emissions and to understand their relationship with driving patterns. For such purposes, this methodology outperforms those based on speed and acceleration.

Improving the driving conditions in major Latin American cities could bring potential economic benefits on the order of billions of US dollars per year. In the case of Bogota, implementing driving patterns similar to those represented by test driving cycles used in Europe or Japan could reduce emissions of CO, CO_2, and HC by at least 11% and by as much as 20% for NO_x. Modifying driving conditions usually requires hefty, expensive, and difficult to build infrastructure. However, simpler actions, such as incorporating educational programs aimed at raising awareness regarding drivers' responsibilities, could be a sound starting point. In this context, eco-driving becomes a cost-effective alternative to reduce vehicle emissions, especially if the practice is prioritized for large-engine vehicles and those lacking emission control technologies.

The identification of the emissions activation VSP bin provides evidence that smog check programs based on static (i.e., idle) emissions testing require revision across Latin American cities. The engine load conditions during such tests, which are still widely utilized, are not representative of real-world driving conditions and are below the point at which engines start emitting significant amounts of air pollutants.

The driving conditions in Bogota and similar cities are characterized by heavy traffic and low speeds. This results in low VSP values and potential energy waste. Such a context appears to be highly appropriate for hybrid engine technologies, which could further strengthen the emissions reductions and fuel saving programs described in this research.

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