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ORIGINAL PAPER

Well-to-Wheels emission inventory for the passenger vehicles of Bogotá, Colombia

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Abstract
Emission inventories are essential in air quality management; they identify the main sources of atmospheric pollution and define mitigation strategies. Most vehicle emission inventories estimate direct emissions, including combustion and, in some cases, wear and dust resuspension emissions. However, emission inventories typically do not account for indirect fuel production, storage, and transportation emissions. This study quantifies the Well-to-Wheels emissions from all passenger transport vehicles in Bogotá, Colombia. This inventory estimates direct emissions from fuel combustion, wear and dust resuspension, and indirect emissions. This study analyzes all vehicle technologies and fuels used to transport passengers in the city and estimates $PM_{2.5}$, SO_2, CO, NOx, Volatile Organic Compounds, and greenhouse gas (CO_2-Eq) emissions. COPERT model was adapted to local conditions to estimate direct combustion emissions and European Monitoring and Evaluation Program and U.S. Environmental Protection Agency methodologies to estimate wear and dust resuspension emissions. We used the OpenLCA® Software, the ecoinvent 3.4 database, and all locally available information to calculate indirect emissions. As far as is known, this is the first Well-to-Wheels emissions inventory considering all passenger vehicles in Bogotá. To evaluate the consistency of this study, we compared results from this inventory with those published in Bogotá and other cities worldwide. This study highlights the importance of including other emission sources than vehicle fuel combustion in emission inventories.

Keyword Air quality · Climate change · Direct and indirect emissions · Life cycle assessment · Mobile sources

Introduction

Emission inventories are an essential tool in air quality management, and they are used to identify the primary sources of atmospheric pollutants and define mitigation strategies (Boulter and Mccrae 2007; Lents et al. 2009). The use of internal combustion engine vehicles (ICEVs) causes issues for the environment and human life (air pollution, global warming, rapid depletion of oil resources, and respiratory and cardiovascular diseases, among others) (Thomas 2015; Khreis et al. 2017; IEA 2021). Numerous ICEVs emissions inventories have been developed for cities and regions worldwide (Gómez et al. 2018; Liu et al. 2018; Policarpo et al. 2018; Sun et al. 2021). Most of the emission inventories concentrate on the estimation of direct emissions, which include combustion or exhaust, and in some cases, wear (i.e., brake, tire, and road surface wear) and dust resuspension emissions (W&R) (Padoan et al. 2018; Thouron et al. 2018).

Vehicles also have indirect emissions linked. These occur during fuel production, transportation, storage, and distribution. Although indirect emissions usually occur outside cities, they can be higher than direct emissions (Eriksson and Ahlgren 2013; Cuéllar Álvarez 2016; Xu et al. 2020; Zheng and Peng 2021). Up to now, emissions inventories have focused on direct emissions while excluding indirect emissions. Well-to-Wheels life cycle analysis (WTW) considers direct and indirect vehicle emissions (Van Mierlo et al. 2017). This approach has been widely used to evaluate the

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impact of various vehicle technologies and energy sources in different scenarios (Messagie et al. 2014; Cuéllar Álvarez et al. 2015; Wang et al. 2015; Li et al. 2016; Falaguerra and Rodriguez 2017; Mansour and Haddad 2017; Gupta et al. 2020; Mao et al. 2020; Puig-Samper Naranjo et al. 2021). However, most WTW studies assess individual vehicles, categories, or small fleets. In addition, WTW-based inventories do not consider W&R emissions, an essential source of coarse and fine particulate matter (TSP, PM_{10}, and $PM_{2.5}$).

Bogotá-Colombia is one of the largest cities in Latin America, with more than 7 million inhabitants, and ranks fourth among the capital cities with the worst air quality (IQAir 2018). Several emission inventories have been conducted in this city using different approaches, information sources, activity factors, emission factors, and methodologies (Zárate et al. 2007; Secretaria Distrital de Ambiente 2010; Carmona Aparicio et al. 2016; Pachón et al. 2018; Mangones et al. 2019; Ramirez et al. 2019). Developing countries like Colombia have no standardized, updated system for obtaining vehicle emission factors. In Bogotá, alternative approaches have been assessed to estimate vehicle emissions (e.g., IVE and MOVES models). This study used COPERT because it includes a wide range of vehicle categories and fuels in the city. It is updated periodically and operates an independent equation for the average traffic speed.

Bogotá has made some progress in including W&R emissions within the inventories (Beltrán et al. 2012; Secretaría Distrital de Ambiente (SDA) 2015a; Pachón et al. 2018). WTW emissions generated by the local Bus Rapid Transit (BRT-TransMilenio) were recently estimated and compared against other passenger transport vehicle types (Cuéllar et al. 2016). However, that study only considered emissions from individual vehicles per kilometer traveled and passenger transported.

This study aims to estimate WTW emissions from Bogotá, Colombia's entire fleet of passenger transport vehicles. It considered all the city's technologies and energy sources for passenger transport and estimated emissions of greenhouse gases (CO_2-Eq), CO, $PM_{2.5}$, SO_2, NOx, and Volatile Organic Compounds (VOC). This inventory includes direct (combustion and W&R) and indirect emissions. Combustion emissions were calculated using the COPERT model, based on fuel type and vehicle technology (Kouridis et al. 2018), and W&R emissions were estimated using the EPA (US EPA 2001a, b) and EMEP (European Monitoring and Evaluation Program) methodologies (Ntziachristos and Boulter 2016; Kouridis et al. 2018). Indirect emissions were estimated using the OpenLCA® software, the ecoinvent 3.4 databases, and available information for this case study (CUE 2012; Cuéllar et al. 2016; Ecoinvent Association 2018; Greendelta GmbH 2018). This inventory were contrasted against the results from Bogotá already published and the literature inventories.

Since the indirect emissions are linked to fuel production processes, other systems that require fuel combustion to operate, different from vehicles, take part in these indirect emissions. This approach uses emission factors based on the amount of fuel consumed by the vehicles (i.e., grams of indirect pollutant emitted by a gram of fuel consumed), which allows scaling the indirect emissions only to the vehicles.

Materials and methods

This work computed aggregated emissions for the different vehicle categories. A vehicle category is defined based on the mobility service it provides to the users:

- Private cars (PC): owners are private individuals, passenger car type.
- Taxis (Tx): public service individual, passenger car type.
- Traditional buses (B-Tr): public service, type: Bus and Light Commercial Vehicles.
- Bus Rapid Transit System TransMilenio (BTR-TM): massive public service, urban articulated, and biarticulated bus type.
- Motorcycle (Mt): owners are private individuals, motorcycles with 2 or 4 strokes.
- Special transport buses (B-Ts): Private service vehicles (business and school transport); Bus and Light Commercial Vehicles.

These vehicle categories were chosen since other mobile source inventories in Bogotá published used the same. Therefore, to compare our results with the results of these studies, this study uses the same categories.

The emissions of vehicle categories in tons per year are computed as the sum of the emissions of different vehicle types (Eq. 1). $E_{p,V}$ emission of the vehicle category V (i.e., private cars, taxis, …)

$$E_{p,V} = \sum_{v} E_{p,v} \quad (1)$$

Vehicle type emissions (g/year) is the product between activity and emission factor according to Eq. 2, in which p is the pollutant (i.e., CO_2, $PM_{2.5}$, NOx, SO_2, CO) and v is the vehicle type (i.e., Gasoline Pre-Euro, Gasoline Euro I, III, IV, and V; Diesel pre-Euro, Diesel Euro I, III, IV, V; CNG Euro IV, etc.).

The activity is evaluated in terms of kilometer traveled (km/veh) or energy consumed (kWh/veh). Emission factors correspond to the mass of pollutant emitted per kilometer traveled (g/km/veh) or per energy consumed (g/kWh). Direct emissions use kilometers traveled, while indirect emissions use energy consumed. A single-vehicle type includes vehicles whose technical characteristics are the same, i.e., they have the same standard (EURO I, EURO II, …), and the same engine and fuel type (diesel, gasoline, compressed natural gas -CNG-, 2 strokes, 4 strokes, etc.). Therefore, vehicles of the same *type* have the same emission factor.

$$E_{p,v} = A_v \times EF_{p,v} \tag{2}$$

$$A_v = N_v \times a_v \tag{3}$$

In Eqs. 2 and 3: A_v is the activity, and $EF_{p,v}$ is the emission factor. The vehicle type group activity is computed using the activity of a single-vehicle (Eq. 3) in which N_v is the number of vehicles of type v, and a_v is the unit activity (i.e., the activity of a single-vehicle) of type v. It corresponds to the VKT (vehicle kilometer traveled per year) or the VEC (vehicle energy consumption per year). VEC by type of vehicle stands for multiplying the VKT and the fuel consumption (kWh/km).

The base year used in this study is 2015. This year 90% of the vehicles in Bogotá were private, 9% public, and 1% official (Secretaría Distrital de Ambiente (SDA) 2015b). Bogotá's fleet in 2015 consisted of 2.1 million vehicles in total, with passenger vehicles having a 98% share. Table 1 shows the number of vehicles by category, vehicle technologies, and fuels used in Bogotá at the defined base year. According to the retrieved data, most light vehicles use gasoline as an energy source; 78% are passenger cars (more than 1.5 million vehicles), 22.3% are motorcycles (Mt) (about 0.5 million vehicles), and 0.2% are Light Commercial Vehicles. Traditional and articulated public transport buses of the TransMilenio system operate mainly with diesel as an energy source. A small number of vehicles use natural gas. Fuel supplied to the vehicles in Bogotá in 2015 contained 10% ethanol-gasoline blend (E10) and 7% biodiesel-diesel blend (B7) (Ministerio de Minas y Energía—MINMINAS- 2017).

The vehicles in Colombia follow the European Union classification or EURO standards (Autoridad Nacional de Licencias Ambientales -ANLA- 2016). Table 1 also shows that most of the fleet in the city is Euro III or older (about 99% of the passenger vehicles in the city). 62% of the vehicles are Euro 1, 23% Pre-Euro, 15% Euro III, 0.9% Euro IV, 0.9% are Euro IV, and less than 0.2% are Euro II or EEV (EEV Enhanced Environmental Vehicles (Kouridis et al. 2018).

The quality of pollutants produced by different driving speeds varies and depends on the climate's seasonal variation. However, to simplify the calculation process, this study used the vehicle traffic speed average and the annual activity per vehicle average. In addition, geographically, Bogotá is located near Ecuador; therefore, this city has no seasons.

Direct emissions estimation

Estimation of emissions from internal vehicular combustion (exhaust)

COPERT estimates emissions from vehicles manufactured with European emission standards (Kouridis et al. 2018), making it compatible with the standards of the vehicles circulating in the city. The COPERT emission factors are stated as a function of average vehicle speed. They are obtained from a binomial regression analysis performed on a sizable data set of vehicle measurements categorized by vehicle type and technology. The emission factors (EFp,v) were calculated as a speed function by adapting the COPERT 2018 model (Kouridis et al. 2018) to the city's traffic conditions. The COPERT approach follows the IPCC Guidelines, and the air pollutant emission inventory guidance from European Environment Agency's (EEA) includes it (Kouridis et al. 2018). COPERT calculates emissions of all significant air pollutants (CO, NO_x, VOC, PM, NH_3, SO_2, and heavy metals) as well as greenhouse gas emissions (CO_2, N_2O, CH_4) from a variety of vehicle categories, including passenger cars, light trucks, heavy-duty trucks, buses, motorcycles, and mopeds (Kouridis et al. 2018). In the case of this study, COPERT allowed us to use a wide range of vehicle categories, including articulated buses, to have the existing biofuel blends in the city, to use the equations independently for the average traffic speed, and it is periodically updated and includes EF for new vehicle technologies.

The exhaust emission factor used in this study refers to hot emissions from the COPERT model and omits evaporative emissions or other losses. Appendix A of the supplementary material summarizes the equations and parameters used to estimate emissions from the COPERT model. Table 1 shows the activity factors (VKT, Number of vehicles, and average speed), the emission factors, and the average fuel consumption of the fleet. Public transport vehicles (buses and taxis) have the highest activity in kilometers traveled per year. The highest average traffic speed corresponds to motorcycles, followed by private cars, and the slowest are public transport vehicles (buses and taxis).

Emission estimates from tire, brake, and road surface wear and dust resuspension (W&R)

Tire, brake, and road surface wear emissions were determined using the EMEP / EEA methodology (Ntziachristos and Boulter 2016), while dust resuspension emissions were obtained using the EPA AP-42 methodology (US EPA 2001a). Vehicular activity by road type was distributed as follows: Paved 99.3%, Unpaved Public 0.4%, and Unpaved Industrial 0.3% (East et al. 2021). Appendix B of

Table 1 Number of vehicles by vehicle technology and the fuel used in Bogotá (2015), activity factor (VKT), average speed, emission factors, and average fuel consumption used to calculate emissions from internal combustion (exhaust)

Category [a]	Type	Fuel [b]	Standard [c]	Fleet 2015	VKT	Speed	Emission factors (g/km) [e]						Fuel consumption [e]
				[Number of vehicles]	[km/year.veh] [d]	[km/h] [d]	CO	NOx	VOC	$PM_{2.5}$	SO_2	CO_2-Eq *	[kWh.km-1]
PC	Passenger Cars	Gasoline	pre-Euro	394 559	12 436	28.27	34.325	1.942	2.994	0.003	0.053	342.564	1.185
			Euro I	897 990	12 436	28.27	2.274	0.317	0.231	0.003	0.037	204.126	0.823
			Euro III	187 618	12 436	28.27	0.492	0.082	0.018	0.001	0.037	204.223	0.835
		Diesel	pre-Euro	25 509	12 436	28.27	0.794	0.603	0.201	0.253	0.003	223.735	0.839
			Euro III	16 536	12 436	28.27	0.135	0.795	0.024	0.033	0.002	174.227	0.656
			Euro IV	10 279	12 436	28.27	0.131	0.657	0.017	0.033	0.002	174.220	0.656
		CNG	Euro IV	298	12 436	28.27	0.173	0.067	0.047	0.001	0.000	174.782	0.848
Tx	Passenger Cars	Gasoline	pre-Euro	167	73 000	23.28	38.611	1.844	3.425	0.003	0.059	383.724	1.326
			Euro I	36 206	73 000	23.28	2.629	0.343	0.268	0.003	0.040	224.934	0.906
			Euro III	5 560	73 000	23.28	0.489	0.084	0.021	0.001	0.041	225.614	0.923
		Diesel	pre-Euro	57	73 000	23.28	0.888	0.647	0.242	0.281	0.003	245.256	0.920
		CNG	Euro IV	8 084	73 000	23.28	0.165	0.073	0.047	0.001	0.000	190.371	0.924
Mt	Motorcycles 2-stroke	Gasoline	pre-Euro	2 812	15 000	31.03	16.137	0.025	10.205	0.200	0.016	115.239	0.369
			Euro I	32 400	15 000	31.03	10.645	0.039	3.181	0.080	0.015	99.676	0.340
			Euro III	8 591	15 000	31.03	4.647	0.020	1.054	0.012	0.015	90.250	0.340
	Motorcycles 4-stroke	Gasoline	pre-Euro	25 313	17 483	31.03	16.558	0.269	1.582	0.020	0.015	109.943	0.344
			Euro II	291 602	17 483	31.03	3.798	0.234	0.501	0.005	0.011	67.267	0.252
			Euro III	77 328	17 483	31.03	2.096	0.220	0.312	0.005	0.011	64.591	0.252
BRT-TM	Urban Buses Articulated	Diesel	Euro III	1 177	82 486	23.28	3.475	12.506	0.560	0.253	0.018	1325.963	4.981
			Euro IV	117	82 486	23.28	1.555	8.143	0.087	0.063	0.017	1245.749	4.690
		CNG	EEV	1	82 486	23.28	0.971	4.128	0.996	0.011	0.000	1155.569	5.609
	Urban Buses Biarticulated	Diesel	Euro III	10	82 486	23.28	3.822	13.756	0.615	0.278	0.019	1458.560	5.479
			Euro IV	155	82 486	23.28	1.711	8.957	0.096	0.069	0.018	1370.324	5.159
B-Tr	Light Commercial Vehicles	Gasoline	pre-Euro	53	21 900	23.28	28.545	2.371	3.117	0.003	0.059	367.474	1.324
			Euro I	5	21 900	23.28	8.992	0.497	0.334	0.003	0.069	391.828	1.550
			Euro III	1 458	21 900	23.28	4.676	0.105	0.047	0.001	0.069	385.046	1.550
	Urban Buses Rigid	Diesel	pre-Euro	8 357	65 700	23.28	5.765	17.061	2.070	0.816	0.016	1238.749	4.638
			Euro I	708	65 700	23.28	2.609	10.512	0.825	0.434	0.014	1040.096	3.908
			Euro II	3 564	65 700	23.28	2.362	11.437	0.568	0.205	0.013	1000.737	3.761
		CNG	Euro I	4	65 700	23.28	8.400	16.500	7.000	0.020	0.000	1535.740	7.400

Table 1 (continued)

Category [a]	Type	Fuel [b]	Standard [c]	Fleet 2015	VKT	Speed	Emission factors (g/km) [e]						Fuel consumption [e]
				[Number of vehicles]	[km/year.veh] [d]	[km/h] [d]	CO	NOx	VOC	$PM_{2.5}$	SO_2	CO_2-Eq *	[kWh.km-1]
B-Ts	Light Commercial Vehicles	Gasoline	pre-Euro	2 080	21 900	23.28	28.545	2.371	3.117	0.003	0.059	367.474	1.324
			Euro I	265	21 900	23.28	8.992	0.497	0.334	0.003	0.069	391.828	1.550
			Euro III	35	21 900	23.28	4.676	0.105	0.047	0.001	0.069	385.046	1.550
	Urban Buses Rigid	Diesel	pre-Euro	8 517	65 700	23.28	5.673	13.821	2.707	0.866	0.015	1109.356	4.151
			Euro II	95	65 700	23.28	2.362	11.437	0.568	0.205	0.013	1000.737	3.761
			Euro IV	92	65 700	23.28	1.273	6.239	0.071	0.051	0.013	972.478	3.661

[a]Where: PC: Private cars, Private service vehicles class: Passenger Car; Tx: Taxis, Public service vehicles class: Passenger Car; B- Tr: Traditional buses, Public service vehicles class: Bus and Light Commercial Vehicles; BRT-TM: BRT-TransMilenio, Public service vehicles class: Articulated and Bi-articulated Buses; Mt: Motorcycles, Private service vehicles class: Motorcycle; B-Ts: Special transport buses (business and school transport), Private service vehicles class: Bus and Light Commercial Vehicles

[b]CNG: Compressed Natural Gas; Gasoline is a 10% ethanol-gasoline blend (E10), and diesel is a 7% biodiesel-diesel blend (B7)

[c]Following EURO standards, vehicle technologies are classified as follows: light petrol, diesel, or natural gas vehicles are categorized into Euro 1, 2, 3, 4, 5, and 6; while for heavy diesel or natural gas vehicles, there are Euro I, II, III, IV, V and VI (Chambliss et al. 2013; Kouridis et al. 2018). EEV refers to Enhanced Environmental Vehicles according to COPERT (Kouridis et al. 2018), in which emissions in terms of NOx limit are equal EURO V standard, but in terms of PM, the level is one-third lower

[d]SDA (2015a)

[e]They were estimated based on the COPERT model (Kouridis et al. 2018). Emission factor refers to hot emissions, and evaporative emissions or other losses are omitted. *The CO_2-Eq emission factor was obtained from the global warming potential of the IPCC 2007

the supplementary material summarizes the equations and parameters used to calculate emissions from tires, brake, and road surface wear and dust resuspension (W&R).

Estimation of indirect emissions

Indirect emissions are related to energy production processes, i.e., all processes from well extraction to the vehicle tank ("*Well-to-Tank"*—WTT) for fossil fuels. "*Well-to-Wheel* (WTW studies usually cover the entire life cycle of the energy carrier (i.e., fuels or electricity) used to drive the vehicles as well as driving the vehicle itself (Van Mierlo et al. 2017). This study used the WTW approach to estimate the total emissions (direct plus indirect emissions), following the methodology used by Cuéllar et al. (2016). The open-source OpenLCA®, for life cycle assessment, was used as a calculation tool (Greendelta GmbH 2018). The system boundaries comprise the entire fossil and biofuel production chain (extraction of raw materials, transport, refinery, biomass cultivation, production, transport, distribution, and energy source in the vehicle fleet). However, the manufacture of agricultural machinery, plant construction, vehicle parts, manufacture, and assembly are excluded from the analysis. These are processes outside the well-to-wheel approach, focusing on the energy source's life cycle rather than the vehicle's intermediate production processes (Van Mierlo et al. 2017).

The functional unit is the amount of pollutants emitted in mass units per year for the total fleet of vehicles. The category of global warming impact, expressed in the reference unit of kg of CO_2 equivalent (CO_2-Eq), over the 100-year time horizon (GWP100) (Hauschild and Huijbregts 2015); and the emissions of CO, NOx, $PM_{2.5}$, SO_2, and VOC, were assessed based on the energy sources used from vehicle activity and fuel consumption. Equations (1) and (2) calculate the indirect emissions.

The life cycle inventory (LCI) data for each vehicle energy source is available mainly in ecoinvent 3.4. database (Ecoinvent Association 2018). Ecoinvent is a database of LCIs validated and recognized worldwide as a suitable tool for developing life cycle assessment studies (Ecoinvent Association 2018; Greendelta GmbH 2021). This database has LCI information for different industrial sectors with around 17 000 data sets in fields such as energy supply, agriculture, transport, biofuels and biomaterials, chemicals, building materials, wood, and waste treatment, among others (Ecoinvent Association 2018).

For diesel, gasoline, and natural gas production processes, the production modules of the ecoinvent 3.4 database were the input data for the OpenLCA® software (Ecoinvent Association 2018). This study found that the CO_2-Eq emissions of the reference process created from the database are similar to the official reports from the Colombian Petroleum Company (Ecopetrol) (Ecopetrol S. A. 2013). The differences between the official data and the results obtained here are around 12% for gasoline and 18% for diesel (Cuéllar Álvarez 2016).

The CUE Consortium (CUE 2012) information for biofuels was used to estimate life cycle emissions from biodiesel and bioethanol production. In Colombia, bioethanol is produced from sugarcane and biodiesel from palm oil.

Results from OpenLCA® were used to obtain the emission factors by energy source for the pollutants included in this study (Table 2). Appendix C of the supplementary material presents all the emission factors used by fuel type.

Results and discussion

Direct and indirect emissions

Figure 1 shows the estimated direct and indirect emissions for each vehicle category, and pollutant analyzed. Results indicate that 70 to 87% of the CO_2-Eq, NOx, VOC, and CO

Table 2 Emission factors by fuel used to calculate indirect emissions

Fuel	Emission factor by fuel (mg kWh^{-1})					
	CO_2-Eq	$PM_{2.5}$	CO	NOx	SO_2	VOC
Gasoline E10[a]	83 976	49	1 694	214	428	419
Diesel B7[b]	59 614	25	110	194	354	270
Natural Gas[c]	45 863	23	53	83	150	750

[a]E10 blends refer to the 10% by volume ethanol-gasoline blend (Ministerio de Minas y Energía—MINMINAS- 2017). Density (kg/m^3): Ethanol, 794, and Gasoline, 750. Calorific value E10 Gasoline: 43.774 MJ/kg

[b]B7 blends refer to the 7% by volume biodiesel-diesel blend (Ministerio de Minas y Energía—MINMINAS- 2017).Density (kg/m^3): Biodiesel, 890, and Diesel, 840. Calorific value Diesel B7: 42.695 MJ/kg

[c]Calorific value Natural Gas: 48.0 MJ/kg

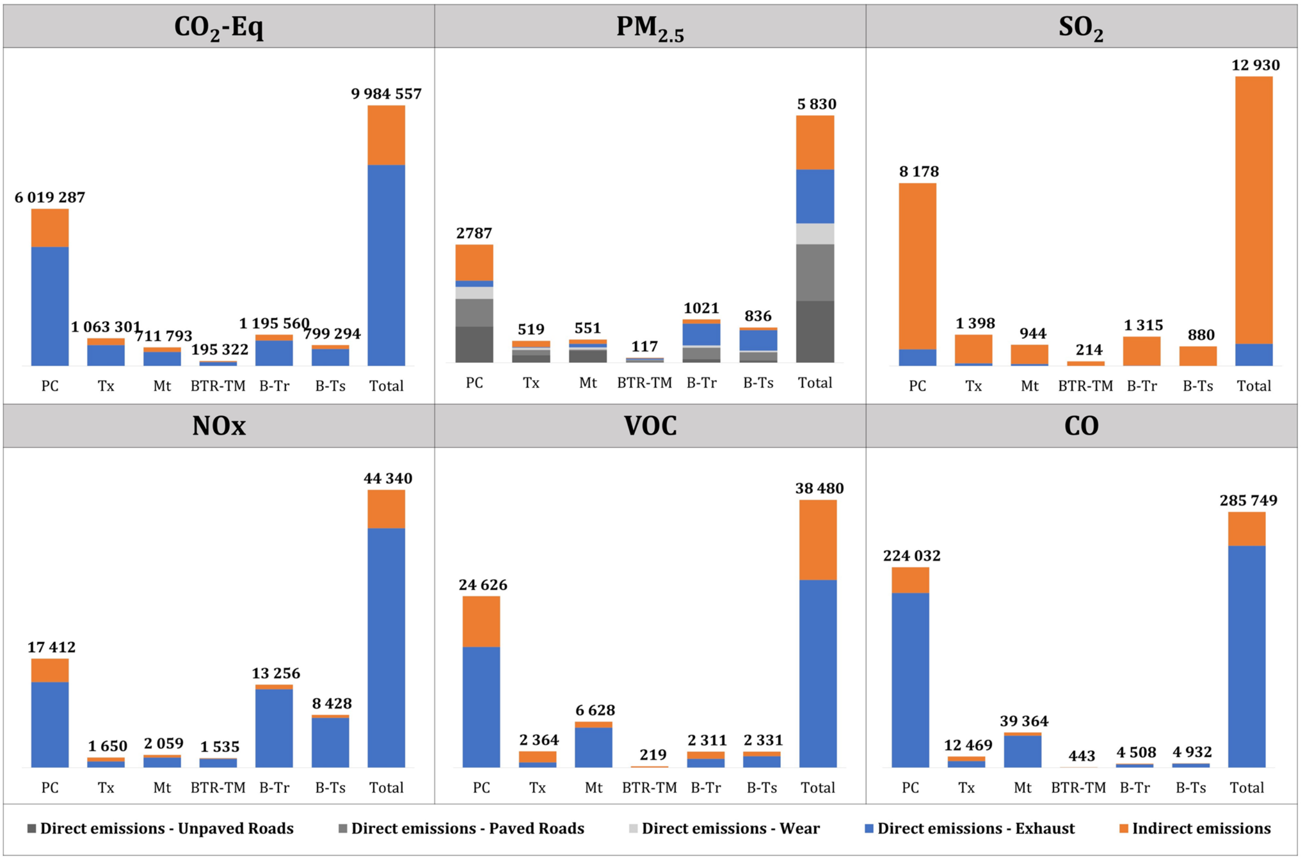

Fig. 1 Contribution to direct and indirect emissions of pollutants CO_2-Eq, $PM_{2.5}$, SO_2, NOx, VOC, and CO by vehicle category (tons/year). Where: PC: Private cars; Tx: Taxis; B- Tr: Traditional buses; BRT-TM: BRT-TransMilenio; Mt: Motorcycles; B-Ts: Special |transport buses (business and school transport). *The vertical axis scale in the graph differs for each pollutant. **$PM_{2.5}$ includes emissions by W&R (Wear and Resuspension)

emissions are released in the city for all vehicle categories (direct emissions). As previously stated, most of the passenger vehicles in the city are Euro III or older, and thus exhaust emissions are significant. The progressive renewal of the fleet will reduce direct emissions of these pollutants; however, policies should also focus on indirect emissions to avoid increasing this type of emissions. The International Energy Agency (IEA) states that electric vehicles will account for about 7% of the global fleet by 2030 (IEA—International Energy Agency—2020). This change in the fleet will reduce or eliminate direct emissions in cities but may increase indirect emissions depending on the energy source used to generate electricity.

Stages before vehicle combustion generate most of the SO2 emissions; the WTW analysis reveals that the oil and gas processes (mainly, extraction of fossil fuels, heavy fuel oil burned in refinery furnaces, and manufacturing of refined petroleum products) release most of these emissions. Only 8% of the SO2 emissions are direct. Appendix D of the supplementary material shows the direct and indirect emissions estimated for each vehicle category and pollutant analyzed.

Private cars are the vehicle category that generates higher emissions of all pollutants. This vehicle category has an essential contribution to total CO_2-Eq, $PM_{2.5}$, VOC, and CO emissions. They cause 6 019 287 tons/year of CO_2-Eq, 2 787 tons/year of $PM_{2.5}$, 24 626 tons/year of VOC, and 224 032 tons/year of CO, which are 60, 48, 64, and 78% of the total emissions, respectively. Traditional and special transport buses also generate significant CO_2-Eq, $PM_{2.5}$, and NOx emissions. Motorcycles generate an essential fraction of VOC. A large part of emissions from these vehicle categories is direct for all pollutants, except SO_2, mainly due to old vehicle technologies used in the city and poor maintenance. Conversely, BRT buses generate much lower emissions of all contaminants. In 2015, most of this type of bus were Euro III and had the highest VKT of all categories; only 1 460 BRT buses made this fleet (Table 1).

Data regarding the indirect and exhaust EF is only partially available for TSP and PM_{10}; differently, information is available for $PM_{2.5}$. Therefore, only $PM_{2.5}$ Wear and dust resuspension (W&R) emissions are included in this study. W&R, in terms of $PM_{2.5,\ W\&R}$ represents 56% (3 285 t/year) of the total emissions of this pollutant. Paved roads emit 23% (1 336 t/year) of the total $PM_{2.5}$ emissions, while unpaved roads emit nearly 25% (1 463 t/year), despite their activity representing only 0.7%. These results are coherent with data published in previous studies for Bogotá and other cities worldwide (Amato 2018; Padoan et al. 2018; Thouron et al. 2018; Gulia et al. 2019). A recently developed study found that resuspended dust from unpaved roads is the largest local source of $PM_{2.5}$ (East et al. 2021). These results agree with what was found in this study.

The ratio of W&R emissions to exhaust emissions (W&R/exhaust) found is PC (12.3), Tx (32.7), Mt (4), BRT-TM (2.9), and for B-Tr and B-Ts is lower than 0.8. It means the W&R emissions are more critical in Tx and PC, the most significant vehicle number in the fleet.

On the other hand, 30% of private car emissions are indirect; these emissions are much more extensive for the different vehicle categories. Direct exhaust emissions of B-Tr and B-Ts are more prominent than in the other vehicle categories, and this is because more recent emissions standards predominate in these categories.

Contribution by fuel type to direct and indirect emissions

Figure 2 shows the ratio of indirect to direct emissions sorted by fuel type and pollutant. In this section, direct emissions refer only to exhaust emissions to compare fuel emissions; therefore, $PM_{2.5}$ W&R emissions were not included. Gasoline-powered vehicles show high indirect to direct $PM_{2.5}$ and SO_2 emissions ratios (0.88 and 0.91, respectively). This case indicates that gasoline vehicles' upstream stages of vehicle operation release an essential fraction of PM2.5 and SO2 emissions, which occur outside the city, such as fuel production and refining. However, these CO_2-Eq, NOx, and CO ratios range from 0.13 to 0.24; thus, emissions from gasoline vehicles for these pollutants are primarily released in the city during vehicle operation. Diesel-powered vehicles also show a high ratio of indirect to direct SO_2 emissions (0.99) and VOC (0.39), while the proportions are much smaller for the other pollutants. CNG vehicles show high ratios for most pollutants, especially $PM_{2.5}$, SO_2, and VOC. However, this and previous studies find that direct emissions from CNG vehicles are negligible compared to vehicles using other energy sources. Therefore, in recent years, local authorities started programs to replace gasoline and diesel-powered with CNG vehicles. It will undoubtedly reduce direct emissions, but Fig. 2 indicates that it will also increase indirect emissions.

Comparison with other emission inventories

The emissions inventory was compared with already published vehicle emissions inventories of Bogotá to evaluate the consistency of the results: SDA (2015a) and Carmona Aparicio et al. (2016). In addition, the W&R results from this study were compared against the results reported by Beltrán et al. (2012) and SDA (2015a). Table 3 shows the main characteristics of the emissions inventories used to evaluate the obtained results from this study.

Direct combustion emissions

This study compared the exhaust emissions presented with results reported by SDA (2015a) and Carmona Aparicio et al. (2016). Figure 3 shows a comparison of combustion emissions with these emissions inventories. Results indicate that CO_2-Eq, $PM_{2.5}$, and NOx exhaust emissions are within the same order of magnitude as the other emission

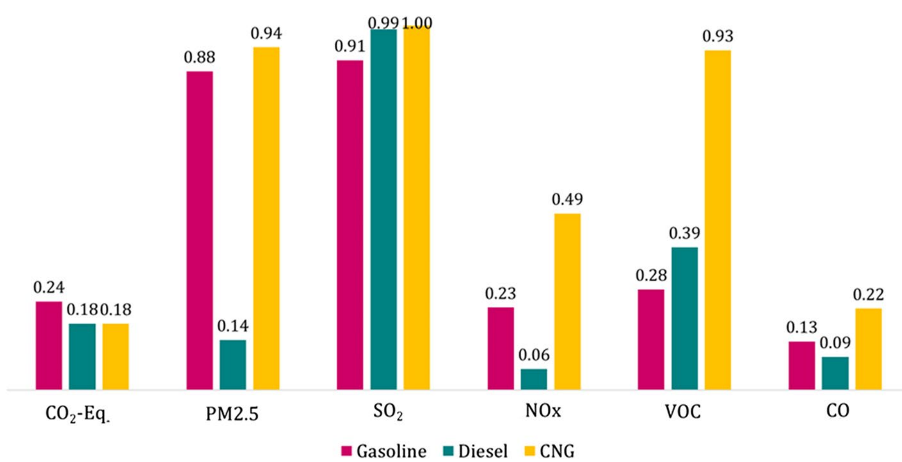

Fig. 2 Relationship between the exhaust and indirect emissions from fuels. The numbers on the bars correspond to the ratios of exhaust/indirect emissions. It sorted the results by type of fuel and pollutant. *$PM_{2.5}$ does not include W&R emissions

Table 3 Main characteristics of the emissions inventories used to evaluate results from this research

Inventory	Base year	Model to estimate the Emission Factor – Fuel combustion	Model to estimate the Emission Factor—W&R
Carmona Aparicio et al. (2016)	2013	Rodríguez and Behrentz (2009) MOVES IVE	*
SDA (2015a)[a]	2014	MOVES US-EPA	EMEP (Ntziachristos and Boulter 2016) EPA (US Environmental Protection Agency (US EPA) 2001a, b) From field measurements
Beltrán et al. (2012)[b]	2012	*	EMEP (Ntziachristos and Boulter 2016) EPA (US Environmental Protection Agency (US EPA) 2001a, b)
Cuéllar et al. (This study)	2015	COPERT	EMEP (Ntziachristos and Boulter 2016) EPA (US Environmental Protection Agency (US EPA) 2001a, b)

*No data reported

[a]SDA (2015a) does not report W&R emissions by vehicle category. Therefore, in this part of the study, it was necessary to include W&R emissions from all vehicle categories in the city. These values include emissions generated by freight vehicles

[b]Beltrán et al. (2012) present W&R emissions disaggregated by vehicle categories in the city

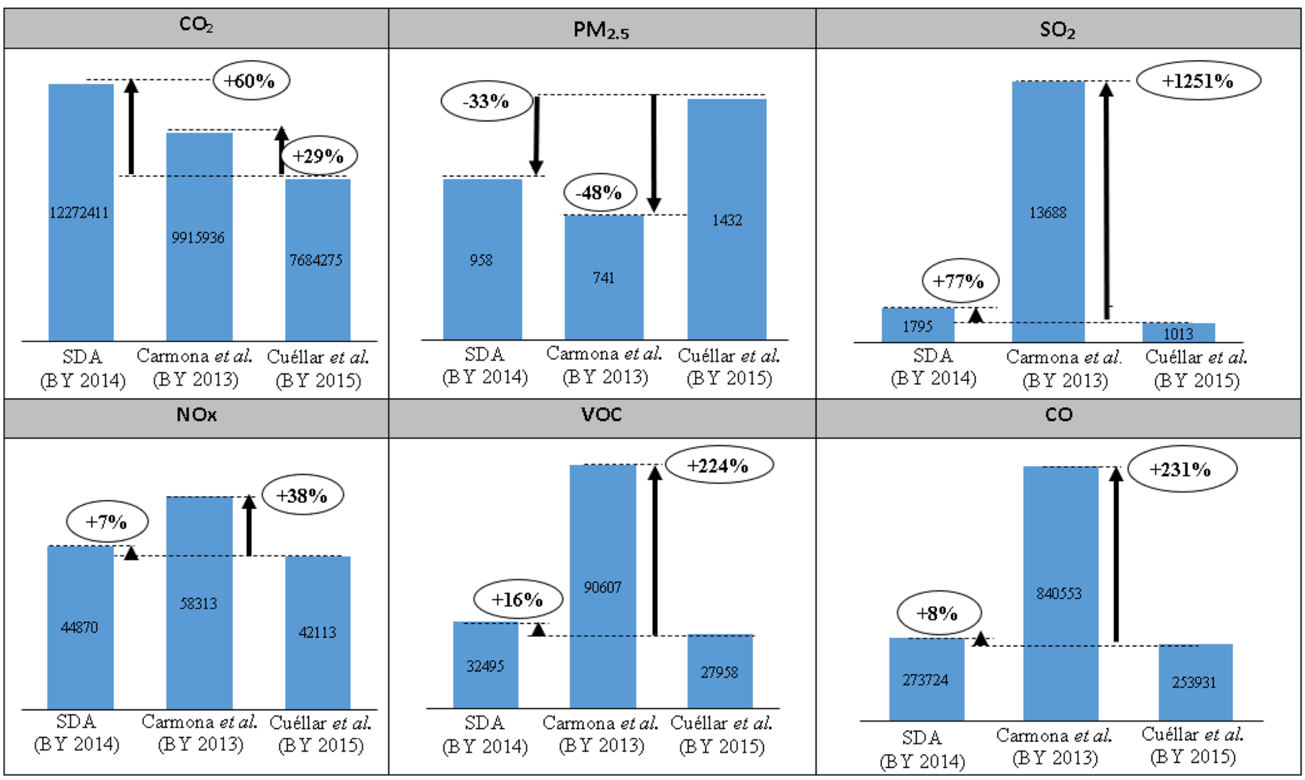

Fig. 3 Comparison of combustion emissions estimated in this study with other emission inventories. The percentages shown are the difference between the result from this study and the other inventories (Secretaría Distrital de Ambiente (SDA) 2015a; Carmona Aparicio et al. 2016). (BY: represents base year). *The numerical scale of the vertical axis in the graph is different for each pollutant. **All the inventories mentioned were developed using the Bottom-Up approach

Table 4 Comparison of $PM_{2.5}$ W&R emissions with other studies (tons/year)

Inventory	Base year	Wear	Dust Resuspension		Total–W&R
			Paved roads	Unpaved roads	
SDA (2015a)	2014	14,430	11,815	4794	31,039
Beltrán et al. (2012)	2012	320	1160	1380	2860
Cuéllar et al. (This study)	2015	516	1495	2040	4051*

*Note that these values include emissions generated by freight vehicles. SDA (2015a) does not report W&R emissions by vehicle category; therefore, in this part of the study, it was necessary to include W&R emissions from all vehicle categories in the city. Beltrán et al. (2012) estimated desegregated emissions on all city roads and by vehicular category

inventories, even though all these studies adapted emission factors from different sources and used different methodologies (Table 3). NOx presents minor differences, ranging from 7 to 38%, and CO_2 and $PM_{2.5}$ differences range from 33 to 48%. This study's SO_2, VOC, and CO emissions are closer to those reported by SDA, ranging from 8 to 77%. On the other hand, Carmona et al. report SO_2, VOC, and CO emissions that are well above SDA, and this study, ranges from nearly 224–1251%.

Nevertheless, other cities' studies report similar or even more significant differences (Gallardo et al. 2012). Potential sources of discrepancies are differences in activity or emissions factors used. Therefore, a deeper evaluation of local emission inventories is needed to identify the sources of uncertainties and to estimate more accurate emissions.

Direct emissions from tires, brakes, road surface wear, and dust resuspension (W&R)

Table 4 compares results from this study with those reported by Beltrán et al. (2012) and SDA (2015a). This comparison indicates that $PM_{2.5}$ emissions from wear and paved roads from this study are within the same orders of magnitude as those reported by Beltran et al. Emissions from wear, paved and unpaved roads from this study are 38, 22, and 32% above Beltran's results, respectively. These two emission inventories use emission factors from the same databases but use different vehicular activities and methodologies. Beltran estimated desegregated emissions in all city roads, while we reported aggregated emissions in the city. Comparing the total emissions of each category in this study with Beltran's results is possible. SDA results from wear and paved roads are about 28 and 8 times above the other inventories.

On the other hand, all inventories show that dust resuspension emissions from unpaved roads are within the same others of magnitude (between 1 380 and 4 794 tons/year),

Table 5 Comparison of direct traditional bus emissions (B-Tr) relative to total emissions (in percentage) with other studies

Pollutants	Diesel				CNG	
	Li et al. (2016)	Falaguerra and Rodríguez (2017)	Wang et al. (2015)	This study	Wang et al. (2015)	This study
CO_2	79%	NA	80%	82%	76%	82%
$PM_{2.5}$	NA	NA	70%	85%	45%	11%
SO_2	NA	NA	5%	1%	0%	0%
NOx	NA	94%	90%	95%	92%	90%
VOC	NA	NA	58%	57%	53%	56%
CO	NA	43%	94%	91%	93%	96%

a. Li et al. (2016) evaluated a fleet of 26 buses.

b. Sulfur content in diesel ≈10 ppm (Wang et al. 2015).

c. Since this comparison refers to the results from WTW from the fuels, it does not include W&R emissions.

[a]Li et al. (2016) evaluated a fleet of 26 buses

[c]Sulfur content in diesel ≈10 ppm (Wang et al. 2015)

[c]Since this comparison refers to the results from WTW from the fuels, it does not include W&R emissions

although results from this study are much closer to those reported by SDA (2 040 and 1 380 tons/year, respectively). Results from these inventories indicate that emissions from unpaved roads are an essential source of $PM_{2.5}$ and must be controlled. These results are also consistent with results recently reported by East et al. (2021). As previously stated, vehicular activity on unpaved roads is a crucial parameter; here, only 0.7% of total VKTs are traveled on unpaved roads; however, this small percentage produces significant resuspension emissions. Nevertheless, additional efforts are needed to reduce uncertainties and validate these emissions. Although the information available to the city make it difficult to estimate the uncertainty of the results, they offer new research opportunities for the future.

Direct and indirect emissions

This study used the WTW approach to estimate the fuel's total emissions (direct plus indirect emissions). To our knowledge, WTW emission inventories for all passenger vehicles in a city have yet to be made available. Therefore, most studies evaluate individual cars, vehicle categories, or small fleets. Thus, we compare our results from some vehicle categories with already published studies in the literature. Table 5 compares direct traditional bus emissions (B-Tr) relative to total emissions (in percentage) with other studies in other countries. This comparison shows that these percentages are close for most pollutants and confirms the consistency of results reported in this research. For example, this study indicates that direct CO_2 emissions from traditional buses are 82% of total emissions, while the other studies report percentages ranging between 76 and 82%.

Moreover, all studies indicate that this percentage varies between 0 and 5% for SO_2. On the other hand, this study found that 11% of $PM_{2.5}$ emissions from CNG buses are direct, while Wang et al. report 45%. This difference is due to the emission factors used in that study to quantify direct emissions. Finally, we also compare emissions from passenger cars with results from Lucas et al. (2012), which found that 80 to 90% of CO_2-Eq emissions are direct and close to what we found here.

Conclusion

This study quantifies the Well-to-Wheels (WTW) emissions from all passenger transport vehicles in Bogotá, Colombia. This WTW inventory estimates direct emissions from fuel combustion, wear, and dust resuspension (W&R); the inventory includes indirect emissions produced before vehicle combustion, such as raw material extraction, fuel refinery, transportation, and storage. As far as is known, this is the first WTW emissions inventory using all passenger vehicles in a city, considering other emission sources than vehicle combustion.

Vehicle operation (direct emissions) produces many CO_2-Eq, NOx, VOC, and CO emissions. Passenger cars have the highest total pollutant emissions; a large part of PM2.5 and SO2 emissions from this category are indirect and are associated with gasoline and diesel production. It is mainly because most passenger vehicles are Euro III and older, and thus exhaust emissions are significant. On the other hand, stages before combustion produce most SO2 emissions, and the WTW analysis exposes that the oil refinery process generated most of these emissions.

In contrast, buses from the massive transport system (BRT-TransMilenio) produce the lowest total pollutant emissions. In 2015, BRT buses were mostly Euro III and had the highest VKT of all categories, but only 1460 buses conform this fleet. This result highlights the importance of massive transport systems in cities.

Wear and dust resuspension emissions are significant in Bogotá since they account for 56% of $PM_{2.5}$ total emissions. Resuspension emissions due to traffic on unpaved roads are around 25% of total $PM_{2.5}$ emissions, although these roads' vehicular activity is only 0.7% of total VKTs. City policies should implement strategies to reduce $PM_{2.5}$ W&R emissions, such as limiting heavy freight traffic, road maintenance, street cleaning, and encouraging alternative modes of transportation.

To evaluate the consistency of this study, we compared results from this WTW emission inventory with those published in Bogotá and other cities. The comparison shows that direct combustion emissions from this research are within the same order of magnitude as other emissions inventories available in the city for most pollutants. W&R $PM_{2.5}$ emissions are also within the same order of magnitude as those reported by other studies. Moreover, all inventories in the city find that emissions from unpaved roads are an essential source of $PM_{2.5}$. Potential sources of discrepancy or uncertainties are emissions factors or activity used; identifying the sources of uncertainties to estimate more accurate combustion emissions needs additional effort.

Nonetheless, more field measurement studies are needed to confirm and validate these results. Here it also compared WTW results with other WTW studies, and the WTW emissions from this study are very close to previous research for most pollutants.

Finally, results from this work highlight the importance of including other emission sources in addition to vehicle combustion in emission inventories. Here we found that direct emissions are still a significant source of most of the pollutants in Bogotá. However, progressive replacing old vehicles with newer technologies will reduce direct emissions but may increase indirect emissions. In addition, using alternative energy sources such as electricity will reduce or eliminate direct emissions, but this might lead to an increase in indirect emissions depending on the energy mix used to produce electricity. Therefore, environmental authorities and policymakers should start considering indirect emissions on inventories.

The methodology used in this work can support policy development related to air pollutants and greenhouse gases, considering direct and indirect emissions and not just local impacts. Although European and North American countries mainly use the WTW, it is necessary to highlight the importance of disseminating knowledge for air quality planning at regional and local scales in developing countries (e.g., Colombia). The proposed methodology can be applied to compare scenarios for renewing vehicle technologies and substituting energy sources.

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Declaration

Conflict of Interests The authors declare that they have no competing interests.

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