Road Traffic Air Pollution, Bogotá, Colombia

Greenpeace Research Laboratories Technical Report GRL-TR-02-2021, September 2021

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Key findings and recommendations

- Colombia is rapidly urbanising, increasing the number of people exposed to urban air pollution (Section 1.1).
- For many important air pollutants, the local regulations are not as strict as World Health Organisation air quality guidelines (Section 1.2).
- Annually in Bogotá thousands of premature deaths are linked to air pollution. Health effects of air pollution are a significant burden for the Colombian economy (Section 1.3).
- Approximately 2.1 million vehicles were registered in Bogotá in 2015, and the number of vehicles is increasing rapidly (Section 2.1.1).
- Heavy congestion on Bogotá's narrow, hilly, enclosed streets contributes to some of the highest air pollution levels in Latin America (Section 2.1.1).
- Bogotá has an extensive and well used public transit network. Modernization of the vehicle fleet to reduce air pollutant emissions could significantly reduce people's exposure to air pollution from road vehicles (Section 2.1.2)
- Mobile sources of air pollution, principally road transportation, emit more carbon monoxide (CO), carbon dioxide (CO_2), particulate matter (PM_{10}), nitrous oxides (NO_x) and sulfur dioxide (SO_2) than any other sector in Bogotá – private vehicles make a disproportionately large contribution to air pollution (Section 2.2).
- Measures to remove internal combustion engine vehicles, especially older vehicles that do not meet modern emission standards, will improve air quality throughout Bogotá (Section 2.2, 4.2, 4.3)
- Air pollution monitors in Bogotá are positioned such that they do not measure the worst roadside pollution. Despite this, measured annual mean concentrations for particulate matter (both $PM_{2.5}$ and PM_{10}) regularly exceed WHO guidelines and MADS regulations (Section 3).
- Unpaved roads are a major source of particulate matter, especially in low income neighbourhoods. Improving transport infrastructure must be a policy priority and roads need to

be designed to encourage low-carbon transport such as walking and cycling (Section 2.2, 4.1, 4.5).

- Combined, strategies designed to target the greatest emitters of fine particulate matter ($PM_{2.5}$), including reducing private vehicle use, controls for industrial sources, low and zero emission vehicle fleets, and road cleaning systems will help achieve good air quality in the short and long-term. The growing number and wide distribution of cars and light vehicles means that actions to reduce emissions from these vehicle types have great potential to reduce air pollution exposure throughout the city. The number of private vehicle trips must be reduced, and encouraging public transport use, walking or cycling can help achieve this (Section 4.3).
- Authorities in Bogotá need to address air pollution by transforming vehicle fleets so that zero and low-emission vehicles replace polluting fossil fuel-powered vehicles; reducing the demand for motorised transport by investing in public transport, walking and cycling; and improving infrastructure to create safe and accessible walking and cycling routes while removing unpaved roads, which also contribute significantly to particulate pollution.

Contents

1 Introduction

This report investigates existing road traffic air pollution in Bogotá, Colombia. It reviews the literature and measurement data from the city to examine the current state of Bogotá's air, the impact on the health of Bogotá's residents and the causes and potential solutions to problems associated with road traffic-induced air pollution.

1.1 Bogotá and the study area

Bogotá is the capital city of Colombia and is one of the largest cities in South America. Colombia has a rapidly urbanising population and Bogotá has a population of almost 10 million, a figure that is projected to increase to more than 12 million by 2035 *(Sources: Rueda-García, 2003; OurWorldInData.org).* As more people move into Colombia's cities there is a worrying potential that exposure to urban air pollution will increase.

1.2 Air pollutants and policy

A wide variety of chemicals and substances contribute to air pollution. Pollutants can be either gases such as nitrogen dioxide (NO_2) or sulfur dioxide (SO_2), or they can be solid or liquid particles that have become suspended in the air called particulate matter (PM). **Box 1** briefly describes the air pollutants discussed in this report.

Box 1: Types of air pollution

Particulate matter (PM_{10} and $PM_{2.5}$)
Particulate matter is pollution in the form of small liquid or solid particles suspended in the atmosphere. PM pollution is described according to the size of the particles, rather than the chemicals within them. PM_{10} refers to any particle that has a diameter of 10 micrometers or less; it is sometimes known as 'coarse particulate matter' or 'respirable suspended particles' (RSP) because it can be inhaled and enter the lungs. $PM_{2.5}$ refers to any particle that is less than 2.5 micrometers across; it is sometimes known as 'fine particulate matter' or 'fine suspended particles' (FSP). $PM_{2.5}$ particles are small enough to penetrate deep into the lungs to the gas-exchange region (Morakinyo et al., 2016).

Sulfur dioxide (SO_2)
Sulfur dioxide is a gaseous air pollutant produced by the combustion of fuel that contains sulfur. This can include fossil fuels such as coal and oil. SO_2 is toxic and has been linked to many health problems. Sulfur dioxide can also react with moisture in the air causing acid rain.

Nitrogen dioxide (NO_2)
Nitrogen dioxide is a gaseous air pollutant produced by all combustion processes, including from fossil fuel use in vehicles and power stations. NO_2 is toxic and has been linked to many health problems. NO_2can react with moisture in the air to cause acid rain. In the presence of sunlight and volatile organic compounds (see below), NO_2 can contribute to the formation of ground level ozone, sometimes called

photochemical smog.

Ozone (O_3)
Ground level O_3 is a gaseous pollutant that forms in the atmosphere when other pollutants such as NO_2 and VOCs react. O_3 contributes to damage from acid rain, can damage plants and crops and can cause respiratory problems in people. It is toxic to humans.

Volatile organic compounds (VOCs)
VOCs are chemicals that contain carbon and evaporate readily. An important source of VOCs leading to air pollution is evaporation from fossil fuel during use, storage and transportation. Many VOCs are toxic to humans.

Colombian national regulations provide the policy framework for air quality management in Bogotá. These regulations set thresholds for the average daily concentrations of key air pollutants (Ministerio de Ambiente y Desarrollo Sostenible de Colombia [MADS], 2017) (**Table 1**). The World Health Organisation (WHO) also publishes Air Quality Guidelines, which are a widely used benchmark for assessing air quality with regard to minimising health impacts. In most cases, local regulations are not as strict as WHO guidelines. To encourage progress towards the guidelines, the WHO publishes interim targets for some pollutants (**Table 2**).

Table 1: Maximum allowable levels for selected criterion contaminants in the air, MADS Resolution 2254 (2017).

Pollutant	Concentration ($\mu g/m^3$)	Averaging period
PM_{10}	50	Annual
	100	24-hours
$PM_{2.5}$	25	Annual
	50	24-hours
SO_2	50	24-hours
	100	1-hour
NO_2	60	Annual
	200	1-hour
O_3	100	8-hours

Source: Ministerio de Ambiente y Desarrollo Sostenible de Colombia (2017)

Table 2: World Health Organisation Air Quality Guidelines, interim targets and comparison with Air MADS Regulations.

Pollutant	Guideline Concentration ($\mu g/m^3$)	Latest WHO Interim Target ($\mu g/m^3$)	Averaging period	WHO Guideline comparison with Air MADS

SO_2	500	-	10 minutes	No direct comparison
	20	50 (Target 2)	24 hours	WHO stronger
PM_{10}	50	75 (Target 3)	24 hours	WHO stronger
	20	30 (Target 3)	Calendar Year	WHO stronger
$PM_{2.5}$	25	37.5 (Target 3)	24 hours	WHO stronger
	10	15 (Target 3)	Calendar Year	WHO stronger
O_3	100	160 (Target 1)	Maximum 8-hour running mean	Equal
NO_2	200	-	1 hour	Equal
	40	-	Calendar Year	WHO stronger

The Colombian national government and local authorities in Bogotá have both published strategies for the management and improvement of air quality. The national strategy was published in 2019 (Ministerio de Ambiente y Desarrollo Sostenible de Colombia, 2019) and aims to improve air quality with a focus on reducing particulate matter pollution. Five pillars of the strategy require stronger regulatory tools, improved scientific knowledge, health-based guidelines for citizens, support for air quality management and guidelines for governance. The city of Bogotá published an air quality plan in 2021 (Secretaría Distrital de Ambiente, 2021). The plan also has a strong emphasis on reducing $PM_{2.5}$ concentration and directs efforts towards achieving the national standards and WHO interim target 3 (15 µg/m^3 annual mean); it does not require the city to meet the WHO guideline (10 µg/m^3 annual mean).

A simplified overview of other relevant policies is provided in **Box 2**.

Box 2: Legislative context

National context

Law 99 of 1993

Law 99 of 1993 was established by the then Ministry of the Environment and created functions to mitigate or eliminate the impact of polluting activities, as well as determine environmental standards, emission limits and regulations and to control and reduce air pollution emissions.

Resolutions 2604 of 2009, Resolution 1111 of 2013, Resolution 910 of 2008, Resolution 2604 of 2009 and Law 1205 of 2008

The resolutions establish and modify emission limits for vehicles and take into account improvements in fuel quality.

Resolution 2254 of 2017

The resolution adopts the air quality standards for particulate matter less than 2.5 microns ($PM_{2.5}$) and includes a goal to achieve intermediate objective 3 of the World Health Organisation (WHO) by 2030 for PM_{10} and for $PM_{2.5}$, SO_2 and NO_x.

CONPES 3943
The legislation suggests actions to reduce pollutant emissions to the air from mobile and fixed sources.

National Development Plan 2018-2022, adopted by Law 1955 of 2019
The National Development Plan states that the Ministry of Environment and Sustainable Development must modify emission standards for vehicles until reaching the Euro VI standard.

Law 1972 of 2019
The law requires mobile sources with a diesel engine that are manufactured, assembled or imported into the country must comply with limits corresponding to Euro VI technologies after January 1, 2023. Motorcycles that are manufactured, assembled or imported into the country must comply with limits corresponding to Euro 3 technologies by January 1, 2021.

City Context
Directive 7 of 2005:
The directive provides guidance to ensure a healthy environment and adopts the Environmental Management Plan described in Decree 456 of 2008.

CONPES 06 of 2019
This policy aims to increase the quantity and quality of public space contributing to welfare and reduction of emissions.

Agreement 367 of 2009
Ensures the full and prompt publication of data from the Bogotá Air Quality Monitoring Network.

District Decree 596 of 2011
This District Environmental Health Policy includes air quality interventions as relevant for public health.

Decree 098 of 2011
The degree adopts a Ten-Year Air Decontamination Plan for Bogotá, which aims to decontaminate the air in the city.

Decree 623 of 2011
The decree classifies air pollution sources and establishes measures to reduce pollution generated by stationary sources.

District Decree 566 of 2014
This policy applies measures towards sustainable development and planning, including with respect to climate change and air pollution.

Decree 595 of 2015
This decree adopts the air component of the Environmental Early Warning System of Bogotá.

Resolution 2410 of 2015
The resolution adopts the Bogotáno IBOCA Air Quality Index for the definition of air pollution alert levels in Bogotá.

District Development Plan 2020–2024

The plan is an instrument for planning which includes goals for the reduction of particulate matter pollution.

Strategic plan for the comprehensive management of the air quality of Bogotá 2030 (2021)
See **Section 1.2** and **Section 4.6**.

1.3 How is the population affected by air pollution?

Exposure to air pollutants such as those described in **Box 1** is associated with increased incidence of diseases including ischaemic heart disease (IHD), chronic obstructive pulmonary disease (COPD), lung cancer, lower respiratory infections, premature birth (preterm birth), type II diabetes, stroke and asthma (Wang et al., 2014; Han et al., 2016; Cohen et al., 2017; Sunyer et al., 2019).

The Colombian government released a report in 2017 that analysed the health and financial cost of environmental degradation in Colombia and found that in 2015, 3,219 deaths (10.5% of total deaths that year in Bogotá) were attributed to urban air pollution. Countrywide, 10,527 deaths and 67.8 million hospital visits were attributed to poor air quality across Colombia in 2015. The health costs of urban air pollution in Colombia in 2015 were an estimated $15.4 trillion pesos (approximately US$4 billion) (DNP, 2017).

An economic cost from air pollution is incurred through the healthcare burden and when people are unable to work because of illness. The estimated global annual financial burden associated with air pollution from fossil fuels is US$2.9 trillion, or roughly US$8 billion per day; the impact of fossil-fuel related air pollution in Colombia for the year 2018 has been estimated to be US$2,400 million (Farrow et al., 2000).

2 Transport and air pollution in Bogotá

2.1 Travel in the city

Data from 2012 suggest that of trips taken in Bogotá, 30% are made using public transportation, 11% are in private vehicles, 3% are in taxis and 2% are on motorcycles. Trips made on foot or bicycle amount to approximately 50% of travel across the city (Pachón et al., 2018).

2.1.1 Road traffic in Bogotá

Bogotá's historic streets are typically narrow, hilly and lined with buildings and are generally not well suited to the quantity and size of modern vehicles. The combination of these factors and heavy traffic contribute to the city having some of the highest air pollution levels in Latin America and some of the world's greatest traffic congestion. The solution is not to widen the streets to accommodate more traffic, but to limit vehicle access and instead provide a safe, clean environment for walkers and cyclists. The challenge for policymakers is how to achieve such a scenario rapidly and effectively.

Estimates of the size of the vehicle fleet in Bogotá vary, which is partly explained by the fact that the number of vehicles is growing rapidly. The emissions inventory of the city of Bogotá for the year 2018 records approximately 2,400,000 vehicles registered in the city (Secretaría Distrital de Ambiente, 2021). Analysis by Mangones et al. (2020) reports that in 2015, transport in Bogotá comprised 2.1 million motor vehicles: 73% light-duty vehicles; 21% motorcycles; 1% transit and BRT buses; 2% taxis; and 1% trucks. Earlier data from 2012 reported that approximately 1.8 million vehicles were registered in Bogotá, of which 75% were passenger vehicles and pick-up trucks, 20% were motorcycles, 3% were taxis, 1.2% were heavy trucks, and less than 1% were buses (Pachón et al., 2018). The increase in the number of vehicles between 2012 and 2018 follows the trend in the overall increase in the number of vehicles in the city. Approximately 400,000 vehicles were registered in 2002, and between 2004 and 2014, the annual growth rate in the number of privately registered vehicles in Colombia was 14% for light vehicles and 129% for motorcycles (Mangones et al., 2020). An especially rapid growth in motorcycle trips has been seen in recent years (East et al., 2021).

The fleet of vehicles in Bogotá and Colombia in general is ageing. The average age of freight vehicles is 21 years, six years older than the average age in 14 other Latin American countries (CONPES 3963, 2019). Nationally, Colombia's vehicle fleet comprises 4% heavy diesel vehicles. Of these as many as 25% are Pre-Euro I emissions standards, which were introduced in July 1992, meaning that their emission controls are significantly outdated. 60% have Euro 2 (January 1996) technology and only 15% have Euro IV (January 2005) or later technology. Despite making up less than 2% of the total vehicle fleet, Pre-Euro heavy vehicles generate about 25% of the emissions of particulate matter (Ministerio de Ambiente y Desarrollo Sostenible de Colombia, 2019).

Drivers of private vehicles are unlikely to be using their time efficiently: in 2019, the average speed of peak-time traffic was 19 kilometers per hour (kph) and only slightly faster (20 kph) in off-peak periods. The (slow) average speed of vehicles in Bogotá was similar in 2017 and 2018 (INRIX, 2020).

The city has high levels of congestion throughout the day. INRIX, a mobility analytics firm, estimates that in 2019, drivers in the Colombian capital lost 191 hours because of traffic congestion. The INRIX 2019 Global Traffic Scorecard rated Bogotá as the world's most congested city, above Rio de Janeiro, Mexico City, Istanbul and São Paulo (INRIX, 2020). Bogotá was ranked 3rd worst of 416 world cities for congestion in

2020 by the satellite navigation firm TomTom (TomTom International BV., 2021). The city has been 2nd or 3rd worst in the annual ranking since rankings began in 2017.

2.1.2 Public transport

Every day, around 11 million journeys are made on Bogotá's public transport system or on foot. Bogotá's Bus Rapid Transit (BRT) system accounts for 35% of journeys and walking accounts for 32% (Mangones et al., 2020). Bogotá has one of the world's largest Bus Rapid Transit (BRT) systems. The city's BRT – the TransMilenio – opened in 2000 and has a high number of users: in 2016, the TransMilenio transported an estimated 701.5 million passengers. The system has 113 km of dedicated BRT lanes and 149 bus stations (Morales Betancourt et al., 2019). An information request to Empresa de Transporte del Tercer Milenio (Appendix 1) found that as of March 17, 2021, there are 6,181 buses operating within the TransMilenio zonal service, and 2,415 buses in the Integrated Public Transport System (SITP). There are a further 3,292 buses of varying designs in the Technical Directions of the BRT system. Many buses in the fleet are old, and the majority are diesel powered, potentially exposing passengers and other road users to air pollution.

A study by Morales Betancourt et al. (2019) found extremely high levels of pollutants inside the BRT cabins of Bogotá's TransMilenio. The study's results report the in-bus average concentration of 176 μg m^{-3} of $PM_{2.5}$, 90 μg m^{-3} of equivalent black carbon (eBC), and 4.8 parts per million of carbon monoxide (CO). The study used portable sampling devices for $PM_{2.5}$, eBC and CO and aimed to realistically replicate a typical commute with trips of an average duration of 140–160 min. Sampling took place between February and December of 2017, on weekdays during the morning rush hour between 7am and 10am. Samples were taken in BRT stations – at one underground station, air pollution concentrations were more than 500 μg m^{-3} of $PM_{2.5}$. The suggestion is that a substantial amount of air pollutants are from the BRT buses themselves. The in-bus and in-station air pollution concentrations detected in this study were several times higher than outside air concentrations. The authors of the study suggest that upgrading the fleet to electric vehicles or to vehicles with stricter emissions standards would have a significant impact on reducing BRT passengers' exposure to air pollution.

It is important to put pollution associated with the BRT into a wider context. Pollutants associated with the BRT are less than or similar to those from traditional public transport, and much less than emissions from private vehicles and motorcycles in all cases – NO_x, SO_2, CO_2, CO, VOC and PM (see **Fig. 1**).

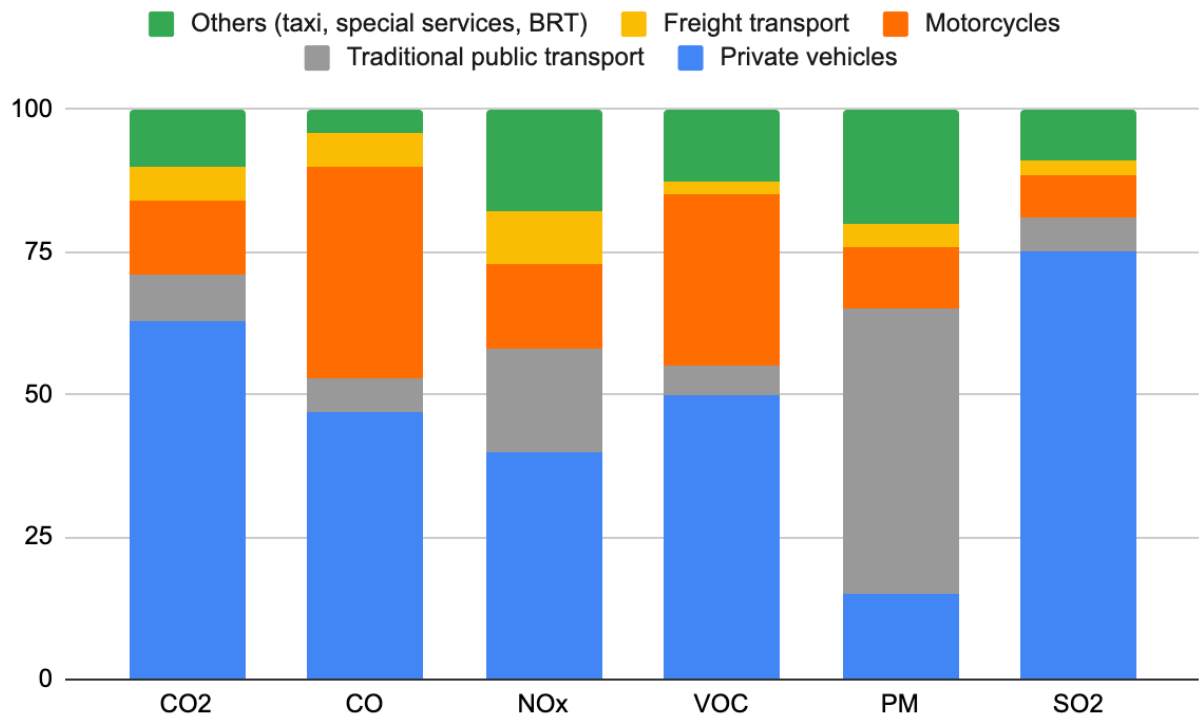

***Figure 1**. Pollution from mobile emissions in Bogotá, 2012. Source: Redrawn from Pachón et al., 2018.*

A gondola-style cable car system, the TransMiCable, which opened in December 2018, reflects a trend seen in other South American cities (Metrocable in Medellín and Mi Teleférico in La Paz, Bolivia, for example) to cleanly and rapidly connect distant neighbourhoods with other city locations. The Bogotá cable car system currently operates one line with four stations, is just over 3km in length and is an extension to the TransMilenio (https://www.transmilenio.gov.co/TransMiCable/). The cable car initiative aims to reduce socio economic imbalances as well as provide health benefits, which will be evaluated as part of an ongoing study (Sarmiento et al. 2020).

A 2020 report 'Urban Transformations and Health: Evaluation Results of the TransMiCable' (Sarmiento et al., 2020) seeks to understand how the TransMiCable and the accompanying urban transformations impact the health of citizens. It took into account factors such as safety, free time, air quality, physical activity and quality of life. One of the key findings of the report is that the interventions in transportation together with urban transformations are an opportunity to improve the health of communities. The TransMiCable experience has decreased the travel times of residents, increased their satisfaction with the neighborhood, reduced exposure to pollutants and increased time available for socialising and exercise in parks. After the development of the TransMiCable, residents have reported a reduction in theft and robbery and a reduced perception of insecurity (Guevara, 2020).

2.1.3 Cycling

Bogotá has approximately 550 kilometres of bike lanes, or *Ciclorrutas de Bogotá*. Plans to expand the network by a further 280km by 2024 were announced in February 2020 by the city's mayor (Jaramillo, 2020). The coronavirus pandemic prompted the mayor of Bogotá to open 80km of temporary bike lanes – repurposed from existing car lanes – to allow people to travel in a COVID-19-safe way around the city by reducing overcrowding on the BRT, with the co-benefits of easing traffic congestion and pollution (IDRD, 2020). A reported 610,000 trips are made by bike annually in Bogotá, according to a report published in 2015 (IDB, 2015). Exposure to pollution by cyclists is a concern, however, because the bike lanes are alongside traffic-congested roads (Hernández et al., 2021).

Approximately 7% of trips in Bogotá are made by bike, which the present mayor, Claudia López, is planning to expand to 50% in the long term (Jaramillo, 2020). However, since the coronavirus pandemic and the expansion of Bogotá's bike lane system, the proportion of people travelling by bike has increased to around 16% (WHO, 2020b).

2.2 Air pollution sources

The principal sources of atmospheric pollution within the study area are road transport emissions, the resuspension of particulate matter (dust), industry, and commercial activities such as restaurants and street vendors (Pachón et al., 2018).

Stationary pollution sources contribute between 18–22% of particulate emissions. Of this contribution, brick kilns and coal boilers emit about 50% and 23% of PM_{10}, and 40% and 18% of $PM_{2.5}$, respectively (Secretaría Distrital de Ambiente, 2017).

Air quality in Bogotá is also influenced by pollutants that originate outside of the city including from biomass burning, which has a seasonal effect on the city (Ballesteros-González et al., 2020; Mendez-Espinosa et al., 2019).

Mobile sources of air pollution, principally road transportation, emit more CO, CO_2, PM_{10}, NO_x and SO_2 than any other sector in Bogotá (Pachón et al. 2018). Private vehicles make a disproportionately large contribution to emissions. Although only 11% of trips across the city are made in private vehicles, this form of transport is responsible for between 40–70% of all CO, CO_2, VOC, NO_x and SO_2 emissions from mobile sources. As the number of privately owned vehicles with conventional internal combustion engines increases, so too do the air pollution levels. Traditional public transport make a large contribution to particulate matter emissions in Bogotá (**Fig. 1**) (Pachón et al., 2018).

An estimated 90% of PM_{10} emitted across Bogota is resuspended particulate matter. Unpaved roads, which are more common in the outskirts of Bogotá than in the central areas, are a key contributor to these emissions. Vehicles travelling across unpaved roads generate five times more PM_{10} and twice as much $PM_{2.5}$ than on paved roads (Pachón et al. 2018). Consequently unpaved roads make a disproportionately large contribution to PM_{10} emissions and the contribution from resuspended dust to PM_{10} in Bogotá is significantly greater than that from fuel combustion (Pachón et al., 2018; Nedbor-Gross, 2018) (**Fig. 2**).

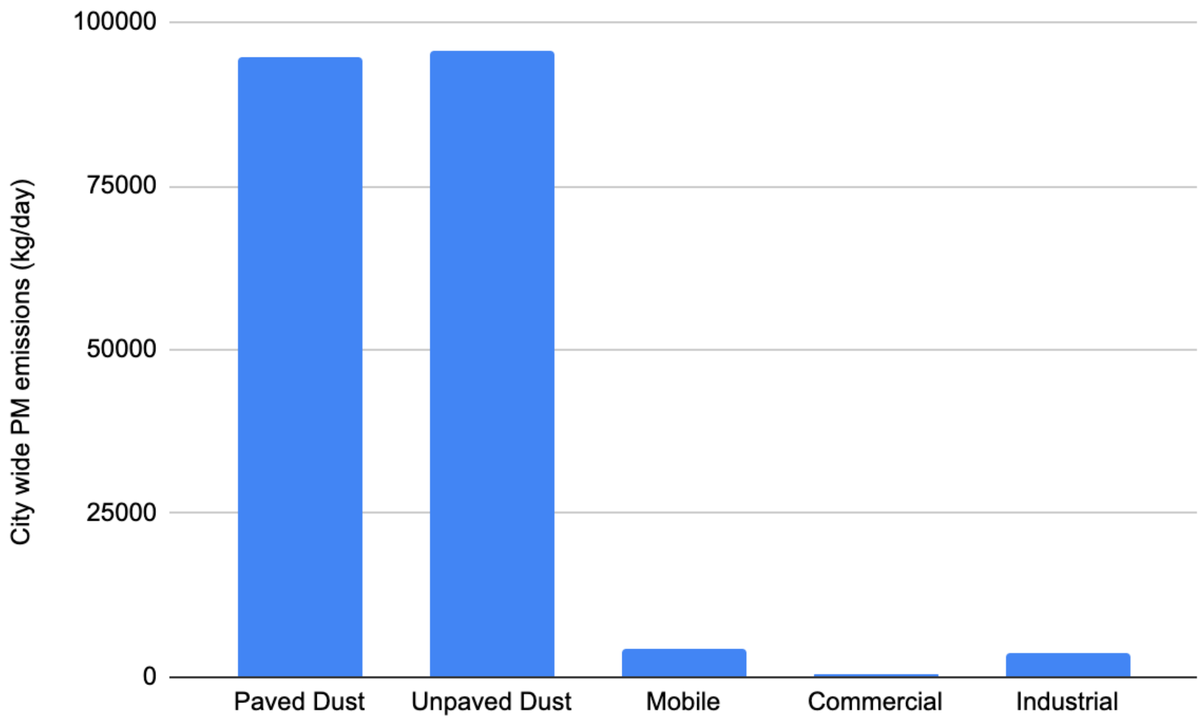

Figure 2. *Total daily total particulate matter emissions (kg/day) from paved and unpaved roads, mobile sources, commercial point sources and industrial point sources. Source: Nedbor-Gross (2018).*

2.2.1 Road traffic and air pollutant concentrations

Bogotá's sources of CO_2, CO, VOC, NO_x, SO_2 and $PM_{2.5}$ for the year 2012 have been quantified on a 1km resolution grid (Pachón et al., 2018). Mobile sources, principally transport, dominate emissions of CO_2 (80%), CO (99%), VOC (68%), NO_x (95%), and SO_2 (85%) in Bogotá (**Fig. 3**). Such large contributions are in part due to high traffic volumes and the large number of old vehicles without zero-emission or emission reduction technology. Emission amounts are increasing in line with a long-term trend in the number of vehicles in circulation.

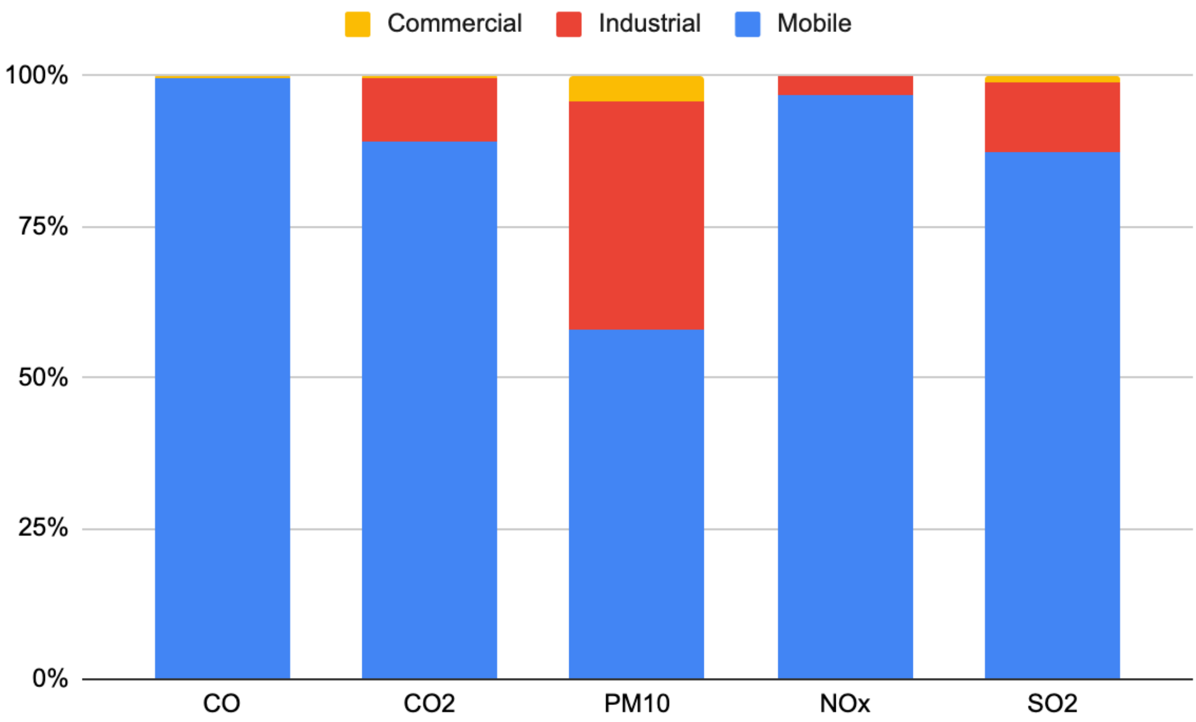

Figure 3. *Comparison of emissions for point and mobile sources (ton/year) Source: Pachón et al (2018).*

Emissions of air pollutants from road traffic are typically estimated using activity data and emission factors. Activity data describes the number, type and usage of vehicles on a road. Emissions factors are used to convert the activity data into emission amounts, and are estimated using emission models such as the COPERT model (Ntziachristos et al., 2009), Motor Vehicle Emission Simulator (MOVES) (US-EPA, 2010) or the International Vehicle Emissions model (IVE) (ISSRC, 2008), or acquired from international databases, such as the Core Inventory AIR emissions CORINAIR database (EEA, 2013).

Although emission estimates in different studies vary according to the choice of emission model and database (Pachón et al., 2018), studies that assessed air pollutant emissions in Bogotá show a consistent and growing trend. Research published in 2018 estimates that larger emissions of CO and NO_x can be explained by the dramatic increase in vehicles in the city from approximately 600,000 in 2002 to 1.7 million in 2012 (Pachón et al., 2018).

An emission inventory for 2012 estimated that vehicle sources in Bogotá emitted approximately: 7,000,000 to 10,500,000 tons CO_2; 700,000 to 870,000 tons CO; 48,000 to 67,000 tons of NO_x; 74,000 to 92,000 tons VOC; 1,100 to 1,300 tons of PM; and 12,000 to 14,000 tons SO_2 (Carmona et al., 2016).

2.2.2 Which areas are worst affected?

Areas to the south and southwest of the city with heavily trafficked highways, industrial and commercial zones have the highest air pollutant emissions. Many of these areas, such as the locality of Kennedy in the southwest of the city, also have elevated resuspended dust concentrations because some roads are unpaved (Pachón et al., 2018). **Fig. 4** compares the emissions of particulate matter per kilometer from paved and unpaved roads.

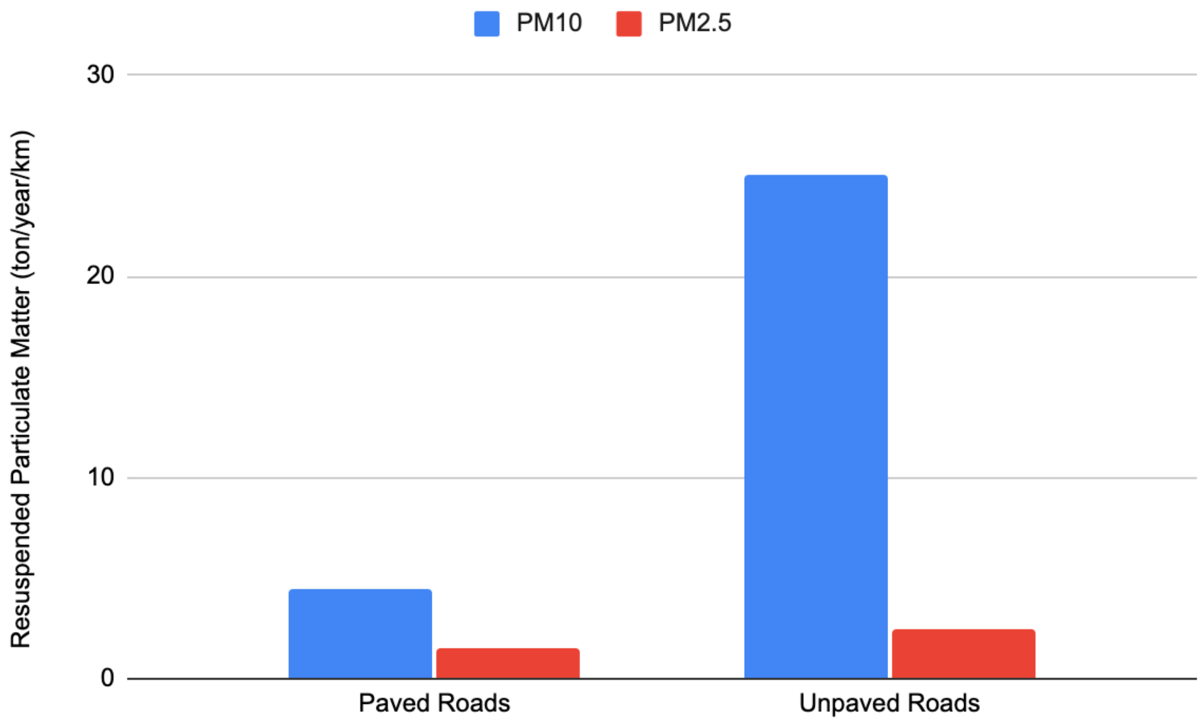

Figure 4. *Resuspended particulate matter emissions from paved and unpaved roads (ton/year/km) Source: Pachón et al. (2018).*

2.2.3 The impact of the coronavirus pandemic on CO_2 emissions

The abrupt decrease in global travel in response to the Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) pandemic had a marked, but short-lived, impact in reducing air pollutant and climate pollutant emissions from fossil fuel use. During the first 3 months after the WHO declared a Public Health Emergency, April 7 saw the greatest change to CO_2 emissions globally. Worldwide on this date the change in daily fossil CO_2 emission in comparison to the mean daily 2019 levels in the surface transport sector (cars, light vehicles, buses, trucks and shipping) was -36% (-28% to -46%), which is a reduction by -7.5 $MtCO_2$ per day (-5.9 to -9.6). To put this into context, the total global decrease in emissions from all sectors on April 7, 2020 compared to mean daily levels in 2019 was -17%, a mean of -17 $MtCO_2$ per day (Le Quéré et al., 2020).

Concentrations of PM_{10}, $PM_{2.5}$, and NO_2 decreased during the COVID-19 lockdown in Bogotá. During the strict lockdown in Bogotá (March 20 to April 26, 2020), traffic-related NO_2 fell by -62% in comparison to the pre-lockdown period (February 21 to March 19, 2020), PM_{10} fell by -37% and $PM_{2.5}$ fell by -36% (**Fig. 5**) (Mendez-Espinosa et al., 2020).

In an effort to reduce overcrowding on public transport systems during the pandemic, the authorities in Bogotá expanded the city's bike lane system by reallocating some roads as cycle lanes, which encouraged more people to travel by bike (see **Section 2.6**). The take-home message is that making simple changes to daily transportation, such as by walking or cycling instead of taking a car journey, and policy measures to improve vehicle technology can help to reduce emissions, improve air quality and bring the co-benefits of boosting physical and mental health. However, the reductions described above have been short lived. They mainly occurred during the initial response to the health crisis and over the course of 2020 it is estimated that global fossil CO_2 emissions fell by as little as 6% (Tollefson, 2021; IEA, 2021), underlining the need for long-term and managed efforts to reduce atmospheric pollutant emissions.

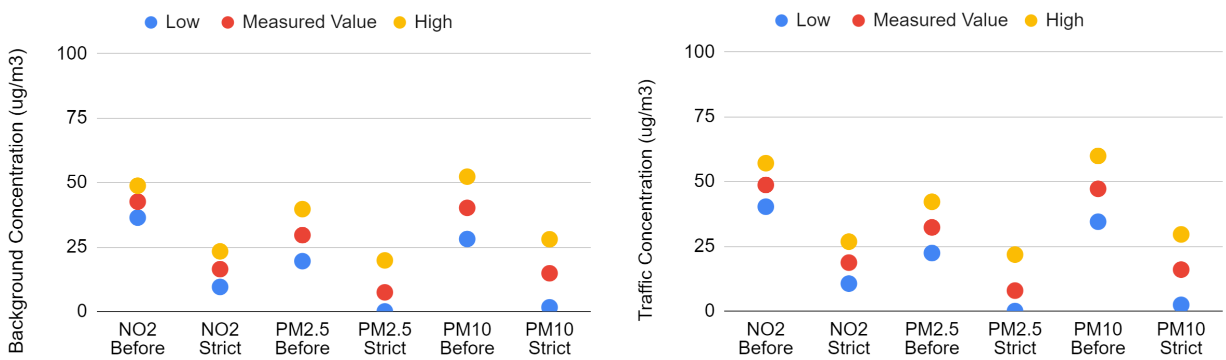

Figure 5. The impact of the COVID-19 pandemic on emissions. *Data showing the impact of the lockdown restrictions on locations with background pollution concentrations (left) and with strong influence from traffic (right) in Bogotá. Concentrations of NO_2, $PM_{2.5}$ and PM_{10} are shown for a period before lockdown* (February 21 to March 19, 2020) *and during strict lockdown* (March 20 to April 26, 2020). *Source: Mendez-Espinosa et al., 2020.*

As activity was curtailed by the COVID-19 restrictions, it was not only CO_2 emissions that were reduced in Bogotá. Significant, but temporary, reductions in greenhouse gas emissions and air pollutants in the transport sector are estimated to have occurred during the lockdown period for pollutants including methane, CO, VOCs, NO_x, SO_2 and particulate matter (Camargo-Caicedo et al., 2021).

3 Measured Air Quality

A network of air quality monitoring stations, the Bogotá Air Quality Monitoring Network (its Spanish acronym is RMCAB), is operated in Bogotá by the District Secretariat of Environment. Since 1998, the monitoring network has measured levels of pollutants including PM_{10}, $PM_{2.5}$, CO, NO_x, SO_2, and O_3 (Mura et al., 2020). The monitoring network is currently expanding with new stations being installed at several locations in the city. In this report we analyse data from the 12 monitoring stations where data are available for the calendar years 2019 and 2020 (Table 3).

Measured hourly mean concentrations of NO_2 and $PM_{2.5}$ were obtained for stationary monitoring sites operating as part of the Bogotá Air Quality Monitoring Network (RMCAB) reporting those pollutant species (**Table 3**, **Fig. 6**).[1] The results from the official monitoring were downloaded from the website of the Bogotá District Secretariat of Environment.[2] Annual mean concentrations are shown in **Table 4** and suggest that, while pollution monitors rarely record exceedances of the annual mean WHO guideline levels for NO_2, annual mean concentrations for both $PM_{2.5}$ and PM_{10} regularly exceed WHO guidelines. Exceedances of the standards described in MADS Resolution 2254 are less frequent because these standards are less strict.

The finding that particulate matter is of particular concern in Bogotá has been well documented over the past two decades in the scientific literature (Pérez-Peña et al., 2017; Vargas et al., 2012; Zárate et al., 2007), in Bogotá's air quality plan (Secretaría Distrital de Ambiente, 2021) and the national air quality strategy (Ministerio De Ambiente Y Desarrollo Sostenible, 2019). Exceedance of the PM_{10} regulations are most common during December to March of each year, and especially in the south and southwest regions of the city (Secretaría Distrital de Ambiente, 2021) where high emissions were identified in **Section 2.2.2**.

Table 3: Bogotá Air Quality Monitoring Network (RMCAB) Stations

Station	Latitude	Longitude	Altitude (m)	Sampling height from ground (m)	Station type
Bolivia	4.74	-74.13	2574	4.6	Background
Carvajal - Sevillana	4.60	-74.15	2563	6	Traffic Industrial
Centro de Alto Rendimiento	4.66	-74.08	2577	4.6	Background
Fontibon	4.67	-74.14	2591	15	Industrial
Guaymaral	4.78	-74.04	2580	4	Background
Kennedy	4.63	-74.16	2580	7	Background

[1] District Secretariat of Environment, Bogotá. http://ambienteBogotá.gov.co/estaciones-rmcab Accessed 09/04/2021
[2] District Secretariat of Environment, Bogotá. http://201.245.192.252:81/report/MonitorReport Accessed 11/03/2021

Las Ferias	4.69	-74.08	2552	4.6	Of traffic
Puente Aranda	4.63	-74.12	2590	13	Industrial
San Cristobal	4.57	-74.08	2688	4	Background
Suba	4.76	-74.09	2571	9	Background
Tunal	4.58	-74.13	2589	3	Background
Usaquen	4.71	-74.03	2570	13	Background

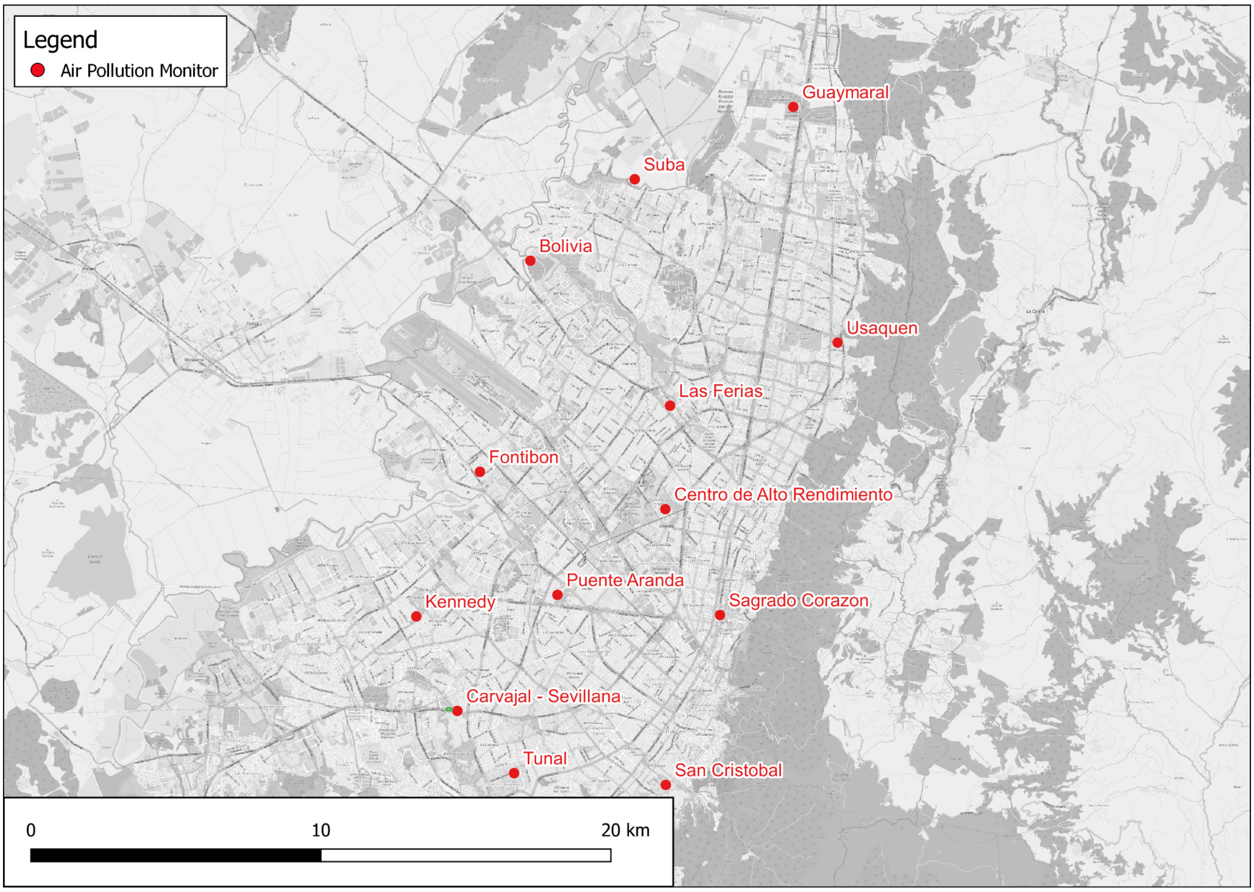

Figure 6. Bogotá Air Quality Monitoring Network (RMCAB).

Although no air quality monitoring network can capture all of the variations in pollution across a city, it is especially important to note that the location of monitors in Bogotá limits the data available to investigate roadside pollution. Nedbor-Gross et al. (2018) note that the current monitoring network is not adequate for measurement of resuspended particulate matter. Greenpeace has previously reported that the air pollution monitors in Bogotá are frequently located away from major roads and at elevated locations such that they may not provide adequate information on the city's most polluted locations (Farrow, 2021). The placement of air pollution monitors may, in part, explain why most measured air pollutant concentrations in Bogotá remain below the WHO guidelines and Colombian air quality standards even in a city in which congested roads and aging vehicles are common. The national air quality strategy highlights the need to improve air quality monitoring (Ministerio de Ambiente y Desarrollo Sostenible de Colombia, 2019) and Bogotá's air quality plan explicitly sets an objective to strengthen representativeness, spatial coverage, quantification and qualification of air quality data (Secretaría Distrital de Ambiente, 2021).

Table 4: Bogotá Air Quality Monitoring Network (RMCAB) annual mean concentrations for 2020 and 2019*.

	2020			2019		
Station	**NO_2**	**PM_{10}**	**$PM_{2.5}$**	**NO_2**	**PM_{10}**	**$PM_{2.5}$**
Bolivia	Missing Data	Missing Data	Missing Data	Missing Data	Missing Data	Missing Data
Centro de Alto Rendimiento	25.6	**21.5**	**13.3**	28.4	**27.1**	**14.9**
Guaymaral	20.4	**25.7**	**13.5**	29.0	**24.7**	**13.5**
Kennedy	35.1	**41.1**	**21.4**	Missing Data	**43.7**	**<u>25.1</u>**
San Cristobal	Missing Data	**23.5**	**11.9**	Missing Data	**24.9**	Missing Data
Suba	Missing Data	**34.2**	**14.7**	Missing Data	**45.8**	**16.1**
Tunal	28.9	**36.4**	**14.5**	27.2	**33.6**	**15.7**
Usaquen	Missing Data	Missing Data	**13.4**	Missing Data	**24.8**	**14.0**
Fontibon	30.9	**33.7**	**19.6**	40.8	**37.2**	**18.4**
Puente Aranda	33.2	**34.2**	**20.5**	35.9	**40.0**	Missing Data
Las Ferias	30.1	**23.6**	**13.6**	33.0	**28.3**	**12.8**
Carvajal - Sevillana	**48.4**	**<u>63.7</u>**	**<u>29.1</u>**	**<u>44.3</u>**	**<u>57.7</u>**	**<u>36.2</u>**
Units	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$
WHO Guideline	40	20	10	40	20	10
MADS Resolution 2254	60	50	25	60	50	25

*Values excluded where data availability was less than 75%. Exceedances of WHO Guidelines are shown in **bold.** Exceedances of MADS Resolution 2254 are shown <u>underlined.</u>

The measured exceedances serve as a warning that air quality in Bogotá is taking a toll on public health. The National Planning Department estimates that in 2015, more than 8,000 premature deaths could be attributed to poor air quality across Colombia. The number of premature deaths linked to fossil fuel air pollution alone during 2018 in Colombia was estimated at 6,900 (Farrow, 2020), underscoring the importance of reducing the use of coal, oil and gas.

4 Towards clean air in Bogotá

4.1 The Ciclovía and Bogotá's bike lane network

In an effort to boost public health, Bogotá's roads have been closed to vehicles on Sundays and public holidays since 1974 for the Ciclovía to allow cyclists, skaters and pedestrians traffic-free access to 127.7 kilometres of roads (https://www.idrd.gov.co/ciclovia-bogotana; https://www.idrd.gov.co/mapa-ciclovia). The aim of the Ciclovía is to encourage more people to take up physical activity, and some people may choose to exercise during Ciclovía precisely because there is no traffic and lower air pollution (Montes et al., 2012). The inclusive nature of the Ciclovía boosts its potential to promote activity in children and help prevent them from developing obesity (Triana et al., 2019). The Ciclovía brings health cost savings, too. The estimated cost–benefit ratio of the Bogotá Ciclovía ranges from US$3.20 to US$4.30 per US$1 invested in the programme (Montes et al., 2012). The range reflects uncertainty in the number of adult users, which, in a study period between 2005 and 2009, was estimated to be between 516,600 and 1,205,635. Although once-weekly street closures mark a positive first step, to have a lasting and positive impact on human health, car-free events should continue regularly and in more locations across the city to attract a high proportion of the community. For open streets events to be successful, the researchers suggest that the route should pass through different neighbourhoods, be promoted among under-represented ethnic and age groups, and have secure funding to ensure longevity (Engelberg et al., 2014).

The city's bike lane network, or *Ciclorrutas de Bogotá*, extends to approximately 500km across the city. As a result of the pandemic, the city created 80 kilometers of temporary bike paths that are being turned into permanent bike paths. However, the bike lanes are not indicated with dedicated signs and run alongside busy highways, and concerns are that cyclists are exposed to poor air quality. Research in which field data were collected in April and May 2013 found that cyclists were exposed to $PM_{2.5}$ at average concentrations between 30 and 136 $\mu g/m^3$ and black carbon at mean concentrations of between 10 and 38 $\mu g/m^3$ (Franco et al., 2016).

4.2 Public transport measures

The extensive bus fleet in Bogotá contains many older vehicles the majority of which are diesel powered. Upgrading the fleet to electric vehicles or to vehicles with stricter emissions standards may have a significant impact on reducing exposure to air pollution (Morales Betancourt et al., 2019). The city of Bogotá plan to introduce zero-emission vehicles according to the schedule described in **Table 5**.

***Table 5**. Planned introduction of 'zero emission' buses. Source: Alcaldía de Bogotá. Transmilenio 2021.*

2022	New zero emissions contracted fleet (agreement 790 of 2020)
2023	Establish emission standard Euro VI
	All trunk buses that are acquired to have zero emissions (Agreement 732 of 2018)
2025	At least 10% of the buses purchased must be zero emissions
2027	At least 20% of the buses purchased must be zero emissions
2029	At least 40% of the buses purchased must be zero emissions
2031	At least 60% of the buses purchased must be zero emissions
2033	At least 80% of the buses purchased must be zero emissions
2035	At least 100% of the buses purchased must be zero emissions
2036	The purchase of buses that are zero emissions prohibited

The TransMiCable, described in **Section 2.6.2**, can be regarded as a clean-air initiative because it serves to reduce the time that residents in peripheral neighbourhoods (i.e. from low-income households) take to travel to the TransMilenio stations by up to 80%. Previously, those residents would have taken on average one hour to reach the TransMilenio station – most transport is in motorised vehicles (Sarmiento et al., 2020).

4.3 Private car measures

Mobile sources, principally transport, dominate emissions of many air pollutants in Bogotá, and private cars are the main contributors to on-road traffic emissions of CO_2 CO, NO_x, VOCs and SO_2 (Fig. 1, **Section 2.2**). Emissions are growing as the number of vehicles in circulation increases.

Rationing the use of private cars in Bogotá did not seem to improve air quality (Bonilla, 2019); however a law passed in Colombia in 2019 will ban diesel vehicles that do not meet Euro VI or equivalent after January 2035. Improvements in public transport and infrastructure for non-motorised traffic such as cycling also have the potential to reduce emissions from motor vehicles by replacing journeys with greener alternatives. Strategies that reduce emissions from light vehicles have the greatest potential to reduce $PM_{2.5}$ across the city when compared to strategies such as cleaning paved roads, controls on industrial emissions or reduction of cargo fleet emissions because of the number of vehicles involved and their distribution across the whole city (East et al., 2021). Combined, strategies designed to target the biggest emitters of $PM_{2.5}$, introducing controls for industrial sources, low and zero emission vehicle fleets, and road cleaning systems, can largely avert projected increases in concentrations (East et al., 2021). Ultimately however, while the number of private vehicles in Bogota is increasing is likely that emissions will also increase in the long-term. Strategies to reduce the number of private vehicle trips by encouraging public transport use, walking or cycling are also needed.

4.4 Vehicle fuels

Colombia has introduced progressively cleaner vehicle fuels in recent years with the permissible sulfur content in diesel being reduced from 4,500 ppm in 2008 to 50 ppm in 2013. Bogotá's TransMilenio phases I and II has used diesel fuel with 10 ppm since 2019 (Ministerio de Ambiente y Desarrollo Sostenible de Colombia, 2019). Improving fuel quality reduces the production of air pollutants, and removing sulfur from fuel not only reduced SO_2 pollution but also the formation of sulfate particles. However, it must be recognised that where transport continues to operate on combustion engine technology the polluting products of that combustion, including all of the pollutants described in **Box 1**, will continue to be emitted into Bogotá's air.

4.5 Paving roads

Areas of the city with unpaved roads contribute to the particulate matter burden in Bogotá (Pachón et al. 2018). Unpaved roads are a key contributor to particulate matter pollution, 90% of PM_{10} emitted across Bogota is resuspended particulate matter from road surfaces (Pachón et al. 2018). Paving roads therefore provides a means to reduce particle pollution, and in some areas of the city it is estimated that paving roads could lead to annual mean $PM_{2.5}$ concentrations being reduced by nearly 10 $\mu g/m^3$ by 2030. As motor traffic continues to increase across the city, air quality will deteriorate significantly in other areas in the absence of additional emissions control measures. Road paving alone is not sufficient to achieve adequate air quality (East et al., 2021). Improving infrastructure should be a priority and where this is done roads should be designed to encourage low-carbon transport, walking and cycling.

A recent report on economic, social and environmental inequality reported that paving roads could address inequality and prevent deaths associated with air pollution leading to a significant economic benefit. Additionally, many neighborhoods in the southwest of the city would meet the WHO $PM_{2.5}$ intermediate objective 2 and areas in the south would achieve intermediate objective 3 (Bonilla et al, No Date).

4.6 Strategic policy

The national air quality strategy (Ministerio de Ambiente y Desarrollo Sostenible de Colombia, 2019) aims to improve air quality and is primarily focused on reducing particulate matter in urban areas for the protection of public health. Five pillars of the strategy require stronger regulatory tools, improved scientific knowledge, health based guidelines for citizens, support for air quality management and guidelines for governance. The strategy sets objectives that include air quality monitoring stations meeting the WHO interim target 3 for PM_{10} and $PM_{2.5}$, but falls short of the WHO's guideline values themselves. The strategy highlights a need for cleaner and more efficient vehicles on Colombia's roads. Zero and low emission vehicles are encouraged by a reduction in tariffs. However no phase-out is set for fossil fuel powered vehicles and reduced tariffs exist for hybrid and fossil gas field vehicles, which continue to produce tailpipe emissions.

In Bogotá, the strategic air quality plan's objective is to assure compliance with the national air quality standards and each WHO interim target 3 for $PM_{2.5}$ and PM_{10} (Secretaría Distrital de Ambiente, 2021). As with the national strategy this sets ambitions short of the current WHO guidelines for particulate matter. The plan's specific objectives include;

- improving the representativeness, coverage and quality of air quality data;
- improving mechanisms for monitoring and controlling pollution sources;
- reducing emissions through increasing energy efficiency, and updating technology in source sectors;
- managing air quality through urban planning; and
- comprehensive governance for air quality management.

The effect of the transport sector on air pollution with be improved through eight projects that focus on incorporation of zero and low emission technologies into the public transport fleet, improving motorcycle emissions through modern technology, new passenger transport means, new cycle-infrastructure, modernization of heavy duty cargo vehicles, and a programme to reduce emissions from urban freight transport among others.

The plan sets medium and long-term objectives to improve air quality. Targets include reducing $PM_{2.5}$ concentrations by 16.6% and PM_{10} by 14.2% to meet the WHO intermediate objective 3 by 2030, with a 10% reduction in PM_{10} and $PM_{2.5}$ concentrations as a city weighted average over the next four years with an ambition to reduce this figure by 18% in the southwest of the city.

In 2020, the mayor declared a climate emergency in Bogotá, which has binding strategies with a budget for adaptation, mitigation and resilience to climate change by 2030. For the energy transition and reduction of greenhouse gases the Capital district commits to adopt urgent measures to replace the use of fossil fuels in the city's transportation systems, in order to reduce greenhouse gas emissions by 50% to the year 2030, with reference to the year 2020.

We consider that the $PM_{2.5}$ and PM_{10} targets are not ambitious and should be fulfilled in a shorter period of time, with strategies and investments prioritized together with the Specific Measures to be effective in a period of less than four years. The target to reduce PM by 18% in the very vulnerable areas in the southwest, Kennedy, Bosa, Tunjuelito, Puente Aranda and part of Ciudad Bolívar are not sufficient.

5 Recommendations

We have reviewed the current air pollution situation in Bogotá with respect to road traffic emissions. Mobile air pollution sources, principally road transportation, is the principal emissions sector for some air pollutants with private vehicles making a disproportionately large contribution to emissions. Future air pollution concentrations in Bogotá will be affected by decisions relating to the future of transport in the city. The impact of the transport sector on air quality is determined by:

- the nature of the current vehicle fleet and its activity;
- demand for each form of transport; and
- the transport infrastructure within the city.

In Bogotá there are specific challenges made more urgent by the increasing population of the city and the growing number of people exposed to urban air pollution. This report identified that annually in Bogotá thousands of premature deaths are linked to air pollution and that the health effects of air pollution are a significant burden for the Colombian economy.

Challenges relating to air quality and transport in Bogotá include ageing and highly polluting vehicles, a growing vehicle fleet, congestion and inadequate infrastructure such as unpaved roads and insufficient provision for cycling. Current air pollution regulations are not as strict as WHO air quality guidelines and the location of air pollution monitors in Bogotá do not provide sufficient data to fully investigate the impact of roadside pollution.

Bogotá therefore needs to address air pollution through:

- transforming its vehicle fleets so that zero and low-emission vehicles replace polluting fossil fuel-powered vehicles;
- reducing the demand for motorised transport by investing in public transport, walking and cycling; and
- improving infrastructure to create safe and accessible walking and cycling routes while removing unpaved roads and particulate pollution they can generate.

Changes in pollutant concentrations by reducing emissions from light duty vehicles have the potential to make significant and far reaching improvements across the city when used in conjunction with measures to reduce dust from unpaved roads and industrial sources.

Glossary

BRT	Bus Rapid Transit system
CO	Carbon monoxide
eBC	Equivalent black carbon, a measure of particle pollution.
Exceedance	A period of time when the concentration of an air pollutant is greater than the appropriate air quality guideline.
kph	Kilometers per hour
MADS	Ministerio de Ambiente y Desarrollo Sostenible de Colombia
NO_2	Nitrogen dioxide
NO_x	Mono-nitrogen oxides
O_3	Ozone
PM_{10}	Particulate matter with aerodynamic diameter of less than 10 µm
$PM_{2.5}$	Particulate matter with aerodynamic diameter of less than 2.5 µm
ppm	Parts per million
SO_2	Sulphur dioxide
SITP	Integrated Public Transport System (Sistema Integrado de Transporte Público)
WHO	World Health Organisation
$\mu g/m^3$	Microgrammes per cubic metre
VOC	Volatile organic compound

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Acknowledgements

The section on the Bogotá Ciclovía is an edited version of text published in Farrow et al., 2020.

Appendix 1. Information Request

BOGOTÁ | EMPRESA DE TRANSPORTE DEL TERCER MILENIO TRANSMILENIO S.A

Bogotá D.C., 23 de marzo de 2021

Señora
TATIANA CESPEDES CLAVIJO
Ciudad

Asunto: Requerimiento recibido en la plataforma Bogotá te Escucha con número 827102021.

Respetada señora Tatiana:

En atención a su comunicación, atentamente le informamos.

Dando respuesta a su solicitud, TRANSMILENIO S.A., se permite informar, para el componente **zonal** (Urbano – Complementario – Especial) y con corte a 14 de marzo de 2021, se tienen vinculados a la operación 6181 buses.

En relación con al SITP Provisional, con corte al 17 de marzo de 2021:

Vehículos en Operación	**Rutas**	**Empresas**
2415	92	42

Por otra parte, el componente **troncal** y de alimentación cuenta con 3292 vehículos vinculados a la operación. A continuación, se presentan los datos por tipología vehicular:

FLOTA VINCULADA DTBRT	
TIPOLOGIA	**CANTIDAD**
ALIMENTADOR (50)	91
ALIMENTADOR (80)	843
ARTICULADO	762
BIARTICULADO	1323
PADRON DUAL	273
Total general 18-03- 2021	**3292**

Finalmente, TRANSMILENIO S.A., le reitera su compromiso de continuar en la búsqueda de alternativas que permitan atender de manera equilibrada las necesidades de transporte de los usuarios con criterios de calidad y eficiencia.

Cordialmente,
TRANSMILENIO S.A.

Proyectó: Deyby Yamith Cárdenas – Dirección Técnica BRT.
Néstor Monroy – Dirección Técnica de Buses.
Elena Vásquez – Dirección Técnica de Buses.

Aprobó: Ingrid Jarley Pinilla – Dirección Técnica BRT.
Armando Illera – Profesional Especializado Dirección Técnica de Buses.
Marcela Carrascal – Profesional Especializado Dirección Técnica de Buses.

Consolidó: Paula Luna – Servicio al Usuario.
Código: 807

Nota: Los vistos buenos de las personas que han intervenido en la proyección y aprobación del presente documento fueron tomados a través del correo electrónico institucional de la Entidad.

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ALCALDÍA MAYOR DE BOGOTÁ D.C.