Assessment of the impact of vehicle emissions on air quality changes during COVID-19 lockdown in Bogota, Colombia.

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Abstract

The COVID-19 pandemic has forced governments to implement rigorous containment measures on reduction or cessation of human mobility, transportation and economic activities, to control the spread of the virus. This is considered as a unique opportunity to study the impact of local lockdowns periods, especially, on the vehicle emission levels, and urban air quality in cities with high pollution levels, such as Bogota, Colombia. The first case was confirmed in Colombia on March 6, 2020, since then to prevent its propagation, the government declared a national lockdown starting from March 20 until August 31, 2020. Therefore, this study attempted to analyse the air quality in Bogota by assessing the concentrations of the atmospheric pollutants NO_2, SO_2, O_3, CO, $PM_{2.5}$ and PM_{10} during the lockdown period and the corresponding concentrations levels during the same period in 2018 and 2019. The data for this pilot study was obtained from the air quality monitoring stations of Bogota. The present work applied a descriptive and inferential statistical analysis of the data to quantify the average variation in concentration levels for each air pollutant and their trend before and during the lockdown period, in addition with a discussion about possible correlation with the volume flow rate of traffic. The lockdown period indicated a considerable reduction in traffic flow patterns and a drop in emission levels by -13% and -22% in NO_2, -11% and -20% in SO_2, -23% and -34% in CO, -7% and -15% in $PM_{2.5}$, -25 % and -16% in PM_{10} compared to base values of 2018 and 2019 respectively; On the contrary, levels of atmospheric ozone were found to be increased by 31.3% and 14.1% from reference values. The analysis suggests possible correlations between the atmospheric O_3 and the NO_2 levels during lockdown period. The outcome of this pilot study will enable the policy makers to forecast the impact of electrification of transportation on atmospheric ozone levels in urban areas.

Introduction

One of the main sources of air pollution is concerned with road vehicle transport, particularly in highly congested urban areas. The combustion process of hydrocarbon fuels in internal combustion engines produces undesirable emissions of gases and particulate matter which affects air quality, human health, and contribute to climate change [1]. Global environmental agencies categorize the air pollutants emissions of primary concern in the ambient air that have the greatest impact on human health in urban areas by the exposure levels of carbon monoxide (CO), lead (Pb), nitrogen dioxide (NO_2), ozone (O_3), particulate matter (PM), and sulphur dioxide (SO_2), unburned hydrocarbons (HC) [2]. Among these, some are primary pollutants which are directly linked with common engine types for automotive applications operated with gasoline and diesel [3]. For example, exhaust hydrocarbon emissions are the results of incomplete combustion process in the combustion engine. NOx emissions are produced in the combustion chamber due to Arrhenius type reaction at elevated gas temperature. However, the tailpipe-emission levels are many orders of magnitude lower than the engine out emission levels since, they are regulated by the respective emission standards of the individual countries. Secondary pollutions are produced when these emission species such as HC reacts with Oxides of Nitrogen (NOx) and sunlight and create ground-level ozone, which is a major component of smog. It is known that smog is the most widespread and intractable ambient air-polluting problem [3] in major cities across the world. In addition, pollutants species can travel long distances in terms of days under favorable meteorological conditions, regardless of emissions being derived from localized point sources, therefore their effects are not confined to limited areas.

Addressing the relationships between emissions-generating activities, air pollution concentrations levels, and health impacts, the United Nation Environment Programme (UNEP) through the Climate & Clean Air Coalition (CCAC) encourage the global effort of governments, civil society and private sector to commit with the air quality improvement and protecting the climate in next few decades by reducing short-lived climate pollutants across sectors. The CCAC reported that poor air quality and climate change are already affecting vulnerable populations and environment especially in the Latin American and Caribbean region (LAC) resulting in premature deaths, crop yield losses, and ecosystem damage [4]. Therefore, the CCAC called for the introduction of new light-duty vehicle emission limits to comply with real driving conditions for achieving Euro VI equivalent emission standards, with substantial reduction in PM using after-treatment system; elimination of high emitting vehicles, to improve air quality and mitigate adverse health impacts due to air pollution [5].

In this context, powertrain manufacturers and transport scientific community are also developing improved technologies in combustion and injection systems for further emissions reduction, various studies have been conducted to assess variations in the combustion engine calibration parameters in terms of injection strategy, balancing hydraulic flow injection rates and compression ratio. Some comprehensive approaches showed significant evidence of the advantages in the adoption of a proper advanced fuel injection strategy, and nozzle hydraulic flow rate for the reduction of engine-out HC, NOx, CO, CO_2, O_2 gaseous emissions levels, maintaining a rated power performance targets in diesel engines [6]. For example, compression ratio (CR) variation of a single-cylinder engine in dual-fuel (natural gas-diesel) mode has found to have an impact in the performance and pollutant emissions levels including the PM size count and CO_2 saving over the New European Driving emission homologation Cycle (NEDC) [7].

In a large city as Bogota, transport activity is associated with the main source of direct and indirect pollution, it is estimated that over 40% of PM10 and 75% of NOx of the total emissions come from the transport activity as mobile sources weighted 29% [8], a similar relative source strength is found for other Latin-American cities such as Santiago and Mexico City [6]. Emissions inventory for Bogota shows the contribution of the on-road traffic emissions for light and heavy vehicles, with 99% PM_{10}, 96% NOx, 84% CO and 65% SO_2 of the total traffic emission. Moreover, it is described that only 5% of the total fleet corresponds particularly to heavy vehicles such as buses and trucks using diesel as fuel, where only a small portion of the fleet accounts for a large part of the air pollution as shown in Table 1 [8].

Table 1. Traffic emission factors in Bogota, for light and heavy vehicles.

Pollutant	**Light** (gkm^{-1} veh^{-1})	**Heavy** (gkm^{-1} veh^{-1})
CO	8.27	385.2
NOx	0.11	18.9
PM_{10}	0.27	2.38

Source: Zarate et al. (2007)

Covid-19 and Local Lockdowns

In the early days of 2020, the world began to face the pandemic threat of COVID-19, caused by the novel infectious virus SARS-CoV-2 which has an unprecedented spreading contagious effect over the population. The WHO declared the pandemic alert on March 11, 2020 [9], subsequently the governments of almost all the nations of the world implemented local lockdown to tackle the rapid rate of infections. In view of this, the Colombian government took early action and on 25 March 2020, the country entered into a nationwide lockdown to break down the infection chain, starting an isolation phase with planned gradual de-escalation for weeks after [10]. Thus, these actions immediately minimized displacement patterns for industrial activities, urban and freight transport systems, in an unprecedented way, allowing a unique opportunity to measure how lockdown modified the effect of anthropogenic activities on air quality in the most populated cities.

Currently, researchers from various countries are evaluating the impact of lockdown on air pollution levels. For instance, over 40 cities in China, reported a decrease in concentrations of SO_2, PM, $PM_{2.5}$, PM_{10}, NO_2, and CO in 7%, 6%, 14%, 25%, and 5%, respectively. This trend was mainly associated with a 70% of reduction in vehicular flow [11]. A similar study [12] carried out a comparative analysis of the variation in the PM_{10} and $PM_{2.5}$ levels in 12 cities across the globe from countries highly affected by COVID-19. The values of concentrations were collected from ground-based data of 162 monitoring stations. It was found that concentrations of $PM_{2.5}$, PM_{10} and NO_2 were reduced by 20–34%, 24–47% and 32–64%, respectively, due to restrictions on anthropogenic emission sources during the lockdown. However, the achieved improvements were temporary as the pollution level gone up again in cities where lockdown was gradually lifted. Adding in this way, other studies [13] [14] [15] [16] also describe the behavior of air pollutants during the lockdown period compared to previous weeks without a lockdown from the 50 most polluted capital cities in the world and South America, where was observed a variation in atmospheric pollutant concentration as is summarized in Table 2.

Table 2. Air pollutants variation concentration during lockdown in cities.

Pollutant / City	**PM10**	**PM2.5**	**NOx**	**CO**	**O3**
Milan	-47%	-47%	-58%	-49%	20%
Barcelona	-31%	-45%	-51%	--	58%
New Delhi	-50%	-50%	-50%	-31%	0%
Rio de Janeiro	-24%	-24%	-45%	-49%	48%
Lima	-40%	-31%	-46%	--	13%
Santiago	--	11%	-54%	-13%	63%
Graz	-14%	--	-41%	--	34%

Source: Adapted from Rodríguez-Urrego et al. (2020), Toro et al. (2021) and Lovríc, M, et al. (2021)

Because of the changes observed in atmospheric emissions associated with the lockdown period, might be inferred that in general there was a trend of decrease in the level of concentrations of PM_{10}, $PM_{2.5}$, NO_2, and CO, and an increase in the concentration level of O_3 correlated to the records of either the pre-lockdown period or previous years.

In this context, this pilot study aims to analyze the changes in air quality parameters during the COVID-19 lockdown measures in Bogota, Colombia. Comparing the emissions values with the records obtained during 2018 until 2020, assessing the concentrations of the atmospheric pollutants NO_2, SO_2, O_3, CO, $PM_{2.5}$ and PM_{10}. Is expected that the presented results might offer to the policymakers useful evidence for the development of strategies to improve air quality related to the impact of electrification of transportation and atmospheric ozone levels.

Materials and Methods

Study Area

Bogota, the capital of Colombia, (4.6°N and 74.1°W) lies in a plateau on the Eastern side of the Andes Mountains. It is the third-highest capital in the world averaging 2,640 meters (8,660 ft) above sea level and a relatively constant cool climate with an average temperature of 13°C (55°F). Bogota is the fifth biggest city in Latin America with an extension area of 1,587 km^2 with approximately 12 million inhabitants [8]. The emissions inventory of the city in 2018, records 2.5 million vehicles registered in the city, 90.84% correspond to private vehicles, 3% to official public transport, 2.7% to cargo transport, and 2% to individual public transport. Nearly 1.5 million vehicles circulating every day, among which 71000 are diesel-powered vehicles [17]. Atmospheric pollution levels are reported to regularly exceed the WHO Air Quality Standards for PM_{10}, $PM_{2.5}$, and O_3 in specific local areas. High levels of air pollution in Bogota are associated with a correlation of the anthropogenic activity, its geographic location, meteorological conditions, and vehicle fleet technological backwardness of at least 10 or 20 years [18].

Air Quality Data

Air quality data was provided by the local environmental authority, with the raw datasets for each of the existing monitoring stations. The Bogotá Air Quality Monitoring Network (RMCAB) is made up of 18 stations, where 17 are fixed, and 1 is mobile as shown in Figure 1. The RMCAB are made up of monitors, analyzers, and automatic sensors that collect averaged hourly data on the state of air quality. The network monitors and analyzers operate under specific measurement methods that are established in Title 40 of the Code of Federal

Regulations (CFR), which are approved by the United States Environmental Protection Agency (EPA) [19]. A specific reference method is defined for each pollutant PM_{10}, $PM_{2.5}$, O_3, SO_2, NO_2 and CO, in accordance with the equivalent technique for the operation of each monitor, also established in the Subpart A of Part 53 - Summary of Applicable Requirements for Reference and Equivalent Methods for Air Monitoring of Criteria Pollutants 40 of the CFR [20].

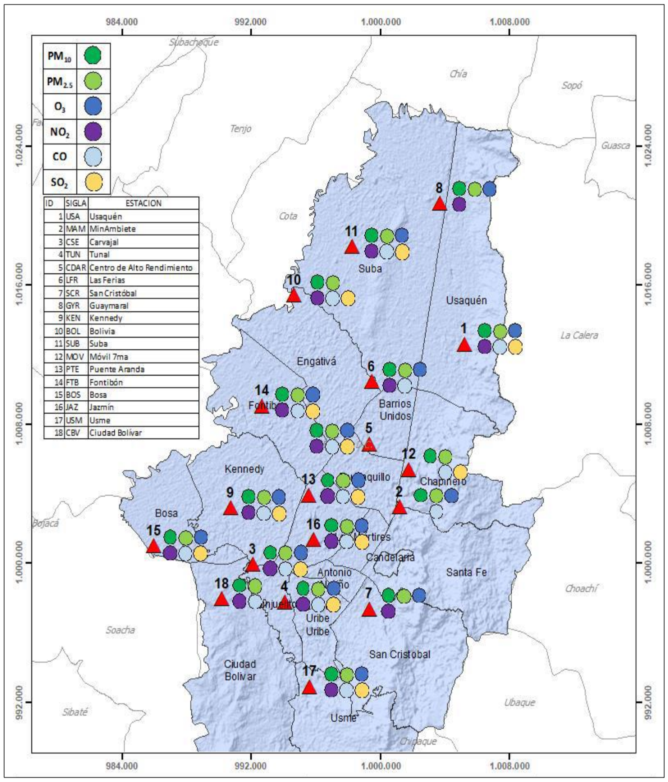

Figure 1. Locations of the Air Quality Monitoring Stations (RMCAB) in Bogota 2020 *[19]*.

For this pilot study the experimental data obtained computed the 24 hours records of the maximum values of the criteria pollutants previously cited during the 2018 to 2020 period. The available set of data allowed its characterization to define the scope and statistical significance for analyzing the results.

Descriptive Analysis

This study applied a descriptive statistical analysis of the data to quantify the change in the mean of the criteria pollutant concentrations. The experimental data obtained by the monitoring stations were initially verified to identify spurious data, then these were classified in 1-hour average values. For the comparison of the data obtained from all monitoring stations, the arithmetic mean value was calculated considering every single value in the hourly data recorded by each monitoring station. Then, the calculated hourly mean values were compiled monthly to clearly identify a trend along the time. The main reason for using the mean in measuring a central tendency is because it resists the fluctuation between differing samples, especially when the sample size is large enough [21]. To assess any relative difference in the mean percentage values during the LP an estimation of the uncertainty through the standard deviation analysis and t-student test were carried out. Additionally, cumulative hourly values were calculated by adding up each hourly mean obtained from all the stations, this allowed to quantify a difference in the total amount of concentration in each pollutant in a certain period.

The current analysis covers the period from January 2018 to December 2020. In order to determine any influence of the lockdown period on air quality in 2020, the same period in 2018 and 2019 has been compared with that of lockdown period. The lockdown period in Bogota was enforced by authorities from the 20th of March 2020 with a gradual lift in restrictions until the 31st of August 2020. Therefore, the data obtained from 2018 and 2019 is considered as the control group for comparison purposes of the relative difference in the means of any given pollutant, i.e.

$$\left(\frac{mean\ 20 - mean\ 19}{mean\ 19}\right) \times 100\% \qquad (1)$$

It is worth mentioning that RMCAB reports pollutant concentrations under standard conditions (1 atm and 25°C). Thus, this allows us to carry out a comparison with concentrations levels during the same period of base years 2018 and 2019.

Results and discussion

Air pollution assessment during COVID-19

A recent assessment by Economic Commission for Latin America and the Caribbean (ECLAC) on the evolution and effects of the COVID-19 pandemic in Latin America and the Caribbean (2020) and the measures taken by governments in the framework of the COVID-19 pandemic shows the relationship between reduction of economic activities with the reduced levels of human mobility. In addition to this finding, the report also anecdotally observed the contribution of reduced mobility with improving air quality in Latin American cities [22].

Similarly, the Annual Report of the Air Quality in Bogota in 2020 [14] estimates the emissions inventory by mobile sources and vehicle categories generated during the 2020, it indicates a remarkable reduction in the daily levels of pollutants ($PM_{2.5}$, PM_{10}, SO_2, CO, NO_x and Volatile Organic Compounds - VOC) during the first half of the year. This behavior is mainly attributed to by the impacts on mobility at the urban level, changes in activity and travel patterns, which were reduced about 80% compared to the baseline of the near 22 million people daily trips, for example in terms of urban transport the BRT system (Transmilenio) and regular buses (SITP) that compose public transport in the city reduced their operation at a maximum of 35% of their capacity, and the registered weekly freight trips (20.000) diminished around 38% on average during the mandatory lockdown [23].

Assessing variations in pollutant concentrations

Hourly average air quality data from 18 monitoring stations in Bogota RMCAB for 2018, 2019 and 2020 were used to estimate monthly average levels of various pollutants. The measured pollutant levels from 2018-2019 were considered as reference value to quantify the effect of lockdown on air pollution levels in 2020.

Figure 2 shows the results of the mean monthly concentration level (μg/m^3) for each pollutant covering the whole year from January to

December for the period described above. As a general trend, concentration levels varied with substantial differences among pollutants where primary pollutant concentrations associated with vehicle tailpipe emissions NO_2, SO_2, CO, $PM_{2.5}$, and PM_{10} showing a decrease since the lockdown period was imposed in late March until August 2020 (green line dots), in contrast to the seasonal trend observed during the base period 2018 and 2019 (blue and red line dots).

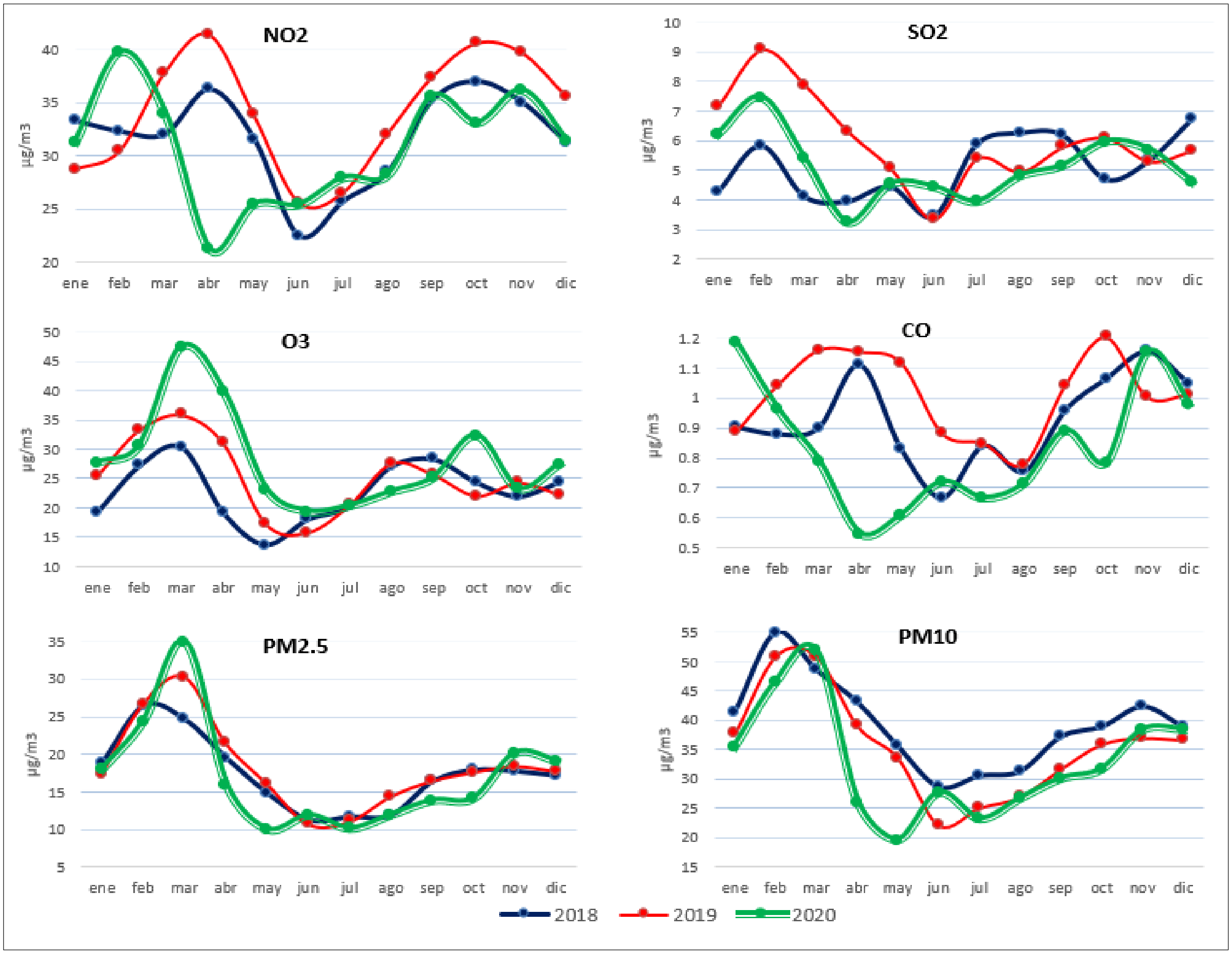

Figure 2. Estimated monthly average concentrations (µg/m3) of NO_2, SO_2, O_3, CO, PM2.5 and PM10 in Bogota from 2018 to 2020.

The reduction in concentrations correlates with the restrictions on the activity of emission sources between April and August, likewise the patterns of the pollutants analyzing the variation in average concentration levels during the lockdown. The mean concentration for NO_2 during the lockdown period is 25.37 µg/m3 and was found to be significantly ($p<0.05$) reduced by -13% and -22% in comparison to the same period in 2018 and 2019 respectively. The NO_2 levels drop is mainly attributed to the considerable reduction in emissions mainly from the transport sector and industrial processes [15]. The variation in the SO_2 showed a mean concentration of 4.2 µg/m^3 with significant reduction ($p<0.05$) by -11% and -20% for 2018 and 2019 respectively. This downward trend can be attributed to lower activity in gas-powered factories and use of diesel engines and the resulting combustion generated pollutants.

Ambient CO levels also show significant level of drop ($p<0.05$) with a mean concentration of 0.645 µg/m3 dropping by -23% and -34% in comparison to the base period. Sources of CO are many, however, one of the main sources of CO is the combustion engines used in vehicles.

Therefore, the reduction in vehicle activity and the levels of CO levels measured by during the lockdown period seems to correlate like other pollutants. A portion of CO is emitted directly by nature, and another part comes from anthropogenic emissions, by incomplete combustion of fossil fuels (oil, coal, among others), providing valuable information on the intensity of vehicle flux during the LP.

Similarly, the average concentration levels estimated from the measured data for $PM_{2.5}$ was 13.6 µg/m^3 and it is 7% and 15% ($p<0.05$) lower than the base value measured in 2018 and 2019 respectively. PM_{10} also exhibit similar trends. The average concentration of PM_{10} during lockdown period is 26.1 µg/m^3 and it is 25 % and 16% lower than the base values of 2018 and 2019 respectively. Particulate matter represents the mass of particles composed of different substances such as heavy metals or soot, which come from all types of combustion and some industrial processes, the emissions of PM_{10} and $PM_{2.5}$ show a significant level of reduction during the lockdown period when compared to that of base levels, since these are associated mostly with heavy-goods vehicles and public transport. Heavy goods vehicles and public transport vehicles are mainly diesel-powered and are considered as the main contributors of particulate matter emissions. Even though, the clear reduction in mean concentrations of PM and NO_2 during the lockdown period is mainly associated with the vehicular flux reduction; However, with the recorded data is not possible to examine the influence of other factors such as the transport of air masses and meteorological parameters. Therefore, is possible to correlate the reduction in PM and NO_2 levels with lower activity in urban mobility accordingly with the Bogota Emission's Inventory Report (2020) during the lockdown period was estimated that BRT public transport system (Transmilenio) and regular buses (SITP) limited its operation to up 35% of the total fleet, while heavy good vehicles registered a 38% less of daily trips [17].

The O_3 mean concentration during the lockdown period is 26.8 µg/m^3. This level is 31.3% and 14.1% higher than base levels of 2018 and 2019 respectively. This increase in O_3 levels negatively correlates with the vehicle activity in Bogota during the lockdown period. It is known that O_3 is formed through complex photochemical reactions of CO, CH_4 and other volatile organic compounds (VOCs) in the presence of NOx. The increase of O_3 concentration is chemically linked to the NOx reduction, this phenomenon is called termed titration [19], which means that reducing NOx levels reduces the amount of O_3 being destructed via reaction with NO, and this essentially increases O_3 [24]. The correlation of O_3, NO, and NO_2 under atmospheric conditions is established by the following reactions [25]:

$$NO_2 + hv \rightarrow NO + O \quad (2)$$

$$O + O_2 \rightarrow O_3 + M \quad (3)$$

$$O_3 + NO \rightarrow NO_2 + O_2 \quad (4)$$

Where:
M represents a molecule of N_2 or O_2
hv represents the energy of a photon, with a wavelength of < 424 nm
O represents an active monoatomic oxygen molecule

These reactions represent a closed system in which the NOx (NO and NO_2) components and the O_X (O_3 and NO_2) components relate separately. During daytime hours, NO, NO_2 and O_3 are typically equilibrated reaching a photostationary state, then, the level of O_3 increases rapidly at small values of $[NO_2]/[NO]$. When O_3 concentration is close to set a photostationary state it is possible to forecast the O_3 concentration during the daytime by using the polynomial function [26]:

$$[O_3] = 19.678 \times \ln [NO_2/NO] + 1.378 \quad (5)$$

Where:
$[NO_2 / NO]$ is in ppb

Therefore, the present results suggest that a lower O_3 titration by NO_2 reduction concentration levels as the dominant cause for explaining the O_3 increases in Bogota. In other words, lower NO_2 emissions levels mainly from the road transport sector resulted in less ozone being depleted rising to unprecedented levels.

Figure 4 shows the NO_2 and O_3 levels measured in 2018, 2019 and 2020. The cumulative levels shown in this figure clearly indicate the correlation between decreased NO_2 levels and increased O_3 levels in the ambient air in Bogota. This inverse trend forces to evaluate the role of NO_2 on secondary pollutant such as O_3. Also, it is possible to observer an inverse trend between the behavior of the total amount of emissions levels for NO_2 and O_3, while NO_2 registered a reduction of -18% in total emission levels, O_3 increased by 22%.

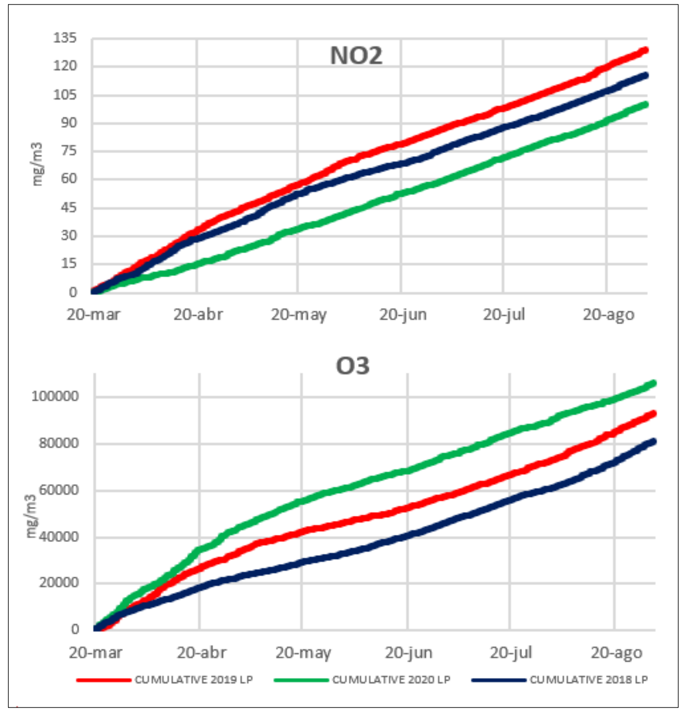

Figure 3. Cumulative maximum values for NO_2 and O_3 for same LP from 2018 to 2020.

Table 3 shows the average concentration and the percentage variation of all pollutants considered in this study only during the lockdown period and are compared with base levels registered during the same period in 2018 and 2019. In general terms, primary pollutant particles showed the most reduction in emissions, where CO and PM_{10} presented the greatest reduction among all pollutants analyzed, while O_3 as secondary pollutant particle sharply rose concentration levels.

Table 3. Averages relative changes of pollutant levels (Lockdown period-LP)

Pollutant	A: LP mean (µg/m^3) 2020	B: LP mean (µg/m^3) 2019	C: LP mean (µg/m^3) 2018	Relative change (A,B)	Relative change (A,C)
NO_2	25.373	32.688	29.233	-22.38%	-13.20%
SO_2	4.205	5.219	4.718	-19.42%	-10.86%
CO	0.645	0.974	0.843	-33.73%	-23.46%
$PM_{2.5}$	13.639	16.135	14.659	-15.47%	-6.96%
PM_{10}	26.082	31.088	34.809	-16.08%	-25.05%
O_3	26.864	23.540	20.455	+14.11%	+31.33%

Consequently, an apparent improvement in the air quality of Bogota in 2020 is explained by lockdown measures related to the COVID-19 pandemic; however, exceedances of standards were even observed. Considering that the World Health Organization (WHO) recently updated the recommended air quality guidelines (AQG) standards of air pollutants for long- and short-term exposure, associated with important risks to public health. The guidelines values seen in Table 4 can be useful for policymakers to set quality limits or standards, as these offer a scientific basis to identify the levels at which air pollution can cause a significant and unacceptable health impact [5].

Table 4. Recommended 2021 AQG levels

Pollutant	Guideline Value
Fine particulate matter (PM2.5)	5 µg/m3 annual mean 15 µg/m3 24-hour mean
Coarse particulate matter (PM10)	15 µg/m3 annual mean 45 µg/m3 24-hour mean
Ozone (O_3)	60 µg/m3 peak season 100 µg/m3 8-hour mean
Nitrogen dioxide (NO_2)	10 µg/m3 annual mean 25 µg/m3 24-hour mean
Sulfur dioxide (SO_2)	40 µg/m3 24-hour mean
Carbon Monoxide (CO)	4 mg/m3 24-hour mean

Source: WHO 2021

The lockdown period has enabled us to evaluate the impact of vehicle emission on ambient air quality and foresee the level of improvement decarbonization of transport can achieve. The annual mean levels of various pollutants recommended by AQG shown in table 4 when compared with levels of those pollutants measured during lockdown period shown in Figure 2, suggests that it is possible to achieve significant levels of reduction in air pollution by decarbonization of the vehicles. However, it also shows that, transport alone can not achieve required levels of reduction for meeting the air quality standards.

Summary

This study examined the impact of lockdown on ambient air quality in Bogota. The main findings of this work can be summarized as follows:

- The levels of main criteria pollutant, NO_2, SO_2, CO, NO_2, PM_{10}, and $PM_{2.5}$ linked to internal combustion engine show significant level of reduction when compared to corresponding period from 2018 and 2019.
- This pilot study revealed that an increase in O_3 concentrations between 14% and 31% in comparison to 2018 and 2019. This increase in O_3 seems to correlate with reduction in NO_2 levels.
- The correlation between the decreased level of NO_2 and increased level of O_3 warrants further research on the implications of electrification of transport and atmospheric O_3 levels.
- The outcome of this study suggests that it is possible to achieve significant levels of improvement in air quality by decarbonization of the vehicles. However, transport alone cannot achieve required levels of reduction for meeting the air quality standards.

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Definitions/Abbreviations

CO	Carbon Monoxide
Pb	Lead
NO_2	Nitrogen Dioxide
PM	Particulate Matter
O3	Ozone
SO_2	Sulphur Dioxide
HC	Hydrocarbons
VOC	Volatile Organic Compound
LP	Lockdown Period
WHO	World Health Organization
RMCAB	Air Quality Monitoring Network of Bogota
UNEP	United Nation Environment Programme
CCAC	Climate & Clean Air Coalition
CR	Compression ratio
NEDC	New European Driving Cycle
CFR	Code of Federal Regulations
AQG	Air Quality Guideline
LAC	Latin America & Caribbean