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RESEARCH ARTICLE

Impact of the mobility alteration on air pollution over different cities: a vision for citizen awareness

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Abstract

Every year the concern from environmental pollution increases as it affects human health. In the current paper, it is analyzed the evolution of the air quality in different cities on international level related to the reduction in mobility trend due to the emergence of the pandemic. The air pollution is studied in order to achieve healthier cities in the future and create an awareness for the citizens. The COVID-19 pandemic situation was declared during the first months of 2020 and has shown (indirectly) the effects that restrictions on human activity and road traffic have on atmospheric pollutant values. This pandemic condition derived, in most cases, in mobility restrictions in order to decrease the spread of the virus through the density of population in different places and, as a result of these restrictions, pollutant presence decreased equally. This article analyzes some of the largest cities around the world, such as Tsuen Wan district in Hong Kong (China), Los Angeles (USA), London (UK), São Paulo (Brazil), Bangalore (India), Johannesburg (South Africa), and Sydney (Australia) in order to check the different mobility restriction policies established in each location, and how those restrictions led to decrease the levels of some pollutant particles such as NO_2 in the atmosphere. This should serve as a focus of awareness of the city and political interests of how it affects human activity, and those measures should be taken to reduce pollutants.

Keywords Pollution · Traffic · COVID-19 · Air pollutants · Mobility

Introduction

The pandemic of SARS CoV-2 started in 2019; several countries experienced few cases by the end of the same year. The rapid increase of infected cases was alerted by the World Health Organization (WHO). This situation led from several cases to an epidemic. As a result of this outbreak, a novel coronavirus was spread worldwide transforming into a pandemic (Cucinotta & Vanelli, 2020). The WHO identified this virus as easily transmitted from human to human (Wiersinga et al., 2020) which led to an exponential increase of COVID-19 cases.

Highlights
- Mobility restrictions impacted positively on the environment.
- Traffic alteration can also modify the presence of air pollutants.
- Significant reduction in air pollutants such as PM_{10} and NO_2 due to no traffic on roads.
- An improvement is possible if mobility is controlled involving public awareness.

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In order to face this highly dangerous pandemic, various countries took measures such as confinement and mobility restriction along with a stoppage of all non-essential activities. The reduction in transport and industrial activities resulted in a positive effect on the air quality over different cities (Sharifi & Khavarian-Garmsir, 2020). Therefore, in this article, the presence of air pollutants will be studied in order to better understand the interconnection between human activities and the planetary impact of them.

Pollution is a contamination that directly affects human and planetary health, along with altering natural ecosystems (Muhammad et al., 2020). There are different kinds of pollution such as air pollution, water pollution, noise pollution, and soil contamination. These various forms of pollution are harmful (Muhammad et al., 2020); however, the air and water pollution represent a high risk to health. However, in the current paper, the air pollution has been analyzed. In Table 1, it can be observed the different cities from different regions with dates used in this paper when COVID-19 started to affect them, most from early 2020, and the density of population of each city by 2020.

For this study, air pollutants from various cities have been analyzed; pollutants such NO_2 is among others the most harmful particles for human health and deteriorates the natural greenhouse effect (Freedman, 2013). Particles of NO_2 and PM_{10} are highly presented in areas with continuous presence of rolled traffic. NO_2, also known as nitrogen dioxide, is one of a group of highly reactive gases which is emitted to the air by burning of fuel (Khaniabadi et al., 2018). These processes take place when there are emissions from vehicles, power plants, and off-road equipment. The health effects of these particles are various, being the main one the damage to the respiratory system of the human body (Setiabudi et al., 2004). In terms of environmental health, their direct effect is the danger to the ecosystem, in many cases ending up in acid rain (Khaniabadi et al., 2017). These issues are common in big cities such as Hong Kong, Los Angeles, London, São Paulo, Bangalore, Johannesburg, and Sydney. Therefore, air pollution is generally created from the concentration of pollutants that take place from different sources such as traffic congestions along with industrial activities (Freedman, 2013). It is worth mentioning the limit of study in this paper, as the aim is to demonstrate the impact of mobility on the environment. The authors have properly researched other papers where the study fields have been extensive and with relevant data, such as those executed by Daniella and Leonardo Rodríguez-Urrego (Rodríguez-Urrego & Rodríguez-Urrego, 2020) and which has been taken into account for this paper.

The analyzed data in this article is strictly necessary in order to evaluate the interconnection of different factors such as socio-ecological and socio-economic with its indirect impact on the environment (Likens et al., 1979). In the case of the pandemic of SARS CoV-2, there are positive effects which benefit the air quality. These changes can be observed before, during, and after the lockdown and outbreak of COVID-19.

This article aims to show a vision of the effect on citizens and political interests on pollution in cities due to road traffic, and that with restrictive measures cause a large drop in the effect of air pollutants. With the data shown, it is noted that by taking strong measures in vehicle restrictions, a marked improvement in air quality in cities is soon achieved, which can help to improve public awareness of the effects that activity (especially transport) influences pollution and measures need to be sought to improve it.

Methodology

In order to study the impact of the mobility activities on the environment during different periods of time from 2020, various open platforms were used in order to collect data. For deep analysis about the pollution and the air quality instruments such as NASA, pollution monitoring satellites (Web 3, 2020) from which can visualize the side effects of the pandemic connected to the air quality of different regions were used. Sentinel-5P is the first Copernicus mission satellite devoted to monitoring our atmosphere. It has a Tropomi instrument which is capable of mapping numerous trace gases, such as nitrogen dioxide, ozone, formaldehyde, sulfur dioxide, methane, carbon monoxide, and aerosols, which affect the breathable air and, therefore, our health and environment. These

Table 1 Lockdown dates for different countries. Source: Own elaboration with data from Website 1. (Web 1, 2020)

Cities	Lockdown dates 2020	Density of population	Lockdown ease 2020
Hong Kong (China)	23rd January	6.764 inhabit/km^2	8th of April
Los Angeles (USA)	19th March	3.046 inhabit/ km^2	15th of June
London (UK)	23rd March	5.713 inhabit/ km^2	19th of July
São Paulo (Brazil)	24th March	8.106 inhabit/ km^2	11th of June
Bangalore (India)	24th March	11.394 inhabit/ km^2	31st May
Johannesburg (South Africa)	26th March	3.425 inhabit/ km^2	25th of July
Sydney (Australia)	31st March	2.951inhabit/ km^2	2nd June

satellite images will provide information on atmospheric quality, stratospheric ozone, and solar radiation, in addition to monitoring the weather. The impacts of wind and changing temperatures have been taken into account for this paper; however, the main focus has been to show the relation between mobility trend and the environment through the study of air pollutants measured by above-mentioned methods, as climate factors represent a dynamic variable characteristic which can be balanced by the socio-ecological support.

It is known that the presence of air pollutants indicates the air quality within the cities where the measurements take place. These measurements have been collected from the database available online on real-time Air Quality Index (AQI) (Web 1, 2020). In the case of air pollutants such as NO_2 and PM_{10}, it is worth mentioning the levels that they can reach and how to interpret them; thus, the values from 0 to 50 μg/m^3 indicate a good level and there is no risk in the air quality. Values from 51 to 100 μg/m^3 indicate a moderate level of air quality. The unhealthy level for sensitive groups starts when values go from 101 to 150 μg/m^3; in this level, citizens with respiratory issues must avoid prolonged outdoor exertion. Definitely the unhealthy level starts when values' range is 151–200 μg/m^3; in this level, the health issues appear more frequently both on adults and on children. From this level on, the value range is 201 μg/m^3 up to 300 μg/m^3 and more than 300 μg/m^3, where the first range corresponds to very unhealthy level which affect the entire population and come with a warning from the health organizations; on the other hand, values above 300+ μg/m^3 indicate a hazardous level with health alert leading to serious health effects.

Hence, in this current paper, the air pollutants and their impact on the environment have been studied according to these values, and the studied element has been the NO_2. Nevertheless, the analysis of the mobility activity has been studied through the walking and driving tendency in different periods of time. These factors were deeply analyzed based on the database available online such as Apple mobility trend (Web 2, 2020). Through this application, it can be seen the total percentage of user that have downloaded the Apple mobility application, where it is counted through the number of requests made to Apple Maps for directions.

With different databases and instruments, the paper has been structured with a focus on two main points as the mobility evolution of the cities and, on the other hand, the evolution of particles such as PM_{10} and NO_2, but mainly the second particle due to its main source. In order to analyze these factors, the mentioned materials were used, and the impact of this situation have been represented in the "Results and discussion" section.

Case study

For this paper, the study has been conducted on six big cities around the world: Tsuen Wan from Hong Kong (China), Los Angeles (USA), London (UK), São Paulo (Brazil), Bangalore (India), Johannesburg (Africa), and Sydney (Australia). These cities share a high amount of daily rolled traffic on their streets which leads to high quantities of hazardous particles both for human and planetary health such as NO_x, CO, SO_2, PM_{10}, and O_3, among others (McKinney, 2019); however, in the current paper, the air pollutant analyzed is the NO_2. The reason behind these cities is the clear impact shown due to the drop down in mobility.

In order to study these particles, it is necessary to know their source of creation. All particles from NO_2 are mainly originated from road transport, where combustion occurs in high quantities (Stranger et al., 2008). It is remarkable the connection of the rolled traffic with the air quality; therefore, in this present paper, the mobility of the citizens has been studied, as it is a key element in order to complete the analysis. The study of pollutant alterations due to the health disaster from COVID-19 is of high importance along with the mobility trend in cities such as Hong Kong, London, Los Angeles, Bangalore, São Paulo, Johannesburg, and Sydney. These cities have been selected due to their large density and higher activity both industrial and economical.

Analysis and development of Tsuen Wan in Hong Kong

China was the first country to report the COVID-19 case in December of 2019, with only 2 cases in the city of Hong Kong. These cases increased exponentially by the start of 2020. On the 30th of January, the WHO declared the outbreak of COVID-19 a public health emergency of international concern. With this statement, the disease of novel coronavirus was known worldwide and required efficient measures in order to stop the transmission of this virus, also known as SARS-CoV-2. Being the first country to face this pandemic, the Government of China declared a state of alarm on the 23rd of January. With this strict measure, the social and industrial activities faced a high decrease which consequently led to lower values of transmission.

In the current paper, it is analyzed the area of Tsuen Wan due to its high traffic and its impact on the environment. Tsuen Wan is an area of the city of Hong Kong. In the present article, despite studying the impact of traffic in the area of Tsuen Wan, the densities which have been

taken into account have been of Hong Kong in order to better understand the demographic factor of this area, thus being a total density of 6.764 inhab/km^2, being one of the most dense cities when it comes to population.

Regarding the key industries in this, it is worth mentioning the tourism, professional services, financial services, and being one of the biggest the trading and logistic. This last activity makes this area an interesting area of Hong Kong as it is also equipped with a port. Therefore, being the trading and logistic activity one of the main economy engines of this area has a consequence on the environment and the air quality as the activity itself requires so.

Analysis and development of Los Angeles

This American city is well known for its rolled traffic congestion; therefore, measurements in Los Angeles are of particular importance as the city faces a serious problem of traffic jams. In this city, it can be clearly observed how the emergence of the coronavirus disease 2019 (COVID-19) has indirectly affected the air quality over the city. However, it is important to highlight the mobility trend of the city, and how it decreased abruptly with the decree of mobility restriction, announced on 19th of March of 2020 by the government.

Los Angeles with a density of 3.046 inhabitants per each square kilometer shows clearly the high impact it can have on the environment. This impact occurs especially due to the rolled traffic. On the other hand, it is worth mentioning the key industries in the city of Los Angeles, as it is also known for its high diversity activities. Being one the of the main activities is the manufacturing of different materials such as components, electronic products, furniture, and many others. The other activity which impacts the environment is the steel fabrication, which is closely followed by the fashion apparel. This mentioned industry has evolved in the past years. Therefore, steel is used for creating new machinery such as for agricultural uses or related to construction or mining.

Along with the mentioned activities, Los Angeles is also known for its exportation activity, being the nation's largest port regarding the quantity of products it exports and imports. These actions make this city one of the highly polluted cities in this area of the USA.

Analysis and development of London

In the UK, London is well known from reaching high levels of transit. This directly impacts on the particles that are emitted to the atmosphere. Regarding the density of this city, it is worth mentioning the high levels with a total of 5.713 inhabitants/km^2; with values like this, it is very clear the relation between the high presence of air pollutants on citizens. Nevertheless, the lockdown period established due to the COVID-19 situation reduced the number of trips, decreasing in the same way the values of air pollutants.

In the case of London, it is one of Europe's most polluted cities when it comes to air quality. This can be due to its high density of population and also high rolled traffic.

Regarding the key industries of this city worth highlighting, the highest activity is the sector of service. This sector has been evolving in the past years and being on top of sectors such as construction or the production sector. This indicates the high activity in this city where the high density of population also makes an impact on the environment.

Analysis and development of São Paulo

This south American country is where the cases of COVID-19 increased rapidly due to its high population. However, it is worth highlighting the density of population, which is 8.196 inhab/km^2; therefore, the impact of the novel coronavirus affected harshly this city and the whole country. This area faced the disaster which hard hit the country in the month of March of 2020. The measures taken in this country present a great resemblance to those taken in other countries as it is mentioned in this paper.

On the other hand, the industries or sectors that impact on the economy of this area of the country are important to highlight. One of the activities being the information services, with a total of 25.1%; this figure is followed by the business service with a total of 10.5%. Other mentionable activities are manufacturing, distribution, and retail. Regarding the information sector, it has presented an increase of 4.2% in the past years. These tendencies indicate the development of the country as it is focused to the public sector being information services the larger activity. Studying these tendencies can help in knowing the impact these make on the environment and how to improve it by applying different methods or changing their current system.

Analysis and development of Bangalore

Being one of the most populated countries in the world, India had to stop on the 24th of March of 2020 when the COVID-19 was declared a very contagious disease by the World Health Organization (WHO). The total population of India is 1,383,456,868 as of 30th of September (Web 1, 2020) of 2020. In this paper, the city of Bangalore has been studied due to its large number of industrial activities, where on the other hand, the total density of population of this city is 11.394 being the densest city studied in this paper.

In order to know the tendency of the key industry of this city, it has been analyzed the economic growth of it. The city of Bangalore is also known as the "Indian Silicon Valley" as the activity that is presented in high volume is related to the technology being one of the biggest industrial areas in

Asia. One of the areas with the highest activity is known as Peenya. From the 1970s, this city has been increasing various types of activities which are presented in large-, small-, and medium-scale industries.

The functioning of these activities requires movements of citizens which also implies the use of rolled traffic. This makes the direct impact on the air quality of the area along with the activity itself

Analysis and development of Johannesburg

This south African city has also been hard hit by the disease of novel severe acute respiratory coronavirus 2 (SARS-CoV-2) along with the rest of the world. The density of population of Johannesburg is 3425 inhabitants per each square kilometer by 2020 (Web 1, 2020); therefore, the virus spread rapidly among citizens. In order to avoid major disaster, the country took measures such as confinement which led to a stoppage of social and industrial activities.

It is of high interest to know the current key industries in the city of Johannesburg. In order to understand the tendency of the key industries, it has been studied the growth of the economy of this city.

The activities in this city have been divided into different sectors being these the primary, secondary, and the tertiary sectors. The sector with the highest growth through the years have been the manufacturing with a total of 2.7% in the period of time between 2010 and 2015. Other activity which has dominated the city is the trade and work related to finance. The increase on other sectors such as the tertiary sector is also noticeable. This diversity in the sectors also impacts the air quality of where it is implanted; these features are studied in the "Study of the impact of mobility on air quality in Johannesburg" section of this article where the impact of the mobility has been studied on the environment.

Analysis and development of Sydney

The management of the country of Australia about the pandemic situation is one of the most successful in the most developed countries during the past months, given the fact that the number of cases per day did not reach the 1000 cases at any moment. This city is the one with lowest density in population compared to other areas analyzed in the current paper, being a total of 2951 inhabitants per each square kilometer in the city. This factor played a very important role in the development of the virus.

In the study of the industrial growth of this city, it can be said that the financial and insurance services are the state's largest industry; this industry has increased its share of GSP (gross state product) by more than four percentage points over the last 20 years, demonstrating its economic diversity. One of the analyzed areas is the (NSW) New South Wales which contributes the largest state share of national output not only in services (33%) but also in manufacturing (34%). NSW has particular strengths in food product manufacturing, primary metal and metal product manufacturing, and machinery and equipment manufacturing.

In 2012–2013, financial and insurance services, health care and social assistance, professional, scientific, and technical services and mining made the strongest industry contributions to NSW's economic growth

Results and discussion

Study of the impact of mobility on air quality in Tsuen Wan in Hong Kong, China

China was the first country to declare a state of alarm as a governmental measure to avoid major transmission of the SARS-CoV-2. A strict lockdown took place in early March when most areas of the country faced a major shutdown of industrial and social activities. The area of Hong Kong was hard hit by the disease of COVID-19. The World Health Organization (WHO) ordered citizens to remain at home except for those with essential activities; the transport system was banned all around the Asian country along with social gatherings.

It is very well known the pollution problem in China (Zhu, 2005) reaching dangerous levels of pollutants during the whole year; however, with the emergence of COVID-19, the air pollutant reduction is noticeable, and it can be observed in Fig. 1.

In the case of Hong Kong, more especially in the district of Tsuen Wan, it occurs in a similar scenario as in other cities except from its period of state of alarm, which started earlier in this city than in any other area of the world. This Chinese city also presents a high amount of traffic congestion which indirectly affects the air quality where many air pollutants are presented; this is also due to the high density in population in the country with a total of 6764 inhab/km^2. The traffic system presented a stoppage in the starting of the year 2020 (Bao & Zhang, 2020) which led to an improvement in air quality and pollution over this city. Through this graph, a tendency can be seen in three phases, where the first phase represents the fall of mobility activity driving and walking from 140 to almost 40% walking and 60% driving; this phase corresponds to the starting of state of alarm.

Regarding the walking activity, it has been under the 50% being lower than the driving tendency. These alterations can be seen in the lockdown period (represented between dashed lines) where the walking decreased from the driving tendency, indicating the interest of users in taking motorized vehicles instead of walking. This kind of pattern can also be seen in the second wave of COVID-19, where the difference

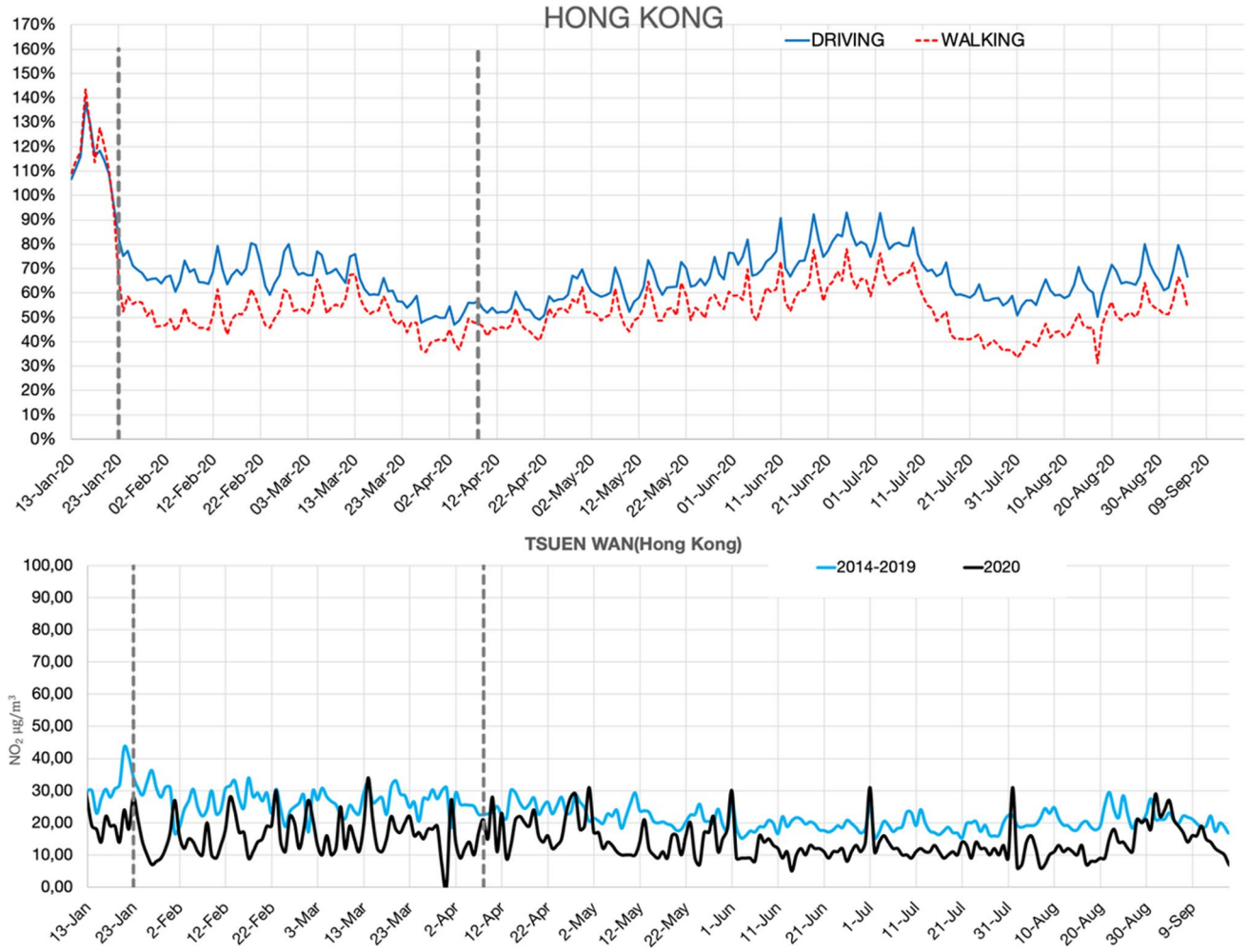

Fig. 1 Mobility evolution and NO_2 evolution in the district of Tsuen Wan (Hong Kong) in China in different period of time. Source: own elaboration with data from AQICN (Web 1, 2020) and Apple mobility trend (Web 2, 2020)

between driving and walking increased for several months, starting in July until August.

It can be observed a clear impact of the mobility reduction on the air quality in this Asian city. Levels of traffic (tracked by the percentage of users) in the city drop down from 140 to values below 40% once the pandemic hit this country. The analysis has been carried out by studying different phases, where the first phase corresponds to the harsh reduction of mobility which impacted directly on air pollutants; hence, the decrease of these pollutants took place. The second phase represents the period where the restrictions were being tested and finally represents the lifting of these restrictions and state of alarm. As consequence of this, the mobility activity started to increase and so did the air pollutants as it can be seen in Fig. 1.

The high levels of NO_2 from 2014 until 2019 and early 2020s indicate the pollution problem described in this paper. Even though levels of NO_2 during the beginning of the year 2020 were reaching values up to 30 µg/m^3, these values decreased drastically on the 23rd of January when state of alarm was declared. Therefore, in the case of China, it is remarkable the difference of values of NO_2 from the past years (2014–2019), and the 2020 with the emergence of COVID-19. Those values went from 30 µg/m^3 to values below 10 µg/m^3, a clear reduction of harmful particles' presence in the air. After that first refresh in the Chinese polluted atmosphere, the values of NO_2 started oscillating around 25 and 30 µg/m^3 for the following 2 months, when Fig. 1 shows a continued but slow increase in the values of air pollutant, getting to reach up to 30 µg/m^3 during the month of May (4 months after the decree of the state of alarm). In Fig. 1, it has been marked the difference of air pollutants present in the environment in 2020 and its comparison with the past years (2014 to 2019).

Analysis of the impact of mobility on of air quality in Los Angeles, USA

In Fig. 2, it can be observed the city of Los Angeles known for its high density of traffic and mobility trend. This mobility factor can be related to the density of population of this city, being a total of 3046 inhab/km^2. Thus, with the restrictions, an important reduction in both driving and walking can be seen. In this case, the relation between mobility and the presence of air pollutants has been studied as it is shown in Fig. 2.

In Fig. 2 which indicates the mobility trend evolution in the city of Los Angeles, it is shown the clear impact of the restrictions on the traffic and mobility.

Regarding the mobility evolution, values normally go around 150 and 180% to values below 40% when the pandemic emerged. It is remarkable the period of low-mobility activities that took place in the city. This period is represented in Fig. 2 with two discontinuous lines; as it can be seen, it is a short period of time; this occurs due to the high activity regarding the mobility in the city of Los Angeles, being a big city where high levels of traffic take place on a daily basis. This high activity of mobility decreased when the lockdown was declared on the 19th of March but remained on lower levels for a short period of time as mentioned before. It is also worth noticing the decrease in values even before the lockdown started; this phenomenon is mainly due to the alarming news about the health crisis which started to spread before the lockdown.

Having in account the analyzed variation on mobility in Los Angeles during the state of alarm decreed on March 19th, it is easy to deduce that the presence of pollutant particles such as NO_2 would decrease in the same way, as can be seen in Fig. 2. A significant difference in NO_2 values among 2020 and past years (2014–2019) can be observed. The starting of both years indicates very high

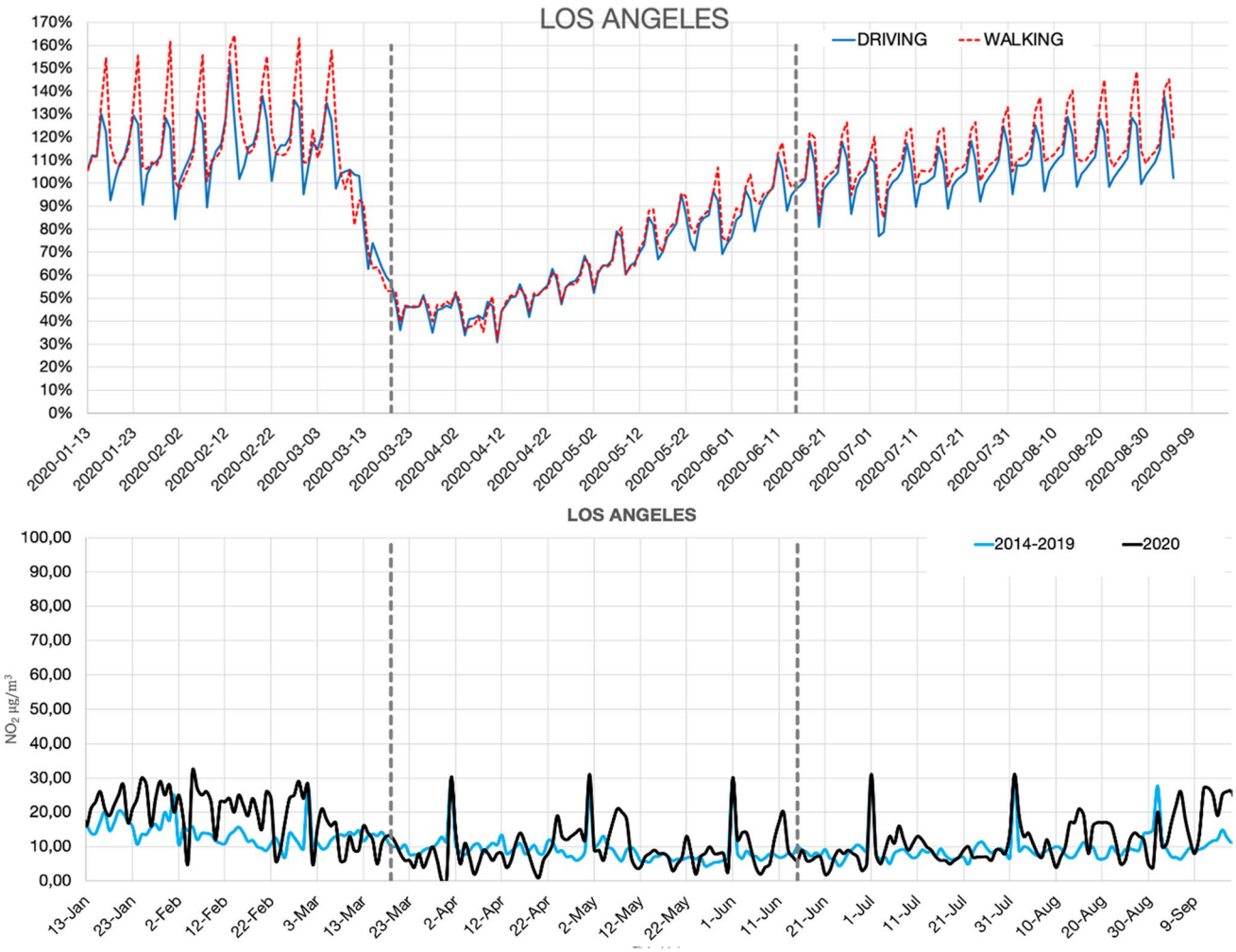

Fig 2 Mobility evolution and NO_2 evolution in Los Angeles in different periods of time. Source: own elaboration with data from AQICN (Web 1, 2020) and Apple mobility trend (Web 2, 2020)

values of NO_2; however, these values start to differ when the lockdown was declared.

This tendency can be seen clearly in how the presence of these particles, before lockdown, were around 30 μg/m^3, and on the lockdown date with strict mobility restriction, the values decreased up to 83.33%. This low value tendency remained in similar situation even after the lockdown, where values remained lower than the period after the outbreak of COVID-19. During 2020 it can be seen the values remain lower than the past years, indicating a clear impact of the pandemic over the air quality.

On the other hand, the rise of these values took place on mid-August. Therefore, these values present a gradual increase as the lockdown was being lifted gradually. It can also be observed the increase in industrial activities as social activities were allowed again, but never increasing up to values prior to the pandemic.

Analysis of the impact of mobility on of air quality in London, UK

The city of London, also known for its high density of traffic, has been analyzed; thus, results are obtained as it can be seen in Fig. 3, where the fall down of mobility trend is linked to the state of alarm and mobility restrictions practiced due to the pandemic.

In Fig. 3, the mobility evolution along the air pollutants such as NO_2 is shown. Air pollutants' figures have been recorded by the air quality measuring station located in London. From Europe, the city of London has been chosen due to the clear impact of COVID-19 on this city. The amount of air pollutants is high as a consequence of large amount of traffic in this city; therefore, with the emergence of the novel coronavirus outbreak, the dropdown of these mobility tendencies has been produced drastically as it can be seen

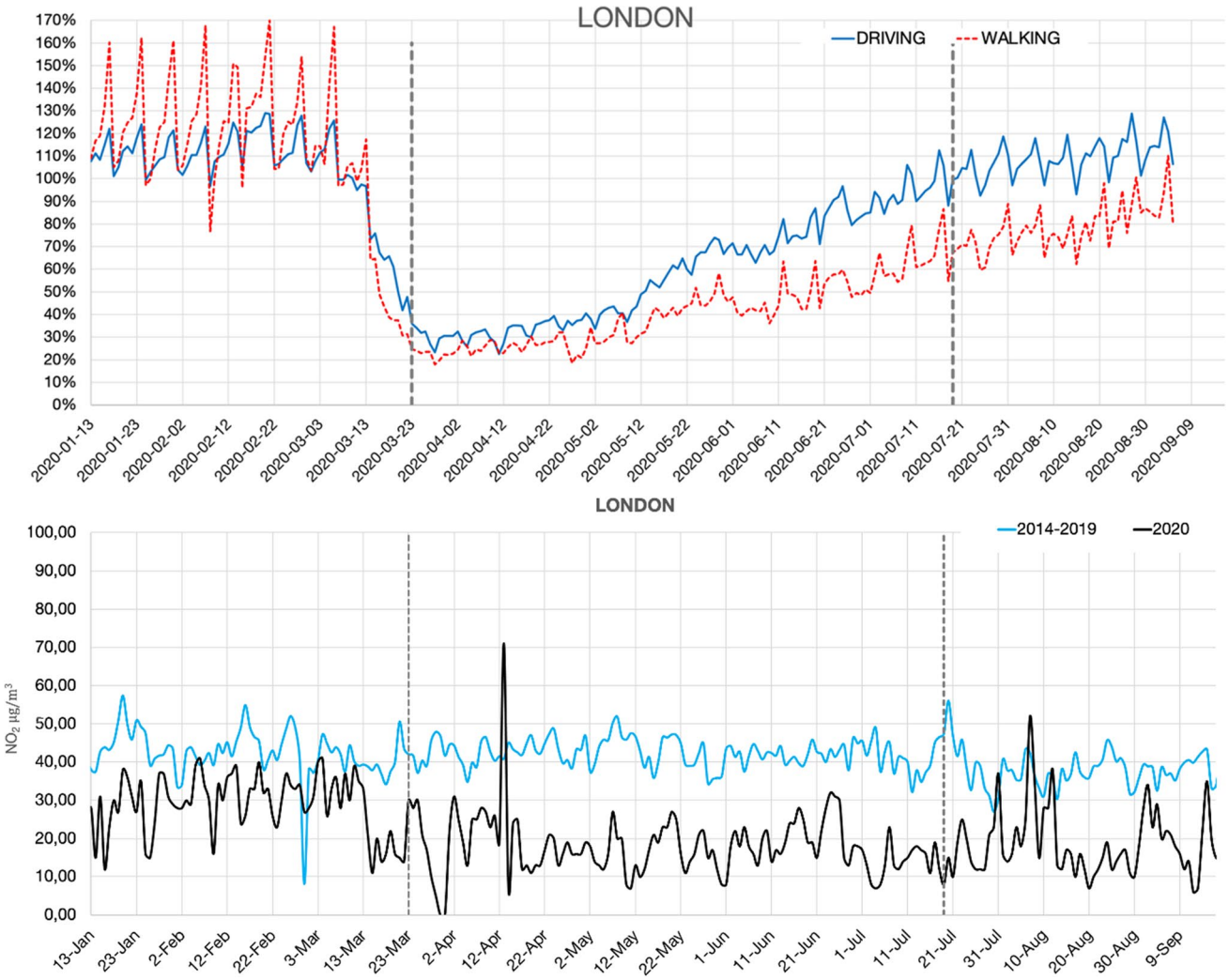

Fig. 3 Mobility evolution and NO_2 evolution in in London (UK) in different periods of time. Source: own elaboration with data from AQICN (Web 1, 2020) and Apple mobility trend (Web 2, 2020)

in Fig. 3; the values drop down from 120 to almost 20%, in the driving tendency, showing a clear decrease of 83.33%.

As can be seen in Fig. 3, the mobility trend decreased drastically even before the state of alarm was established in London on March 23rd. With this new condition, the traffic remained on low levels for almost 3 months. After this period of low values in mobility, the increase took place slowly from May 2020. These values started to get to the same values registered during the beginning of the year, when the virus was not still spread. Despite an increase in mobility, it can be seen how the walking trend remained lower than the vehicular mobility. This is due to the concern of infection in British citizens.

In the case of air pollutants, it has been studied in different periods which indicate values that vary in each situation. In the month prior to the state of alarm, the values indicate a high presence of particles in the environment with values around 30 and 40 $\mu g/m^3$; these values dropped drastically as it occurs in other major cities, but in the case of London, it dropped down to 15 and below 5 $\mu g/m^3$. After this point, the values have remained lower than the previous years where there were no mobility restrictions. The rise of the low tendency of values slowly took place after the restrictions in mobility started to lift; this can be seen in the next month to the lockdown, where the presence of these air pollutants has increased slowly, however mainly never reaching the values of pollution that were recorded in a period prior to the outbreak of COVID-19. It is also remarkable in the case of London, that even though the presence of NO_2 started to increase, they remained with high difference from the average values of past years as it can be seen in the Fig. 3.

Study of the impact of mobility on air quality in São Paulo, Brazil

As Brazil is a country where most of the economic sector depends on industrial activities, this led to a re-increase of air pollutant concentrations which means the restrictions in this city started to lift quickly after the state of alarm. This can be seen in Fig. 4, which indicates that the values before almost resemble the pre-COVID-19 concentrations. Therefore, as soon as the lockdown measures began to ease, the vehicular traffic and industrial and social activities started to get back to the "new normality" which has an indirect impact on the air quality of São Paulo.

In Fig. 4, which has been created with the data collected from the measuring station located in Santa Gertrudes and available on the website Air Quality Historical Data Platform (Web 1, 2020) and through the Apple mobility trend official website (Web 2, 2020), it can clearly be seen how the vehicular movements dropped from values around 190 and 320 (driving and walking) to almost reaching below 20%. In the case of São Paulo, the values also remained in lower numbers for almost 3 months. Once the city declared state of alarm, the difference between walking and driving tendency has been clearly separated from normal tendency; this shows a public awareness and concern about the spread of virus. However, the increase of these values took place slowly compared to other cities; this is due to the continuous restrictions from the government in order to control the spread of SARS-CoV-2 (coronavirus). This south American city is characterized by its high density regarding population; therefore, the restrictions have remained for longer period of time compared to other countries or cities. The different stages of the lockdown can be observed and easily differenciate the before and after lockdown period.

In the case of Brazil, the data collected from the website AQICN, it can clearly be seen as the reduction of air pollutants when the state of alarm was declared on 24th of March in the city of São Paulo. Compared with previous years and their air pollutants. It began with lower values similar to the starting of 2020, these values started to increase in February in both years, in fact the air pollutants of NO_2 are higher in the year 2020 than previous years. The detailed values can be observed in Fig. 4, where the mobility evolution and air pollutants tendency are represented.

The same tendency was seen in the case of air pollutants, where the starting of both years have similar values, which are lower than 10 and 20 $\mu g/m^3$, this is due to the low activity in the starting of the year, however the months goes by, these values started to increase as the industrial and mobility activities are taking place on daily basis. In the year of 2020, the drop down of values occurred on 24th of March, as consequence the number of hazardous particles decreased.

Analysis of the impact of mobility on of air quality in Bangalore, India

India is one the largest countries with a high number of populations in the world, being a country where industrialization took place rapidly leading it to high amounts of pollution levels all around the country. In this paper, Bangalore has been studied, as it is one of the most polluted cities in India (Web 1, 2020).

It is well known the sources of air pollution in India, as large congestions take place on Indian roads on daily basis, creating hazardous expulsion from vehicular, industrial, and biomass combustions along with road dust. With the emergence of COVID-19 and state of alarm, these pollution matters decreased significantly as it can be seen in Fig. 5 (Web 1, 2020), which shows the tendency of NO_2 during various periods of time in Bangalore along with the mobility evolution in these periods.

Despite being one of the most populated country in the world, the clear influence of COVID-19 was also able to observe on many factors in this country such as air quality and mobility trend. Therefore, the control on traffic was

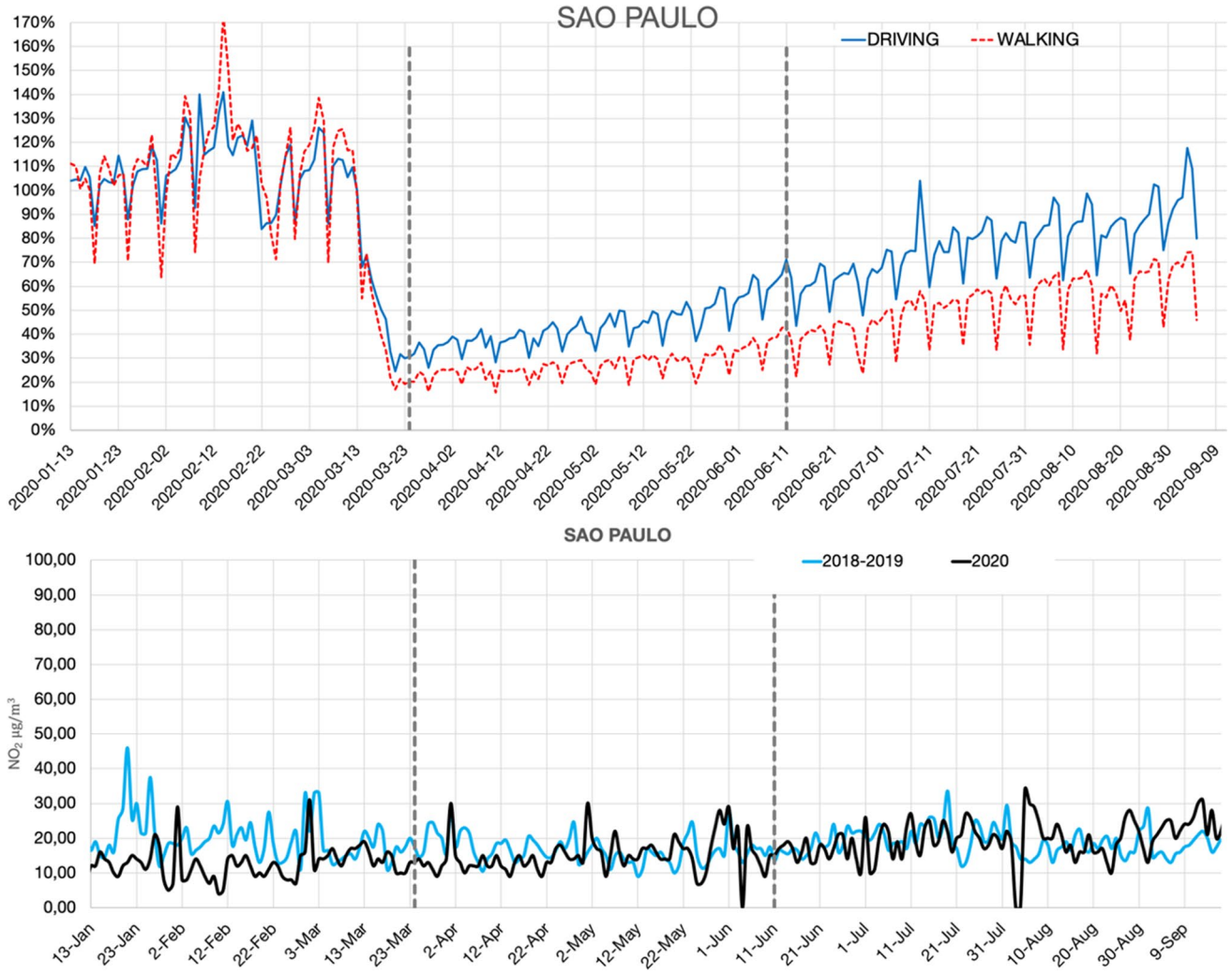

Fig. 4 Mobility evolution and NO_2 evolution in in the city of São Paulo in Brazil in different periods of time. Source: own elaboration with data from AQICN (Web 1, 2020) and Apple mobility trend (Web 2, 2020)

achieved in early March of 2020, when the infection started to break out; as consequence of this, state of alarm was declared with the mobility restriction measure being this the most important measure to avoid major infections. In India it can be seen the mobility activities started to drop down from values 140 to 15%, showing a clear decrease of 89.29%. The mobility activity in this city can be compared to the city of Los Angeles due to the same tendency of rapid re-increase in mobility trend of the city. This type of scenarios is characteristic of large cities where the economy is interconnected with the industrial activity; therefore, the traffic is an important part of the city and congestions are frequent on a daily basis, therefore increasing concentrations of air pollutants and mobility. In the case of Bangalore, it is worth mentioning the walking and driving tendency of citizens have a different pattern from other cities analyzed in this paper, which is the similar values for walking and driving; therefore, after the state of alarm, both the walking and driving tendency have been on the same levels; meanwhile, in other cities, there has been a difference between these two factors. However, during the lockdown, this same tendency was changed; thus, more users were registered in walking tendency than driving.

After a relatively short period of time, values started to increase but not reaching to the state before the emergence of COVID-19.

Regarding the air pollutants, it can be observed a barely regular oscillation in the average values from 2014 to 2019, which kept its trend during the first weeks of 2020, until the decree of the state of alarm on March 24, when the values of NO_2 decreased significantly, reaching levels below 5 µg/m^3. Having in account the average values during the previous months, which was around 20 µg/m^3, the instant decrease is highly noticeable. After the main stroke

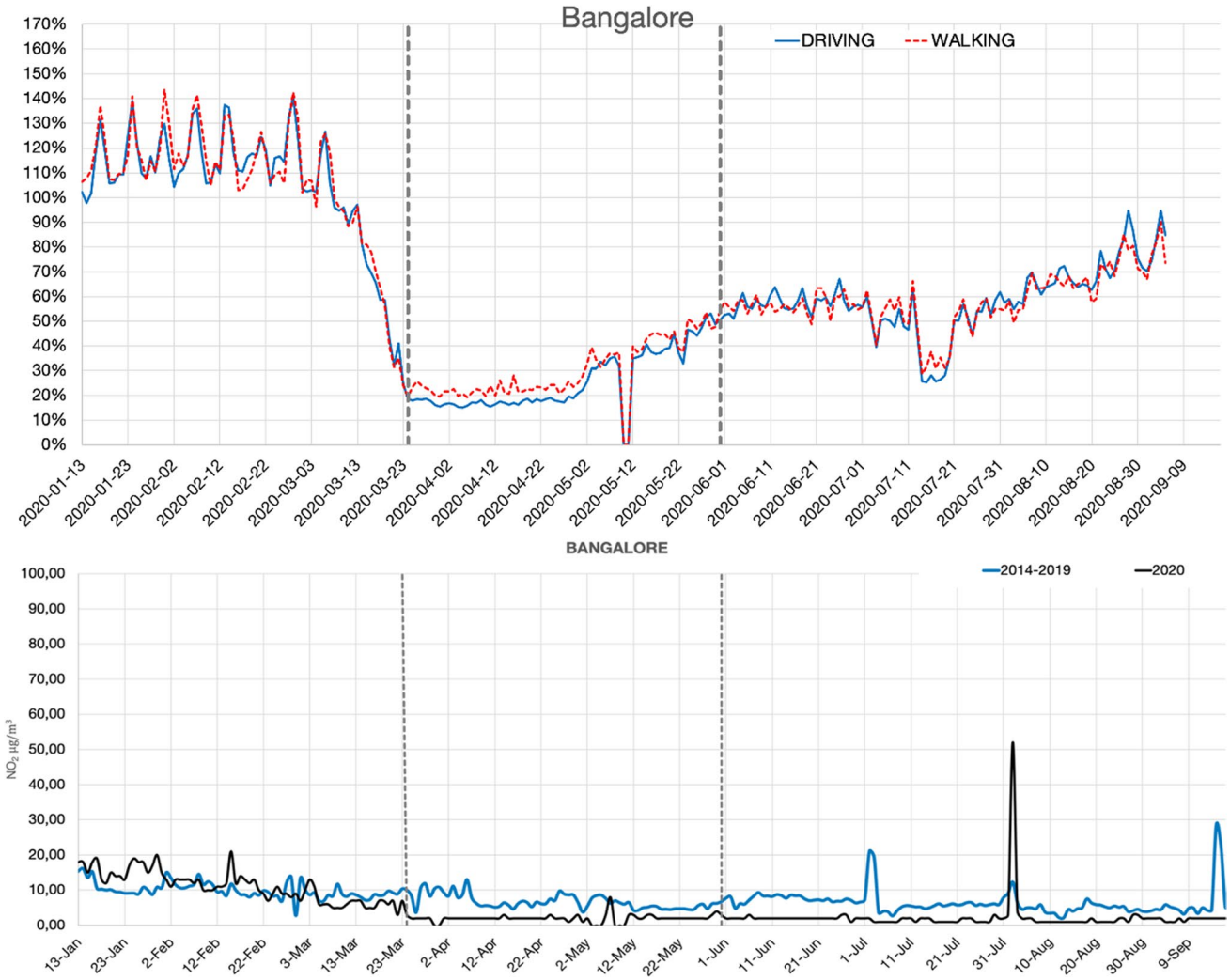

Fig. 5 Mobility evolution and NO_2 evolution in in Bangalore (India) in different periods of time. Source: own elaboration with data from AQICN (Web 1, 2020) and Apple mobility trend (Web 2, 2020)

during the month of march, the levels of NO_2 remained constant during the following weeks, oscillating around 5 µg/m^3, until late July, when the values seemed to start increasing again.

The major impact can be seen even 1 month after the state of alarm in Bangalore, where values are on lower points compared to the last year when the presence was about 15 µg/m^3 for NO_2, and in 2020, these values barely reached above 5 µg/m^3. This high difference in amount continuous until late July of 2020, where values of current year started to resemble concentrations from past year. It is mentionable the decrease of air pollutants in the past year in Bangalore is due to the reduction in coal usage and how this action can impact air quality. As consequence of reduction in coal dependency, an improved air quality was recorded in 2019.

Study of the impact of mobility on air quality in Johannesburg

Johannesburg experienced a big difference in mobility density due to the pandemic situation. This difference became evident right before the state of alarm, and then, as consequence of these measures, the air quality improved as there was a minimum emission from vehicles and industrial plants. This improvement can be found in Fig. 6.

In relation to mobility trend in this city and its impact on the environment, it can clearly be seen in Fig. 6. The values of mobility activities decreased drastically. As a result of strict measures, the transit reduced almost 93.33% on 26 March, as can be observed in Fig. 6. Worth mentioning is the tendency of walking related to driving, where the walking trend was lower than driving; meaning before the emergence

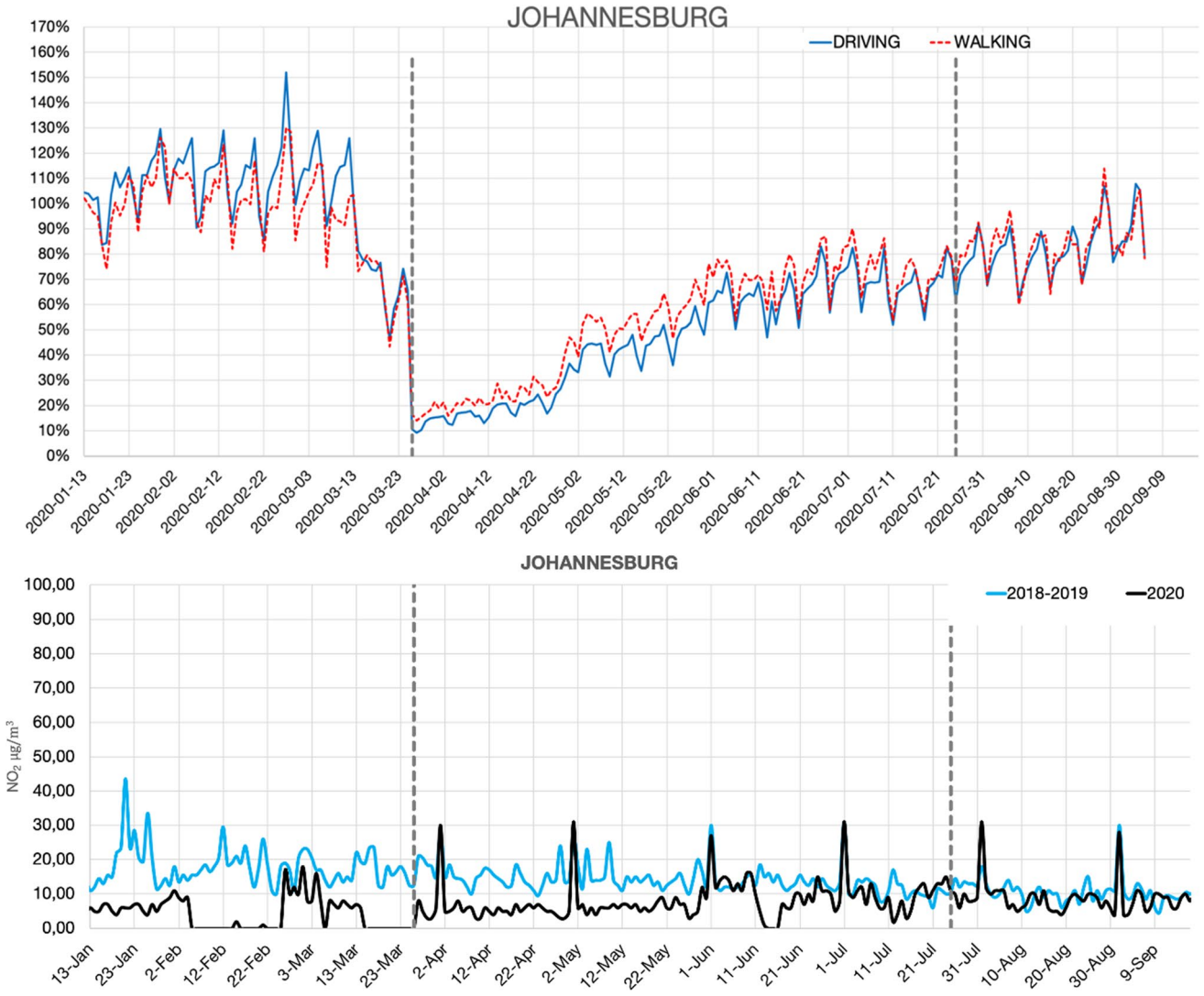

Fig. 6 Mobility evolution and NO_2 evolution in in the city of Johannesburg (South Africa) in different periods of time. Source: own elaboration with data from AQICN (Web 1, 2020) and Apple mobility trend (Web 2, 2020)

of COVID-19, the user has been travelling from one place to another through motorized vehicles; however, once the state of alarm started, the walking took one step ahead being on top of driving tendency, showing the decrease in the motorized vehicles during this period of time. Unfortunately this pattern took place only during the lockdown period (represented between dashed lines), as once these restrictions ended the driving was also preferable by the users.

In addition, it can be seen how, slowly, the mobility levels got to normal within the following 4 months. In driving, the mobility trend showed a decrease of 85% during the first half month of March, getting to levels of 15%. After that first period, when the values got to the lowest point, they started to increase gradually, getting levels which reached 100% in a short period of time. This behavior is very similar to other "fast cities" such as Bangalore, Los Angeles, or Sydney. In this case, the retention of low activity in traffic is due to the rapid recovery and control over the disease of COVID-19. The country took strict measures to reduce the numbers of deceased and infected citizens; this tendency can be seen in Fig. 6 period covered from late March until early April.

Regarding the air pollutants, as NO_2, the concentration of this hazardous particles has been seen during the study period. Even in the start of 2020, the values of this air pollutant were lower than the average values of the past years in this case from 2018 and 2019; however, the values of NO_2 increased rapidly in late February; this is due to the activity increase in this south African city. On the other hand, once the mobility restrictions started to show in this city, on the 26th of March result of the state of alarm, these values dropped down from 20 µg/m^3 to values almost below 2 µg/m^3. In the case of this city, the values of NO_2 have been

suffering increases and decreases, having therefore up and downs even in the lockdown period; this can be due to the modifications in the restrictions by the state authorities.

Once the state of alarm was being lifted, it can be seen a rise in the air pollutants; however, this increase remained lower than the average values from the past years, as can be seen in Fig. 6, indicating an impact of the health crisis over the environment.

Study of the impact of mobility on air quality in Sydney, Australia

In the case of Sydney, the stroke of the COVID-19 pandemic situation was not really hard, probably due to the isolated location of the island, and the extremely low density of population in the country. In any case, the disease affecting the island was unavoidable, and some measurements were imposed, affecting the mobility of Australian citizens, and thereby to pollutant particle concentrations, as can be seen in Fig. 7.

As can be seen in Fig. 7 despite having low impact on the mobility activities, it is still observable how this trend is directly linked to the air quality of this city. Values of mobility activity and air pollutants have been analyzed in different period of times. In the starting phase of 2020, it has been observed mobility values around 155% (normal values for these period); however, with the emergence of COVID-19, values decreased in a total of 80.65%. This meant that

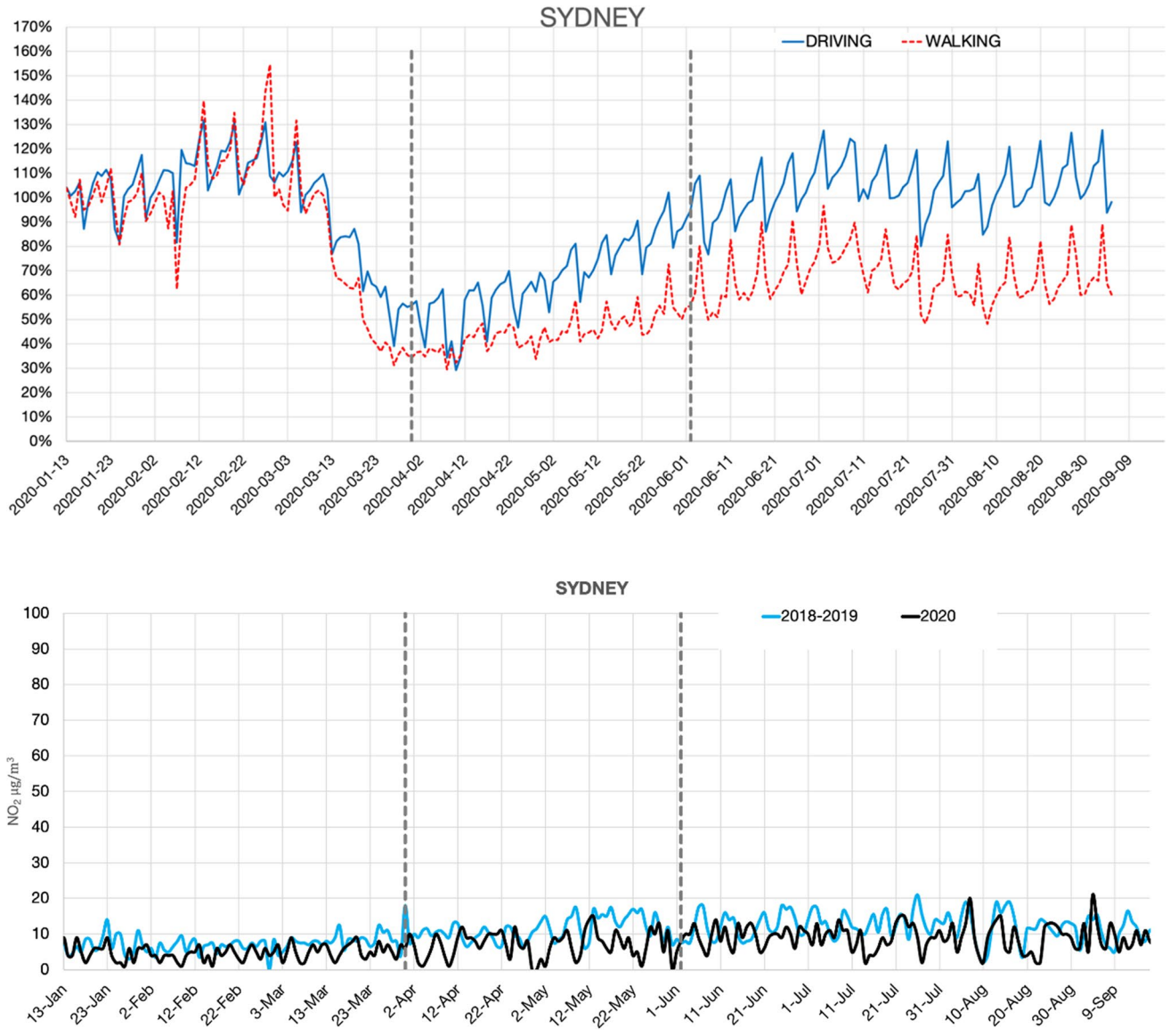

Fig. 7 Mobility evolution and NO_2 evolution in in Sydney (Australia) in different periods of time. Source: own elaboration with data from AQICN (Web 1, 2020) and Apple mobility trend (Web 2, 2020)

the number of movements decreased drastically during the month of April, as can be seen in Fig. 7.

Figure 7 shows, indeed, how both types of mobility values exposed a significant reduction, slightly more noticeable in walking, but still significant in driving transit (showing a reduction of 70%). Something interesting to be deduced the fact that even though driving values recovered completely after 4 months, walking values did not reach the same values as before the pandemic situation, so those values got stable at the 70% of the reference number of movements before the pandemic. It is also worth mentioning the opposite tendency of walking users than other cities, as in the city of Sydney the walking tendency has remained lower than the driving even in the lockdown period, indicating the using of motorized vehicles were more used by citizens than walking in this period of time.

On the one hand, NO_2 levels remain almost constant through time, regardless of the different events that occurred in the country, even during the state of alarm, when the values decreased from 7 to 3 μg/m^3. After that hit, the values started increasing again around the starting of July of 2020, reaching levels up to 20 μg/m^3 during summer. Through these values, it has been clear to see the impact of the mobility on the air pollutants of this city.

Conclusions

This paper highlights the negative effect of air pollution on human and our planet health. The current study reveals an overall reduction in pollutants worldwide during the lockdown and the immediate period after the lockdown. COVID-19 is one of the largest pandemics that has stopped human activity. A very similar scenario took place in the 2014 Nanjing Youth Olympic Games, where a mega-event caused a public awareness and enhanced the air quality as in this events it can be easier to promote eco-friendly activities and spreading it widely in order to create an awareness on more sustainable activities (Chen et al., 2021).

The lockdown measures established by the World Health Organization (WHO) and the government of each country have positive results regarding the transmission of the virus and the air quality. It is remarkable the harmful impact of pollution on human and planetary health. In the case of China, a study showing the decrese in carbon dioxide by using social interaction indicates a positive effect on the environment too (Ding et al., 2019). Therefore in the current paper it can be seen how with the state of alarm declared the pollution reduced significantly in large urban areas as mentioned in this paper. These actions show a clear need of long-term measures and modification of regulations and legislation regarding environmental laws.

With this study, it is clear how the correct measures can improve the atmosphere and protect the ecosystem. However, it is also remarkable the re-appearance of high pollution levels once the lockdown is completely lifted and the industrial and social activities are back to normal as it was before the pandemic occurred. This tendency can be seen in this paper in the "Results and discussion" section. The concern of these pollutants is due to their harmful effects on human health, without forgetting the planetary health. It is well known the negative effect that the chemicals that are emitted from different air pollutants. One of the most harmful is the sulfur dioxide or the smoke in general, which if exposed for long time can result in death as has occurred in many parts of the world (Kassomenos et al., 2012).

In conclusion, sustainable and long-term solutions can be provided with the help of new technologies in order to reduce the usage of fossil fuels for both transport systems and energy; as it has shown, the reduction of this usage can be an improvement in air quality around large urban areas where congestion is frequently occurring. With strict and adequate measures, the sustainable impact is possible; therefore, it can lead to better conditions both for human and planetary health along with our ecosystem.

Air pollution and the presence of air pollutants around the cities are still an ongoing concern which need a deep study in order to understand their effect on the human and planetary health and how to improve this issue. It is also known the increasing problems derived from poor air quality which will continue to grow if not taken under control and also comprehending the CO_2 emissions can be enhanced through endogenous green innovation (Luo et al., 2020). The improvement in these cases could be by evaluating new solution such as remote working which increased since the emergence of COVID-19 and the reduction in activities with hazardous pollution concentration into the environment damaging both the human and planetary health.

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Author contribution In this investigation, Javier-Cárcel Carrasco and Carolina Aparicio conceived and designed the experiments; Javier-Cárcel Carrasco and Aurora Martínez Corral performed the experiments; Javier-Cárcel Carrasco and Aurora Martínez Corral analyzed the data and contributed materials/analysis tools; Jangveer Kaur, Javier Cárcel, and Carolina Aparicio wrote the paper.

Data availability All data analyzed in this paper is included in the corresponding section.

Declarations

Ethics approval and consent to participate All authors confirm that the manuscript is original and has not been submitted for publication

in full or in part or is being considered for publication elsewhere. All authors have read and agreed to publish this version of the manuscript through their consent to publish and participate.

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Conflict of interest The authors declare no competing interests.

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