

SPECIAL SECTION

Nitrogen oxides and ozone in urban air: A review of 50 plus years of progress

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Abstract

Nitrogen oxides and ozone impact air quality in many parts of the United States, Europe, China, and many other countries. The greatest air quality challenge in Los Angeles, some other areas of California, and some parts of China is to reduce ozone levels to meet regulations. Background ozone is a major factor which makes it more difficult to reduce urban concentrations in Los Angeles and some other locations. Air pollution from China affects the background ozone entering California. More than 50 years of history are reviewed with an emphasis on reducing concentrations of nitrogen oxides and ozone. During this time period, there has been significant progress in reducing levels of these pollutants in urban air in the United States and Europe; however, ozone concentrations in China have increased since 2013. Cost and benefit analysis has shown that benefits associated with the Clean Air Act of 1970 have greatly exceeded costs to improve air quality in the U.S. over the past 50 years. Further actions to consider to improve air quality include reducing combustion of coal and petroleum products and transitioning to renewable energy. Public education is recommended to inform citizens that the benefits of reducing emissions far exceed costs.

KEYWORDS

air quality, emissions, health, regulations, volatile organic compounds

1 | INTRODUCTION

Air quality is an important global concern with annual costs of more than \$4 trillion per year due to health costs and millions of people dying early because of illnesses associated with poor air quality.^{1–63} While particulate matter smaller than 2.5 μm in equivalent aerodynamic diameter, PM_{2.5}, is the greatest health problem, nitrogen oxides, including nitric oxide (NO), nitrogen dioxide (NO₂), and mixtures of NO and NO₂ (NO_x) are very important as well because they impact health and contribute to ozone (O₃) formation. Air quality issues related to nitrogen oxides and ozone are of significant concern in the United States, Europe, China, and many other locations.^{7–17,55,56} Globally, the impact of poor air quality

reduces life expectancy by 20 months on average, and total air pollution (ambient and indoor) is the fifth greatest cause of death in the world.¹⁷

Nitrogen dioxide is a highly reactive gas that can irritate the human respiratory system. People with asthma have significant risks because of NO₂ in ambient air, and there are more visits to hospitals and emergency rooms when NO₂ concentrations are higher. The effects on respiratory health have been reviewed and the air quality regulations are based on human health impacts of NO₂ in ambient air.^{10,13} Nitrogen oxides in air are important with respect to ozone formation and the formation of small particulates that also contain nitrogen.

Ozone is produced when nitrogen oxides, volatile organic compounds (VOCs), and solar radiation are present in polluted air.^{8,24,38}

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Photochemical oxidation of VOCs produces ozone and other compounds present in smog when the sun shines on warm days. Ozone is a strong oxidant that is responsible for more than 400,000 premature deaths and more than 8 million emergency room visits each year globally.^{14,17} Ozone affects respiratory health and has effects on cardiovascular health as well.¹⁰ Many of the deaths are due to respiratory mortality for those with asthma and chronic obstructive pulmonary disease (COPD). Ozone impacts vegetation and reduces the productivity of ecosystems.³⁸

One of the reasons for this review is to identify cost-effective ways to reduce ozone pollution which is one of the greatest global challenges in 2020.^{1,3,8,14,24,25,38,52} The Clean Air Act of 1970 is now 50 years old and great progress has been made in addressing air quality issues in the United States. However, ozone pollution is still above regulatory standards in Los Angeles and many other locations in the United States, in China, and in many other locations.^{3,7,8,14,38,52} This review covers over 50 years of progress to improve air quality.

In 1991, the National Research Council published a National Ambient Air Quality Standards (NAAQS) comprehensive report on ozone because of the failure to meet the NAAQS for ozone in 60 locations in the United States in 1987.⁴⁶ The report identifies ozone pollution as a "pervasive and stubborn environmental problem".⁴⁶ The study was requested by the U.S. Congress. The report recommends efforts to find better regulations and verification methods to reduce emissions of VOCs and additional research.⁴⁶ The Clean Air Act Amendments of 1990 established new regulations to address ozone attainment; however progress to reduce ozone concentrations has been poor and measured values of ozone continue to exceed the NAAQS in many locations.^{3,7,14} Significant efforts have been made to reduce emissions of methane and other VOCs; however, emissions continue to be greater than reported values.²⁶

There are ways to reduce ozone concentrations, and this review will include information on positive actions that can be implemented. Those who live in urban communities should understand that there are cost effective ways to improve air quality.

Since 1970, air pollution has become more important in industry. Many chemical engineers have contributed to the progress that has been made toward better air quality. Professionals in industry have been very involved in developing new products that have resulted in significant improvements in air quality.^{1,16,22,24,46}

2 | REGULATORY STANDARDS AND HEALTH GUIDELINES

In the United States, the U.S. Environmental Protection Agency (EPA) has set the following values for NO₂. The average value for 1 hr is 100 ppb where this is the 98th percentile of 1 hr daily maximum concentrations averaged over 3 years. The annual mean value should be less than or equal to 53 ppb.¹⁵

For ozone, the EPA regulatory value is 0.070 ppm = 70 ppb where this value is the annual fourth highest daily maximum 8-hr concentration averaged over 3 years (4MDA8).¹⁵ The average values are

recorded for each 8 hr period of the day, and the highest of these is identified and recorded for each day of the year. The fourth highest of these ozone values is recorded for each year. The average over three consecutive years should be less than 70 ppb.

In Europe, for NO₂, the 1 hr limit value is 200 µg/m³ which is equal to 106 ppb at 25°C and 1 atm pressure, and is not to be exceeded more than 18 hr/year. The annual average value is 40 µg/m³ or 21.3 ppb. For ozone, the maximum daily 8 hr mean value is 120 µg/m³, which is equal to 60 ppb, and is not to be exceeded on more than 25 days/year, averaged over 3 years.¹⁰

In China, the regulatory standards for NO₂ in micrograms per cubic meter are 200 for 1 hr and 40 for the annual average value. For ozone, the 1 hr standard is 200 and the 8 hr average value is 160 µg/m³.⁴⁵

The World Health Organization (WHO) has air quality guidelines, which are 200 µg/m³ for NO₂ for 1 hr, which is equivalent to 106 ppb. For NO₂ the annual average value is 40 µg/m³ or 21.3 ppb. The WHO value for ozone is 100 µg/m³ or 50 ppb.¹⁰

There are many countries with other air quality standards³⁸ (see Tables 1 and 2). In Table 1, the annual average value of the nitrogen dioxide standard is largest for the United States. China has the largest regulatory values for ozone (see Table 2).

In the United States and globally, there are many locations where ozone standards and guidelines are exceeded. In the United States, 41.9% of the people live in areas with unhealthy levels of ozone pollution where the regulatory standards are exceeded at least once annually.⁷ In these communities, there are frequently more than 3 days each year where the maximum 8 hr average ozone concentration for the day exceeds 70 ppb. In recent years, approximately 90% of the time that ambient air quality standards are exceeded in the United States, it is due to ozone.^{7,11} Figure 1 provides information on the air quality index for ozone.^{7,62} This guide is used in the United States to provide guidance on ambient air quality of ozone.

In Europe, 14 member states reported exceeding the regulatory value for ozone more than 25 times per year.¹⁰ In Europe, there are more than 50,000 deaths per year from ozone pollution, with Italy, Germany, France and Spain being between 5,000 and 10,000 per year.¹⁸ In 2010 the annual health costs of air pollution in Europe were estimated to be \$1.575 trillion.²⁷

The annual limit value for NO₂ is widely exceeded in Europe,^{10,16} and progress in reducing ozone pollution has been poor in Europe and in many other locations in the world.^{7,8,16,17} In many parts of the world, the most frequently exceeded air quality guidelines and regulations are those for ozone.^{7,8,11,14} Ozone concentrations in China have

TABLE 1 Comparison of regulatory values for nitrogen dioxide in parts per billion (ppb)

Time period	USA	Europe	China	WHO
One hour	100	106	106	106
Annual average	53	21.3	21.3	21.3

Note: WHO values are guidelines.

increased from 2013 to 2017, and the number of premature deaths per year due to ozone has increased from 49,120 to 56,800 during this time period.^{19,20} There is a need to reduce emissions of both VOCs and nitrogen oxides in order to reduce ozone concentrations in the air.^{19,20,21}

Epidemiology research has been used to determine health effects associated with air pollution. For ozone, there are both short term impacts and long term effects. Examples of investigations of each are available in the technical literature.^{55,56} Data was collected from 406 locations in 20 countries for the short term study.⁵⁵ The American Lung Association has a good summary of health studies related to ozone.⁷ The U.S. EPA study to determine the ozone regulatory standard includes an analysis of the results of many studies on the health impacts of ozone.¹¹

There has been a global effort to assess ozone concentrations and develop a comprehensive database with data from 9,600 sites.^{32,33} A comprehensive Tropospheric Ozone Assessment Report is available with information on the different metrics that have been used and the trends over time in different locations.^{32,33} Over the last 30 years the United States and Europe have made some progress in reducing ozone concentrations, while the ozone concentrations have increased in China and some other parts of Asia.^{3,32,33} There are locations in Africa and South America where additional data is needed. There are several different metrics that have been used to describe

TABLE 2 Comparison of regulatory values for ozone in parts per billion (ppb)

Country or region	Ozone level	Averaging time
WHO	50	8 hr mean
EU	60	8 hr mean
USA	70	8 hr mean
UK	50	8 hr mean
Canada	62	8 hr mean
China	100	1 hr mean
	80	8 hr mean
India	90	1 hr mean
	50	8 hr mean

Source: References [10, 15, 38]. Some values are guidelines, objectives, or target values.

FIGURE 1 Air quality index for ozone based on the daily maximum 8-hr average ozone concentration. Source: From State of the Air 2020⁷ and U.S. EPA air quality guide for ozone⁶²

Eight-hour average ozone concentration, ppb	Air quality index level
0 – 54	Good (green), 0-50
55 – 70	Moderate (yellow), 51-100
71 – 85	Unhealthy for sensitive groups (orange), 101-150
86 – 105	Unhealthy (red), 151-200
106 – 200	Very unhealthy (purple), 201-300
Greater than 200	Hazardous (maroon), 301-500

ozone values in air in different parts of the world.³³ Results for ozone at many different locations in the world have been presented with their impacts on health included.³

The high concentrations of nitrogen oxides and ozone occur during the day time. With morning traffic, nitrogen oxide emissions cause ambient concentrations to increase to values that are much larger than late night values. The radiant energy from the sun and the nitrogen oxides cause ozone formation in polluted air where VOCs are present. In the daily cycle nitrogen dioxide concentration often has its peak value before noon while ozone concentration exhibits its peak in the afternoon.^{22,28,29} There may be a second nitrogen dioxide peak associated with early evening traffic when many people are going home from work and other activities.²⁹

Figure 2 shows hourly average values for nitrogen dioxide and ozone for Little Village in Chicago.²² The nitrogen dioxide is directly associated with vehicle emissions and the peak concentration occurs early in the day. The peak in ozone concentration occurs later in the day when the temperature is higher.²²

3 | FIFTY YEARS OF HISTORY

The Clean Air Act of 1970 and the amendments to it have had a great impact on air quality in the United States.^{1,23} In 1943, smog was observed in Los Angeles, and efforts to address air quality issues increased in California and in the Los Angeles area with the formal establishment of the California Air Resources Board (CARB) in 1967.²⁴ The concentrations of particulate matter, nitrogen oxides, VOCs, and ozone impacted health and quality of life significantly in this part of southern California in the period from 1950 to 1980. The health and quality of life concerns resulted in the establishment of the South Coast Air Quality Management District (SCAQMD) in 1976.²⁴ Before 1970, ozone concentrations were above 600 ppb and smog was very visible when the weather was right for ozone and smog formation. California had many excellent highways with many cars at rush hour in 1970, which created air pollution problems that remain important today. The efforts to improve air quality have included restrictions on burning trash, catalytic converters on vehicles, fuel improvements, cleaner systems to generate electricity, and more recently electric vehicles and electric lawn mowers. Since VOCs contribute to ozone formation, restrictions on volatile emissions have

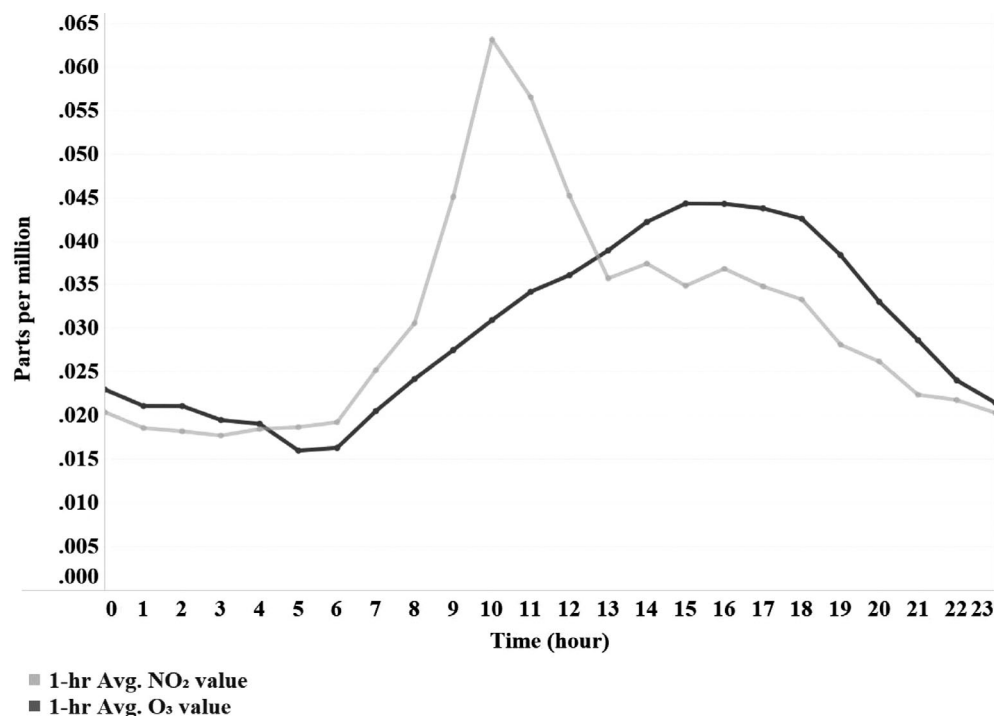


FIGURE 2 Example data showing nitrogen dioxide and ozone concentrations in ppm. Data is from June 2017 in Little Village in Chicago. Source: From M.S. Thesis of Wang²²

been included. California has been a leader during this 50-year period in efforts to improve air quality; however, because of all of the vehicle emissions, industrial contributions, and the geographical features of this part of southern California, improving air quality has been very challenging.^{24,25}

In the last 75 years, there has been great progress in understanding air quality and the chemistry of nitrogen oxides and ozone.^{11,13,38} The formation of ozone in air has a well-developed chemistry which is described in many sources; see Ref. 38 and the references therein. Ozone formation depends on solar radiation, nitrogen oxides, and VOCs; temperature is important because reaction rates are faster at higher temperatures.

One of the major reasons that ozone values do not meet NAAQS in Los Angeles and some other parts of southern California is because of background ozone values.^{25,34,38} The prevailing winds in southern California are from the west, and the ozone concentrations in the air are often above 30 ppb because of natural processes and international anthropogenic air pollution. Ozone is formed when there is sunshine, nitrogen oxides, and VOCs. Thus, ozone, nitrogen oxides, and VOCs from other countries and from the emissions of ships have the potential to increase the amount of ozone in the air that enters California after passing over the Pacific ocean.^{38,47,48} The concentrations of ozone in the air that enters California are greater at higher elevations.²⁵ The background concentrations of ozone have been increasing in many locations because of emissions of ozone precursors.³⁸ The precursors and ozone may travel together from where the precursors are generated to locations where the ozone contributes to the background ozone.³⁸

Sometimes the tropospheric ozone concentration increases because of stratospheric ozone that comes down and gets mixed into

the air near ground level.^{25,34} Another source of ozone is that produced because of wildfires.³⁴ Nitrogen oxides and VOCs from wildfires contribute to ozone formation. Exceptional events such as wildfires may cause communities to experience ozone pollution that impacts health and regulatory compliance.

As of 2019, ozone concentrations still exceed the NAAQS and air pollution is a continuing concern in Los Angeles and other parts of California.⁷ Nitrogen dioxide concentrations have been reduced such that they are in compliance with the NAAQS to a much greater extent than ozone.²⁴ Given the size, population, and vehicle miles traveled, the quality of the air in the Los Angeles metropolitan area is much better than many other large cities with similar populations.^{24,57} The quality of life has been improved greatly with significant benefits to health. Ozone pollution is a major issue in large cities in Europe, India, Japan, China, and South Korea.³ In 2015, about 89% of deaths because of ambient air pollution were in countries with middle level incomes and lower.³⁵

In the United States, more than one third of the people live in counties where the NAAQS for ozone have been exceeded in recent years.⁷ Some major U.S. cities where ozone is a health problem are listed in Table 3. Many of these cities are listed among the 25 most ozone-polluted cities in the United States.⁷ These cities have all had days when the ambient air was unhealthy because the ozone exceeded 70 ppb and the NAAQS. California has the most cities in the top 25 most ozone-polluted cities.⁷ Los Angeles has been the most ozone-polluted city in the United States in most of the last 20 years.⁷

Ozone scores are shown in Table 3 for a number of large cities in the United States that are not meeting the NAAQS for ozone. The values of the ozone scores are reported by the American Lung

TABLE 3 High ozone scores in major cities of the United States during 2014–2016 and 2016–2018

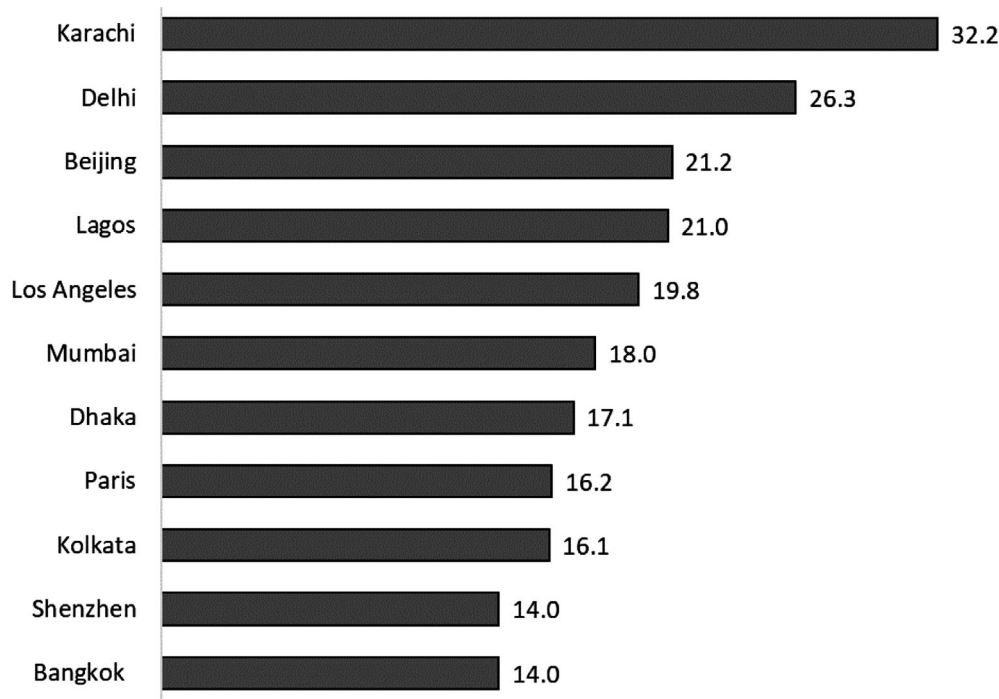
City	Ozone score		County
	2014–2016	2016–2018	
Los Angeles	111.2	111.0	Same
Fresno	92.7	85.8	Same
San Diego	36.8	43.3	Same
Phoenix	31.2	39.8	Maricopa
Las Vegas	20.3	30.2	Clark
Denver	18.5	29.2	Jefferson
Salt Lake City	13.3	25.7	Salt Lake
Houston	22.5	22.3	Harris
New York City	24.2	23.0	Fairfield, CT
	4.0	6.8	Queens
Baltimore	13.7	14.2	Same
Chicago	9.8	19.2	Cook
Philadelphia	9.8	10.8	Same
Atlanta	10.2	7.5	Fulton
Detroit	5.0	7.3	Wayne
Cleveland	4.3	6.7	Cuyahoga
Washington, DC	4.7	5.2	District of Columbia
Saint Louis	4.7	4.7	Same

Note: Ozone score values are annual averages for 2014–2016 and 2016–2018 with air quality index scores as follows: unhealthy for sensitive groups (orange)—1; unhealthy (red)—1.5; very unhealthy (purple)—2; hazardous (maroon)—2.5. Values are from the State of the Air 2018 and 2020.^{7,14}

Association⁷ using the following tabulation process. Each day the maximum 8-hr average ozone concentration is determined and compared with the values in the air quality index for ozone shown in Figure 1. One point is added to the ozone score for each day the value is in the orange range from 71 to 85 ppb; the value added is 1.5 for red, 2.0 for purple, and 2.5 for maroon. The daily value is zero for all values below 70 ppb. The daily ozone scores for the 3-year period are added together and divided by 3 to obtain an annual average score. If all ozone values above 70 ppb are in the orange range, the ozone score is the number of days per year that the maximum daily 8-hr average ozone concentration was above 70 ppb. The county where the values are measured in each metropolitan area is listed in the table. For New York City, Fairfield county in Connecticut is listed to show that there are large values in the New York City metropolitan area. Ozone concentrations are often larger in an area downwind from where emissions are greatest.

The results in Table 3 show that 12 of the ozone scores increased with time. One concern is that the increased temperatures associated with climate change are making it harder for communities to meet NAAQS for ozone.

In Europe, there has been progress in reducing nitrogen dioxide concentrations in the last 10 years; however, about 12% of reporting sites measured values above the annual standard.¹⁰ In 2016, most (88%) of these locations where values exceeded regulatory standards were at sites where traffic emissions were important. For ozone, there were 17% of locations where measured values exceeded the standards; this impacted about 12% of the urban population.¹⁰ The highest values of ozone concentration are in southern Europe.¹⁰ The economic analysis shows that costs of air pollution are about 1% of gross domestic product and that improving air quality would be beneficial.²⁷

FIGURE 3 Ozone air pollution in the major cities of the world. Values are percent of observations above a concentration of 70 ppb. Values are from a tropospheric emission spectrometer aboard NASA's Aura satellite which passes over these cities every 16 days^{57,58}

In Israel, nitrogen oxides in air have been a pollution problem for more than 20 years.^{43,44} Tel Aviv, the largest metropolitan area often has concentrations that exceed target values.^{43,44} Emissions from buses are one of the significant sources.

Figure 3 shows the percentage of days that the ozone concentration is above 70 ppb for each city.^{57,58} The NASA Aura satellite measures the ozone concentration as it passes over each city every 16 days at about the same time of day each time.^{57,58} Since temperature and time of day are important in ozone formation, these results show that ozone pollution is a significant issue in these cities.

The analysis of costs and benefits associated with the U.S. Clean Air Act has shown that the benefit/cost ratio exceeds 40/1.²⁴ The total expenditures associated with efforts to improve air quality in the United States over the past 50 years are of the order of \$1 trillion. Expenditures to replace coal burning power plants with renewable energy installations that reduce greenhouse gas emissions have global climate change benefits as well. In the last 50 years, there have been significant expenditures on subway systems to improve transportation in several large cities also. A good electric train metro system improves air quality and reduces greenhouse gas emissions compared with diesel buses and personal cars.

4 | AIR QUALITY IN CHINA

Air quality is a major environmental concern in China with the first air quality regulations issued in 1982 and then amended in 1996, 2000, and 2012.⁴⁵ Ozone values are often above the Chinese regulatory value of 80 ppb for MDA8, the maximum 8 hr daily ozone concentration.^{20,36,38} There have been recent efforts to reduce air pollution in China, and there has been greater progress in reducing the concentrations of particulates and nitrogen oxides compared with ozone. During the period from 2013 to 2017, there was significant progress in Beijing in reducing nitrogen oxide emissions and the concentration of nitrogen dioxide in the air.⁵²

Efforts to improve air quality in Guangdong Province and the Pearl River delta have been reviewed for the time period from 2006 to 2015. During this period, there was a great increase in cars in China as well as a major effort to improve air quality.²⁰ Emissions of nitrogen oxides decreased 0.5% while VOC emissions increased by 33%. The 90th percentile daily maximum 8 hr average ozone value increased from 73 ppb in 2007 to 82 ppb in 2017.⁴⁹ In Beijing, this measure of ozone has been larger with values just below 100 ppb in recent years.⁵² The United Nations report on air pollution in Beijing states "Ozone pollution has not been effectively controlled in recent years".⁵²

Reducing ozone pollution in China has been a major challenge, and concentrations of ozone in ambient air in China are among the largest in the world.^{8,52,54} Values of ozone concentrations above 120 ppb occur often in the summer in large Chinese cities. Ozone is a much greater mitigation challenge than PM_{2.5}. Ozone concentrations have been increasing from 2001 to 2015 in China in spite of progress to reduce PM_{2.5} and nitrogen oxide concentrations. There are major

respiratory health problems in China because of ozone pollution.^{8,36,37} The increase in temperatures because of climate change is expected to make ozone pollution even worse.¹⁴

In 2008, when Beijing hosted the Olympic Games, significant efforts were made to reduce air pollution by reducing the volume of traffic and reducing industrial operations. As a result, ozone values in August 2008 were about 15 ppb lower at Miyun, which is downwind from Beijing.^{22,50} Health benefits associated with the better air quality were reported.⁵¹ This historical result shows that air quality can be improved by reducing emissions.

5 | IMPACT OF COVID-19 ON AIR QUALITY

Nitrogen dioxide concentrations in ambient air increase with emissions from motor vehicles. A daily cycle is shown in Figure 2. In 2020 there was a significant decrease in travel because of the COVID-19 pandemic.^{59,60} In California, nitrogen dioxide concentrations decreased by 34% during the period from March 20 to April 9 compared with 2017–2019 average.⁵⁹ Ozone concentrations were 5% lower; these are average values for California.⁵⁹

In Wuhan, China, average nitrogen dioxide values decreased by 57% because of the COVID-19 lockdown compared with the average values for the same period in 2017–2019.⁶⁰ However, average ozone concentrations increased by 36% because of lower NO concentrations.⁶⁰ This is because NO reacts with ozone to remove it from air.^{22,61}

In the European cities of Nice, Turin, and Valencia, average nitrogen dioxide concentrations decreased by 30–60% during the COVID-19 lockdown compared with the same time period in 2017–2019; however, average ozone concentrations increased by 2.4–27%.⁶⁰

6 | IMPROVING AIR QUALITY

There are many places in the world where there is a great need to improve air quality. In the most impacted countries, about 25% of deaths are due to pollution.³⁵ One of the most significant challenges is to reduce ozone concentrations. This is an issue in most metropolitan areas of 10 million people and larger where there is significant sunshine.⁵⁷ Since ozone is formed when nitrogen oxides and VOCs are present, actions to reduce concentrations of these compounds can be beneficial.

Table 4 provides a list of actions to take to reduce ozone concentrations in ambient air. While ozone concentrations have local health impacts, some actions to reduce ozone concentrations will be beneficial globally as well as in the country where action is taken.

Nitrogen oxides are formed during burning of fuels, so transitioning away from combustion processes will reduce nitrogen oxides in air. There are many sources of VOCs, including industrial emissions, solvents, cleaning supplies, alcoholic beverages, and emissions from baking bread.

TABLE 4 Proposed actions to reduce ozone concentrations in ambient air

Reduce emissions of nitrogen oxides
Reduce methane emissions
Reduce emissions of VOCs
Reduce vehicle emissions
Reduce emissions from coal
Reduce greenhouse gas emissions
Reduce combustion processes
Reduce amount of travel
Increase electrification of transportation
Increase use of renewable energy
Increase popularity of public transportation
Increase the social value tax on carbon dioxide emissions
Increase research to reduce ozone in ambient air
Improve energy efficiency
Improve land use efficiency
Improve quality and safety of sidewalks and bike paths
Improve building codes and insulation
Improve enforcement of air quality regulations
Monitor methane and VOC concentrations
Establish a social value tax on methane emissions
Expand public education related to air quality and ozone

Because vehicle emissions are important sources of nitrogen oxides and VOCs, actions to reduce these emissions are very important.²⁴ This can be done through emission control technologies that reduce the amount of nitrogen oxides in diesel exhaust.^{22,39,40} There has been significant progress with three technologies: exhaust gas recirculation (EGR), lean NO_x trap (LNT), and selective catalytic reduction (SCR) using ammonia.^{22,39,40} These technologies have been implemented in Europe and there has been progress in reducing NO_x emissions.^{22,39,40}

The electrification of public transportation with electric trains and buses that reduce emissions compared with diesel buses is receiving attention because when health and climate change costs are included, electric buses are very cost effective.^{1,53} In China, there is a major effort to replace diesel buses with electric buses because of the economic benefits.⁵³ In 2018, more than 90% of the electric buses were in China, but there is progress in adding electric buses in cities in the United States and Europe also.¹ Electric bikes are an inexpensive way to reduce emissions; they have been used in China successfully.¹ In an effort to reduce nitrogen oxide concentrations, there is a transition to electric buses and electric taxicabs that is in progress in London.¹

All air pollution sources should be considered in efforts to reduce ozone concentrations.²⁴ This should include efforts to reduce methane emissions associated with oil and gas operations^{26,38} and sources of VOCs. VOCs in ambient air may need to be regulated more comprehensively in order to meet the standards for ozone. Regulations that reduce methane emissions are beneficial for reducing ozone concentrations in two ways. Methane is a precursor for ozone formation,

and methane is a greenhouse gas; increases in temperature because of climate change contribute to greater amounts of ozone formation.⁶¹ One way to reduce methane emissions is to establish a social value of methane tax to encourage reductions in methane emissions. The social value of a tax on methane emissions that includes impacts on ozone concentrations and climate change has been estimated to be more than \$700 per ton of methane.⁶³

China is moving forward with new regulations designed to reduce VOC emissions.^{20,49} Recent research shows that ozone generation in Nanjing can be reduced by controlling VOC emissions.⁴⁹ A study of sources of VOC emissions shows that many of the emissions are associated with transportation.⁴⁹ Monitoring of VOC concentrations is recommended.

Air pollution from home heating, electricity generation, industrial and other sources of VOC emissions, wood burning stoves and fire places, and all other sources of combustion emissions should be addressed. Reducing the use of coal for power generation and industrial processes is a very significant aspect of efforts to reduce nitrogen oxides and ozone in ambient air. Programs to improve insulation and energy efficiency in buildings through codes and public education are recommended. Increasing the tax on carbon dioxide emissions up to the estimated social cost of these emissions when both climate change and air quality impacts on health are included in the analysis is recommended.¹

Public education and citizen participation are important in efforts to increase community will to improve air quality.³⁵ The regulations on emissions need to be for the entire geographical area of the air shed, and they need to be enforced effectively on a continuing basis with updates to address emissions that should be added.²⁴

There are many actions that can be taken that will be beneficial to both air quality and reducing greenhouse gas emissions.¹ If the benefits to air quality and climate change are both considered, many actions to improve ozone air quality will have positive values for society and the community. Actions that reduce ozone pollution and greenhouse gas emissions include a transition to the generation of electricity without burning fossil fuels. Wind and solar energy are now competitive for the generation of electricity especially when air quality and climate change benefits are included. A transition to electric vehicles has the potential to improve air quality, and there is recent data to show that the electrification of transportation is beneficial economically.¹

One important issue is to increase global understanding of ozone air pollution and the need to take action to reduce ozone concentrations.³⁵ In many countries, greater resources are needed to improve air quality, and education is needed to help citizens and leaders understand that there are great benefits associated with pollution control. Many of these actions have benefits for several of the United Nations Sustainable Development Goals and meeting the goals of the Paris agreement on climate change.^{1,42} In low and middle income countries, greater expenditures are needed to develop and enforce pollution control regulations.³⁵ Cooperative efforts among community leaders and elected officials are needed.

7 | CONCLUSIONS

When the benefits to air quality, health, and climate change are all included, there can be progress on reducing nitrogen oxide and ozone concentrations by transitioning from coal burning power plants to renewable electricity from wind and solar energy and from diesel to electric buses in many parts of the world. Air quality benefits associated with actions to reduce concentrations of ozone precursors are local, regional, and global.

The precursors for ozone formation should be reduced locally, regionally, and globally. This should include concentrations of VOCs and methane. Emissions associated with transportation can be reduced by encouraging the transition to electric vehicles.

The global effort to reduce greenhouse gas emissions to meet the goals of the Paris agreement on climate change has the potential to help reduce ozone concentrations. Greater efforts should be made to reduce methane emissions. The transition to electric vehicles can be enhanced by regulations that limit emissions within major cities.¹ Taxes on emissions of carbon dioxide, methane, and VOCs equal to the social cost of the emissions could be assessed with the income used to support the transition to renewable energy, and to provide public education on why reducing ozone pollution is important.

Greater understanding of the importance and value of improving air quality is needed. There are many actions that can be taken to reduce air pollution where the benefits are much greater than the costs. Public education on the social, environmental, and economic benefits of reducing methane emissions, and transitioning to renewable energy, better public transportation, and electric vehicles should be provided.

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