Air Quality and Public Health in Megacities: Has Air Quality Improved Due to Driving Restrictions in Mexico City?

Mexico City, one of the largest urban centers in the world with 22 million inhabitants, is situated over a mile high in the once beautiful Valley of Mexico, surrounded by mountains rising twice as high. When a high pressure system settles over the Valley, with weak airflows, clear skies and high solar radiation, those mountains—while dramatic—can trap air pollution, pushing concentrations of pollutants to dangerously high levels. In fact, in 1992 the World Health Organization named the Mexico City Metropolitan Area (MCMA) “the most polluted in the world” and by 1998 “the most dangerous for children’s health.” Back in those days, watching dead birds drop from the sky was a common scene on the city streets [1].

Over the decades, the city and federal governments have made great strides in monitoring and controlling air pollution using a number of approaches. One of the most controversial of these occurred in June 2014, when Tanya Müller Garcia, Secretary of Environment (SEDEMA) of the government of Mexico City announced a tightening of the Hoy No Circula Program (HNC), or “Today [your car] does not circulate,” also known as No-drive days. The goal of the program, first implemented in 1989, was to improve air quality by taking almost half a million vehicles a day out of circulation in the metropolitan area. As originally implemented, Hoy No Circula banned 20% of private vehicles from the Mexico City roads each weekday based on the last digit of the license plate.

The HNC program had undergone many modifications since it was first implemented; the June 2014 program modifications introduced additional restrictions, banning the use of cars 15 years and older within the MCMA on Saturdays and restricting the use of cars between 9 to 15 years old to two Saturdays per month. The response of certain stakeholders in Mexico City was instantaneous. The new restrictions were particularly unpopular because they seemed to fall disproportionately on the lower socio-economic groups in the area, including farmers who depended on being able to bring produce into the city on weekends, often in the older vehicles that were now banned from city streets. Protesters reacted strongly and blockaded main avenues and access routes into the city for several days, causing massive disruptions.

Despite the new restrictions, however, air quality in Mexico City continued to be an important public health problem. The most accessible indicator of air quality status in the city used by the media and the citizens was whether ozone or PM$_{10}$ (particles with a diameter less than 10 microns) levels exceeded a specified threshold, activating the Environmental Contingencies...
Program\(^1\) tiers, to either a “Pre-contingency” level or a more serious “Contingency.” During the first six months of 2015, even with the tightened Hoy No Circula Program in place, ozone levels were high enough to activate a “Pre-contingency” five times, in contrast to the year prior in which only three “Pre-contingencies” were activated. Then in mid-2015, the new HNC restrictions were reversed by the Supreme Court, allowing many more cars and trucks onto the streets again. A year later, by May 2016, the city had undergone three of the more serious “Contingencies” for ozone for the first time since 2002. In reality, these Contingencies were the result not of increased pollution, but of a tightening of the threshold value that triggered the alerts. However, most citizens and the press interpreted the increase to mean that in 2016 Mexico City was experiencing the worst air pollution events in the last decade.

Secretary Müller was facing increasing pressure to evaluate both the Hoy No Circula Program and SEDEMA’s approach to controlling air pollution in general. She was passionate about wanting to improve the air quality in the Mexico City Metropolitan Area (MCMA) and was particularly concerned about the impact of air pollution on the public’s health. But Secretary Muller knew that the best approach was far from simple or obvious. The economics, politics and transportation needs of the people of MCMA—combined with its geography and climate—made for a mix that was potentially as noxious as the air itself on certain winter days.

Background: Air Pollution in Mexico City

In the late 1980s authorities, researchers, and the public acknowledged the complexity of air quality control in the MCMA, since air pollution problems resulted from a complex ensemble of factors. Among these were the MCMA’s climate and geography; a fleet of vehicles being used in Mexico City that in the late 1980s included nearly 3 million vehicles compared to 75,000 vehicles in the 1950s \(\text{[2]}\); a population that grew from 3 million to over 15 million inhabitants in the same period of time; aging and high-polluting industrial facilities within the city limits; and the use of low quality of fuels (i.e., with high sulfur concentrations).

**Climate, Altitude and Geography in the Mexico City Metropolitan Area (MCMA)**

In the Valley of Mexico, where Mexico City is situated, the accumulation, transformation and dispersion of air pollutants in the atmosphere are influenced by local climate, altitude and geology. At 2240 meters (7,350 feet) above sea level combustion processes are quite inefficient

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\(^1\)The Environmental Contingencies Program (PCAA) was implemented in 1989. Through the years, threshold values for ozone and PM\(_{10}\) that trigger the Program’s “Contingencies” and (since 1996) “Pre-contingencies” have been lowered several times in order to control emissions and reduce the exposure of the population to ambient air pollutants. At first, “Contingencies” were activated when the levels of ozone reached twice and PM\(_{10}\) levels reached almost twice the National Ambient Air Quality Standards (NAAQS) in force at the time. In April 2016, threshold levels that triggered alerts were reduced to 50% of current NAAQS, which had themselves been tightened in 2014. The net effect was that the ozone level that activated “Contingencies” was reduced by almost 50%. Thresholds to activate “Pre-contingencies” were also reduced over the years, and in April 2016, environmental authorities decided to eliminate this tier and directly activate “Contingencies” when pollutant levels exceeded the NAAQS levels in force by 1.5 times. This strategy to activate the PCAA at lower levels was thought to deliver the message to the citizens and authorities that MCMA still has an air quality problem.
given the lower concentration of oxygen\textsuperscript{2}. The MCMA is surrounded almost entirely by mountains that hinder the dispersion of air pollutants \cite{3}. Weak winds and thermal inversions in the Valley of Mexico favor the accumulation of air pollutants emitted during the night and early morning \cite{4}. During the day, intense solar radiation in the Valley enhances the formation of ozone resulting in high concentrations, especially in the southern and southwestern parts of the City \cite{5}.

In the cool-dry season (November to February) frequent thermal inversions inhibit vertical circulation of air into the higher atmosphere, allowing air pollution to accumulate and surface concentrations to increase. In the warm-dry season (March to May) more intense solar radiation causes faster photochemical oxidant formation, with increased aerosol loading due to dust and biomass burning. In the rainy season (June to October) particulate matter concentrations are reduced, but high levels of ozone occur given the intense photochemistry before the afternoon showers hit the city. Air pollution is therefore a year-round concern \cite{3}.

\textbf{Industry and Transportation}

In the late 1980s there were about 30,000 industrial plants in the MCMA. Almost 15\% of these plants were significant pollutant emitters due to obsolescence, lack of controls of combustion processes, and the use of high sulfur content fuels. An estimated 12,000 service establishments had incineration and combustion processes that used fuel oil, high-sulfur diesel, diaphanous oil and LP gas. The equipment in these facilities tended to be old, worn, and in poor operating conditions.

Two thermoelectric power plants “Jorge Luque” and “Valley of Mexico” produced more than 9\% of pollutant emissions in the industrial sector, releasing high volumes of sulfur dioxide (SO\textsubscript{2}), nitrogen oxides (NO\textsubscript{x}), and particulate matter.\textsuperscript{3} Activities related to the production, storage and distribution of fuels generated another 14\% of the pollution from stationary sources.

Since the late 1980s, residents of the MCMA have travelled long distances for work, school, and social interactions. Residents made their daily trips in 2.4 million private cars, 57,000 taxis, 69,000 vans and microbuses, 10,500 buses, eight subway lines, one light rail line, and 450 trolleybuses. The transport sector—passenger cars, taxis, vans, gasoline-burning trucks, as well as vehicles that use diesel, including foreign cargo trucks and passenger buses—contributed 76\% of total air pollutant emissions. Private cars were responsible for about 50\% of the transport sector emissions, generating SO\textsubscript{2}, NO\textsubscript{x}, and lead. Figure 1 summarizes the main sources by pollutant from the 1989 emission inventory.

\textsuperscript{2}At this altitude, the atmosphere contains 23\% less oxygen than is available at sea level, rendering combustion processes less efficient and producing higher levels of air pollution emissions.

\textsuperscript{3}In 1996 the power plant “Valley of Mexico” air and combustion gases system design in the steam generators were modified and by 1998 NO\textsubscript{x} emissions decreased. Two years later, the “Jorge Luque” plant stopped burning fuel oil.
Figure 1: Main emission sources\textsuperscript{4} by pollutant, Emissions Inventory-1989

![Figure 1: Main emission sources by pollutant, Emissions Inventory-1989](image)

Source: PICCA (1990) [4].

**Fuel Consumption and Fuel Quality**

In the late 1980s, gasoline consumption in the MCMA represented approximately 30% of the national total. By 1990 two types of gasoline were sold in the country, “Nova” and “Extra,” both of which contained about 5% methyl tert-butyl ether (MTBE), added to improve combustion at high altitude conditions in the MCMA. From 1985 to 1989 diesel consumption in the MCMA was 16\% of the national total. In May 1986 diesel with lower sulfur content, less than 0.5\% by weight, was distributed in the MCMA, in addition to and along with higher sulfur diesel (1\% by weight). Similarly, by the end of 1986 fuel oil with a maximum sulfur content of 3\% began to be distributed. This fuel accounted for about 42\% of total consumption in the MCMA, mainly due to its very low cost. Limited availability and higher costs of LP gas and natural gas precluded the use of these fuels as cleaner fuel alternatives.

Fuel quality is a fundamental aspect in air pollution control. Certain emission control technologies, like catalytic converters, need fuels with limited lead or sulfur contents for optimum functioning. In the MCMA, by the end of 1990 unleaded gasoline “Magna Sin” was phased-in. This allowed the first introduction (in model-year 1991) of vehicles equipped with one and two-way catalytic converters, and later (in model-year 1993) of vehicles with advanced three-way catalytic converters. As emissions standards for new vehicles have become tighter, emission control technologies have progressed and sulfur concentrations in fuels have been significantly reduced. Sulfur, which is a part of fuels’ chemical makeup, when burnt in

\textsuperscript{4}Point sources are mainly represented by industrial facilities or processes emitting significant amounts of pollutants; manufacturing, heating or power generation are some examples of these kinds of sources. Area sources refers to a set of small and scattered sources which can’t be efficiently included in a point source inventory, but when added together account for a significant part of total emissions of air pollutants. These include, for instance, residential emissions from heating and fuel use, dry cleaners, gasoline stations, bakeries and small manufacturing processes.
combustion processes without advanced pollution control technologies is emitted with a host of other pollutants into the atmosphere.

**Air Quality Standards in the 1980s and the Air Quality Index**

In November 1982, the Federal Government issued the National Ambient Air Quality Standards (NAAQS), with maximum allowable limits for all criteria pollutants (Table 1) [6].

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Maximum Allowable Limit/hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>13 ppm/8 hours</td>
</tr>
<tr>
<td>SO$_2$</td>
<td>0.13 ppm/24 hours</td>
</tr>
<tr>
<td>NO$_2$</td>
<td>0.21 ppm/1 hour</td>
</tr>
<tr>
<td>O$_3$</td>
<td>0.11 ppm/1 hour</td>
</tr>
<tr>
<td>PM$_{10}$</td>
<td>150 µg/m$^3$/24 hours</td>
</tr>
<tr>
<td>TSP</td>
<td>275 µg/m$^3$/24 hours</td>
</tr>
</tbody>
</table>

*ppm= parts per million
*$µg/m^3= micrograms per cubic meter

Source: PICCA (1990) [4].

However, systematic air sampling with automatic and manual monitoring networks (RAMA and REDMA, respectively) did not begin until the late 1980s [7]. Criteria air pollutants have been monitored routinely since then, including carbon monoxide (CO), nitrogen oxides (NO and NO$_2$), ozone (O$_3$), sulfur dioxide (SO$_2$), lead (Pb), total suspended particles (TSP, with an aerodynamic diameter of approximately 50 microns) and PM$_{10}$.

Starting in January 1986, the MCMA authorities developed a Metropolitan Index of Air Quality (IMECA), as a tool to facilitate the communication of air quality to the public. IMECA has also been used to set the values to activate the phases included in the Program of Environmental Contingencies (Figure 2). The IMECA has numerical values that range from 0 (good air quality) to 500 (extremely bad air quality). This index was first compiled for SO$_2$, CO, NO$_2$, O$_3$ and particles. A value of 100 IMECA points has been equivalent to the current maximum allowable limit set in the corresponding National Ambient Air Quality Standard for each pollutant.

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5 In the MCMA, systematic sampling of fine particles (PM$_{2.5}$, particles with a diameter <2.5 microns) in the fixed-site monitoring network started by the end of 2003.

6 IMECA points were assigned to equivalent concentrations for each air pollutant by means of specific algorithms by pollutant. IMECA does not capture concentrations for more than one pollutant at a time to reflect air quality as a mix of pollutants. Equivalent concentrations to IMECA points for any given pollutant have changed the NAAQS in force have been modified; 100 IMECA points have always equaled the NAAQS value.
The response to severe air pollution problems in the late 1980s was the formulation of an air quality plan, called PICCA (Integral Program to Fight Air Pollution). Published in October 1990, PICCA was formulated as a medium-term plan that aimed at curbing air pollution. It is considered the first ever of its kind in a developing country. PICCA was developed with a team composed with representatives of State Secretariats, including, Urban Development and Ecology, Finance, Programming and Budget, Trade and Industrial Promotion, Communications and Transportation, Energy, Mining and State-Owned Industry, Agriculture and Hydraulic Resources, and the Secretariat of Health. Likewise, authorities from Mexico City and the State of Mexico, officers from the state-owned oil and electricity industries (PEMEX and CFE), and the Mexican Petroleum Institute were engaged in the process [4]. Participation of citizens, environmental groups, the Assembly of Representatives of the Federal District and the Congress were also involved [4].

The team also included national scientists and international experts on air quality from Japan, Germany, England, France, Canada and the United States of America. This team of specialists analyzed the international scientific and technological developments in the field and the existing options within an analytical framework of health risks and environmental cost-benefit analysis, as well as technical and financial feasibility.

**Air Quality in the MCMA in the Late 1980s**

The late 1980s were bad years in terms of air quality in the MCMA. Historically, ozone had been the target pollutant to control because it frequently exceeded the National Ambient Air Quality...
Standard. In January 1986 ozone levels were close to 330 ppb (IMECA= 300 points), and that same year there were over 200 thermal inversions in 365 days [9].

In 1988 ozone concentrations exceeded the hourly standard 90% of the days. In September, ozone levels surpassed the ambient air quality standard by fourfold, reaching 405 ppb. Also, particle concentrations (TSP) exceeded the corresponding standard in 181 days.7

In the winter of 1988-1989, authorities launched the Environmental Contingencies Program as a strategy to curb peak ozone concentrations and reduce population exposures to air pollutants. The Contingencies Program included actions such as suspension of sports and outdoor activities, vehicular restrictions, suspension of activities related to painting and repairing of streets using asphalt, 30%-40% reduction of manufacturing activities, 50% reduction of activities at thermoelectric plants “Jorge Luque” and “Valley of Mexico”, suspension of activities involving release of hydrocarbons into the atmosphere in plant distribution and storage of LP gas, calling off classes and developing epidemiological surveillance programs in the most polluted areas of the MCMA. Nearly 7,000 official vehicles were ordered out of circulation during the winter of 1988-1989. Also, activities in the heavily industrialized area of Xalostoc in the State of Mexico were reduced by 50%.

The *Hoy No Circula* Program

As levels of ozone and other airborne pollutant standards continued to exceed standards, Mexico City environmental authorities introduced an unprecedented program on November 20, 1989, *Hoy No Circula*. This program was intended to improve air quality by preventing, minimizing and controlling the emission of pollutants from mobile sources in the MCMA. To achieve the above, most drivers were banned from using their vehicles one weekday per week, based on the last digit of the license plate. Colored holograms (stickers) were placed on each car’s windshield indicating the day the car was not to be used [10]. *Hoy No Circula* was designed to withdraw 20% of private cars from circulation, equivalent to 460,000 vehicles per day.

The *Hoy No Circula* Program was originally adopted by the government as a temporary program, with an end date in February 1990. However, due to frequent thermal inversions in the winter and consistently elevated pollution levels, it became permanent.

A complementary inspection and maintenance program was initiated in that same year. The so-called *Verificación Vehicular* Program aimed at identifying high-emitting vehicles in need of repair, through visual inspection and twice-a-year emissions testing. Owners whose vehicles failed the inspection were forced to repair them as a prerequisite to vehicle registration.

**Modifications to the Hoy No Circula Program**

The *Hoy No Circula* Program was tightened on multiple occasions. In 1991, public transport vehicles were banned from MCMA roads on alternate Saturdays, based on the last digit of their

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7There was no information for PM10 in the late 1980s.
license plate. Vehicles using cleaner fuels, LP gas or compressed natural gas instead of gasoline or diesel, were exempted from restrictions in 1992. As air pollution problems continued, the Program was further revised (July 2008) to prohibit older vehicles from driving one Saturday a month. A few years later (July 2012) these vehicles were also banned from driving during the activation of a “Pre-contingency” (activated at >150 IMECA points) when lasting over three consecutive days, and the day after a “Contingency” (>180 IMECA points) was declared.

To promote the introduction of newer vehicles with increasingly more advanced emission control technologies, the Program was modified in 1996, 1998, and 2007. In 1996, model-year 1993 and newer vehicles, which had catalytic converters, were exempted from circulation restrictions. In contrast, older vehicles were assigned “Doble Hoy No Circula,” which meant they could not circulate two weekdays in case of activation of an atmospheric environmental “Contingency”.

In 1998 vehicles less than 2 years old were exempted from the mandatory Verificación Vehicular Program for the first two years of life. In 2007, new vehicles, which were less polluting and more fuel efficient, were exempted from driving restrictions and were required to have emissions tests less frequently. These vehicles were only required to have an initial emissions test when first bought and by the end of each two-year period, for a total of six years.

**The Impact of the Hoy No Circula Program**

Davis [11] evaluated the efficacy of the Hoy No Circula Program as implemented in 1989 using empirical evidence. This study compared pollution levels before and after the program was implemented and found no evidence that air quality improved as a result of the Program, not even when analyzed as reductions in extreme air pollutant concentrations. In fact, the author found evidence of an increase in the use of vehicles during the hours when the program was not in place—late nights and weekends—which resulted in a rise in air pollution. Moreover, the Program may have had some perverse effects, such as increasing the total number of cars, and inducing a change in the composition of the fleet toward high-emitting vehicles [11].

**Recent Events**

On June 2014, the Mayor of Mexico City announced that the HNC Program would be tightened by taking over half a million vehicles off the roads on the weekends. Vehicles between 9 and 15 years old were prohibited from circulating two Saturdays a month, and those over 15 years old were banned from circulating on Saturdays (Table 2).

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8The strategy of incorporating the fuel efficiency of vehicles into the Program of Verificación Vehicular aimed at encouraging car manufacturers to bring more fuel efficient vehicles to the market, as well as encouraging consumers to buy them. It was also a way to disseminate the concept of fuel efficiency to car distributors, policy-makers, and the public. In Mexico, the first federal standard of fuel efficiency was not enacted until 2013.
This resolution was one of the most damaging actions to the Mayor’s public image during his administration. On Saturday June 23, 2014, and on several other occasions thereafter, hundreds of drivers went out to the streets to protest the new *Hoy No Circula* Program severely damaging the traffic flow in the metropolitan area. After holding meetings with owners of vehicles that were restricted from circulating on Saturdays, mainly low socioeconomic strata citizens, city authorities announced that vehicles over 8 years old, including those over 15 years old, could be classified as banned from the roads only two Saturdays a month, if they successfully passed the emission tests.

A year later, on July 9, 2015, Mexico’s Supreme Court of Justice ruled that the fundamental right of equality among citizens was violated by using “model-year” (age) as the criterion which defined the driving restrictions for a vehicle. Since that decision, restrictions on vehicles have been based on the results from their emissions inspections only.

At the time, SEDEMA estimated that the Supreme Court ruling would weaken the vehicle inspection and driving restrictions, and allow an additional 600,000 cars to circulate daily. With more cars on the road and more old vehicles emitting pollutants to the atmosphere, experts and authorities expected far worse air quality in the MCMA.

However, immediate effects in air quality were not obvious after the Supreme Court of Justice ruling took effect. Table 3 shows the number of days (from January to June) when the former local one-hour air quality standard for ozone (>110 ppb) was exceeded in 2014 and the number of days that the same standard would have been exceeded if it had remained the same in 2015. Also shown are peak ozone concentrations (>150 ppb) and the number of “Pre-contingencies”

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9We compared January to June of 2014 to the same period of 2015, because the program modifications were implemented after July 2014. Also, as the revised air quality standards were enacted in October 2014, IMECA values were estimated using the previous standard in order to be able to compare both periods in terms of this index and of the number of pre-contingencies that would have been activated in 2015.
(>150 IMECA points) for the same period.

**Table 3:** Number of days from January to June exceeding ozone previous and new Ambient Air Quality Standards

<table>
<thead>
<tr>
<th></th>
<th>In force until 2014</th>
<th>In force since 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>One-hour air quality standard for ozone (&gt;110 ppb)</td>
<td>89</td>
<td>68</td>
</tr>
<tr>
<td>Peak ozone concentrations (&gt;150 ppb)</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Pre-contingencies due to ozone</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

Source: Made by the authors with data from SEDEMA (2016)

Between February and May of 2016, three “Contingencies” were activated because of high ozone levels. Although the activation of two of these “Contingencies” resulted from the authorities’ decision to tighten the IMECA threshold level from 180 to 150 points (Figure 3), these three events had a huge impact in every sector of the society. For the previous 11 years, there had been no Contingency events (during those years, Contingencies were triggered by ozone levels between 180 and 241 IMECA points). This time all eyes were on the 2015 Supreme Court resolution. Although the decision required that cars pass emissions test, there was a general sense that the inspection process was subject to corruption and was allowing many high-pollution-emitting vehicles to circulate in the MCMA. And these cars added to the already prolific vehicular fleet flooding this metropolitan area.
In response, President Enrique Peña Nieto spoke up, and asked federal environmental authorities (SEMARNAT) to do something. Among the possible strategies considered were: revising outdated emission vehicular standards; improving public transportation; and focusing on a badly needed integrated and sustainable urban development plan for the metropolitan area. However, authorities decided to, once again, modify the Hoy No Circula program. The Hoy No Circula Program is now mandatory for all vehicles in the City, no matter how new or old they are, or how well or badly maintained they are. This modification was said to be temporary, and set to end in June 2016.

What Does the Future Hold?

With the unrest in 2014, Supreme Court decision in 2015, and the “Contingencies” declared in March and April of 2016, the situation facing Secretary Müller was more complex than ever. Obviously, successful air quality management must incorporate an ensemble of public policy strategies, which needed to be incorporated within the urban planning process. Adding to the complexity, air pollution improvements rarely appear immediately after introducing new
programs, and therefore benefit from continuous evaluations to be able to gauge their efficacy and to adjust them through their lifetime. It would be desirable to conduct a robust assessment of the impacts, benefits and costs of some of the main interventions in air quality public policy in the MCMA, and decide from those that are still in place which should continue and which should be discontinued.

But what options would be politically feasible and acceptable to the many affected groups in MCMA? Secretary Müller wondered where she should focus her efforts first? She knew that the health benefits in the citizens of the MCMA would most certainly be an indicator to evaluate the benefits of these programs but wasn’t sure how to incorporate these into her analyses. Could using these indicators be one method of gaining support from key groups in the city?
Appendix 1: Health Effects of Air Pollution. Evidence in the MCMA and Worldwide

Over the 1990s, the epidemiological evidence about the health effects of air pollution increased exponentially. For the first time a longitudinal study reported that chronic exposure to air pollution in cities with high air pollution levels, mainly fine particles (PM$_{2.5}$), implied a greater risk of death from cardio-respiratory diseases. The “Harvard Six Cities Study” reported the results of a prospective cohort involving randomly selected residents of six US cities [16].

In addition to cohort studies, epidemiologists have also relied on the time-series study design. Time-series studies assess the effects of short-term exposures, in contrast with cohort studies, which evaluate adverse health impacts of long-term exposures.

Time-series studies examine the relationships between day-to-day variations in levels of air pollution and day-to-day variations in mortality. Although there are both study-to-study differences and regional variations in the quantitative relationship between air pollution and mortality, the consensus among experts is that the time-series literature has clearly established the impact of daily fluctuations in air pollution on mortality [17].

A recent report of the Health Effects Institute concludes that there is consistent evidence regarding the effects of particulate matter and ozone on mortality. An analysis of over 100 time-series studies conducted in cities around the world, most of them in North America and Europe, ratified the adverse health effects of particulate matter. For the analysis that included the all-age all-cause mortality studies, the authors reported a risk increase of 1.04% (CI 95% 0.52, 1.56) for a 10 µg/m$^3$ increment in PM$_{2.5}$, with significant regional differences in this risk estimate. Also associated with fine particle short-term exposures are respiratory, cardiovascular, ischemic heart disease, stroke and COPD deaths. Respiratory deaths were not only more strongly associated with fine particles, but there was no regional variability in the risk estimate. Over the past 20 years ten time-series studies have been carried out in the MCMA [18-27]. These time-series studies have reported significant associations linking all-cause, chronic obstructive pulmonary disease (COPD), cardiovascular and cerebrovascular mortality to O$_3$, PM$_{10}$, PM$_{2.5}$, SO$_2$ and NO$_2$ exposures.

In Mexico, because of their high cost, no cohort studies have been ever conducted. A long-term effect resulting from chronic exposures to fine particles and ozone in the inhabitants of the MCMA is not questioned, but there is uncertainty regarding the size that this effect may have. Uncertainty may derive from differences in local conditions versus those from the locations where cohort studies have been carried out, such as exposure characteristics, the chemical composition of airborne particles, the complex mix of pollutants, the range of pollution concentrations in the MCMA atmosphere, the baseline mortality rates, the demographic pyramid, among other factors.

The hypothesis of the Harvard Six Cities study [16] was that individuals living in cities with higher levels of particulate air pollution would experience higher rates of cardiovascular, respiratory, and lung cancer mortality. After 15 years of follow-up, results showed that mortality
rates were approximately 30% higher in the dirtiest city (Steubenville, Ohio) than in the cleanest city (Portage, Wisconsin). These results suggested that for every 1 µg/m³ increase in fine particle levels mortality rates increased by approximately 1.5%.

Shortly after the Harvard’s Six Cities Study was published a larger cohort study that was already underway was used to analyze the chronic effects of air pollution exposures, the American Cancer Society (ACS) study [28]. The ACS study had an initial 7-year follow-up period (1982-1989) [29]. Findings from the ACS study indicated an effect size about 1/3 as large as that seen in the Harvard Six Cities Study, that is, that for each 1 µg/m³ reduction in ambient levels of PM₂.₅, mortality rates would be reduced by about 0.4%.

Re-analyses and extensions of the Harvard Six Cities and the American Cancer Society studies have been conducted [29-32]. Extended follow-up of the Six Cities cohort, for a total 36-year follow-up from 1974 to 2009 [31], reported that for each increment in 1 µg/m³ of PM₂.₅ there were adjusted increased risks of 1.4% for all-cause mortality, 2.6% for cardiovascular mortality and 3.7% for lung-cancer mortality. The authors reported that these concentration-response relationships appeared to be linear down to 8 µg/m³ PM₂.₅ levels. The extended ACS analysis encompassed a total of 18 years (1982-2000) [32]. The results showed positive and significant associations between PM₂.₅ and all-cause mortality, cardiopulmonary disease, ischemic heart disease, and lung cancer deaths. Of the diseases studied, ischemic heart disease mortality was consistently associated with the largest risk estimates, with a 1.5% increase for each µg/m³ in annual average ambient PM₂.₅ levels.

Over the past 5 or 10 years, several entirely new cohort studies have been conducted in the United States, as well as in other countries in Europe, Asia and Oceania. These include: the California Teachers study [33]; the Seventh Day Adventist study [34]; the Dutch Diet and Cancer study [35]; the Nurses’ Health study [36], the Male Health Professionals study [37]; the Women’s Health Initiative [38]; the US Medicare National Cohort [39]; the Vancouver Cohort [40]; the US Trucking Industry study [41]; the Canadian National Cohort Study [42], and the Rome Cohort Study [43], among others.

Despite the lack of cohort studies in the MCMA, many studies of morbidity associated with air pollution have been carried out. They have assessed the effects in the number of cases of respiratory diseases [44], ocular symptoms such as eye irritation, itching, burning, watery eyes, red eyes and eye infection [45], increment in asthma events and changes in lung function [46-50] and rate of lung function growth, wheezing [51], changes in heart rate variability [52-53], decrease in efficient use of broncho-dilators [54], increased levels of inflammatory markers [55-56], and school absenteeism [57], among others.
Appendix 2: Current Ambient Air Quality Standards

Mexico and most countries in the world have set ambient air quality standards, which serve as a yardstick to evaluate air quality and the potential adverse impact of criteria pollutants on human health. As an international organization, the World Health Organization (WHO) has also issued recommendations on the concentrations that must not be exceeded to protect public health. These recommendations are generally tighter than national regulations [58].

Particulate matter is regulated in terms of its aerodynamic diameter\(^{10}\), so permissible limits are established for PM\(_{10}\) and for PM\(_{2.5}\) [59]. Standard for most pollutants include limits for two averaging times, one for acute exposures, and one for chronic exposures. Current Mexican standards and WHO recommended values are listed in Table 4.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Averaging Time</th>
<th>Mexico’s Ambient Air Quality Standard</th>
<th>WHO Recommended Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM(_{10}) (µg/m(^3))</td>
<td>Annual average</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Daily average</td>
<td>75</td>
<td>50</td>
</tr>
<tr>
<td>PM(_{2.5}) (µg/m(^3))</td>
<td>Annual average</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Daily average</td>
<td>45</td>
<td>25</td>
</tr>
<tr>
<td>O(_3) (ppm)</td>
<td>8-hour moving average</td>
<td>0.07</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>1-hour maximum</td>
<td>0.095</td>
<td></td>
</tr>
<tr>
<td>NO(_2) (µg/m(^3))</td>
<td>1-hour maximum</td>
<td>395</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>Annual average</td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>SO(_2) (ppm)</td>
<td>Annual average</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Daily average</td>
<td>0.025</td>
<td>0.007</td>
</tr>
</tbody>
</table>

Source: DOF (2014) [13][57]; WHO (2005)[58].

Regulation of ambient particulate matter (PM) has evolved from controlling TSP to PM\(_{10}\) and finally PM\(_{2.5}\) (called fine particles, with an aerodynamic diameter of less than 2.5 microns) because of evidence of adverse health impacts. In the late 1990s or early 2000 most countries supplemented the PM air quality standards that were in force with the corresponding standards to also regulate PM\(_{2.5}\). The significant adverse health effects of PM\(_{2.5}\) have oriented control programs in urban and industrial settings worldwide.

Fine particles include primary and secondary components that have a large suite of emission sources related with fossil fuel combustion, derived from electric utilities, industry, and motor vehicles; vegetation burning; and the smelting or other processing of metals. Primary fine

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\(^{10}\)The aerodynamic diameter of a particle is the diameter of a unit density sphere which would have the same terminal settling velocity as the particle in question.
particles are directly emitted into the atmosphere, and include elemental carbon (EC) or black carbon (BC) [60]. Secondary fine particles are formed in the atmosphere through reaction, coagulation, or nucleation of the gas phase precursors NOx and SOx11 after being emitted from their sources [60-61]. Additional precursors of secondary PM$_{2.5}$ are volatile organic compounds (VOC).

Air quality management has been most successful in reducing concentrations of carbon monoxide, sulfur dioxide, nitrogen dioxide and lead. Figure 3 shows the effects of these efforts mainly represented by actions undertaken by PICCA and PROAIREs over the past 20 years [62-63].

**Figure 4:** Percentage of effective reduction of air pollutant concentrations with implementation of strategies included in programs to improve air quality (PICCA and PROAIRE). Based on annual average concentrations from 1990 to 2009.

![Percentage of effective reduction of air pollutant concentrations](image)

Trends in the annual concentrations for each pollutants and compliance with the Mexican Standards since the late 1980’s are shown in Figure 5 for CO (a), SO$_2$ (b), NO$_2$ (c), O$_3$ (d), PM$_{10}$ (e) and for PM$_{2.5}$ (f) starting in 2004. Although ozone and particle concentrations have also decreased, these pollutants are the main focus of air pollution management. Fine particles12, unlike the rest of pollutants, don’t show a clear long-term trend.

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11 Sulfur dioxide is frequently considered with sulfates and referred to as SO$_x$.
12 Regular sampling of fine particles in the fixed-site monitoring network of the MCMA began in 2004.
Figure 5: Historic Compliance of the Air Quality Mexican Standards in the Mexico City Metropolitan Area

Source: SEDEMA (2016) [64].
Mobile sources still are a major source of air pollution in the MCMA, being intimately correlated with the fulfillment of mobility needs in this metropolitan area. Because public transportation is not sufficient, reliable or safe, private cars prevail as the main mode of transportation. Private cars are the largest emitters of ozone precursors, such as volatile organic compounds (VOC) and NO$_x$, and important emitters of fine particulate matter (including Black Carbon$^{13}$) according to the Emissions Inventory of 2012 (Figure 6).$^{14}$

Figure 6: Main Emission Sources by Pollutant, 2012

Black carbon is the most strongly light-absorbing component of particulate matter and is formed by the incomplete combustion of fossil fuels, biofuels, and biomass.

$^{13}$ According to the Milagro Campaign—a large-scale air pollution study carried out in the MCMA in 2006—mobile sources play a major role in supplying the NO$_x$ and volatile organic compounds that participate in the formation of ozone. Motor vehicles in the MCMA also produce abundant amounts of primary particulate matter, elemental carbon, polycyclic aromatic hydrocarbons, carbon monoxide and a wide range of air toxics.
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