ANÁLISIS HISTÓRICO DE LOS BENEFICIOS EN LA SALUD DE LA POBLACIÓN ASOCIADOS A LA CALIDAD DEL AIRE EN LA CIUDAD DE MÉXICO ENTRE 1990 Y 2015

HARVARD T.H. CHAN SCHOOL OF PUBLIC HEALTH
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Air quality is a major environmental risk to health, and one of the major challenges cities worldwide are facing in the 21st Century. According to the World Health Organization (2017), 9 out of 10 people in the world breathe poor air quality; moreover air pollution is a silent killer responsible of 7 million deaths in the world every year.

Mexico City was once the most polluted city worldwide (UNEP, 1992). This condition compromised quality of life and health for millions of inhabitants in the city. For over 25 years, the Government of Mexico City has implemented bold policies which have led to a substantial improvement on air quality. Mexico City is no longer the most polluted city in the world, not even in the country, ranking now in the position 88 of the World Health Organization (2016), together with 42 cities that have $PM_{2.5}$ concentrations of 22 ug/m^3.

The implementation of public policies to improve air quality have achieved that pollution levels maintain a downward trend, despite the steady growth of the City and the vehicle fleet. What is the impact in public health of the implementation of these policies? Have we achieved an improvement in health as we have achieved in air quality? How can we continue improving air quality?

Convinced that scientific evidence is key for responsible environmental policies, in 2014 the Government of Mexico City initiated this collaboration with the Harvard T.H. Chan School of Public Health, with the Secretarìa del Medio Ambiente (SEDEMA), Secretarìa de Salud (SEDESA), the Harvard David Rockefeller Center for Latin American Studies (DRCLAS), and with the participation of the Mario Molina Center for Strategic Studies on Energy and Environment, the National Institute for Public Health (INSP), and the National Institute for Geography and Statistics (INEGI). The Historical Analysis of Air Quality in Mexico City from 1990 to 2015 evidence the health benefits in the population related to air quality. The Study also provides information about cost-benefit analysis of measures to continue improving air quality and policy recommendations for further improvements that are necessary for major health benefits.

This administration has prioritized air quality policies for better quality of life; with scientific evidence-based decision making and the participation of academia, recognized international researchers, as well as national research institutes.

Policies to improve air quality must be effective and inclusive, privileging the common good over particular interests; and with a metropolitan and long term vision, as air pollution does not recognize administrative or political frontiers. The challenge is big and of course there is still a lot to be done, but we are decisively advancing in the right direction, committed to guarantee sustainability and quality of life for all.

Tanya Müller García
Secretary of Environment

LETTER FROM
PROFESSOR DOUGLAS DOCKERY

Air pollution is increasingly being recognized as a global, but preventable threat to public health. In a recent analysis[1] it was estimated that there were 4.2 million excess deaths worldwide in 2015 attributable to fine particulate air pollution and another 254,000 attributable to ozone. For Mexico, it was estimated that there were 29,000 excess deaths due to fine particles ($PM_{2.5}$) and 18,100 attributable to ozone (O_3).

Nevertheless, there are remarkable examples of significant achievements in reducing air pollution exposures to the population. Mexico City, once labelled as the most polluted mega-city in the world, has taken the challenge seriously, and has substantially reduced air pollution exposures in the Valley. In this report, we examine whether these policies and the sacrifices that the Mexico City population and economy have had to bear to achieve better air quality have been matched by improvements in health.

The health effects of air pollution have been studied extensively in Mexico and specifically in Mexico City. Mexican investigators have been leaders in understanding the chemistry and transport of air pollution, the advantages and disadvantages of various control strategies, and the associated health effects of air pollution. There is a larger body of evidence on the health effects of air pollution, particularly from developed countries in North America and Europe. These results along with estimates of average air pollution from models and remote sensing have allowed estimates of the burden of disease from air pollution in countries around the world, even those without air pollution monitoring[1].

Our challenge was to apply these approaches at the local level in Mexico City. Our overall goals were to develop tools to support cost-effectiveness analyses, to estimate and validate public health benefits from policies over the past 25 years and provide a basis for estimating benefits of proposed policies. Building on the groundbreaking 2002 analyses, Air Quality in the Mexico Megacity: An Integrated Assessment led by Luisa Molina and Mario Molina[2], we have undertaken a multi-disciplinary, cross-institutional assessment of changes in air pollution, population health, and public policy in Mexico City over the past twenty five years (1990 to 2015).

The project was conducted in collaboration with the *Secretaría del Medio Ambiente* of the Government of Mexico City *(SEDEMA CDMX)* with resources from the Public Environmental Fund. This project has drawn on expertise and assistance from institutions in Mexico and Harvard including the *Secretaría del Medio Ambiente (SEDEMA CDMX)*, the *Secretaría de Salud (SEDESA CDMX)*, the *Instituto Nacional de Salud Pública (INSP)*, the *Centro Mario Molina para Estudios Estratégicos sobre Energía y Medio Ambiente*, the *Instituto Nacional de Estadística y Geografía (INEGI)*, the *Harvard David Rockefeller Center for Latin American Studies (DRCLAS)*, and the *Harvard T.H. Chan School of Public Health.*

We show that the policies to control air pollution in Mexico City over the last twenty-five years have substantial benefits in terms of live saved and increased life expectancies. These health benefits can be monetized for cost-benefit analyses to inform public policy decisions. While the improvements in air quality and population health should be lauded, there is also evidence that further improvements in air quality would lead to additional public health benefits. This project provides the tools to better inform these public policy decisions.

The experience in Mexico City in dramatically improving air quality and population health provides unique evidence for the benefits of clearing the air and will serve as a model for mega-cities around the world.

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BACKGROUND AND OVERVIEW

Air quality in Mexico City (CDMX) in the late 1980s and early 1990s was characterized as the worst of all mega-cities in the world[3]. Most criteria pollutants (lead, sulfur dioxide, carbon monoxide, nitrogen dioxide, ozone, and particulate matter) frequently exceeded national ambient air quality standards. Since then, municipal, state and federal governments have used laws and regulations to control and reduce air pollutant emissions, to improve air quality and protect public health[4]. Federal public policy actions have been implemented, such as standard setting to regulate emissions of mobile and point sources, improvements in fuel quality, and establishing air quality maximum permissible levels for criteria pollutants (Figure 1.1).

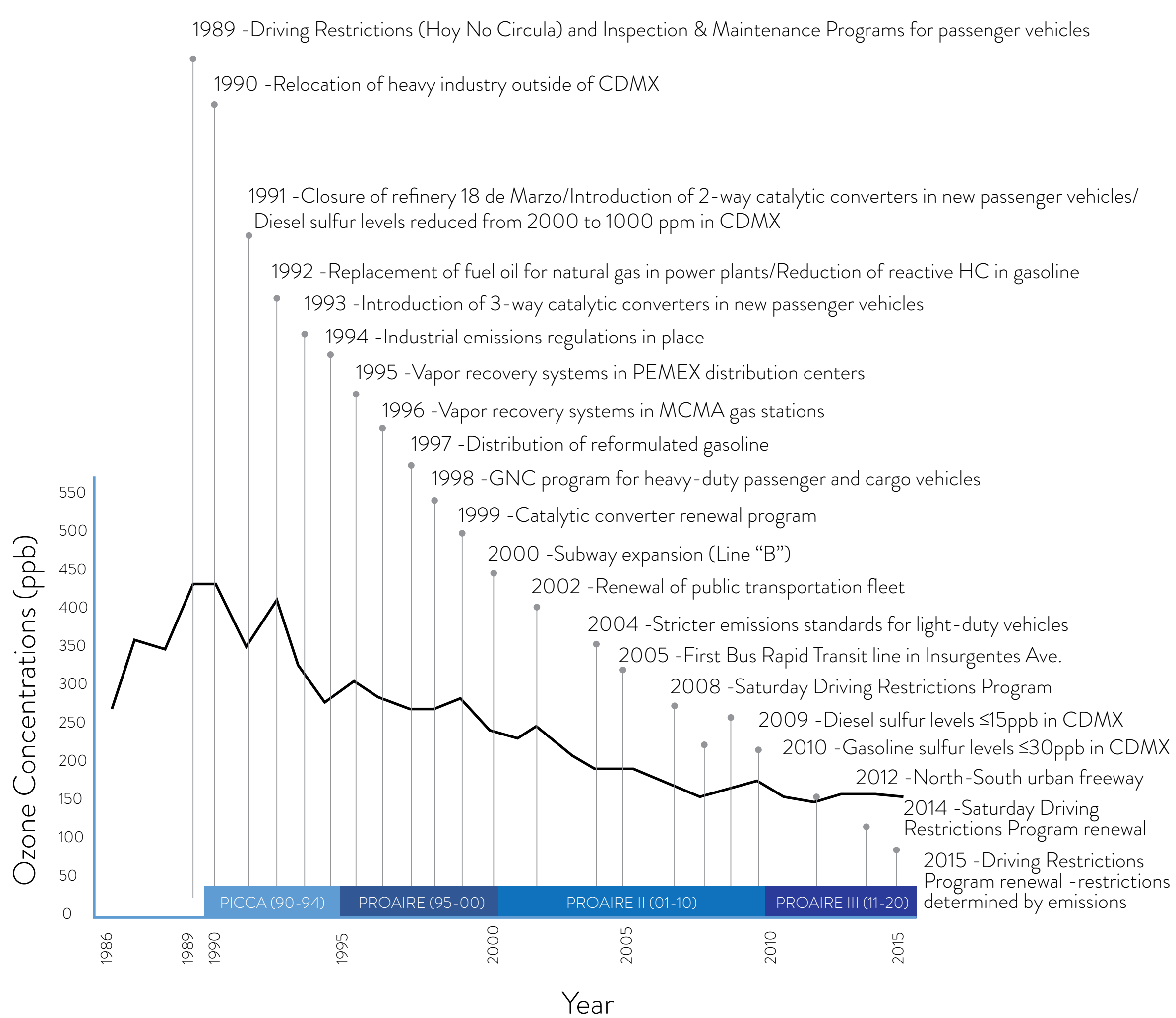

Figure 1.1. Actions implemented aimed at improving air quality in Mexico City since the early 1990

The Government of Mexico City has implemented a series of comprehensive air quality management programs, known as ProAire. These have been developed in coordination with federal authorities, representatives from academia, and the private sector. In addition, several important public policy specific strategies have been launched, including the Environmental Contingencies Program (PCAA), the Hoy No Circula, and the Inspection and Maintenance Programs. These programs have been evaluated and modified in numerous occasions. The now intertwined Hoy No Circula, and Inspection and Maintenance programs have promoted the renewal of the vehicle fleet, accelerated the entry of advanced pollution control technologies, and mandated the continued maintenance of vehicles that circulate in Mexico City and urbanized areas from neighboring states. Such strategies have encouraged the switch to new vehicles and vehicles which comply with in-use emissions standards. In turn, the PCAA seeks to trigger smog alerts for corrective actions to reduce pollutant emissions such as banning circulation of certain vehicles when air pollution exceeds thresholds deemed harmful to sensitive population sub-groups. First stage smog alerts have decreased from 33 per year in 1992 when the program was first launched to zero between 2006 and 2014.

This ensemble of air quality management actions have been successful in reducing emissions and air pollution concentrations in Mexico City (Figure 1.1).

OBJECTIVES

The Secretaries of Environment (SEDEMA) and Health (SEDESA) of the government of Mexico City initiated a program of collaboration with the Harvard T.H. Chan School of Public Health in 2014 (Figure 1.2).

Figure 1.2. Signing ceremony for collaborative project, 14 August 2014.

The overarching theme for this collaborative project is examining the link between the sizeable improvements in air pollution observed in Mexico City over the past 25 years and the public health benefits. We quantified such benefits by means of life expectancy improvements, life of years lost, and attributable deaths avoided. In the following sections we describe the foundation to such analyses, that is the air quality changes, specifically for $PM_{2.5}$ and for ozone, from 1990 to 2015.

We first describe air quality changes as reported using official sources that focus in measurements from fixed-site monitoring sites. Later, in the report, we will present air quality trends at alcaldía level, which is the spatial resolution for our health-related analyses.

AIR POLLUTION LEVELS

OZONE AIR POLLUTION

Ozone air pollution concentrations have decreased substantially since 1990 (Figure 1.3). City-wide average hourly peak seasonal concentrations in 1990 were above 160 ppb and ranged between 117 and 185 ppb among monitoring stations in different alcaldías. The steady decline in ozone concentrations across Mexico City led to 2015 mean levels of 84 ppb, and values below 91 ppb at all monitoring stations. Historically, highest ozone levels have been recorded in the southwestern areas of the city (Pedregal).

In the 1990s the 1-hour standard (110 ppb) was exceeded on over 300 days (with a maximum of 344 days in 1994). Since 2003, the standard exceedances have decreased, with a minimum of 118 days reached in 2012. With the new and more stringent standard, lowered to 95 ppb in 2014, the MCMA has seen more days above the limit (over 200 days in 2015).

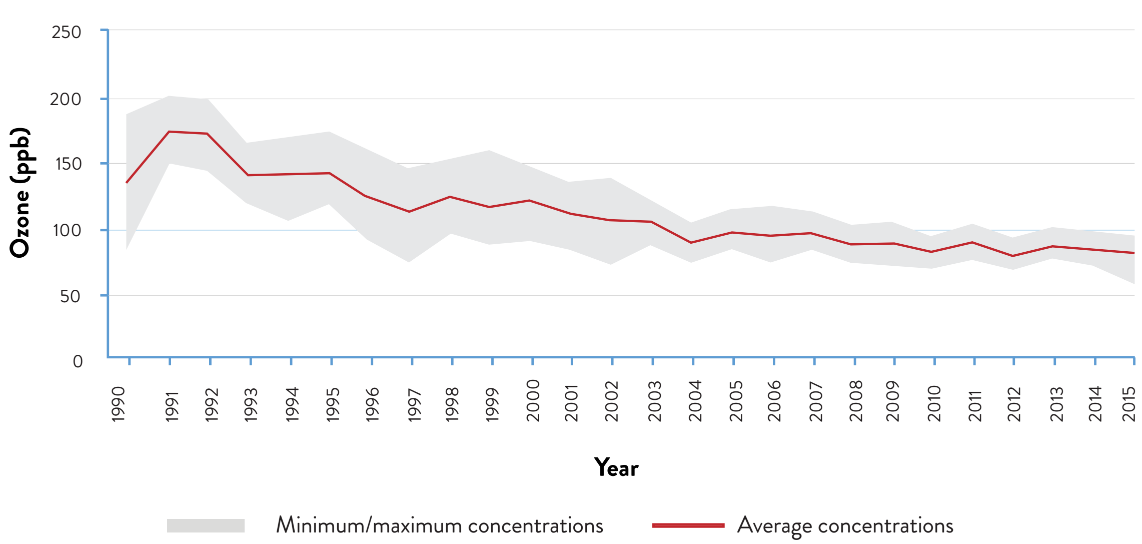

Figure 1.3. Average seasonal (6-month) 1-hour maximum Ozone concentrations in the Mexico City Metropolitan Area, 1990-2015

PARTICLES

Particulate air pollution, measured as PM_{10} (particulate matter less than 10 μm aerodynamic diameter) decreased approximately 60% between 1990 and 2015, from over 110 μg/m^3 to less than 45 μg/m^3 (Figure 1.4). In 2014, the MCMA complied with the previous 24-hour standard (120 μg/m^3). However, if the stricter standard in force since the end of 2014 had been applied, the MCMA would have been out of compliance with both the 24-hour and the annual standards (75 μg/m^3 and 40 μg/m^3, respectively) (INECC, 2016).

Fine particles (particulate matter with an aerodynamic diameter ≤ 2.5 μm, $PM_{2.5}$) have decreased slightly since 2004, when fixed-site measurements started in the MCMA, going from almost 25 μg/m^3 in that year to close to 22 μg/m^3 in 2015 (Figure 1.4). The annual $PM_{2.5}$ air quality standard was 15 μg/m^3 until 2014 and was tightened to 12 μg/m^3 by the end of that year. This $PM_{2.5}$ air quality standard has been exceeded every year and at every single monitoring station (5, 6). Historically, the highest annual concentrations have been reported in the northern part of the MCMA at the monitoring stations of Xalostoc and, more recently, Camarones. The lowest levels are reported in the southern areas of Mexico City, such as Pedregal.

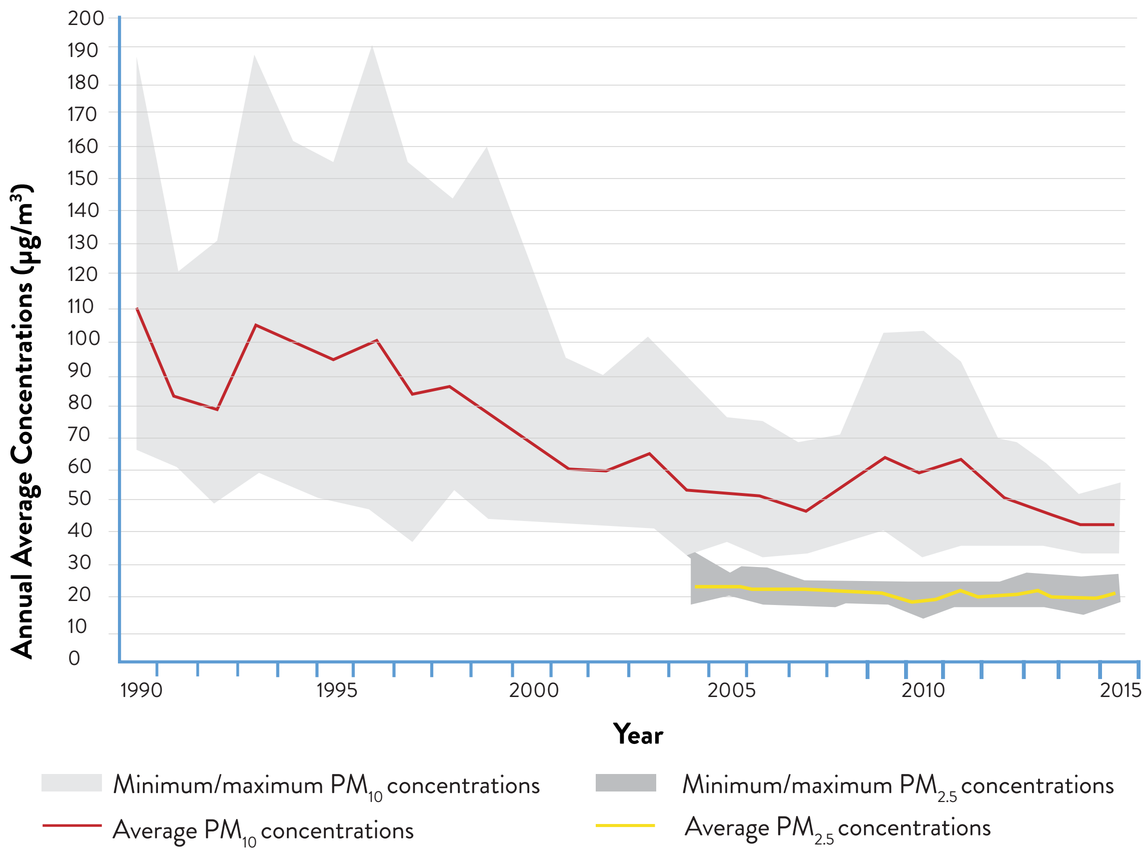

Figure 1.4. Annual PM_{10} and $PM_{2.5}$ concentrations in the Mexico City Metropolitan Area, 1990-2015

OVERVIEW OF ANALYSES

This report presents our findings related with the public health benefits in the population of Mexico City that are attributable to improvements in $PM_{2.5}$ and ozone concentrations since 1990. Epidemiological methods and risk assessment approaches were applied to estimate health benefits that include public health indicators, such as life expectancy, temporary life expectancy, life lost years attributable to death causes that have been determined to be causally associated with air pollution in the GBD analyses and avoided attributable mortality. Finally, this report also includes results of the cost-effectiveness analysis of a public policy strategy to reduce primary particle emissions, improve air quality and protect public health. This policy refers to controlling emissions of in-use heavy-duty diesel vehicles. These analyses are founded on the international state of knowledge relevant to Mexico City.

The study was conducted in four phases. Phase I examined the state of knowledge of the health effects of air pollution in Mexico and the relevance of international studies. Phase II was a risk assessment of the benefits of changes in air pollution in Mexico City over the past twenty-five years. Phase III examined the surveillance data on life expectancy over this same period to validate the risk assessment with observational data. Phase IV presents a tool for cost-effectiveness analyses to improve air quality applied to alternative emission controls of diesel-fueled heavy-duty vehicles that circulate in Mexico City.

PHASE I. STATE OF KNOWLEDGE AND RELVANCE TO MEXICO CITY

Review the state of knowledge and describe the scientific evidence from the most solid epidemiological studies to date, which are to be relied on when interpreting the relationship between air pollutants exposures and adverse health outcomes.

Today, there is robust evidence regarding the adverse health impacts of ambient air pollution. This evidence stems primarily from epidemiological studies, mainly time-series studies of short-term exposures and cohort studies of long-term exposures. These designs complement each other since together the adverse health effects are evaluated for different outcomes and times scales. In Mexico City time-series studies, conducted since the early 1990s, have been the dominant epidemiological design to evaluate the relationship between air pollutant exposures and adverse health impacts [7-10]. These studies reported associations between particle and ozone exposures and total mortality, and between ozone and cardiovascular mortality. Sensitive populations sub-groups were identified, people over 65 years old being more sensitive to ozone exposures, and infants to particle exposures.

The most recent times-series analysis, ESCALA (Study of Air Pollution and Health Effects in Latin America) was conducted as a multicity project, that included Mexico City, estimated all-natural cause, cause-specific and age-specific daily mortality associated with daily exposures to PM_{10} and to ozone[11]. This study found positive associations between daily levels of PM_{10} and all-cause mortality. The highest risk was reported for chronic obstructive pulmonary disease mortality. Ozone was less strongly associated with increased all-cause mortality than were particles.

Even considering the quantitative and regional variations in the association between air pollution and mortality that have been found among time-series studies conducted in cities around the world, the scientific consensus is that daily fluctuations in particulate matter and ozone have an adverse impact on daily mortality[12].

In Mexico no epidemiological studies to evaluate the long-term health effects associated with chronic air pollution exposures have been conducted. However, there is relevant evidence from cohort studies conducted elsewhere.

The first cohort study to examine the mortality impacts of air pollution exposure was the Harvard Six Cities Study[13]. This study showed that individuals living in cities with higher levels of $PM_{2.5}$ air pollution experienced higher rates mortality rates. Figure 2.1. shows that survival rates were much lower (mortality rates higher) in the dirtiest city (Steubenville) than in the cleanest city (Portage). For every 1 µg/m^3 increase in $PM_{2.5}$ concentrations, mortality rates increased by approximately 1.5%. Alternatively, Figure 2.1. shows that those living in Steubenville were dying several years earlier than those in Portage, that is higher $PM_{2.5}$ was associated with shorter life expectancy.

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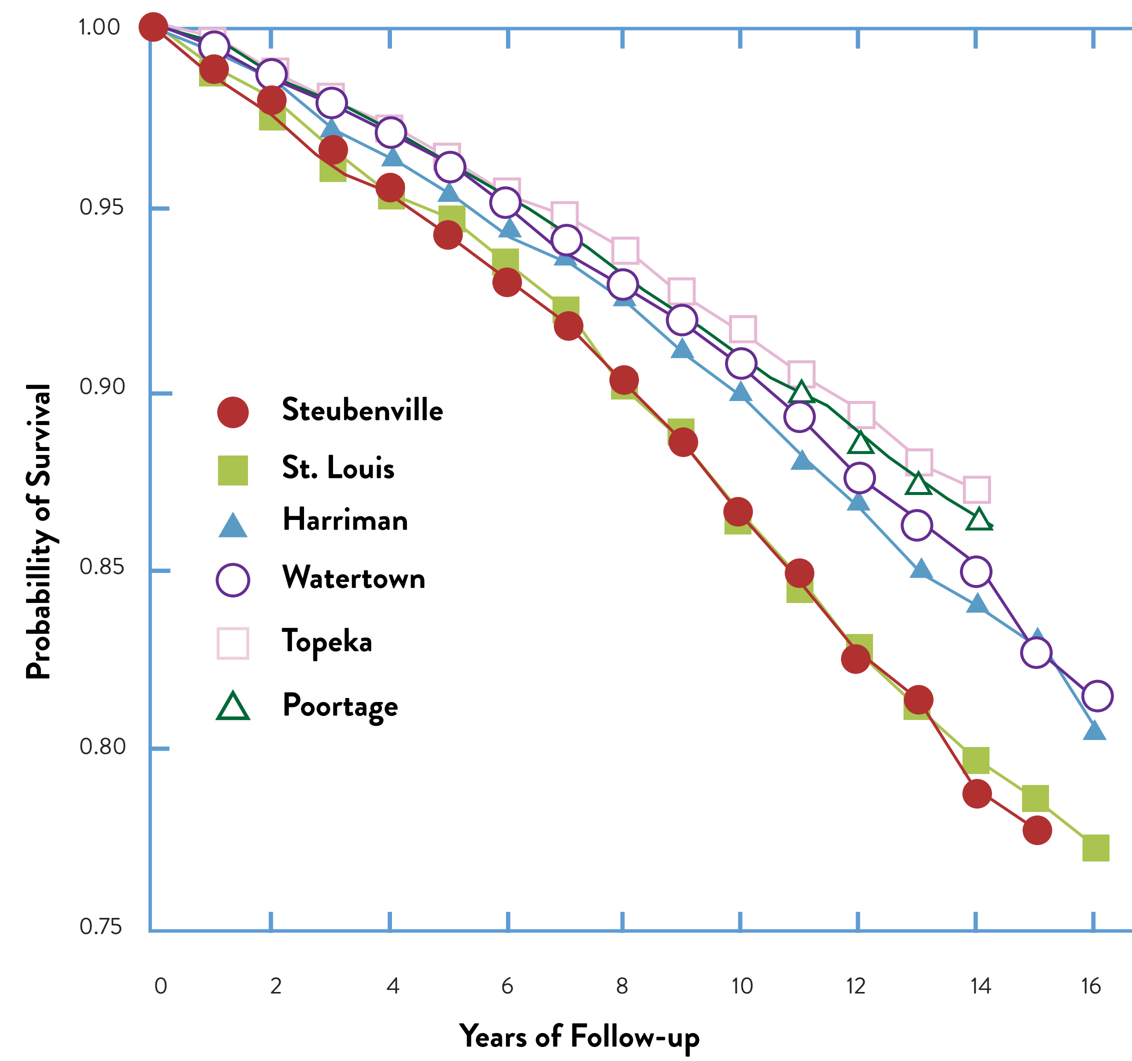


Figure 2.1. Six Cities Study: Crude probability of survival vs. years of follow-up

This study was soon followed by a larger cohort study, the American Cancer Society (ACS) study [14]. Consistent with the Six City study, the ACS study found an association between $PM_{2.5}$ concentrations and mortality. However, the size of the effect was about one third smaller, that is for each 1 μg/m^3 increase in ambient levels of $PM_{2.5}$ mortality rates increased by about 0.4%. The ACS cohort is more than 50 times larger, triples the number of deaths that occurred during the study period; includes white, black and Hispanic subjects (not only white participants); and, improves the statistical analysis and design to control for individual risk factors.

The Six Cities and the ACS study have been vetted thoroughly and have been extended to include prolonged periods of follow-up, that have increased the number of deaths that occurred during the periods under study and the statistical power of the analysis [15, 16]. During the extended follow-up periods, air quality improved in the cities included in these cohorts, and the authors found that mortality was reduced, and life expectancy was extended. This is relevant for our project in Mexico City, given the improved air quality today compared to pollution levels in the 90s.

The qualitative consistency of results from these studies is noteworthy. Both found that cardiovascular mortality (a broad category that includes ischemic heart disease and cerebrovascular stroke) and lung cancer mortality were associated with long-term $PM_{2.5}$ exposures. Also, the concentration-response function was found to be nearly linear within the range of concentrations observed in the cities included in each study -from 5.8 to ~30 μg/m^3 in the ACS, and from 8 to ~30 μg/m^3 in the Six Cities [15-17].

For ozone, only the ACS found a significant association with mortality, possibly because of the broader range of ozone exposures in the cities that were included in this cohort. The association between seasonal (six month)

1-hour maximum concentrations and mortality was preserved when controlling for $PM_{2.5}$, and the primary effect was on respiratory causes of death [18].

Several new cohort studies have been conducted in the United States, Europe, and Asia. Results have been qualitatively consistent, although there is heterogeneity among their estimated risk coefficients (Figure 2.2). This quantitative variability arises because each study yields a concentration-response relationship for a different population sample (for instance, sub-groups with pre-existing medical conditions or specific occupations). In addition, there are differences between studies in analytical methods and in the elements that comprise the causal chain of the exposure-response relationship. A meta-analysis that evaluated over a dozen cohort studies summary coefficients showed that a 1 μg/m^3 increase in annual average $PM_{2.5}$ concentrations is associated with a 0.6% increment in all-cause mortality, and an 1.5% increment in cardiovascular mortality (figure 2.2) [19].

A worldwide effort known as the Global Burden of Disease (GBD), found that ambient $PM_{2.5}$ and ozone air pollution are ranked in the 10th and 21st positions among the nearly 70 risk factors analyzed for 2010 and 2013. A recent analysis[1] estimated that there were 4.2 million excess deaths worldwide in 2015 attributable to fine particulate air pollution and another 254,000 attributable to ozone. For Mexico, it was estimated that there were 29,000 excess deaths due to $PM_{2.5}$ and 18,100 attributable to ozone.

The GBD assessments found that exposure to $PM_{2.5}$ was causally associated with premature deaths from ischemic heart disease, cerebrovascular stroke, and lung cancer, whereas exposure to ozone was causally associated with deaths from chronic obstructive pulmonary disease. The GBD approach was used as the basis for the analyses the effects of air quality improvements on health in Mexico City between 1990 and 2015.

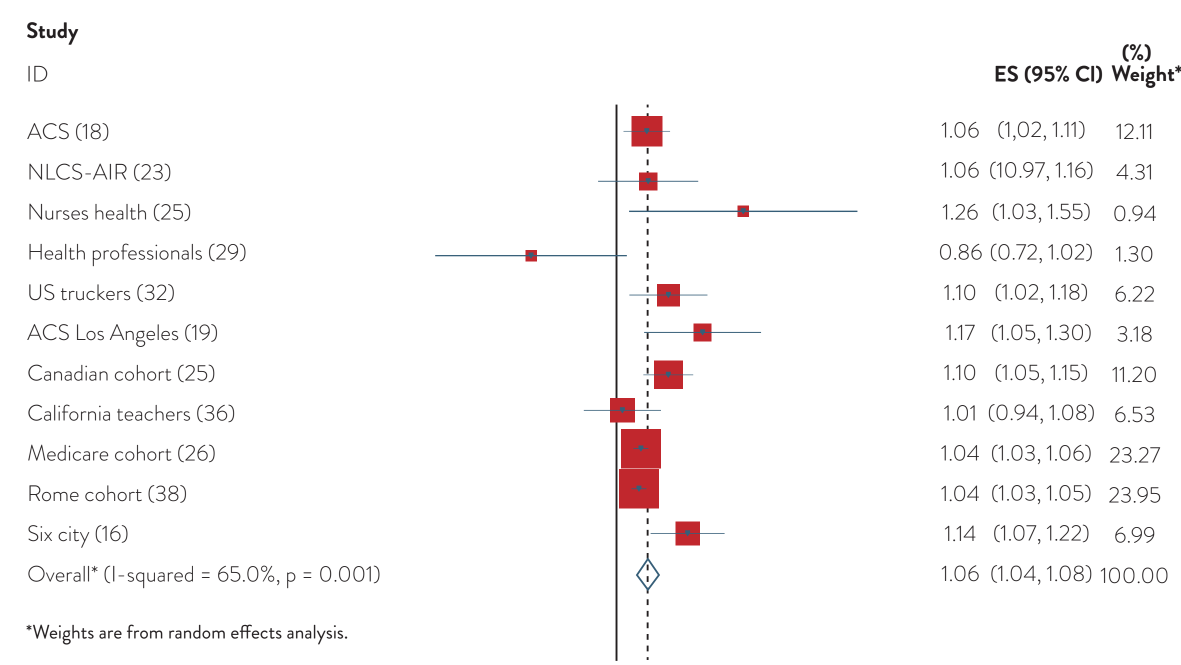
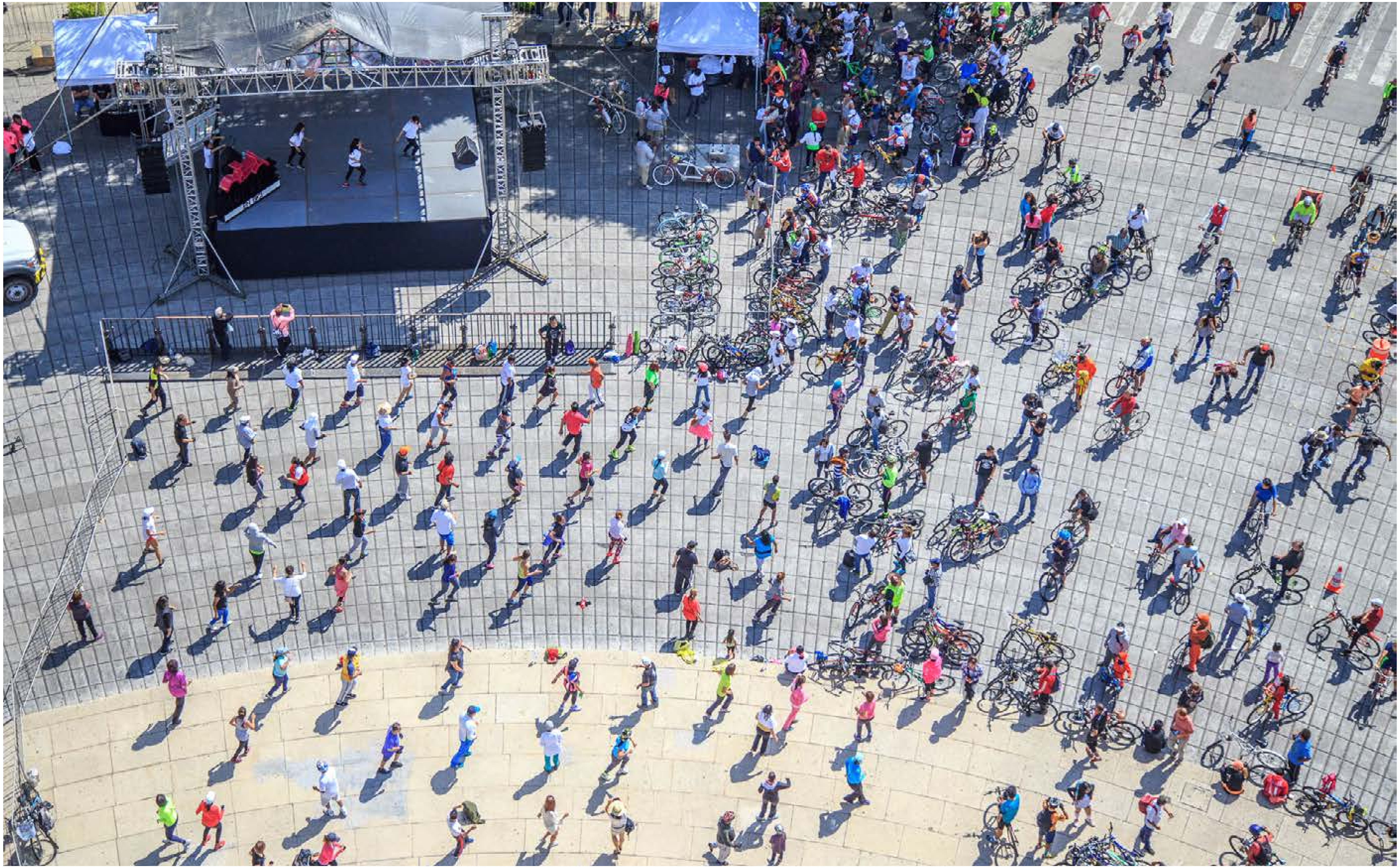


Figure 2.2. Analysis of multiple cohort studies risk estimates for the association between chronic $PM_{2.5}$ exposure and all-cause mortality (Relative Risk per 10 μg/m^3) [19].



PHASE II. ESTIMATION OF THE HEALTH BENEFITS OF AIR POLLUTION IMPROVEMENTS IN CDMX, 1990-2014

Risk assessment of the health benefits attributable to the reductions in fine particulate matter and ozone concentrations that have been achieved, as a result of public policy strategy implementation from 1990 to 2014 in Mexico City.

The impact of air pollution exposures on public health can be measured as "premature deaths" when the assessment refers to the adverse health impacts of air pollution or as "premature deaths avoided" when the assessment refers to the health benefits of air quality improvements. Risk assessment and burden of disease methods have been applied for this purpose globally and locally.

Recently, a worldwide effort known as the Global Burden of Disease (GBD), found that ambient $PM_{2.5}$ and ozone air pollution are ranked in the 10th and 21st positions among the nearly 70 risk factors analyzed for 2010 and 2013 [(20-22)]. $PM_{2.5}$ exposures cause around 3 million premature deaths (GBD 95% uncertainty intervals: 2.6 million to 3.6 million premature deaths). For ozone, the GBD estimated approximately 220 thousand premature deaths (95%UI: 160 thousand to 272 thousand premature deaths) [(20-22)]. The GBD assessments show that exposure to $PM_{2.5}$ causes predominantly premature deaths from ischemic heart disease, cerebrovascular stroke, and lung cancer, whereas exposure to ozone is related with chronic obstructive pulmonary disease.

A few risk assessments have been conducted for Mexico or for Mexico City to assess health impacts of air pollution. $PM_{2.5}$ chronic exposures have been reported to be responsible for 7,600 annual premature deaths per year in Mexico [(23)]. For the Mexico City Metropolitan Area (MCMA) roughly 3,000 premature deaths were attributed to chronic exposures to $PM_{2.5}$, and for Mexico City, 6,100 premature deaths were attributed to PM_{10} chronic exposures [(23, 24)].

The GBD 2010 and 2013 studies analyzed the per-country and per-state burden of disease, including Mexico and Mexico City. For the country, over 13,000 premature deaths attributed to $PM_{2.5}$ chronic exposures, and close to 2,000 to chronic ozone exposures were estimated [(25)]. For Mexico City, estimated attributable deaths per year for $PM_{2.5}$ and ozone were approximately 2,100 and 220, respectively [(25)]. In Mexico City ambient exposures to $PM_{2.5}$ and ozone were among the first 20, out of 70, risk factors that were evaluated (Figure 3.1).

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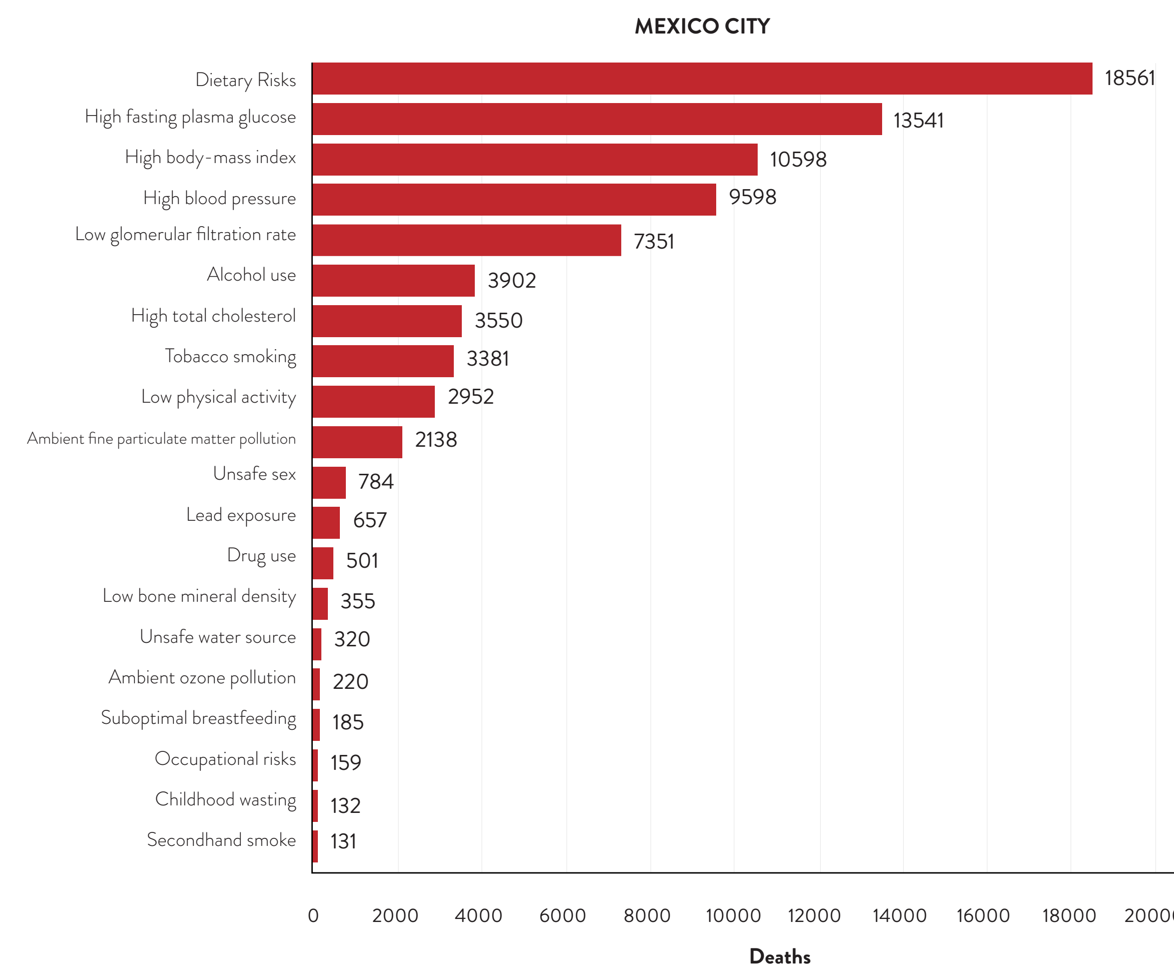


Figure 3.1. Main risk factors and associated premature deaths for Mexico City 2013
Source: Prepared by the authors with information from IHME, 2016.

APPROACH

We applied this indirect method of risk assessment to estimate the benefits associated with air quality improvements in Mexico City in the past 25 years (1990 to 2014). To do so, we characterized the exposure-response relationship to estimate the health benefits accrued due to the improvements in air pollution that occurred in Mexico City since 1990. That is, how much mortality risk decreases for every unit decrease in $PM_{2.5}$ (µg/m^3) or ozone (ppb).

We relied on a novel approach, known as the "integrated exposure response (IER) function", developed and used to support the GBD analyses for 2010 and 2013 [20, 21, 26]. Meta-analysis was used to pool estimates of risk from eight cohort studies of ambient air pollution with results from studies of mortality risk among people exposed to fine particles through active smoking, passive smoking, and use of dirty fuels (coal, dung, wood) indoors for cooking and heating. The GBD analysis of the IER coefficients for fine particle exposures was conducted separately for five classes of disease: for adults, ischemic heart disease, cerebrovascular stroke (haemorrhagic and ischemic), chronic obstructive pulmonary disease, and lung cancer, and for young children, lower respiratory infections.

For ozone, we also followed the approach used by the 2010 and 2013 GBD analyses for estimating mortality risks which relies on analysis of ozone-related mortality in the ACS study [18]. Ozone exposure was assessed as the seasonal average (from 1 April through 30 September) of daily 1-hour maximum ozone values, and the health outcome was chronic obstructive pulmonary disease mortality in adults.

In our analysis the shape of the integrated exposure-response functions for $PM_{2.5}$ and for ozone was constrained by the risk observed in high-exposure settings like active and passive smoking. By constraining the concentration-response functions we were able to better model the risk for $PM_{2.5}$ and ozone elevated concentrations that were observed Mexico City in the 1990s, which were higher than those observed in the cohort studies. In the United States and Europe annual average $PM_{2.5}$ concentrations were lower than 30 µg/m^3 and ozone concentrations did not exceed 104 ppb. In contrast, in Mexico City average $PM_{2.5}$ concentrations from 1990 to 1996 were often on the order of 35 µg/m^3 and were frequently as high as 50 to 60 µg/m^3. In the early 1990s ozone seasonal averages of daily 1-hour maxima were frequently in the range of 120 to 180 ppb, and even reached 200 ppb.

RESULTS

By reducing average ambient $PM_{2.5}$ concentrations from 45 µg/m^3 in 1990 to 20 µg/m^3 in 2014 and simultaneously reducing ambient ozone concentrations from city-wide average of over 160 ppb in 1990 to close to 80 ppb in 2015, Mexico City has been able to reduce the number of deaths attributable to air pollution over this 25-year period by an estimated 22.5 thousand, with a 95% Confidence Interval of 17.9 to 28.0 thousand (Table 3.1.). Roughly 80% of the benefits are due to improvements in $PM_{2.5}$.

Air Pollutant Exposure	Attributable Deaths Avoided (thousands)	CI 95%
Ozone	4.1	(2.7-5.6)
$PM_{2.5}$	18.2	(14.0-23.5)
$PM_{2.5}$ & Ozone	22.5	(17.9-28.0)

Table 3.1. Attributable deaths avoided due to reduction of $PM_{2.5}$ and O_3 exposures in Mexico City, 1990 – 2014

The largest part of the impact is due to reduction of mortality from ischemic heart disease and chronic obstructive pulmonary disease (Figure 3.2, upper panel). Cerebrovascular stroke and lung cancer among adults, and lower respiratory infections among young children also contribute, but together they account for only about one fourth of the mortality benefits of air pollution improvements.

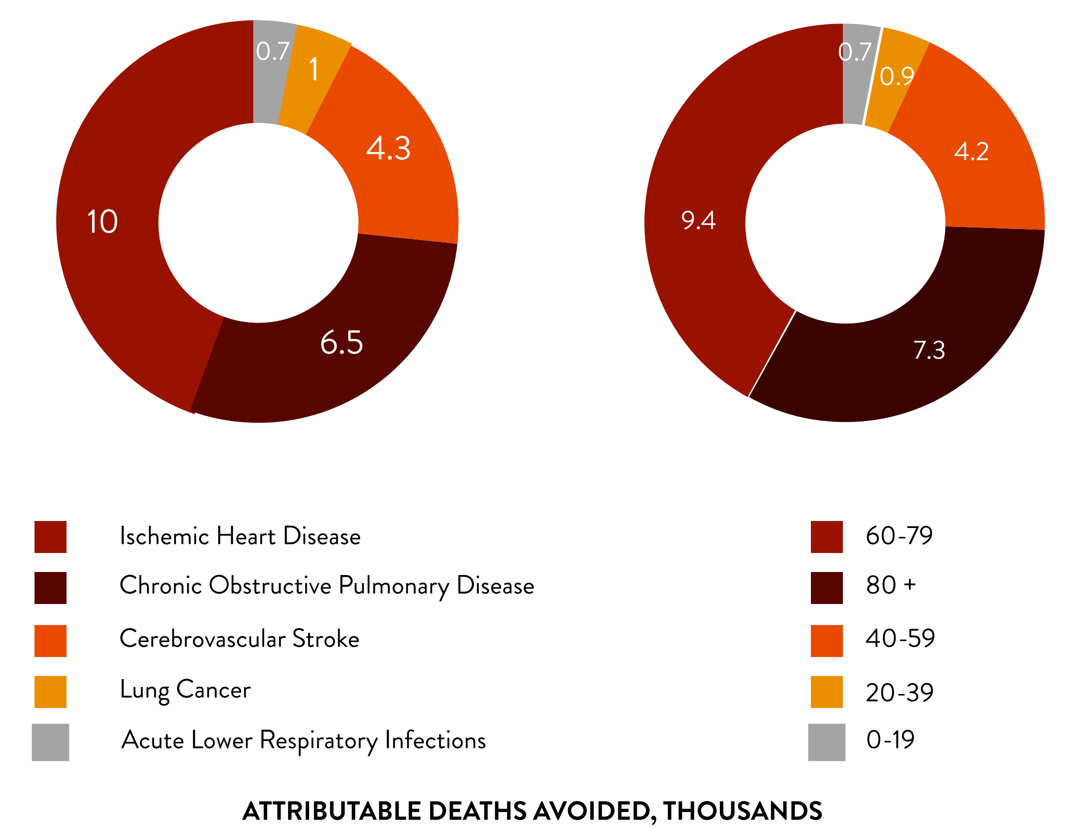


Figure 3.2. Contributions of specific causes of death (upper pane) and age-groups (lower pane) to the expected number of premature deaths (1000's) avoided by reduction of $PM_{2.5}$ and O_3 exposures in Mexico City, 1990 – 2014 (Attributable deaths avoided in thousands).

We also find that the impact of air pollution on mortality is concentrated among the elderly because air pollution primarily affects chronic diseases (Figure 3.2, lower panel). However, when viewed from the perspective of their impact on longevity, deaths among young children from acute lower respiratory infections become much more important. Each of these deaths among children involves many decades of lost life expectancy. In contrast, deaths among adults due to ischemic heart disease, cerebrovascular stroke, chronic obstructive pulmonary disease, or lung cancer typically involve loss of life expectancy of perhaps one or two decades.

The choices made among our analytical assumptions have impacts on our estimates of health benefits. For instance, if we had not constrained the ozone concentration response function, our central effect estimate would have been ~20% larger (27.0 attributable deaths, 95% CI 21.1 to 33.4 thousand). Likewise, if we had used 1993 instead of 1990 as the reference year, our central estimate would have been ~20% lower (17.8 attributable deaths, 95% CI 13.9 to 22.4 thousand).

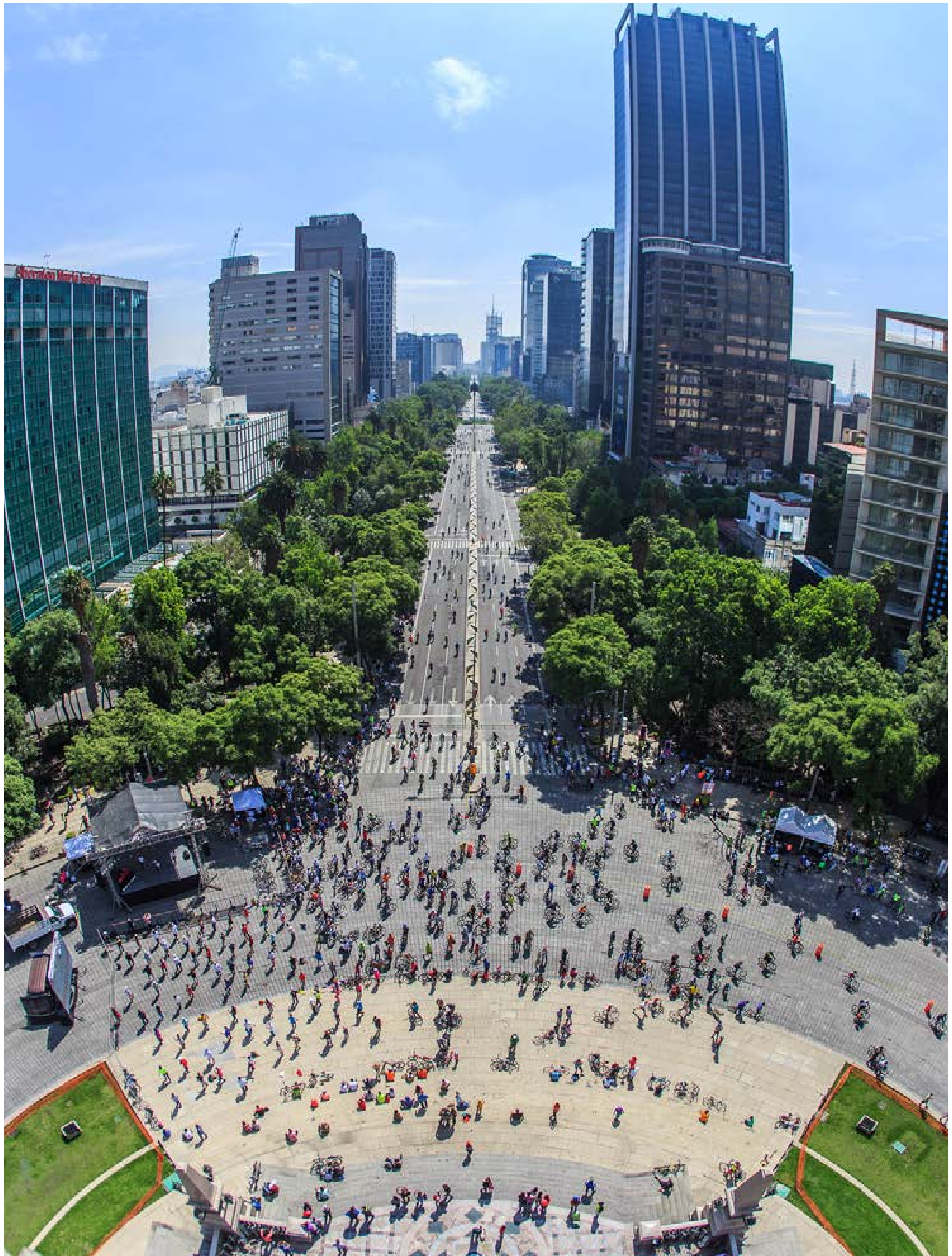
Our estimates have imprecision, with a 95% confidence interval that ranges from almost 18 to 28 thousand deaths attributable to air pollution. This uncertainty arises from the fundamental scientific uncertainty about the true concentration-response functions for $PM_{2.5}$ and ozone, and from uncertainties in the estimates of population exposures. Exposure uncertainties include $PM_{2.5}$ and ozone measurement at monitoring sites, limited monitoring sites in the earlier years of the study period, the spatial interpolation of concentrations from these sites to the alcaldías, and the need to estimate $PM_{2.5}$ concentrations before 2004 when $PM_{2.5}$ was not measured.

INTERPRETATION

The essential finding is that reductions in $PM_{2.5}$ and ozone over the past twenty-five years have led to substantial improvements in health and reductions in mortality, saving ~ 20 thousand lives over the period.

It is important to recognize that, lives cannot be saved by air pollution controls or any other public policy intervention, but rather are extended. This report uses the measure of 'premature deaths avoided' as a proxy for the increases in life expectancy achieved by improvements of air pollution. Reducing air pollution levels leads to increases in life expectancy. The analyses of life expectancy increases associated with air pollution improvements were conducted in Phase III of this project.

Finally, this analysis assumes that, without the rigorous air pollution controls put in place since 1990, air quality would have remained as it was through the study period. In reality with the growth of the population, the size increase of the pool of middle aged and elderly segments of the population who are most susceptible to mortality due to chronic exposure to air pollution, plus growth in economic activity in Mexico City and the surrounding urbanized area, it is virtually certain that without substantial regulation, air pollution levels would have increased. Thus, our estimates of the mortality benefits of these controls almost certainly underestimate the true benefits of government regulations and programs.



PHASE III. VERIFICATION OF HEALTH BENEFITS DUE TO IMPROVED AIR QUALITY IN MEXICO CITY

Quantify the public health benefits of air quality improvements in terms of life expectancy using epidemiological analyses of alcaldía-specific health outcomes, air pollution, and additional risk factors in Mexico City from 1990 to 2015.

The objective of these analyses is to validate that the postulated health benefits of improved air pollution in Mexico City can be observed in surveillance data. That is, can the posited air pollution associated health effects assumed in the risk assessment can be observed in the Mexico City population over the last 25 years. The risk assessment is based on the approach of the Global Burden of Disease (GBD) Comparative Risk Assessment [20-22]. The GBD air pollution associations were based on extensive review of the worldwide literature and meta-analyses to develop exposure response functions which can be applied to populations around the world, including populations lacking direct observational studies of the effects of local air pollution.

Air pollution has been associated with a wide range of health effects ranging from premature death, to clinical conditions such as hospital emergency visits and admissions, or diagnosis of chronic disease, to functional changes such as changes in lung function, blood pressure, or cognitive function, to sub-clinical indicators such as lost school days or increased respiratory symptoms. The GBD and this risk analysis have focused on premature mortality as offering the strongest evidence of association, and the most compelling evidence in terms of economic effects. Moreover, the most compelling evidence came from prospective follow-up studies of time to death in populations exposed to varying levels of fine particle ($PM_{2.5}$) and ozone (O_3) air pollution. The GBD found community annual average $PM_{2.5}$ was causally associated with increased total mortality rates and increased mortality among adults (>25 years) from ischemic health disease, cerebrovascular stroke, chronic obstructive pulmonary disease, and lung cancer. Among children (0-4 yrs) $PM_{2.5}$ was causally associated increased mortality from acute lower respiratory infections. Increased seasonal average peak O_3 was independently associated with increased mortality from chronic obstructive pulmonary disease among adults.

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This should not be interpreted to mean that there are not effects on other health outcomes, for other air pollution components, or for other exposure time periods. Rather these $PM_{2.5}$ and O_3 associations with mortality are well documented and representative of the net effects of the larger range of air pollution exposures.

The objective of these analyses is therefore to evaluate whether the observed changes in health of the Mexico City population over the past 25 years are consistent with expected changes given the improvements in air quality over that time period.

As summarized in Phase I, there is observational evidence of health effects associated with short term air pollution exposures in the Mexico City population. However, there are not as yet longitudinal follow-up studies of mortality in the Mexico City population, consistent with the larger body of evidence for chronic mortality air pollution studies which are the basis for the GBD Comparative Risk Analyses.

We have taken an alternative approach to examine routinely collected alcaldía level surveillance data from death records, census, and environmental monitoring.

This approach examines the substantial differences in life expectancy and air pollution between alcaldías in each of the census years, and the substantial changes in life expectancy and air pollution between census years between 1990 and 2015.

AIR QUALITY

Alcaldía specific $PM_{2.5}$ and O_3 exposure metrics for each year from 1990 to 2015 were estimated based on routine particle and ozone monitoring, extrapolation of the $PM_{2.5}$ record through generalized additive models, and spatial interpolation from monitoring site to alcaldía level.

To illustrate, Figure 4.1. shows the alcaldía-specific mean $PM_{2.5}$ concentrations in three representative years - 1990, 2000 and 2015. In 1990 annual average $PM_{2.5}$ concentrations were estimated to exceed 40 μg/m³ in alcaldías in the north. Average $PM_{2.5}$ concentrations in Mexico City were close to 36 μg/m³. By 2015 levels in all alcaldías were below 23 μg/m³ and city-wide average levels equaled 21 μg/m³.

O_3 also has shown very significant improvements (Figure 4.1). City-wide average levels, estimated as seasonal (6 month) 1-hour daily maximum concentrations, in 1990 ranged between 117 and 185 ppb among Mexico City alcaldías, and were above 160 ppb in the southwest. The steady decline in O_3 concentrations through the City led to 2015 mean levels of 84 ppb, and values below 91 ppb in all alcaldías.

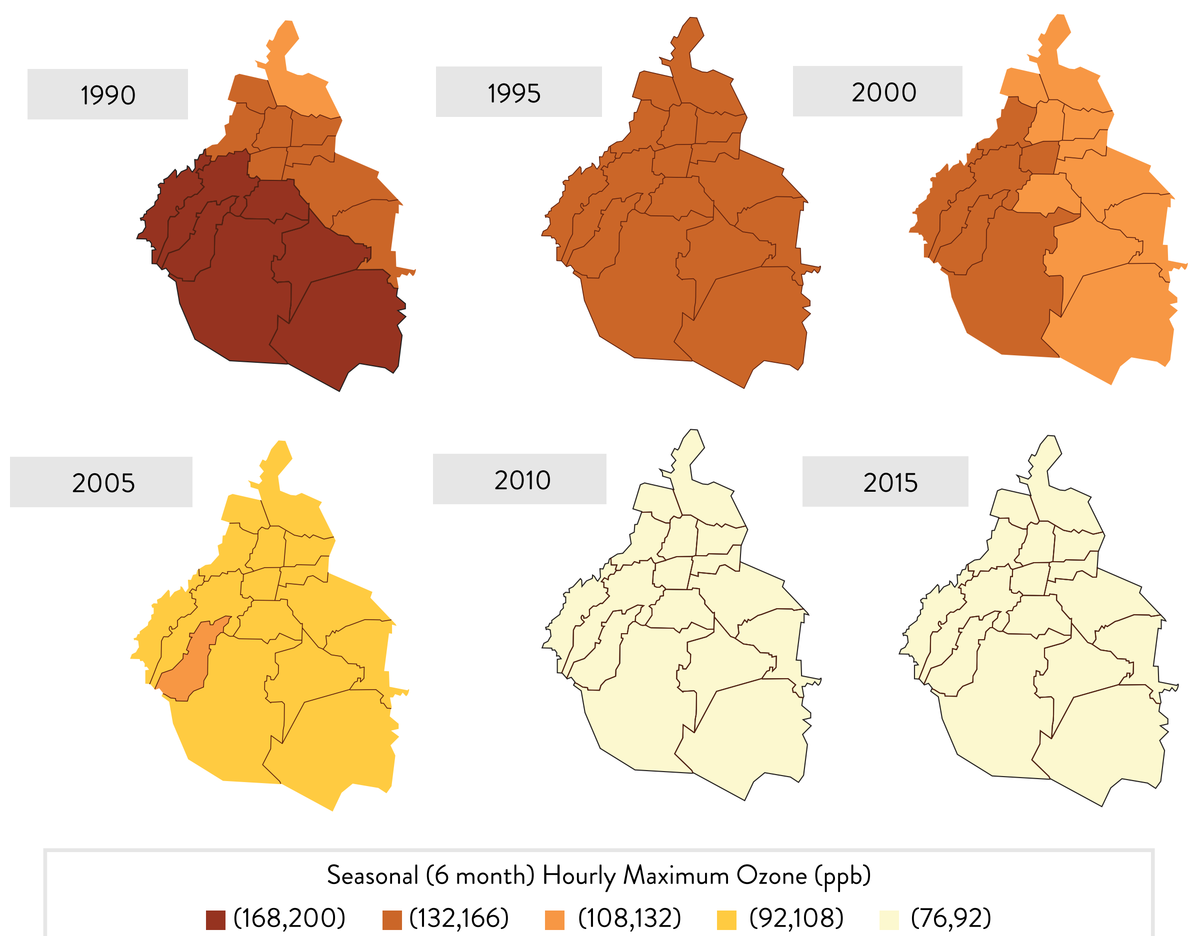


Figure 4.1. Alcaldía-specific mean annual $PM_{2.5}$ and seasonal (6 month) 1-hour maximum O_3 concentrations (ppb) for representative years during study period.

LIFE EXPECTANCY AND YEAR LIFE LOST

Life expectancies for each alcaldía and census year were computed from death counts. Life expectancy at birth for total Mexico City population increased by almost 8% from close to 72 years in 1990 to almost 78 years in 2015 (Figure 4.2).

We calculated interval life expectancies within specific age ranges. For adults aged 25 to 74 years, the interval life expectancy in 1990 was close to 42 years, compared to a total possible of 50 years, rising to almost 44 years by 2015. For children 0-4 years, interval life expectancy increased from 4.87 in 1990 to 4.95 years in 2015.

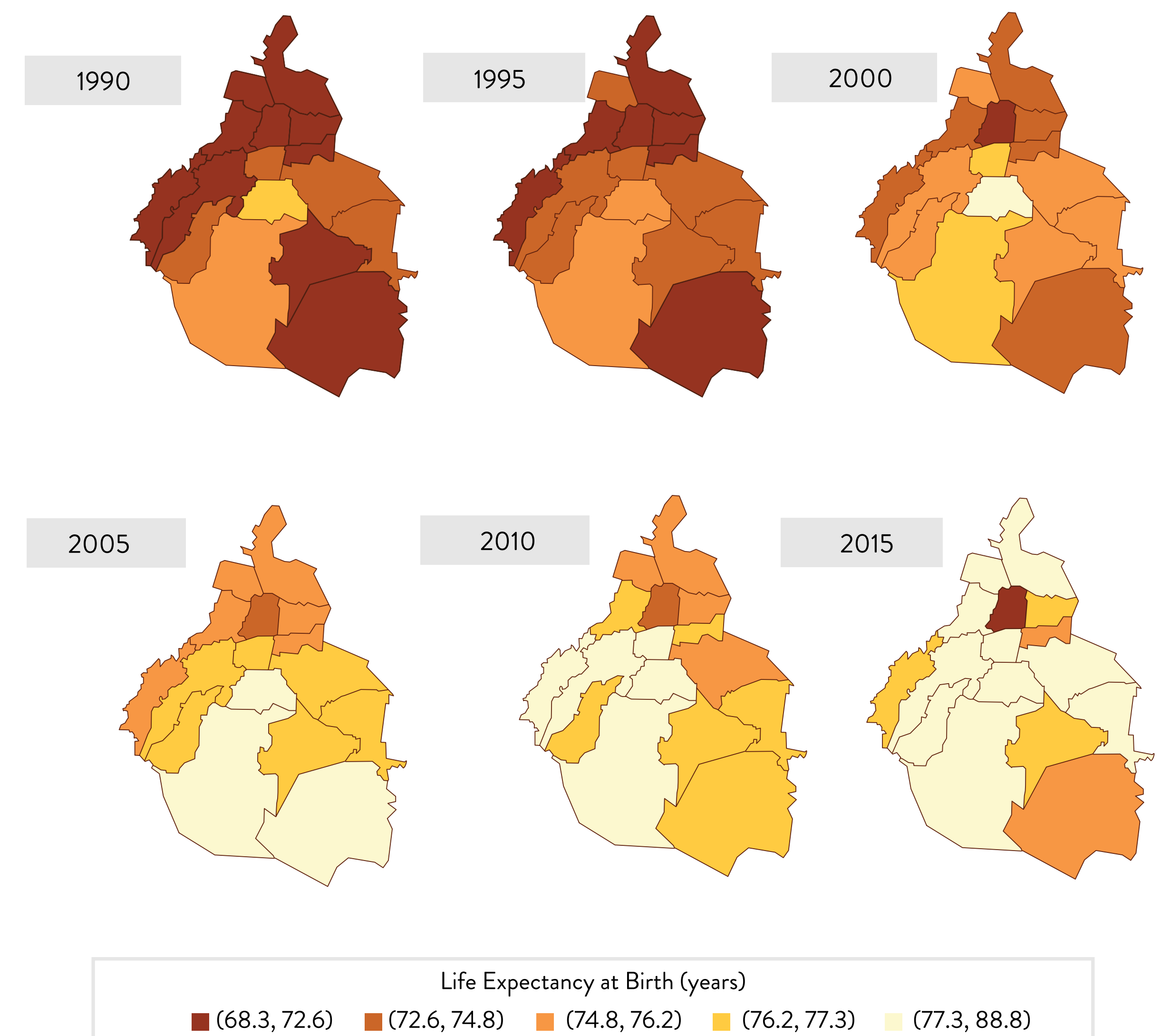


Figure 4.2. Time trends of alcaldía-specific life expectancy at birth (years)

Years life lost is the difference between possible years of life and observed interval life expectancy. In addition to total years life lost, we examined years of life lost from the five selected causes of death associated in the GBD with exposures to $PM_{2.5}$ or O_3 – ischemic heart disease, cerebrovascular stroke, lung cancer, chronic obstructive pulmonary disease among adults (25 to 74 years), and acute lower respiratory infections among children (0 to 4 years). Table 4.1. shows the trends in years of life lost for adults and children for these causes for the entire Mexico City population.

	25 TO 74 YEARS					0 TO 4 YEARS	
CENSUS YEAR	Total	Ischemic Heart Disease	Cerebrovascular Stroke	Lung Cancer	Chronic Obstructive Pulmonary Disease	Total	Acute Lower Respiratory Infections
1990	8.22	0.89	0.20	0.14	0.24	0.125	0.015
1995	7.68	0.86	0.18	0.12	0.18	0.097	0.011
2000	6.69	0.74	0.21	0.10	0.16	0.078	0.006
2005	6.24	0.74	0.17	0.09	0.14	0.071	0.007
2010	6.07	0.70	0.16	0.09	0.14	0.062	0.004
2015	6.17	0.68	0.13	0.08	0.11	0.047	0.004

Table 4.1. Years of life lost between 25 and 74 years and 0 to 4 years of age, total and by causes related to air pollution for Mexico City

SOCIO-ECONOMIC POSITION INDICATORS

Life expectancy also is affected by socio-economic position. This study relies on CONAPO's socioeconomic position indicators constructed from census data. Table 4.2. shows the fraction (%) of the population of Mexico City reporting each of CONAPO's socioeconomic position indicators for 1990 to 2015.

YEAR	Low Income	Overcrowding	Low Education	Illiterate	No Sewer / Toilet	No Electricity	No Running Water	Soil Floor	Small Villages
1990	62	48	17.5	4.4	1.1	1.1	4.3	3.5	1.3
1995	47	47	12.0	3.1	0.1	0.1	2.9	1.1	1.3
2000	42	36	12.2	3.0	0.2	0.2	1.8	1.7	1.1
2005	33	30	9.6	2.6	0.2	0.2	2.0	1.4	1.5
2010	28	26	8.5	2.1	0.1	0.1	2.4	1.2	1.8
2015	28	20	6.5	1.5	0.1	0.1	1.7	0.6	1.8

Table 4.2. Behavior of Socioeconomic Position Indicators for Mexico City (%), 1990-2015

There have been substantial improvements in these socioeconomic position indicators over this 25-year period in Mexico City. To illustrate, the fraction of houses with some degree of overcrowding dropped from 48% to 20% between 1990 and 2015 (Table 4.2). However, as shown in Figure 4.3. there were equally large differences between alcaldías in 1990 which had been substantially reduced by 2015.

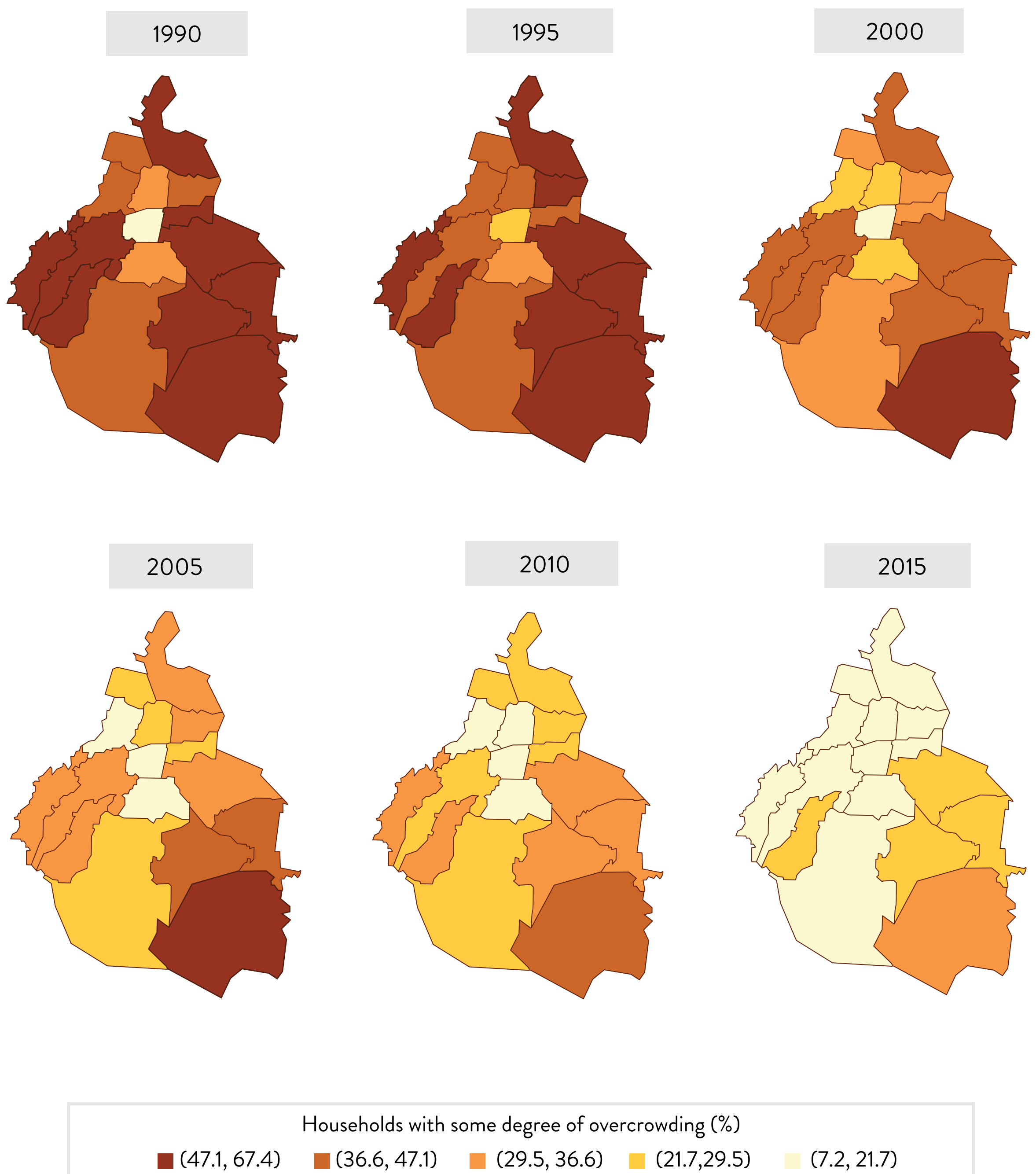


Figure 4.3. Spatial distribution of alcaldía-specific households with some degree of overcrowding (%) by year

REFERENCE CAUSES OF DEATH

Changes in life expectancy or in years of life lost are likely to be associated with factors not captured by the socioeconomic position indicators described above. Such risk factors may include individual behavioral factors like nutrition, or institutional factors such as access to health care. To provide insight into these unmeasured risk factors, we include "reference" causes of death, which are common causes of death not expected to be associated with air pollution. Reference causes of death in these analyses are diabetes, hypertension, colon cancer, stomach cancer, and external causes (including assault).

Diabetes mortality rates increased from 117 per 100,000 in 1990 to 172 in 2015 (Figure 4.4). Hypertension mortality rates also show an increase of close to 30%, with rates of 25 to 33 per 100,000 in 1990 and 2015, respectively. Colon cancer mortality increased as well, with an 80% surge (6.6 in 1990 to 12 per 100,000 in 2015). In contrast, mortality rates of stomach cancer in Mexico City have shown little change from 1990 to 2015, remaining close to 11 per 100,000 throughout the period.

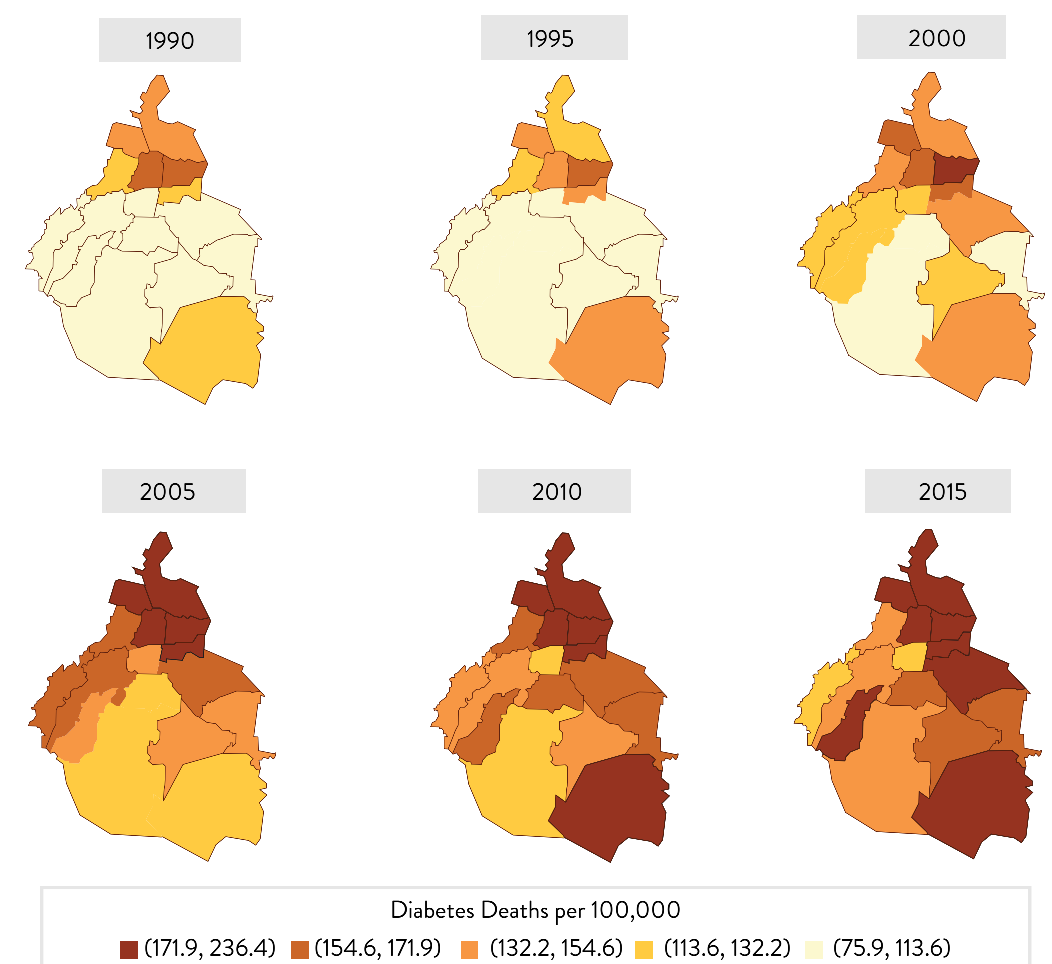


Figure 4.4. Time trends of alcaldía-specific diabetes mortality rates (deaths per 100,000)

External causes include deaths by assault (homicide and injuries inflicted by another person with intent to injure or kill by any means). There is some heterogeneity in the alcaldía-specific rates of mortality due to external causes; it's noteworthy that Cuauhtémoc shows high rates thorough the period and higher rates than the rest of the alcaldías in 2015 (Figure 4.5).

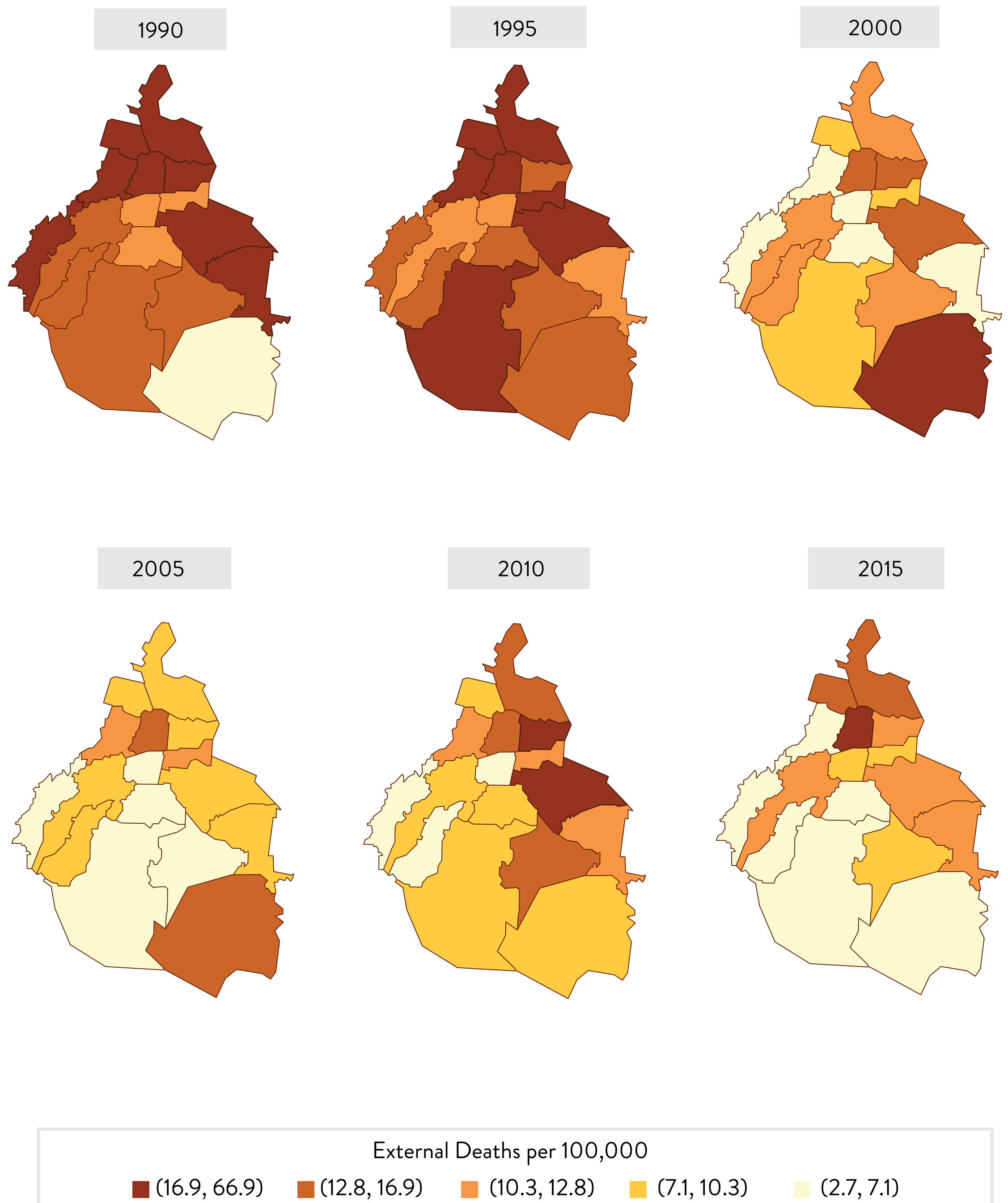


Figure 4.5. Time trends of alcaldía-specific external causes' mortality rates (deaths per 100,000)

SMOKING RELATED DISEASES

Due to limited smoking prevalence data, we used death rates for COPD and lung cancer as proxy indicators of exposure to smoking. The COPD mortality rate in Mexico City dropped during the study period, from 44 to 36 deaths per 100,000 in 1990 and 2015, respectively. There was limited between-alcaldía variability through the period (Figure 4.6).

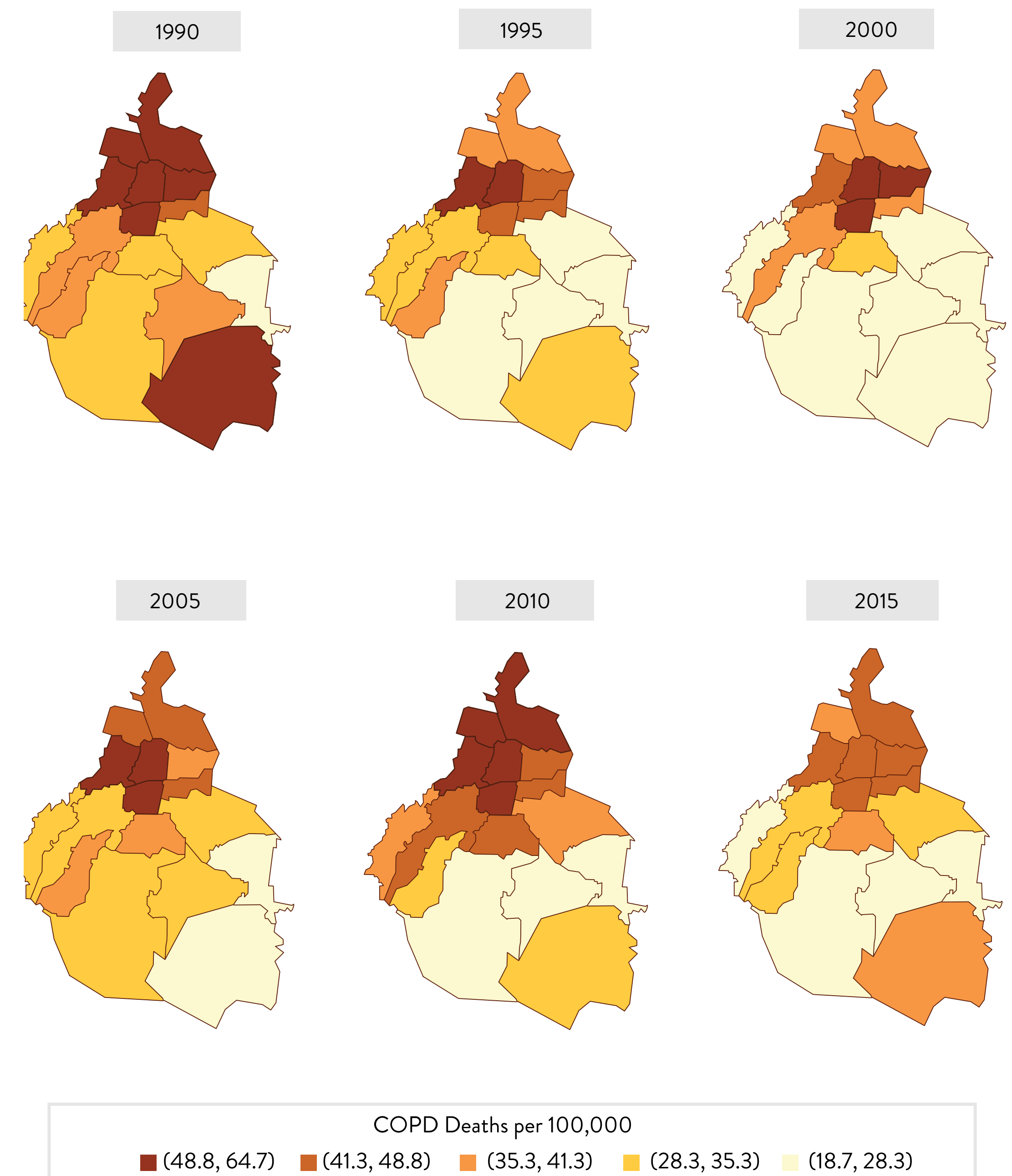


Figure 4.6. Time trends of alcaldía-specific COPD mortality rates (deaths per 100,000)

Lung cancer mortality rates in Mexico City have changed little over the 25-year study period, from 13 to 12 deaths per 100,000 between 1990 and 2015 (Figure 4.7).

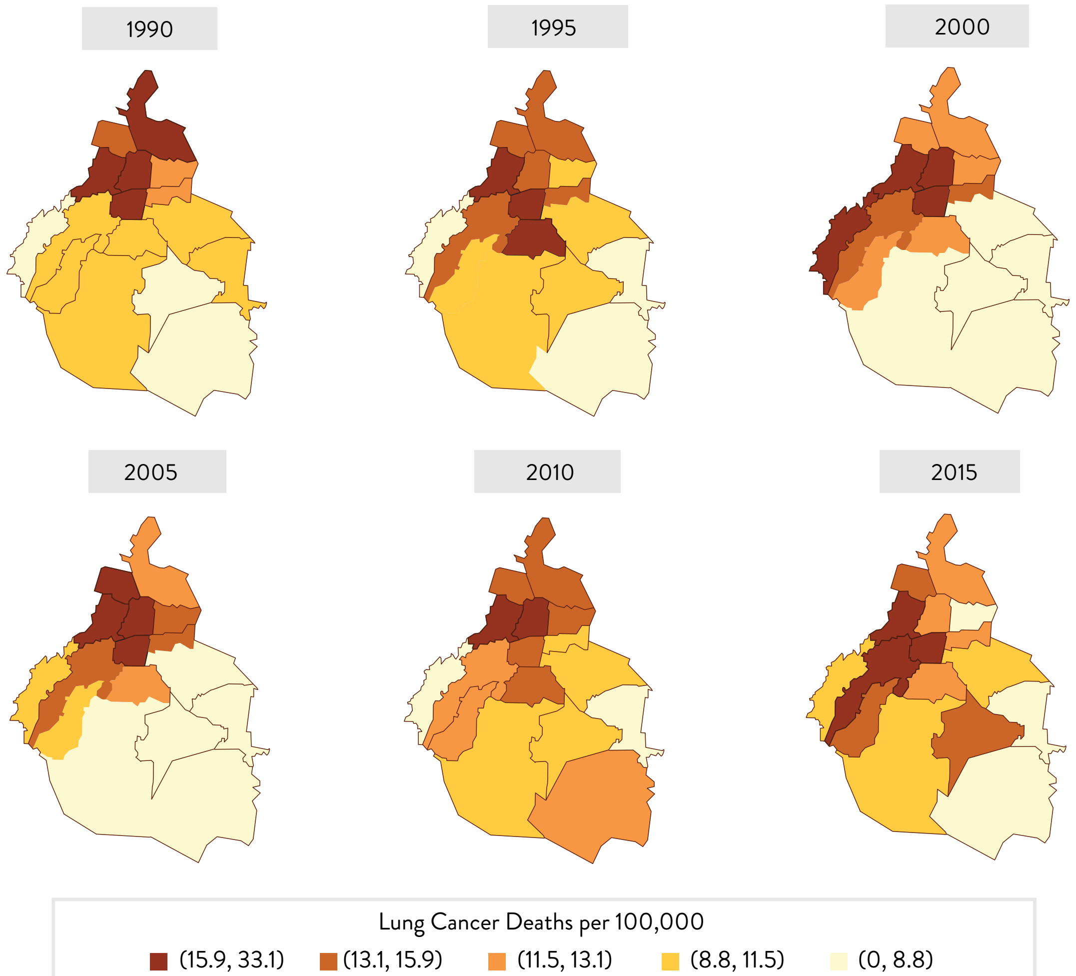


Figure 4.7. Alcaldía-specific lung cancer mortality rates (deaths per thousand) in 1990, 2000, and 2015

AIR POLLUTION ASSOCIATIONS

Our analyses seek to assess how life expectancy and years of life gained are affected by alcaldía-specific air pollution controlling for possible confounding by individual, population, and community risk factors.

Plots of life expectancies versus air pollution suggest negative associations between alcaldía- and year-specific life expectancy and both $PM_{2.5}$ (Figure 4.8) and O_3 (figure not shown).

The following figure presents the same data showing the longitudinal relations by alcaldía between life expectancy and $PM_{2.5}$ (Fig. 4.9).

Negative longitudinal (within each alcaldía) associations between life expectancy and $PM_{2.5}$ are observed. A similar negative pattern was noted for the ozone longitudinal relation with life expectancy (figure not shown).

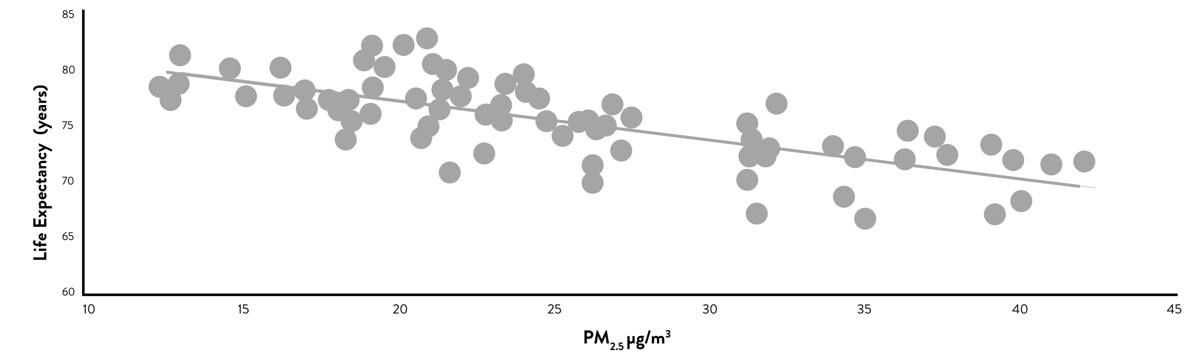


Figure 4.8. Scatterplot and fitted line of alcaldía- and year-specific life expectancy versus corresponding measures of annual average $PM_{2.5}$ concentrations

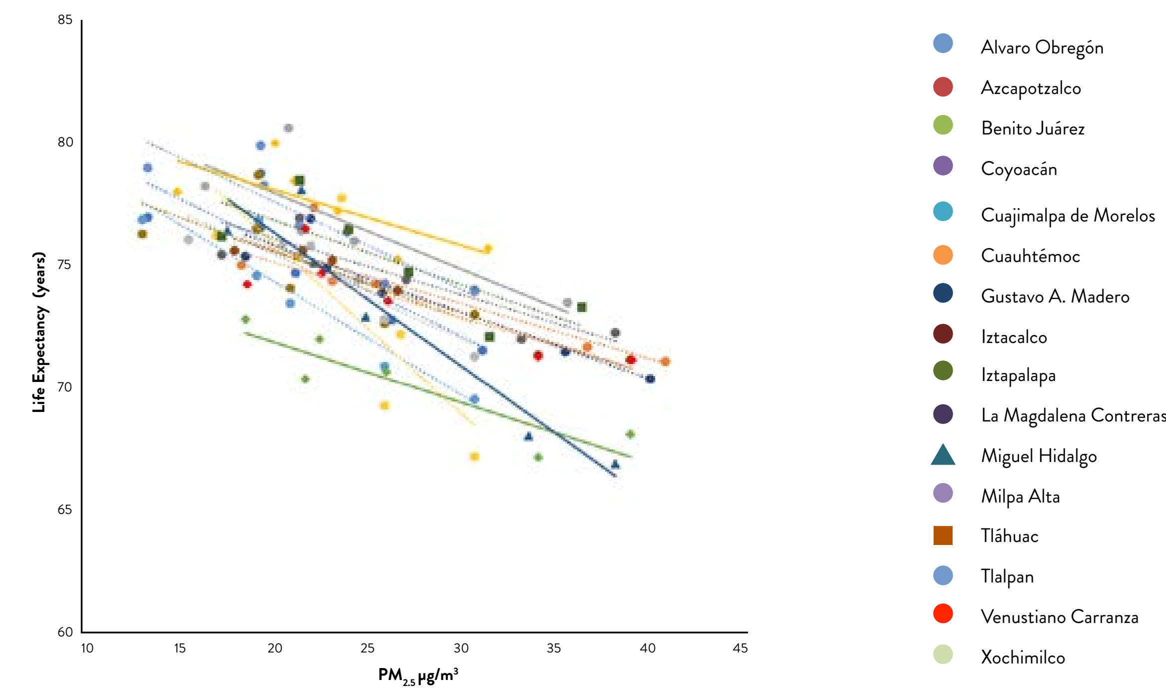


Figure 4.9. Scatterplots and fitted lines of year-specific life expectancy versus annual average PM2.5 concentrations by alcaldía

We built mixed models for the associations of life expectancy with $PM_{2.5}$ and O_3 in a stepwise fashion. We first assumed a linear association of $PM_{2.5}$ and O_3 with life expectancy, and that each alcaldía and that each census year had a separate, random level of life expectancy. We gave more weight to the points with larger populations, weighting by the square root of the population. We added all nine-socio-economic position (SEP) indicators, the death rates for the five reference causes of death and the two proxy indicators of smoking (lung cancer and COPD death rates) for each alcaldía and census year. In this full model, there were only significant associations with ozone, diabetes and COPD death rates, and the random indicator for alcaldía. Therefore, we built a parsimonious model that eliminated in backward stepwise regression all nonsignificant predictors, other than those we defined a priori as critical. This final, parsimonious life expectancy model included the air pollution effects ($PM_{2.5}$ and O_3), the random effects of alcaldía and census year, fixed effects for one SEP indicator (% overcrowding), fixed effects of three reference death rates (diabetes, colon cancer, and external causes), and the two proxy indicators of smoking (lung cancer and COPD death rates).

RESULTS

We applied one Parsimonious Model to each of our health outcome indicators: total and sex specific life expectancy at birth; years of life lost for children and adults; and years of life lost due to specific mortality causes expected to be associated with air pollution (Table 4.3).

Health Outcome	$PM_{2.5}$ (10 µg/m³)	O_3 (10 ppb)
Lifetime	0.89 *	0.24 **
Men	0.79	0.36 ***
Women	0.79 *	0.13
Ages 0-4 year	0.0070	0.0037 *
Acute Lower Respiratory Infections	-0.0033 *	0.0004
Ages 25-74 year	0.56 ***	0.103 **
Ischemic Heart Disease	0.09 *	0.003
Cerebrovascular Stroke	0.023 +	0.001
Lung Cancer	0.013 +	0.003
Chronic Obstructive Pulmonary Disease	0.037 *	0.0052

For these values +P<0.10, * P<0.05, ** P<0.01, *** P<0.001.

Table 4.3. Effects of $PM_{2.5}$ and O_3 in Parsimonious Models of total years of life lost, sex-specific, for two-age groups (0 to 4 years and 25 to 74 years), and for causes of death associated with air pollution, with one model per health outcome

For total life expectancy, the Parsimonious Model showed that improvements in O_3 (10 ppb mean seasonal peak) were significantly associated with 0.24 years of increased life expectancy (95% CI 0.08 to 0.40 years). There was an independent, significant association of improved $PM_{2.5}$ (10 µg/m³ annual mean) with an increase of 0.89 years life expectancy (95% CI .14 to 1.65 years). We found no difference between men and women in their association with $PM_{2.5.}$ The association with O_3 was stronger among men than women, although the confidence intervals of these sex-specific associations were overlapping.

Our results further indicate a statistically significant association of life of years lost between ages 25 and 74 years with $PM_{2.5}$ (0.56 years) and with O_3 (0.103 years). For this age-group $PM_{2.5}$ was associated with significant increases in years of life lost attributable to ischemic heart disease (IHD) and chronic obstructive pulmonary disease (COPD); also, there were positive, marginally statistically significant (p<0.10) associations for cerebrovascular stroke and lung cancer with $PM_{2.5}$. We found a positive, but statistically nonsignificant association of O3 with COPD and lung cancer deaths. Recall that the Global Burden of Disease Comparative Risk Analyses found causal associations of $PM_{2.5}$ with these four causes of death among adults >25 years of age The GBD also found causal associations of O_3 with deaths only from chronic obstructive pulmonary disease.

For children between ages 0 and 4 years, we found modest, statistically non-significant increases in years of life lost associated with $PM_{2.5}$ and O_3, but no association with acute lower respiratory infections (ALRI). In comparison, the GBD analyses postulated a causal association between ALRI and $PM_{2.5}$ in this age group.

INTERPRETATION

Life expectancy in Mexico City inhabitants is affected by exposures to air pollution. We found that over the past 25 years air quality improvements in Mexico City have been associated with increased life expectancy.

For $PM_{2.5}$ we found that for each 10 µg/m³ improvement in annual mean, there was an increase of 0.89 years life expectancy (95% CI .14 to 1.65 years). The evidence for longer life expectancy in Mexico City associated with reduced $PM_{2.5}$ is very consistent with, although larger than, similar studies of county-specific life expectancy changes in the United States. Pope et al. (27) and Correia et al. (28) reported, respectively, that life expectancy increased by 0.61 years (95% CI 0.22 to 1.00) and 0.35 years (95% CI 0.04 to 0.66) associated with each 10 µg/m³ improvement in annual average $PM_{2.5}$.

There is limited evidence that living in communities with higher O_3 is associated with increased mortality and shorter life expectancy independent of $PM_{2.5}$. It is likely that the differential spatial variability pattern of O_3 and alcPM2.5 concentrations in Mexico City, with high O_3 levels in the southwest vs. high $PM_{2.5}$ levels in the north and northeast, allowed the identification of an independent effect for O_3. The finding in Mexico City that improvements in life expectancy are associated significantly with reductions in O_3 may have been also possible due to the wide range of concentrations seen across the study period, spanning 80 to 160 ppb, which provides the statistical power to detect an association. This is an important contribution to the scientific evidence of population health benefits that result from air quality improvements.

What is the overall effect of the improvements in air quality in Mexico City over the last 25 years? If we apply the Parsimonious Model results to the observed changes in $PM_{2.5}$ and O_3, we can estimate the net benefits. Annual average $PM_{2.5}$ concentrations have decreased by almost 15 µg/m³ from 1990 to 2015, which would imply an increase of 1.3 years in life expectancy. Improvements for ozone, with decreased seasonal 1-hour maximum daily concentrations of almost 80 ppb, would imply an increase in life expectancy of close to 1.9 years. Thus, the joint net benefit associated with improvements in both pollutants represents an increase in life expectancy of 3.2 years. As seen in Figure 4.10, net benefits present a different spatial pattern for $PM_{2.5}$ and O_3.

Greater improved $PM_{2.5}$ air quality in the north has led to larger gains in life expectancy (up to 1.7 years) in those alcaldías attributable to $PM_{2.5}$. Greater improvements in O_3 air quality in the south have led to larger gains in life expectancy (up to 2.6 years) attributable to O_3. Together, the joint effects of the improvements in $PM_{2.5}$ and O_3 have led to substantial improvements in life expectancy (2.6 to 3.4 years) in all alcaldías (Figure 4.10).

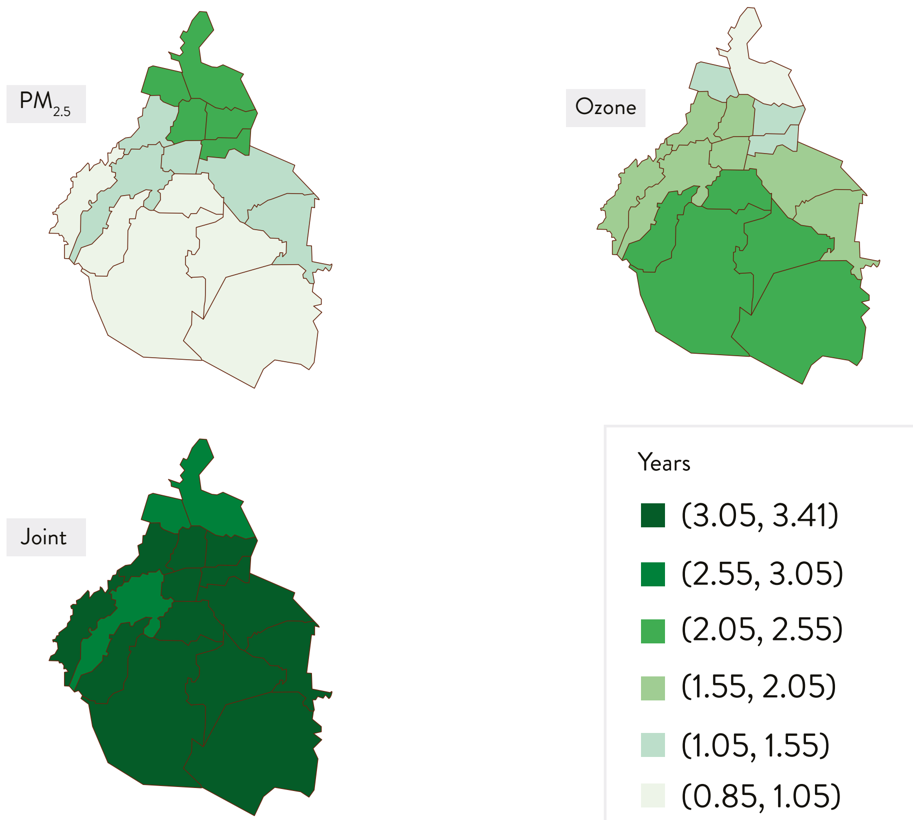
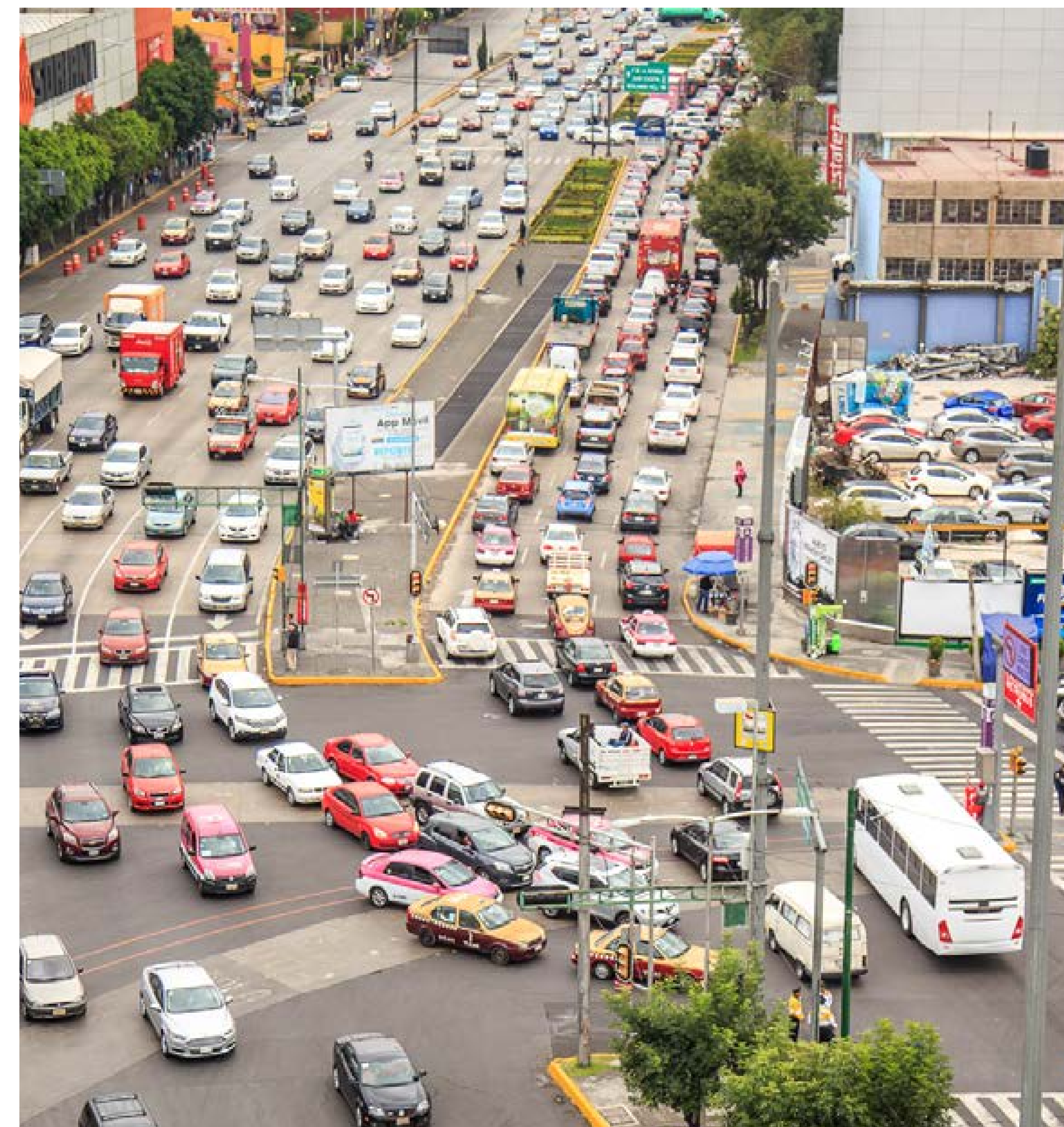


Figure 4.10. Independent and joint net benefits measured as life expectancy gains (years) from improved annual average $PM_{2.5}$ concentrations and seasonal maximum 1-hour daily ozone concentrations in Mexico City, 1990 – 2015

A recent estimation of the net effect of air pollution on life expectancy using the GBD approach estimated that current $PM_{2.5}$ exposures reduce life expectancy globally by 1.03 years, and O_3 exposures by 0.05 years (29). They suggest that if all countries met the World Health Organization Air Quality Guideline for $PM_{2.5}$ of 10 μg/m^3, median life expectancy could increase by 0.6 years (interquartile range of 0.2–1.0 year), a benefit of a magnitude that is similar to that of eradicating lung and breast cancer together. They report an average $PM_{2.5}$ for Mexico (i.e. the whole country) of 18.3 μg/m^3 which implies an average of 0.48 years life lost due to $PM_{2.5}$. Our results, based on analyses using direct alcaldía-specific information on air quality and health-related outcomes, adjusting for socio-economic position indicators and proxy indicators of accumulated exposure to smoking, are consistent with world-wide most recent findings that indicate that air quality improvements have beneficial public health effects, measured as increased life expectancy and reduced life years lost. Therefore, public policies aimed at further improving air quality should be encouraged as they will continue to benefit public health.



PHASE IV. SPECIFIC CONTROL POLICY: CLEANING IN-USE HEAVY DUTY VEHICLES

Cost-effectiveness analyses of the technologies to control emissions of primary fine particles from heavy-duty diesel vehicles in Mexico City

We performed a cost-effectiveness analysis focused on heavy-duty diesel vehicle emission controls in Mexico City because of the potential adverse health impacts of diesel emissions to the atmosphere and the fact that the Air Quality Management Plan PROAIRE 2011-2020, specifically Strategy 3 Quality and energy efficiency in all sources, Measure 21, refers to the renewal of diesel vehicles by adopting emissions controls.

Diesel vehicles are a major source of air pollutant emissions, most importantly fine particles. The most recent inventory for Mexico City and the 2014 MCMA Emissions Inventory (30), indicates that mobile sources account for 33% of total primary $PM_{2.5}$ emissions for Mexico City. Heavy duty diesel vehicles, despite their small share of the vehicle fleet (less than 6%), are responsible for 24% of primary fine particle total emissions.

We conducted cost-effectiveness analyses of control technologies for in-use heavy-duty diesel vehicles in Mexico City. The elements involved in our analysis can be summarized as follows (Figure 5.1.):

(I) Control efficiency for reducing baseline diesel particulate matter emissions;

(II) Impacts of emissions reductions on primary fine particle ambient concentrations and resulting reduction in population exposures;

(III) Health benefits from emissions controls and ambient air quality improvements, estimated as reductions in attributable mortality;

(IV) Costs of potential control technologies, i.e., cost of the equipment, installation, associated reduced fuel economy, periodic inspection and maintenance of the equipment; and

(V) Societal values in monetary units of health benefits with the estimated net benefit --comparison of benefits and costs.

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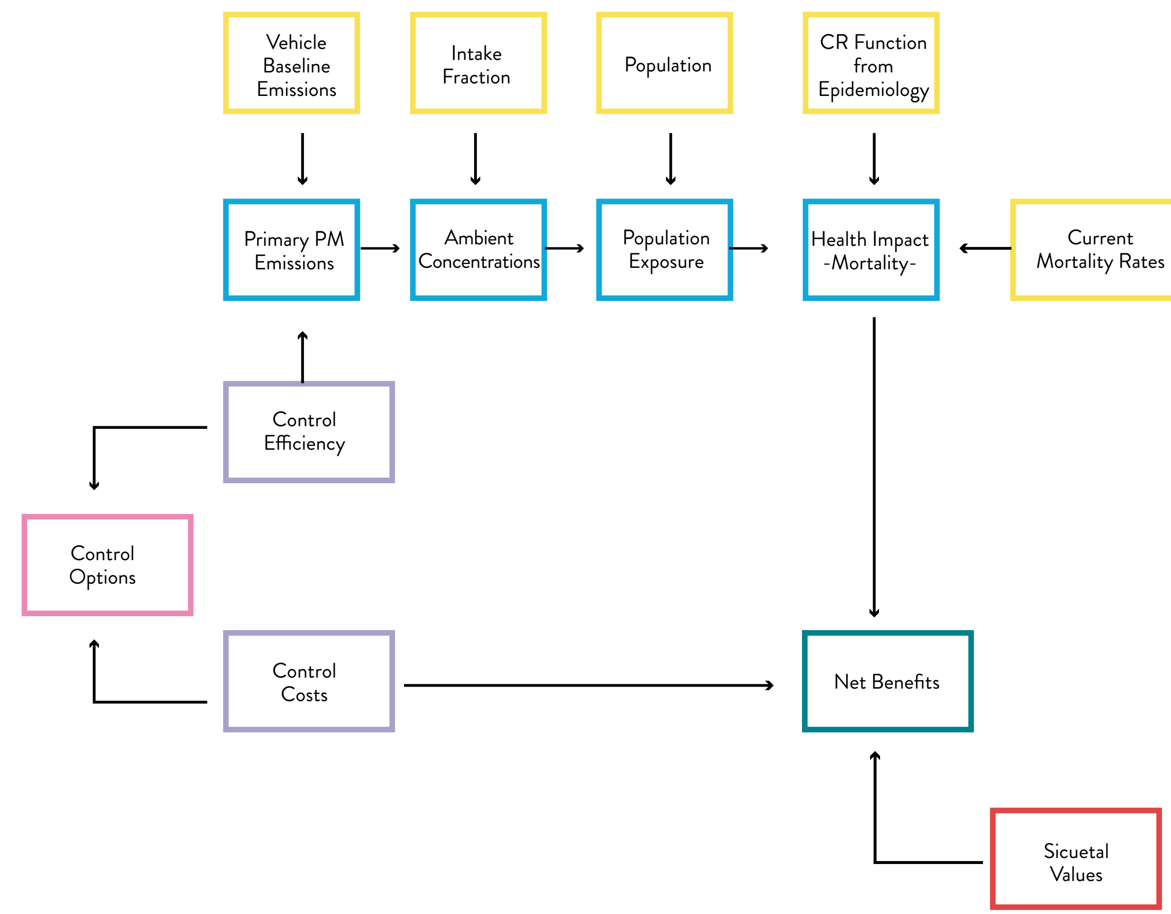


Figure 5.1. Conceptual Model for the Cost-Effectiveness Analysis to Retrofit Heavy-Duty Vehicles in Mexico City, 2014

In Mexico City there are over 100,000 in-use heavy-duty diesel-fueled vehicles, grouped in three main categories which are further divided in 10 classes:

- **Buses:** M1 public transportation, school and personnel, concession, and Metrobús, with local plates; and tourism and passenger with federal plates.
- **Trucks ≥ 3.8 tons:** Medium-sized delivery trucks with local plates (4.6 to 27.2 tons), or federal plates (11.8 to 14.9 tons).
- **Long-Haul Trailers:** Large vehicles, such as tractor trailers, and food supply vehicles weighing over 27.2 tons, with either local or federal plates.

License plates for heavy-duty vehicles may be local or federal, depending on whether they circulate only within the City or on highways that are under federal jurisdiction, regardless of the use of the vehicle, i.e. passengers, tourism or goods.

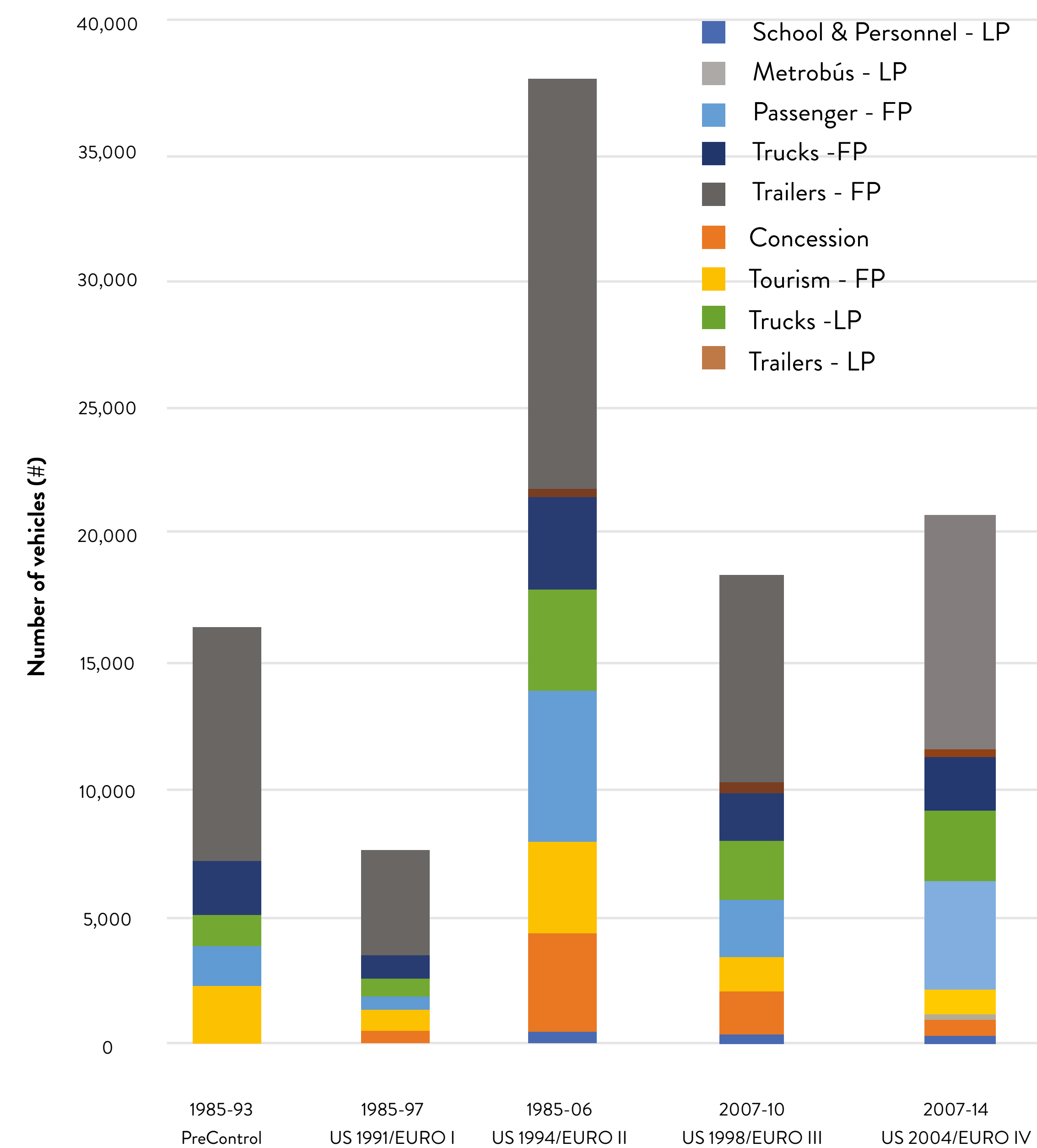


Figure 5.2. Composition of Heavy-Duty Vehicles by Class and Model-Year Group

Our unit of analysis is a single vehicle. We evaluate representative vehicles from each vehicle class and model-year group --to span the range of vehicle types, uses and model years in the heavy-duty fleet operating in Mexico City. We include vehicles from model years 1985 to 2014 in the following model-year groups: 1985-1993 (pre-control); 1994-1997 (US 1991/Euro I); 1998-2006 (US 1994/Euro II); 2007-2010 (US 1889/Euro III); and 2011-2014 (US 2004/Euro IV). We exclude those older than 1984 because the 2014 Emissions Inventory, pools them in one category aggregating a wide range of technologies, and those that were retrofitted under the Autorregulación Program (n=45).

APPROACH

The analysis begins by characterizing each vehicle in terms of its nature (bus, truck, tractor trailer) and age (model-year group), its activity level (vehicle km travelled each year), its baseline emissions rates (g/km travelled) and fuel economy (km/L), and its remaining useful lifetime (yr). Data on age, activity and baseline emissions rates come from the official emissions inventory for 2014 (30), and data on fuel economy from U.S. Department of Energy [31].

Long-haul tractor trailers make up almost half of the fleet, most of them having federal plates. Buses account for about one third of the fleet, with two thirds of these having federal plates serving as tourism or passenger buses. Trucks, split equally between those with local plates and federal plates, account for the remaining 20% of the fleet. The heavy-duty diesel fleet is relatively old (Fig. 5.2.), with roughly 60% of the vehicles of more than 10 years old, 20% of more than 20 years old, and only 20% of vehicles belonging to the most recent model-year group.

Annual kilometers traveled within Mexico City vary considerably between within classes. Concession buses-local plate and long-haul trailers-federal plate account for the most vehicle kilometers travelled (VKT) with averages exceeding 16 million VKT. RTP buses-local followed in activity levels, with an average of almost 9 million VKT. In sharp contrast, the average activity levels for school & personnel buses-local plate and for long-haul trailers-local plate were only 800,000 and 440,000 VKT, respectively.

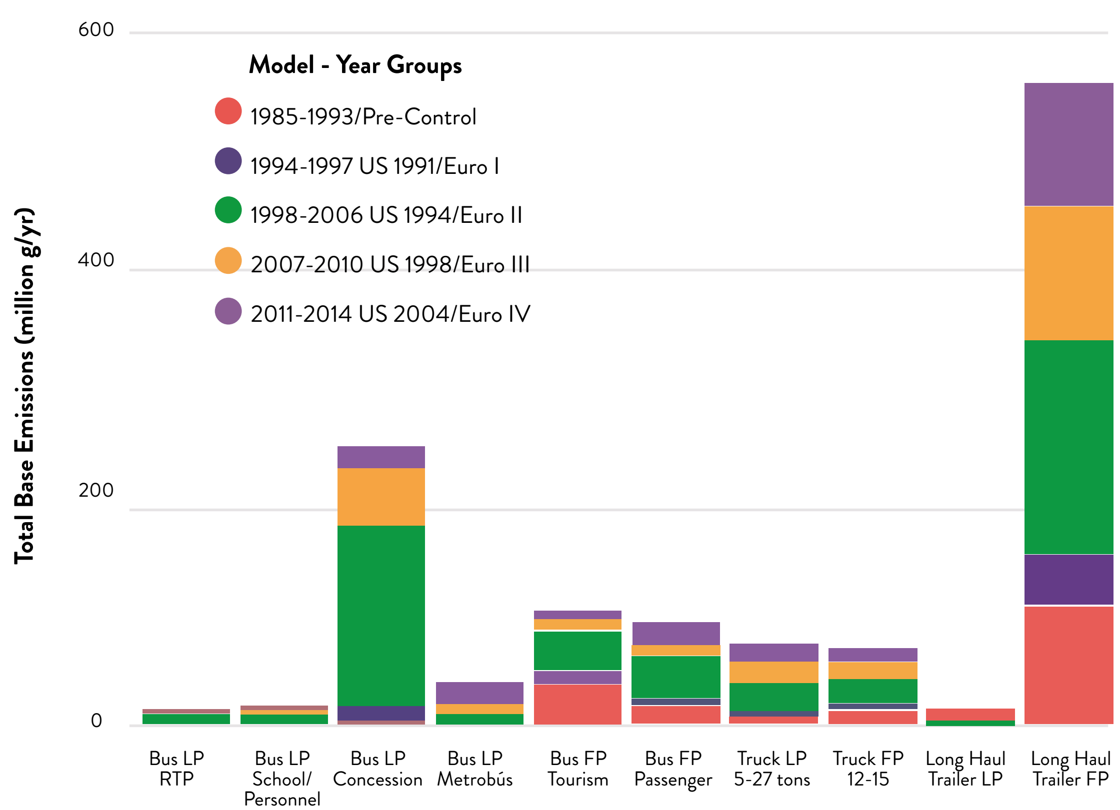


Figure 5.3. Annual Emissions of Primary Particles by Vehicle Class and Model-Year Group

The number of vehicles, age, and activity determine their emissions. For all vehicles, the total annual emissions of primary particles are close to 1000 metric tons. The largest emitters are long-haul trailers with federal plates (more than 50%), followed by concession buses with local plates (25%) (Figure 5.3.). The remaining 20-25% of primary particle emissions is roughly equally split between tourism and passenger buses with federal plates, and trucks (local and federal plates). Two categories of vehicles – school & personnel buses with local plates, and long-haul trailers with local plates make inconsequential contributions to primary particle emissions.

Our cost-effectiveness analysis considers four possible controls:

1) diesel oxidation catalyst (DOC).
2) diesel particulate filter, active regeneration (DPF-a).
3) diesel particulate filter, passive regeneration (DPF-p).
4) a hypothetical control – i.e., one which is 100% efficient in reducing emissions of primary PM and which has no cost. The hypothetical control provides an upper bound on the net benefits of any possible emission-control technology.

As shown in Table 5.1. DPFs, active and passive, are more efficient in reducing PM emissions than are DOCs. All DPFs trap particulate matter and must undergo a process called "filter regeneration" to burn off captured particles (releasing carbon dioxide and water). This process cleans the trap and avoids clogging, which would result in high back-pressure affecting the engine performance. There are two different technologies to regenerate the filter –passive or catalyzed and active regeneration.

Diesel oxidation catalysts are easy to retrofit and maintain. Although DOCs are less expensive, they are much less effective at removing solid PM. DOCs remove fine particulate mass by oxidizing the soluble organic fraction of the particulate matter. DPFs and DOCs are likely to remain effective for the life of the vehicle, generally five to ten years or 10,000 or more hours of operation –they have been reported to maintain performance for as much as 10 to 15 years or for over 600 000 km.

Control Technology	Emissions Control Efficiency (%)	Cost ($USD)	Fuel Penalty (%)	Ultra Low Sulfur Diesel	Other requirements
Diesel Oxidation Catalyst	~ 20 to 25	~ 500 to 1,500	None	Not required	None
DPF-Active Regeneration	~ 820 to 90	~7,000 to 9,000	2	Benefits from	Increased exhaust temperature
DPF-Passive Regeneration		~6,000 to 8,000	0.4	Required	Some highway-speed driving

Sosurces: CARB Diesel Certification & Verification Procedure, and technology-specific corresponding Executive Orders (from 2013 to 2015).

Table 5.1. Retrofit technologies to control primary particle emissions in heavy-duty vehicles. Main characteristics

We have assumed that since ultra-low sulfur fuel is the only type of diesel fuel available in Mexico City that the introduction of retrofit technology has no impact on SO_2 emissions. Similarly, we assume that oxidation catalysts and diesel particulate have no impact on NOx emissions.

Catalyzed DPF are not compatible with pre-1994 Mexican diesel technologies and require ultra-low sulfur (ULS) fuel for reliable regeneration and optimal function. ULS diesel (≤15 ppm) has been available in Mexico City since 2009 but is not yet available in a large portion of the country where it may contain as much as 500 ppm sulfur. Therefore, vehicles that drive outside of the city (i.e. with federal plates) are not candidates for DPFs with catalytic regeneration. Active regeneration DPFs do not require ULS diesel. Most active DPF models are suitable for 1993 and newer vehicles, and to our knowledge only one model can be used in older models (pre-1993 vehicles).

Estimates of the capital costs and annual maintenance costs are taken from recent SEDEMA bids for diesel retrofit devices [32, 33], and estimates of the fuel use penalties for each control device came from MECA (1999)[34]. The equivalent annual control cost for each device was computed by converting the capital cost to an equivalent annual cost stream using the capital recovery factor and adding the result to the annual maintenance cost and any additional cost related to the decreased fuel economy of vehicles equipped with DPFs. The discount rate used in our analysis was 3% per year.

To estimate the vehicle´s contribution to population exposures we used the intake fraction, which depends on all the variables that influence the relationship between emissions and exposure, such as the nature and location of the source, the pollutant´s physicochemical properties, the population receptor features, among other factors. Using intake fraction and emissions estimates, we calculated the city-wide average annual concentration change due to the emissions of the pollutant from each vehicle type under each type of control.

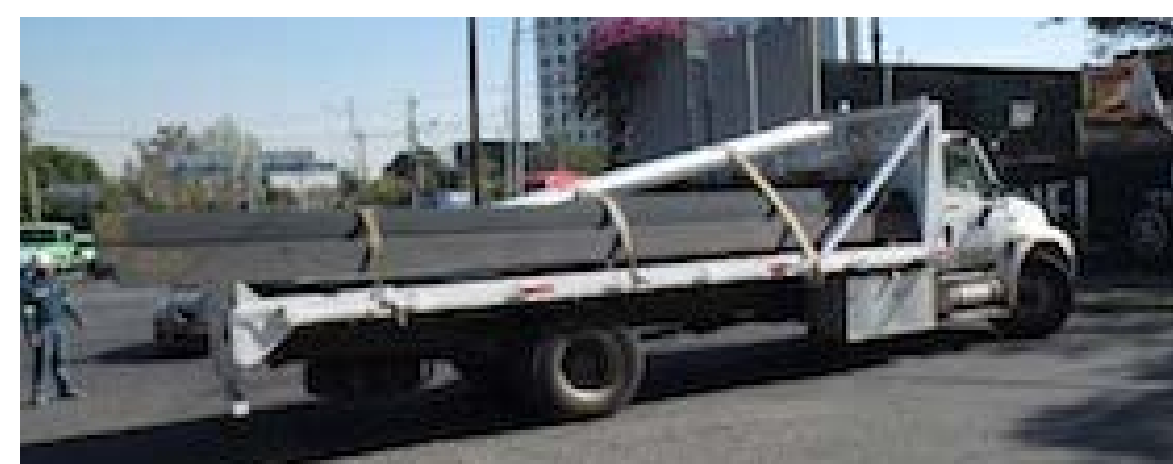
The impact on mortality of the reductions in air pollution exposure caused by emissions controls from a representative vehicle was computed using the integrated exposure response function (IER) applied in our risk assessment, and that was developed to support the Global Burden of Disease analysis [26]. We applied the IER for the five diseases that the GBD analyses determined as causally associated with long-term $PM_{2.5}$ exposure: ischemic heart disease, cerebrovascular stroke, chronic obstructive pulmonary disease (COPD), and trachea, bronchus and lung cancers in adults, and, among young children, acute lower respiratory infections.

Here we rely on a linear approximation to the IER, since for small decrements in $PM_{2.5}$ the change in relative risk can be approximated by the product of the slope of the tangent to the IER evaluated at current levels of $PM_{2.5}$ in Mexico City --the annual average $PM_{2.5}$ level in 2014 was 22.8 $\mu g/m^3$ (35). Also, we introduced a cessation lag as the reduction of risk of diseases associated with $PM_{2.5}$ exposure reductions may start immediately (first year) and continue for some time (15 years).

The monetary value of the reduction in mortality risk is calculated by multiplying the population risk reduction (i.e., the reduction in deaths attributed to PM) times the rate at which mortality risk is valued, the Value per Statistical Life (VSL). Estimates for VSL resulted from recommendations to extrapolate values from the United States to countries lacking high quality estimates of VSL.

RESULTS

Emissions within the City lead to exposures and health risks in the City and throughout the metropolitan area, so the results consider the benefits in the Mexico City Metropolitan Area. Our results are presented for the status quo, for the three control technologies, and for a hypothetical control for each type of vehicle and model-year group. These results include emissions reductions, attributable deaths avoided, monetized benefits of the avoided deaths, control costs, and the overall measure of tradeoffs between benefits and costs, that is net benefits, per vehicle and per year.



	Emissions Reduction (kg/veh-yr)	Deaths Avoided (#/1000 veh-yr)	Benefits (1000 USD/veh-yr)	Control Cost (1000 USD/veh-yr)	Net Benefits (1000 USD/veh-yr)
Bus Concession-Local Plate					
Status Quo	0.00	0.00	0.00	0.00	0.00
DOC	9.35	0.83	2.41	0.14	2.27
DPF -- Active	35.56	3.14	9.17	2.42	6.75
DPF -- Passive	35.56	3.14	9.17	1.43	7.74
Hypothetical Control	40.64	3.59	10.48	0.00	10.48
Long-Haul Tractor Trailer-Federal Plate					
Status Quo	0.00	0.00	0.00	0.00	0.00
DOC	2.68	0.24	0.69	0.09	0.60
DPF -- Active	10.18	0.90	2.63	1.06	1.56
DPF -- Passive	10.18	0.90	2.63	0.86	1.77
Hypothetical Contro	11.64	1.03	3.00	0.00	3.00

Notes: DOC stands for Diesel Oxidation Catalyst. Rows in green highlight the retrofit technology that maximizes the expected net benefits. The row in light gray highlights the retrofit technology that is not adequate for such vehicle category and model-year group.

Table 5.2. Results for Bus Concession – Local Plate and for Long-Haul Tractor Trailer – Federal Plate. Model Years 1998 to 2006 US 1994/Euro II

Table 5.2. gives illustrative results for the two largest emitter categories, bus concession with local plate and long-haul trailer with federal plate, for one model-year group (1998-2006 EU 1994/Euro II).

For the approximately 4 thousand concession buses with local plates, which are heavily used (each travel ~70 thousand km per year), the largest expected net benefits are generated by choosing to retrofit with a catalyzed DPF. The catalyzed DPF retrofit is expected to reduce emissions by 35.6 kg per vehicle-year, reduce premature deaths attributable to air pollution by about 3 per 1000 vehicle-year, with benefits of US$ 9.2 thousand and costs of only 1.4 thousand US$ per vehicle-year. The expected net benefits of this strategy (health benefits minus control costs) are almost 8 thousand US$ per vehicle year.

Retrofitting the approximately 16 thousand long-haul trailers with federal plates with a catalyzed DPF would yield the largest expected net benefits of almost 1.8 thousand US$ per vehicle-year. Unfortunately, the catalyzed DPF is not an option because these long-haul trailers with federal plates, are driven both in Mexico City and outside of the city, where ultra-low sulfur fuel is not widely available. The second-best option would be to retrofit with an active regeneration DPF, with the second largest expected net benefits of close to 1.6 thousand US$ per vehicle-year. Active DPFs generate the same emission reductions (10.2 kg per vehicle-year) and health benefits (1 per 1000 vehicle-year deaths attributable to air pollution) as the catalyzed DPF but are roughly 20% more expensive.

The control options that maximize the expected net benefits for all vehicles analyzed are presented in table 5.3. Note that there is no category or model-year group for which some retrofit is not cost-effective. We must add, that there is always uncertainty about the health benefits and costs of policies to reduce air pollution. Our analysis quantifies uncertainty about some of the most important inputs, including the relationship between emissions (in this case emission reductions) and population exposure (summarized by the intake fraction), the slope of the exposure-response functions relating mortality to air pollution, the monetary value of reductions in mortality risk (summarized by the value per statistical life), as well as the efficiency and cost of control options.

Type of Vehicle & Plate		1985-93 Pre-Control	1994-97 US 1991/EURO I	1998-06 US 1994/EURO II	2007-10 US 1998/EURO III	2011-14 US 2004/EURO IV
Transportation Buses	RTP- Public Transport Local Plate	n.a.	n.a.	DPF-p 80	DOC 70	n.a.
	School and Personnel Local Plate	DPF-a 99	DPF-p 97	DPF-p 97	DPF-p 80	DPF-p 78
	Concession Local Plate	DPF-a 96	DPF-p 99	DPF-p 99	DPF-p 99	DPF-p 99
	Metrobús Local Plate	n.a.	n.a.	DPF-p 72	DPF-p 99	DPF-p 99
	Tourism Federal Plate	DPF-a 99	DPF-a 96	DPF-a 95	DPF-a 86	DPF-a 82
	Passenger Federal Plate	DPF-a 90	DPF-a 74	DPF-a 70	DOC 98	DOC 98
Delivery Trucks >3.8 tons	Trucks Local Plate	DOC 99	DPF-p 80	DPF-p 80	DPF-p 80	DOC 96
	Trucks Federal Plate	DOC 99	DOC 99	DPF-a 65	DPF-a 74	DPF-a 58
Long-Haul Tractor Trailers >27.2 tons	Trailers Local Plate	DOC 91	DOC 93	DPF-p 84	DPF-p 93	DPF-p 87
	Trailers Federal Plate	DPF-a 95	DPF-a 88	DPF-a 95	DPF-a 97	DPF-a 94

Notes: Vehicles are grouped in five model-year groups, except for RTP public transportation and Metrobús vehicles, which have vehicles than belong to only two and three model-year groups, respectively. Delivery Trucks > 3.8 tons with local plates weigh between 4.6 to 27.2 tons, those with federal plates weigh from 11.8 to 14.9 tons; local and federal plate long-haul tractor trailers weigh >27.2 tons. DOC stands for Diesel Oxidation Catalyst; DPF-p stands for Diesel Particulate Filter with catalyzed regeneration (passive), DPF-a stands for Diesel Particulate Filter with active regeneration, and n.a. stands for not applicable.

Table 5.3. Retrofit options which maximize expected net benefits by vehicle type and model-year group, and estimated probability (%) that net benefits of indicated retrofit options are positive, Mexico City, 2014

By doing so we can estimate the probability that the benefits of the reduction in mortality risk exceed the cost of the specified retrofit technology, that is, that the net benefits of the identified retrofit program are positive. These probabilities are displayed in Table 5.3. below the specified best control option. For most vehicle types and model-year groups, the probability that the identified retrofit option will yield benefits greater than its cost is 80 percent or larger. For vehicle categories and model-year groups with lower probability values, such as trucks - federal plate of model years 1998 and newer, such probabilities are tied to the selected control option –DPF active. However, this does not imply that these vehicles should not be controlled, since a much larger probability of 99% is estimated if retrofitted with oxidation catalysts.

INTERPRETATION

It is reasonable to ask what the aggregate benefits and costs of such a strategy would be. The fully implemented strategy of retrofitting every vehicle with the control which maximizes expected net benefits for that vehicle type and model-year group would result in close to 109 million US$ net benefits.
This strategy has the potential to:

- reduce annual emissions of primary fine particles by 950 metric tons.

- cut the annual population-weighted mean concentration of $PM_{2.5}$ in the Mexico City Metropolitan Area by 0.90 $\mu g/m^3$.

- reduce the annual number of deaths attributable to air pollution by close to 85, and.

- generate expected health benefits on the order of 250 million US$ per year.

The expected annual costs would be of less than 93 million US$ per year – consisting of 61 million US$ in 'amortization' of capital cost of retrofit devices; 19 million US$ in annual maintenance costs; and 11 million US$ in fuel use penalties.
Retrofit programs have been put in place in other countries and have been on the radar of policy makers in Mexico for decades. Diesel retrofit technologies, such as DOCs and DPFs, can reduce diesel particulate matter with similar control efficiencies to emission controls from newer diesel vehicles [36]. In Mexico City, a retrofit program was put in place over 10 years ago. Two fundamental lessons were learned as key to the success of the program: Selecting appropriate buses for retrofitting through previous careful testing, and training operators on how the emissions control devices worked, how they were installed, and driving techniques for best performance of the equipment.

Retrofitting the heavy-duty diesel vehicle fleet would represent a small, but important, step towards further improvement of air quality in Mexico City. We encourage authorities in Mexico City to consider moving forward with the design and implementation of such a program.

FINAL REMARKS

Reductions in $PM_{2.5}$ and ozone over the past twenty-five years have led to substantial improvements in public health in Mexico City. We have measured health benefits from enhanced air quality as life expectancy gains, life years increased by five causes of death determined to be causally associated with fine particles or ozone, and as reductions in attributable mortality for these five causes of death. We conducted a population-based epidemiological analysis and a risk assessment to quantify and value such health benefits.

By reducing city-wide average ambient $PM_{2.5}$ concentrations from 35 μg/m^3 in 1990 to 20 μg/m^3 in 2015 and simultaneously reducing ambient ozone concentrations from over 160 ppb in 1990 to close to 84 ppb in 2015, Mexico City has been able to increase life expectancy, increase life years lived attributable to certain diseases, and reduce attributable deaths associated with air pollution. Our risk assessment shows that deaths attributable to fine particles and ozone during this 25-year period were reduced by 22.5 thousand (95% CI: 17.9 to 28.0 thousand). Roughly 18.0 thousand of these avoided deaths are due to improvements in $PM_{2.5}$ (95% CI: 14.0 to 23.5 thousand), and 4.0 thousand to ozone (95% CI: 2.7 to 5.6 thousand).

Our findings are consistent with state of the art knowledge in that long-term exposure to fine particles and ozone are related with chronic diseases that mainly affect adults. For the population between 25 and 74 years old, we found that a decrease of 10 μg/m^3 in the annual average concentration of $PM_{2.5}$ was associated with an increase in mean years of life of 0.56 (95% CI 0.28 to 0.83) years. Also, a decrease of average 1-hour peak seasonal ozone levels was associated with an increase in mean years of life of 0.10 (95% CI 0.03 to 0.17) years. Our risk assessment, also in agreement with the above, showed that most attributable deaths avoided due to air quality improvements in the last 25 years were among adults older than 25 years of age. Over 65% of avoided attributable deaths were among adults between 25 and 74 years old, and only 3% were among those of less than 19 years old.

Epidemiological analyses of data from the United States have reported for that improvements of 10 μg/m^3 in average annual fine particle concentrations are associated with an increase in life expectancy of 0.61 (95% CI 0.22 to 1.00) years (27), results that are very similar to our adult findings from Mexico City.

We also found a significant increase of life gained attributable to ischemic heart disease in adults over 25 years old of 0.094 (95% CI 0.027 to 0.160) years (equivalent to 34 days), associated with a decrease of 10 μg/m^3 in the annual concentration of $PM_{2.5}$. Our analyses using risk assessment methods, very consistently indicate that around 10 thousand attributable deaths due to ischemic heart disease were avoided because of improved fine particles levels in the past 25 years.

Results for life gained attributable to chronic obstructive pulmonary disease, among the population of over 25 years of age, showed a positive and significant increase of 0.037 (95% CI 0.007 to 0.067) years with improved annual PM2.5 concentrations (10 μg/m^3). A positive, but non-significant association was found for ozone (P=0.14). Our risk assessment indicated that 6.5 thousand attributable deaths due to COPD were avoided as fine particles and ozone levels decreased in the city since 1990.

For life gained due to lung cancer and cerebrovascular stroke there were positive but marginally significant ($p<0.10$) associations with $PM_{2.5}$. These potential associations should be further explored in other studies.

Among children aged 0 to 4 years we found a modest, statistically non-significant increase in years of life lost between ages 0 and 4 years associated with $PM_{2.5}$ (0.0070 years or 2.5 days) and a significant small increase with O3 (0.0037 years or 1.3 days). We found no positive association with years of life lost from acute lower respiratory infections (ALRI). Results from our risk assessment revealed that less than 3% of attributable deaths were among the youngest stratum of the population.

For our 25-year study period there was a life expectancy at birth increase of 1.3 and 1.9 years due to $PM_{2.5}$ and O_3 air quality improvements, respectively. With annual average $PM_{2.5}$ concentrations and seasonal hourly ozone peaks improving by close to 15 μg/m^3 and 77 ppb, correspondingly, and the estimated effects for each pollutant in our model, we calculate a net increase of almost 3.2 years in life expectancy for the population of Mexico City. Similarly, there was an important increase in interval life expectancy for adults aged 25 to 74 of 1.6 years, with almost equal contributions by $PM_{2.5}$ and ozone of roughly 0.8 years each. Other factors likely contributed simultaneously to such improvements and they were accounted for in our models, which controlled for socioeconomic position indicators, proxy indicators for smoking, and for reference diseases.

Estimates from other countries and globally using indirect methods, i.e. with either cohort risk estimates or with integrated exposure-response functions, find reductions in life expectancy associated with long-term exposures to $PM_{2.5}$ and O_3. In the United States, the loss was estimated to be between 0.35 and 0.61 years with an exposure of 10 μg/m^3 (27, 28). Current global $PM_{2.5}$ and O_3 long-term exposures have been associated with a decrease in life expectancy of 1.03 years and 0.05 years respectively [29]. The authors report that the potential benefits of reducing current $PM_{2.5}$ to levels that would meet the World Health Organization's guideline would be of a similar magnitude to the benefits of eliminating lung and breast cancer together. For Mexico (countrywide), they also indicate that current estimated $PM_{2.5}$ levels reduce on average 0.48 years of life lost.

The results of our epidemiological analyses and our risk assessment are an incentive to further improve air quality. This study shows that public policies that aim at improving air quality benefit public health, with gains in life expectancy and reductions in attributable mortality in large populations.

The cost-effectiveness analysis conducted for Mexico City heavy-duty vehicles clearly shows that performing retrofit with either Diesel Oxidation Catalysts (DOCs) or with Diesel Particulate Filters (DPFs) can reduce particulate matter emissions, lead to improvements in air quality, and have public health benefits among the inhabitants of the Mexico City Metropolitan Area.

For the three vehicle categories responsible for the greatest share of primary PM emissions, bus concession - local plate, long-haul trailer - federal plate, and bus tourism - federal plate, DPF retrofits, which have expected emissions reductions between 80 and 90%, provide the maximum possible expected net benefits for all model-year groups.

For other vehicle categories such as bus passenger - federal plate, the fourth largest primary PM emitter, and trucks with local or federal plates, DPFs are not cost-effective for some model-year groups, but oxidation catalysts are, for which projected emissions reductions range between 20% and 26%.

If every vehicle were retrofitted with the control which maximizes the expected net benefits the aggregated net benefits would be of close to 109 million US$. Such a strategy could potentially generate expected health benefits on the order of 250 million US$ per year. Annual emissions of primary fine particles would be reduced by 950 metric tons, the annual population-weighted mean concentration of $PM_{2.5}$ in the Mexico City Metropolitan Area would decrease by 0.90 µg/m3, and close to 85 less annual deaths attributable to air pollution would be expected.

The importance of cleaning the heavy-duty fleet in Mexico City has been recognized by experts and authorities in Mexico and Mexico City. Mexico's City and MCMA Air Quality Management Plan, PROAIRE 2011-2020, lays out a strategy and corresponding measure to clean heavy-duty diesel vehicles, either by substitution of engines of by retrofitting control technologies.

We close by noting that this one small step must be viewed from the wider perspective suggested by the air quality management program in place and by the Mario Molina Center's 2016 position paper on air quality in the Mexico City Valley [37] (Table 6.1). As these documents suggest, in addition to reducing emissions from heavy-duty vehicles, many other programs and strategies -- such as the development of an integrated public transportation system, the promotion of the rational use of cars, the reduction of emissions from industrial sources and fires, and redesign of the MCMA area to reduce urban sprawl -- must be analyzed and implemented to make significant strides forward in the control of air pollution and its public health impacts.

PROAIRE, 2011-2020	Mario Molina Center
Strategy 3. **Energy Quality and Efficiency in all sources** **Measure 21.** Renewal of diesel vehicles with motor substitution and by adapting emission controls. **Action 21.1.** Design a program to replace diesel motors that have been in use for 10 years or more, and adapt emissions control equipment.	**Strategic Priorities** **May, 2016** 1. Hasten the development of quality, low emissions public transportation, integrated a metropolitan scale. 2. Promote rational use of cars and clean technologies. **3. Drastic reduction of emissions from freight transportation.** 4. Update regulations for vehicles inspection and ensure enforcement & compliance. 5. Reduce emissions from industrial sources and from fuel/diesel distribution, as well as prevent and control fires. 6. Contain urban sprawl to reduce demand for transportation.

Table 6.1. Strategic Priorities for Air Quality Management in the MCMA: PROAIRE 2010-2020 and Mario Molina Center

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