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Santiago Megacities Partnership: Assessment of Air Quality Management in the Santiago Metropolitan Region

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ACRONYMS

AGIES	General Analysis of Economic and Social Impacts
BenMAP-CE	Environmental Benefits Mapping and Analysis Program
CASEN	National Socio-Economic Characterization Survey
CONAMA	National Environmental Commission of Chile
DF	Degradation Factors
ECF	Emissions-Concentration Factor
IEc	Industrial Economics, Inc.
INE	Chile's National Institute of Statistics
MMA	Government of Chile's Ministry of Environment
NAAQS	National Ambient Air Quality Standards
NH_3	Ammonia
NO_X	Nitrogen Oxides
OAQPS	Office of Air Quality Planning and Standards
$PM_{2.5}$	Fine Particulate Matter
PPDA	Decontamination Plan
SEREMI	Regional Secretariat of Chile's Ministry of Environment
SINCA	National Air Quality Information System
SO_2	Sulfur Dioxide
USEPA	United States Environmental Protection Agency
VMT	Vehicle Miles Traveled
VSL	Value Per Statistical Life

CHAPTER 1 | INTRODUCTION

The United States Environmental Protection Agency (USEPA) and the Government of Chile's Ministry of Environment (MMA) are collaborating under the Megacities Partnership to advance air quality management in the Santiago Metropolitan Region. The primary goals of this partnership are (1) to identify needs and provide technical assistance to support air quality management activities in Santiago and (2) to help Santiago serve as a regional model for addressing air quality issues in countries facing similar challenges. These objectives are being accomplished by drawing upon innovative tools and techniques proven effective for U.S. cities and states, adapted to address differences in policy and technical contexts.

This report presents results from a comprehensive assessment of the benefits and costs of air quality management in the Santiago Metropolitan Region over the past three decades. During this time period, regulatory actions led to significant improvements in the region's air quality. While these improvements are well documented, the benefits and costs of the regulatory action remain poorly understood. Currently, benefit-cost analyses of environmental regulations are done prospectively, or prior to implementation of regulations. No analysis has systematically assessed the realized benefits and costs of the universe of environmental regulations impacting air quality in the region. We aim to address this gap by designing and conducting a benefit-cost analysis spanning the years 1990 through 2020.

Additionally, within this retrospective benefit-cost analysis, we conduct a quantitative assessment of the effectiveness of MMA's critical episode management system, which restricts certain polluting activities in the region in anticipation of air quality 'episodes', or days with very poor air quality during winter. We assess monitored air quality, modeled air quality, and meteorological data available to the MMA team, in a retrospective manner, to understand which set of these variables best predict an air quality episode, and also calculate economic benefits and costs associated with an episode declaration. In this case, we define episode declaration as days where mitigation measures were put into place to decrease $PM_{2.5}$ concentrations when they are forecasted to be above a certain threshold concentration.

1.0 BACKGROUND

The regulation of air pollution to achieve air quality goals in the Santiago Metropolitan Region of Chile dates from at least 1994, when the National Environmental Commission (CONAMA) was first established under the General Environmental Basis Law (No. 19300). In the following years, the Chilean National Ambient Air Quality Standards

(NAAQS) were first established. As in the U.S., the Chilean NAAQS apply to six criteria pollutants: particulate matter, ground-level ozone, carbon monoxide, sulfur oxides, nitrogen oxides, and lead. Regions nearing the standards (latent areas) and those exceeding the standards (saturated areas) are required to implement air quality management plans, or Planes de Prevención y Descontaminación Atmosférica (PPDAs).

Several PPDAs have been implemented to address poor air quality in Santiago, as ambient concentrations of fine particulate matter ($PM_{2.5}$) have exceeded the annual standard of 20 $\mu g/m^3$.[1] The geography of Santiago creates an area that is ripe for air pollution, with mountain ranges to the east and west and low inversion layers during some seasons that keep urban pollutants from dispersing. This phenomenon is especially pronounced in the winter months, when daily concentrations of $PM_{2.5}$ occasionally exceed 150 $\mu g/m^3$. Compounding these meteorological conditions, Santiago's growing population of seven million residents accounts for nearly half of Chile's total population. Regional PPDAs aimed at lessening the region's emissions have built upon actions required under national regulations, including those for electric generating units, vehicle emissions, and sulfur content in fuels.

A crucial component of the PPDAs is the critical episode management system. Each day during the Chilean winter, MMA must predict whether the next day's PM_{10} or $PM_{2.5}$ concentrations will exceed one of three concentration thresholds: Alert (>80 ug/m^3 $PM_{2.5}$); Pre-emergency (>110 ug/m^3 $PM_{2.5}$); or Emergency (> 170 ug/m^3 $PM_{2.5}$) for an 'episode' to be declared. Episode declaration of each type sets into action a set of policies aimed to minimize particulate matter emissions, with the least restrictive policies implemented during an 'Alert' and most restrictive policies implemented during an 'Emergency'.

By several metrics, national and regional environmental regulations are substantially improving air quality in Santiago. Annual concentrations of $PM_{2.5}$ exceeded 60 $\mu g/m^3$ in the early 1990s. Now, measured values approach the national annual standard of 20 $\mu g/m^3$. The number of verified air pollution episodes (i.e., days with very poor air quality) is decreasing. Compared to the 139 critical episodes declared during the five-year span from 1997 to 2001, only 78 were declared for the more recent five-year timespan between 2012 and 2016 (SEREMI 2016).[2]

Based on these experiences addressing air pollution over the past three decades, Chile has gained significant expertise in air quality monitoring; critical episode forecasting and management; development of air quality management plans; and benefit-cost analysis of regulatory actions. However, MMA's experience with benefit-cost analysis has exclusively focused on estimating regulatory impacts prospectively, or before

[1] PPDAs in Santiago before 2012 were aimed at addressing other pollutants, including PM_{10}, O3, and NO_X, but still helped to address $PM_{2.5}$ emissions.

[2] We note that some discretion is involved in declaring critical episodes.

management actions are implemented. This is comparable to the experience in the U.S., where the vast majority of benefit-cost analyses conducted by Federal regulatory agencies take a prospective approach. However, there has been increased interest in retrospective benefit-cost analysis over the past decades.[3] Such efforts have historically been implemented on an *ad hoc* basis, and many academics and regulatory agencies have discussed the need to more formally integrate retrospective review into their regulatory programs (Aldy 2014, OECD 2014).

The appeal of retrospective benefit-cost analysis in the Santiago context relates to three primary objectives of this study. First, such analysis can be used to evaluate whether environmental regulations continue to be justified in economic terms. Retrospective benefit-cost analysis can be used to assess whether regulations have produced positive net benefits, and add a cumulative perspective rather than the typically incremental approach of prospective benefit-cost analyses. Second, we aim to identify sets of environmental regulations proven to be most effective in Santiago to provide insight into implementation of similar actions elsewhere in Chile and South America. Third, retrospective analysis can inform future prospective analyses. The results of retrospective analyses may be compared to the original, prospective estimates and provide insights into key sources of uncertainty in prospective analysis.[4] Learning is an important component of retrospective analysis.

In addition to a programmatic retrospective benefit-cost analysis, we closely assess the critical episode forecasting process to empirically evaluate the most predictive air quality meteorology variables. Further, we aim to dive more deeply into the episode forecasting policy to assess benefits and costs associated with the critical episode declaration process. Our analytic design, aimed to address these three broad goals, is presented below.

1.1 ANALYTIC DESIGN

The key challenge in benefit-cost analysis is isolating the incremental effects of regulation. For both prospective and retrospective analyses, identifying incremental effects requires comparing two scenarios: the world with the regulation and the world without the regulation, or "factual" and "counterfactual" scenarios, respectively.[5] In prospective analyses, both scenarios occur in the future; neither is observed. Both the baseline and incremental scenarios are subject to significant uncertainty associated with

[3] Prospective and retrospective analyses are commonly referred to as ex ante and ex post analyses, respectively.

[4] For example, a review (Harrington et al., 2000) of *ex post* analyses prepared in the United States revealed that regulatory costs tend to be overestimated. One reason for this overestimation is unrealistic assumptions about compliance rates. In more recent reviews, the results are mixed or inconclusive (see, for example, Aldy 2014, Harrington 2006, USEPA 2014).

[5] The relevant comparison is the world with and without the regulation, not the world before and after the regulation is implemented. Attributing the decline in fine particulate concentrations from 1990 to 2017 solely to regulations may ignore important shifts in technology or market conditions, including reduced use of woodstoves for home heating or changes in the availability of low-sulfur fuels. And, the difference in concentrations over this time period does not explicitly account for how emissions may have grown due to population and economic growth.

assumptions about likely future health and economic conditions without the regulation, compliance with the regulation, and behavioral responses that may affect implementation (e.g., innovation by the regulated community).

In retrospective analysis, uncertainty may be reduced because the world with regulation can be observed. What were included as probabilities or expected values in the prospective analysis can be replaced with actual outcomes, to the extent that it is possible to separate the effects of the regulation from other factors, such as exogenous technological improvements or changes in economic activity. The regulatory agency may have data on compliance rates, or it may be able to obtain more accurate information on key assumptions, such as actual emissions rates. However, analysts must still model the counterfactual scenario (i.e., the world without regulation), which cannot be observed. Assumptions about what the world would have been like without the regulation introduce uncertainty to estimates of the incremental impacts. Below, we elaborate on the scope and analytic steps of our analyses.

1.1.1 ANALYTIC SCOPE

The geographic, temporal, and regulatory scope of the retrospective and critical episode studies was determined through discussions with MMA leadership and staff. As we discuss in greater detail below, the retrospective analysis addresses regulations affecting air quality in the Santiago Metropolitan Region from 1990 to 2020. Thus, our retrospective analysis also includes a short prospective component (i.e., 2018-2020). We exclusively focus on ambient concentrations of $PM_{2.5}$ because it has the greatest impact on human health. And, $PM_{2.5}$ and its precursors are emitted from many common sources, including industrial, mobile, and area sources. Finally, local monitoring data for $PM_{2.5}$ are available dating back to before 1990. For these reasons, choosing to focus on PM likely captures the largest component of benefits and costs of air pollution regulation for Santiago. There may be, however, other benefits and costs of regulation associated with co-benefits of source controls focused on $PM_{2.5}$ (for example, reductions in ozone concentrations).

Retrospective Benefit-Cost Analysis

In accordance with the objectives of the Megacities Partnership, we focus on regulatory actions aimed at reducing emissions in the Santiago Metropolitan Region. These actions include those required by regional and national regulations. Similarly, we estimate human health benefits realized within the Santiago Metropolitan Region. In some instances, regulations significantly affect the emissions from regional sources that impact Santiago air quality (e.g., nearby copper smelters). We do not assess the benefits or costs of these regulatory actions; however, we account for these air quality impacts, which are assumed to be equal in the factual and counterfactual scenarios.

Our retrospective analysis examines air quality trends from 1990 to 2020. As we describe below, Chile began regulating air pollutant emissions around 1990, thus providing a natural starting point for our analysis. Additionally, the Santiago air quality monitoring network was first launched in 1988, providing reliable data for our study period. By extending the analysis to 2020, we aim to assess the benefits and costs of existing regulations for several future years. In conducting this prospective extension, we model the major emissions control measures required under the newest PPDA, which took effect at the end of 2017.

We aim to model the effects of all regulations impacting emissions in Santiago during this time period. In many instances, we are constrained to assessing the aggregate impacts of regulations rather than the benefits and costs of specific control measures. For example, we comment on the suite of regulations impacting the emissions in the industrial sector as a whole, rather than individual regulations.

Critical Episode Analysis

For the critical episode analysis, we model the effects of declaring an Alert, Pre-emergency, and Emergency episode in the Santiago Metropolitan region. We examine air quality episodes during 2015 and 2016 based on data available within MMA records on episode declaration and verification status. Costs and benefits associated with these analysis years are meant to be representative of present day impacts. To calculate the benefits associated with declaring a critical episode, we define a counterfactual scenario representing the air quality if the episode had not been declared. In doing so, we isolate the days in which an episode occurred but was not declared as such (i.e., no control measures were required).

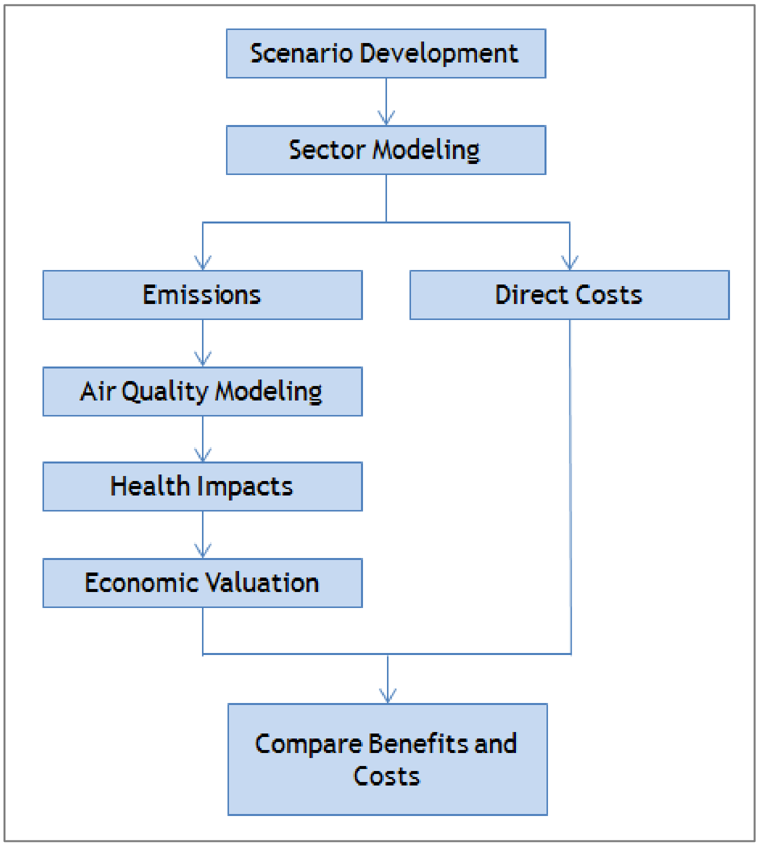
1.1.2 ANALYTIC SEQUENCE

The analytic steps for preparing our analyses are summarized below and explained in greater detail throughout the main text of this report.

Retrospective Benefit-Cost Analysis

The steps involved in preparing a retrospective benefit-cost analysis are illustrated in Exhibit 1-1.

EXHIBIT 1-1. STEPS IN RETROSPECTIVE BENEFIT-COST ANALYSIS



Source: Adapted from USEPA (2011).

The basic steps involved in retrospective analysis are similar to those in a prospective benefit-cost analysis. The primary difference, as discussed above, is the availability of better information at various steps in the process. Following scenario development (i.e., defining the scope of the analysis, as above), there are six basic steps, which we describe briefly below.

First, we estimate the effect of regulations on emissions in Santiago. The process of emissions estimation is sector-dependent but broadly involves construction of emissions inventories; projecting emissions using relevant driver data (e.g., number of vehicles, economic activity); and constructing a counterfactual scenario consistent with 1990 levels of regulation. Our emissions estimation accounts for directly-emitted $PM_{2.5}$ and three precursors of ambient $PM_{2.5}$. Concurrently, we estimate the direct costs of reducing emissions (e.g., installing emissions abatement technology).

Second, we use these emissions estimates to inform air quality modeling for the region. We employ two distinct air quality models that translate emissions into ambient concentrations of $PM_{2.5}$. Third, these concentrations are used to estimate the health outcomes associated with air quality (e.g., premature mortality, hospitalizations). We employ concentration-response functions from the epidemiological literature to relate health effects with changes in air quality. Fourth, we estimate monetized benefits by applying economic values to the reductions in adverse health effects. We further account for fuel savings benefits stemming from specific policies.

Finally, we compare the monetized benefits with costs to yield an estimate of the overall economic impact of air environmental regulations in Santiago. And, we discuss the uncertainties surrounding our estimates of both benefits and costs.

Critical Episodes Analysis

Our critical episode analysis occurs in two phases: First, we assess the influence of data available to MMA in their episode declaration forecasting process. These factors include meteorological data, air quality models, and air monitor data. We use regression modeling to understand which of these factors are most predictive of a critical episode occurrence the following day. Second, we evaluate the benefits and costs of declaring an episode in Santiago.

The benefit-cost analysis for critical episode management follows many of the same steps as those presented in Exhibit 1-1. However, we do not model air pollutant emissions and instead use monitored $PM_{2.5}$ concentrations from MMA's Sistema de Información Nacional de Calidad del Aire (SINCA) network to understand the air quality impact of declaring an episode. We then similarly estimate health impacts and monetize these effects to facilitate the comparison with costs. Costs are calculated concurrently and reflect impacts to sectors that are forced to decrease activity levels. We then compare benefits and costs associated with critical episode declaration.

1.2 REPORT ORGANIZATION

The organization of this report largely parallels the analytic sequence described above. Chapters 2 through 6 present results from the retrospective benefit-cost analysis, while Chapters 7 and 8 discuss the critical episode analysis. The remainder of our report includes the following:

- In Chapter 2, we provide an overview of our approach to estimating emissions from six source categories: onroad motor vehicles, non-road engines and vehicles, residential wood-burning, industrial sources, wildfires, and regional contributions.
- In Chapter 3, we summarize our direct cost estimation strategy from the above source categories.
- In Chapter 4, we provide an overview of two air quality models we employ to translate estimated emissions into concentrations of fine particulate matter in Santiago. We compare emissions estimates from the models and apply calibration or bias correction factors where necessary to match observed concentrations in the region under the factual scenario.
- In Chapter 5, we discuss the estimation of adverse health impacts stemming from fine particulate matter. Using USEPA's BenMAP-CE program, we apply concentration-response functions from the epidemiological literature to relate improvements in air quality with reductions in premature mortality. We then apply

economic values to estimated human health benefits, thus allowing us to more easily compare direct costs with monetized benefits.

- In Chapter 6, we compare the monetized benefits and costs for each sector.
- In Chapter 7, we describe the methodology used to identify the set of variables that provide the most predictive power in forecasting a critical episode and present the results of the analysis.
- In Chapter 8, we discuss our estimation of costs and benefits associated with the critical episode forecasting system. We use monitored air quality concentrations with concentration-response functions described in Chapter 5 to calculate episode-specific declaration benefits and compare those to daily sector-specific costs.
- In Chapter 9, we discuss results of these analysis and present areas for future research.

Estimating pollutant emissions serves as the starting point for our retrospective assessment of benefits and costs. As discussed previously, we focus primarily on ambient concentrations of fine particulate matter ($PM_{2.5}$). In addition to estimating directly emitted $PM_{2.5}$, we consider emissions of pollutants that contribute to the atmospheric formation of fine particles: nitrogen oxides (NO_x), sulfur dioxide (SO_2), and ammonia (NH_3). For each pollutant, we estimate sector-specific emissions under two different scenarios for the years 1990 through 2020:

1. A **factual scenario** that aims to reflect observed conditions, including the implementation of air environmental regulations beginning in 1990; and
2. A **counterfactual scenario** that reflects hypothetical conditions assuming no air environmental regulations had been implemented after 1990, while allowing for changes in emissions due to changes in economic activity and population.

We estimate emissions under the two scenarios for six major source categories: onroad motor vehicles, non-road engines/vehicles, residential sources, industrial sources, wildfires, and regional contributions. Examples of emitters in each category are presented in Exhibit 2-1, as well as regulatory actions that potentially impact emissions from each source.

EXHIBIT 2-1. MAJOR EMISSIONS SOURCE CATEGORIES

SOURCE CATEGORY	EXAMPLES	EXAMPLE AIR REGULATORY ACTIONS
Onroad motor vehicles	Cars, buses, trucks	Vehicle emissions standards, fuel standards, driving restrictions during critical episodes
Non-road engines/vehicles	Construction equipment, mining equipment	2018 PPDA: emissions standards for new equipment
Residential sources	Wood-burning in homes	Prohibition of firewood burning in central Santiago; stove technology restrictions elsewhere
Industrial sources	Cement manufacturing, electric generating utilities, boilers	Emissions reductions requirements for large emitters
Wildfires	Fires in woodland, pasture, and shrub	None[6]
Regional contributions	Copper smelters, coastal sources	Emissions reductions requirements for copper smelters[7]

[6] PPDAs have regulated agricultural burning, which is not included in this analysis.

The remainder of this chapter includes sections that summarize our emissions estimation approach for each of the six major source categories. Additionally, we present our aggregate emissions estimates for the period between 1990 and 2020.

2.1 ONROAD MOTOR VEHICLES

Santiago's vehicle fleet has experienced significant growth over the past three decades. With fewer than half a million vehicles in 1990, Santiago's vehicle fleet now exceeds two million cars, trucks, buses, and motorcycles. To help counteract the growing emissions, increasingly stringent emissions standards have been implemented over this time period. And, national and regional fuel standards have required that petroleum products sold in the region meet limits for sulfur content. We model the emissions of onroad vehicles as a function of fleet size, fleet composition (fuel use, emission standard, vehicle type), and vehicle miles traveled (VMT). We also apply emissions factors (EF) and degradation factors (DF) specific to vehicle and emissions class. Specifically, we estimate emissions using the following formula, adapted from GEASUR (2015a):

$$Emissions = N° \, of \, vehicles * VMT * EF\,(v) * DF$$

In the following sections we explain the main steps for emissions estimation, fleet projection and application of emission and deterioration factors.

2.1.1 DATA SOURCES

We use data from GEASUR (2015a, 2015b) to estimate average VMT by vehicle type. These estimates were generated using data from inspection facilities from 2011 to 2014. And, we estimate fleet size using data from Chile's National Institute of Statistics (INE). We obtained annual registration data for the time period from 2007 to 2015. For each vehicle, the data includes information on the fuel type, vehicle type, make, and model year. For earlier years (i.e., pre-2007), fuel type, make, and model year are not available. Thus, we collected aggregate statistics on the number of vehicles by vehicle type using published information and older reports physically available at INE's library. To address missing vehicle characteristics for the pre-2007 vehicle fleet, we assume that the fleet composition by fuel type and vintage was equal to the composition in the years 2007 to 2009 for each vehicle type.[8] After 2015, we project the fleet size using growth rates for each vehicle type (e.g., passenger vehicles, taxis, buses) from MMA (2016b). We assign the observed 2015 distribution of fuel type and vintage to the 2016-2020 fleets.

For the factual scenario, we assign new vehicles purchased after 1991 to regulatory classes in accordance with emission standards implemented in the Santiago Metropolitan

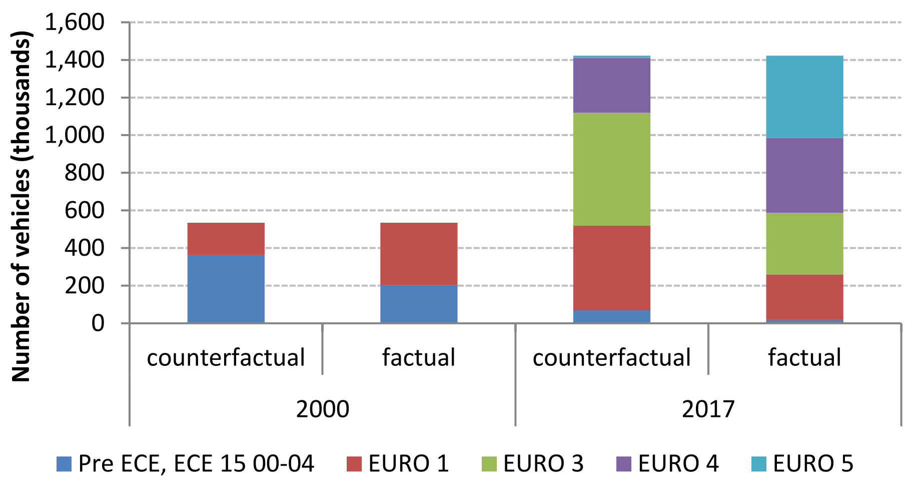
[7] Copper smelters near Santiago are heavily regulated and have significantly reduced their air emissions. However, we do not assess the benefits and costs of these regulations in this study.

[8] For example, we may observe in the 2007 data that 20 percent of passenger vehicles are gasoline-powered and two years old. Thus, we would assume that 20 percent of all passenger vehicles in 1998 were gasoline-powered and model year 1996. We implicitly assume that scrappage rates by vintage and fuel type do not change over time.

Region in 1992.[9] For example, new vehicles sold in Santiago in 1992 were required to meet the EURO 1 emission standard.[10] For vehicles sold before 1992, we assign vehicles to emission standards in place in the U.S., the primary exporter of vehicles to Chile.

For the counterfactual scenario, we assume a five-year delay in the adoption of cleaner vehicles relative to the factual scenario. This delay reflects our assumption that imported vehicles would nonetheless incorporate new and improved emissions technologies, based on requirements in the exporting countries (mostly the U.S. and Europe), albeit at a slower rate. Exhibit 2-2 presents the household vehicle fleets in 2000 and 2017, differentiated by emissions class for both scenarios.

EXHIBIT 2-2. HOUSEHOLD VEHICLE FLEET COMPOSITION, 2000 AND 2017



2.1.2 EMISSION AND DETERIORATION FACTORS

After modeling the vehicle fleet in Santiago, we assign emission factors specific to vehicle type, fuel type, and emission standard. We collected emissions factors from COPERT IV (as summarized in European Environment Agency 2016) and from two local sources (MODEM 2015, GEASUR 2015a). The emission factors are dependent on circulation speed, which we obtained from MODEM (2015) for the year 2012. As we discuss below, we calibrate our model by adjusting annual circulation speeds such that the gasoline consumption predicted in our model is consistent with observed fuel sales in the region.

Emission factors for SO_2 are dependent upon fuel consumption and sulfur content, the latter of which has declined considerably since 1990 due to a series of increasingly

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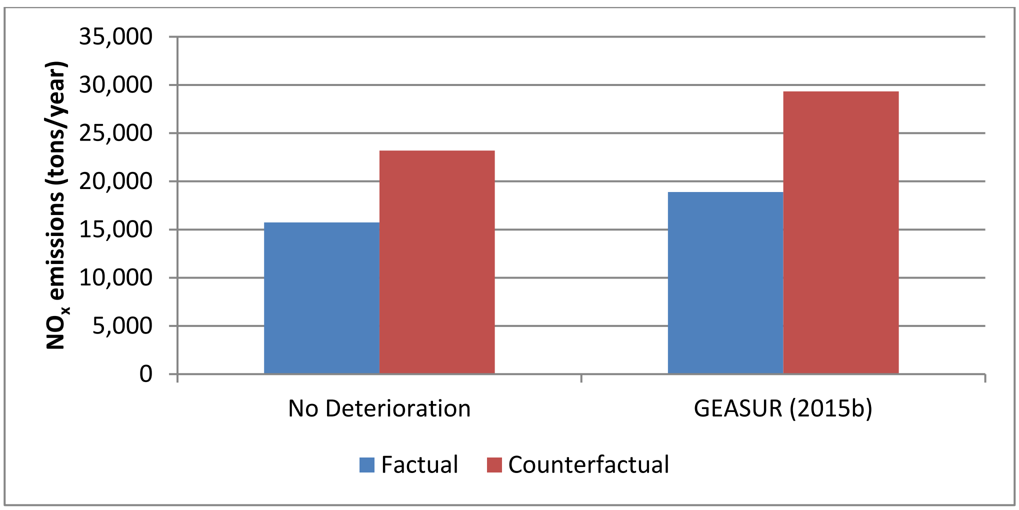
[9] Used cars cannot be imported to Chile.

[10] For additional information on the European emissions standards, see https://ec.europa.eu/clima/policies/transport/vehicles/cars_en.

stringent fuel standards. To estimate fuel consumption, we again draw upon fuel consumption factors from COPERT IV, MODEM (2015), and GEASUR (2015a). These factors relate fuel consumption with vehicle attributes, circulation speed, and VMT. For the factual scenario, we multiply fuel consumption by the sulfur content limit required by the most stringent regional or national standard.[11] Exhibit 2-9, included later in this report, demonstrates how the sulfur content in gasoline and diesel fuels declines over time, following Santiago Metropolitan Region standards. For the counterfactual scenario, we assume that sulfur content in fuels would remain at 1990 levels for the entirety of our study period.

For NO_x and $PM_{2.5}$ emissions, we account for deterioration of emissions controls over a vehicle's lifespan. Such an approach increases predicted emissions from used vehicles. We draw upon deterioration factors from GEASUR (2015b), which employs remote sensing devices to estimate emissions factors from over 300,000 vehicles in the Santiago Metropolitan Region. Exhibit 2-3 presents estimated 2017 NO_x emissions from onroad vehicles under both the factual and counterfactual scenarios.

EXHIBIT 2-3. EFFECT OF DETEORATION FACTORS ON 2017 TRANSPORT NO_X EMISSIONS



Application of deterioration factors increases estimated 2017 NO_x emissions from onroad vehicles by 11 percent in the factual scenario and 19 percent in the counterfactual scenario.[12] The effect is much larger for $PM_{2.5}$, as deterioration factors double estimated emissions in 2017. After implementing these deterioration factors, onroad sources

[11] Observed data on sulfur content is largely unavailable in Chile; however, the limited data summarizing testing of fuels indicate that sulfur content regularly approaches the binding standards in place.

[12] COPERT IV also includes deterioration factors, which yielded a similar, but lesser, effect on emissions. We apply GEASUR (2015b) degradation factors because the study relies upon local data and includes deterioration factors for more pollutants (COPERT IV does not include factors for $PM_{2.5}$) and vehicle categories.

contribute roughly 900 tons of directly emitted fine particulate matter under the factual scenario and 1,800 tons under the counterfactual scenario.[13]

2.1.3 CALIBRATION

We calibrate our onroad emissions model by comparing predicted fuel consumption in the factual scenario with observed fuel consumption in Santiago from 1999 to 2015.[14] For each year, we estimate the ratio of predicted and observed fuel consumption. We then fit a linear trend between these values to calculate an annual adjustment factor for circulation speed. This adjustment is done using gasoline sales data because onroad sources account for nearly all of gasoline fuel consumption in the region.[15] We assume that pre-1999 circulation speeds are equal to the 1999 value and that post-2015 circulation speeds are equal to the 2015 value.

2.2 NON-ROAD ENGINES AND VEHICLES

Non-road engines and vehicles comprise machinery related to construction, mining, and related industries and processes. This machinery is primarily imported to Chile and has remained unregulated until the 2018 PPDA. We combine fleet and emissions data for nonroad sources to construct a time series of emissions from 1990 to 2020. The data and methodology presented in this section stem primarily from GEASUR (2014) and MMA (2016a, 2016b).

GEASUR (2014) provides the number of nonroad sources for the period between 2000 and 2013.[16] We extrapolate these counts using projections from MMA (2016a) for 2013 to 2020.[17] For the period prior to 2000, we assume a one-to-one relationship between sector-specific GDP growth for the Santiago Metropolitan Region and growth in the number of nonroad units. GDP growth data was obtained from the Banco de Chile. Exhibit 2-4 presents the results of our fleet projections.

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[13] All tons presented in this report refer to metric tons (i.e., 1,000 kilograms).

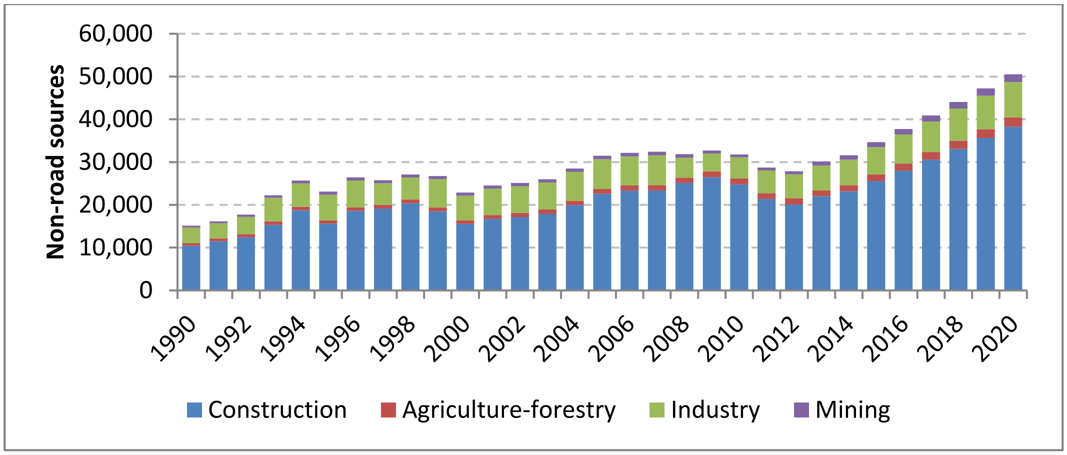
[14] Fuel sales data were obtained from the Superintendencia de Electricidad y Combustibles: http://www.sec.cl/portal/page?_pageid=33,3429539&_dad=portal&_schema=PORTAL.

[15] We are able to exclude gasoline used in aviation from our calibration; however, some industrial, non-road, and residential sources may use gasoline.

[16] Non-road sources are defined as individual pieces of machinery (e.g., one engine or vehicle).

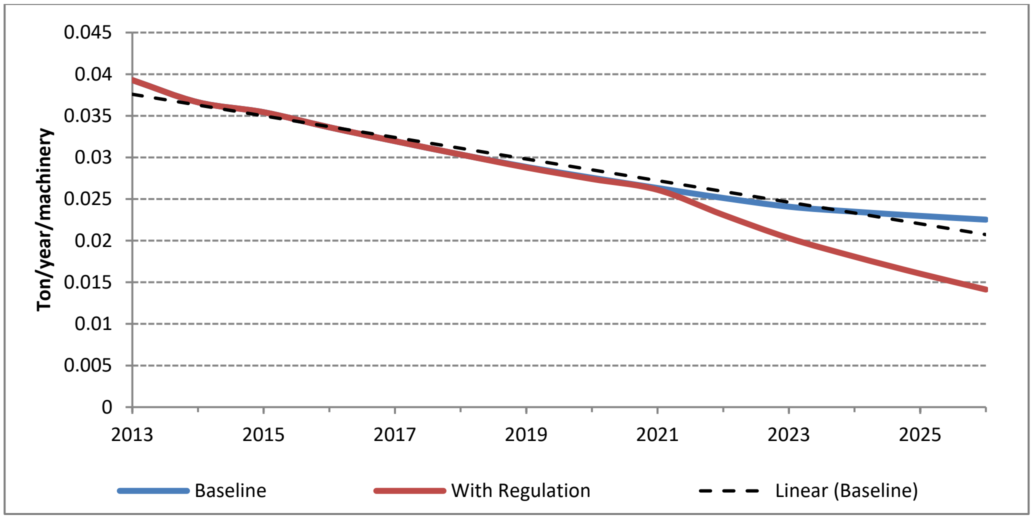
[17] MMA (2016a) adapts projections from GEASUR (2014).

EXHIBIT 2-4. NONROAD SOURCES, 1990-2020



We estimate that roughly 40,000 non-road sources were in use in 2017 in Santiago. The majority of these sources in the Santiago Metropolitan Region are construction machinery, accounting for roughly three-quarters of the fleet. We combine these fleet projections with unitary emissions (i.e., average emissions per non-road source) data from MMA (2016a), which provides data for the years 2013 to 2025. We backcast unitary emissions using sector-specific linear time trends fit to the factual scenario, as displayed in Exhibit 2-5 for $PM_{2.5}$ emissions from construction units.

EXHIBIT 2-5. NON-ROAD $PM_{2.5}$ EMISSIONS PER SOURCE, CONSTRUCTION 2013-2025



Finally, we estimate total emissions from the non-road sector by multiplying the number of sources by the corresponding unitary emission rates. Because this sector is not currently regulated, the counterfactual scenario diverges from the factual scenario only in 2020, when the newest PPDA begins to impact the non-road sector. This effect is captured through lower unitary emissions in the factual scenario, as displayed in Exhibit 2-5.

2.3 RESIDENTIAL SOURCES

Residential sources are a significant contributor to ambient $PM_{2.5}$ in Santiago, particularly during winter months when firewood is used by many households for heating (Barraza et al. 2017). Regional regulations have addressed these emissions through air emission standards for new heaters, banning of open fire places, and restrictions to firewood use during critical episodes. We estimate residential emissions by combining survey data on the number of devices that use firewood and the emission factors for these devices.

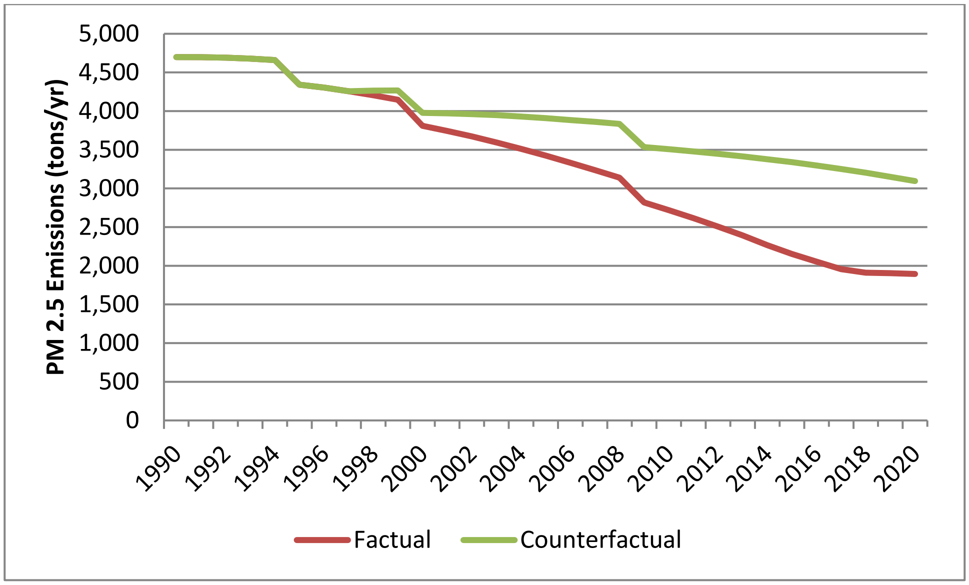
To quantify the number of wood-burning devices, we rely on two data sources. First, the National Socio-Economic Characterization Survey (CASEN) provides data on whether households use firewood for any purpose at home. These surveys were distributed in 2006, 2013, and 2015. Second, 1992 and 2002 Census data from INE provide information on the number of homes that use firewood explicitly for cooking. We linearly interpolate between these data points and extrapolate to the missing years to calculate the proportion of homes from 1990 to 2020 that use firewood for cooking or heating.[18] Finally, CDT (2012) provides detailed information on the types of wood-burning devices in households in the Santiago Metropolitan Region.

In the counterfactual scenario, we assume that fewer households would switch away from firewood as a cooking or heating fuel. We assume that the rate of growth of firewood use would roughly approximate growth in a similar region without regulations. We considered two nearby regions with similar climates to the Santiago Metropolitan Region: Valparaiso and O'Higgins. After considering regional GDP, GDP per capita, and the evolution of home and apartment construction over time, we ultimately selected Valparaiso for our counterfactual construction.

We apply device-specific emission factors to our time series of wood-burning devices in the Santiago Metropolitan Region. Emissions factors are dependent upon both the wood moisture content and its calorific value. We use estimates for these parameters, and for average heating demand from MMA (2016b). The resulting emissions estimates for directly-emitted $PM_{2.5}$ are presented in Exhibit 2-6. Our analysis also considers emissions of NO_x, SO_2, and NH_3.

[18] We assume that firewood is used either for cooking or heating. Thus, any firewood consumption not used for cooking is assumed to be for home heating. We project the number of homes from 2015 to 2020.

EXHIBIT 2-6. RESIDENTIAL EMISSIONS OF DIRECTLY-EMITTED $PM_{2.5}$



We note that residential emissions decline in both the factual and counterfactual scenarios, reflecting a general trend away from firewood use for cooking and heating among households. Increasingly, residents are living in apartment buildings, which rarely burn firewood.[19] Implementation of air quality management policies in the Santiago Metropolitan Region has accelerated the reduction in emissions in the factual scenario, relative to the counterfactual scenario.

2.4 INDUSTRIAL SOURCES

Our approach to estimating emissions from industrial sources differs by pollutant. This methodology reflects a dichotomy in the relative importance of large point sources to directly-emitted $PM_{2.5}$ when compared to emissions of NO_x and SO_2. Whereas $PM_{2.5}$ emissions are attributable to many, diffuse industrial processes in Santiago, NOx and SO_2 emissions stem largely from a handful of large emitters. Thus, we model the emissions of NO_x and SO_2 from individual, major emitters and supplement this modeling with aggregated emissions modeling for small emitters of NO_x and SO_2. Due to the diffuse nature of $PM_{2.5}$ emissions from industrial sources, we also employ an aggregated modeling approach for all $PM_{2.5}$ emissions stemming from these sources.

2.4.1 INDUSTRIAL EMISSIONS OF NITROGEN OXIDES

We estimate industrial sector emissions of NO_x by first modeling the emissions of the 10 largest emitters. These sources contributed to roughly 35 percent of NO_x emissions in 2005 and have been subject to strict emissions reporting requirements since 1997.

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[19] Emissions from apartment buildings are modeled with industrial sources, as heating boilers are contained within industrial sector data sources.

Additionally, these sources are required to cease operations during “emergency” and “Pre-emergency” declarations under the critical episode management plan. Exhibit 2-7 presents the 10 sources which we model individually, as described below.

EXHIBIT 2-7. MAJOR NO_X EMITTERS

COMPANY	INDUSTRY	2005 EMISSIONS, TONS (% OF TOTAL)
Cemento Polpaico S.A.	Cement Manufacturing	2,121 (17.2%)
Cristalerías de Chile S.A.	Glass Manufacturing	1,048 (8.5%)
Papeles Cordillera S.A.	Paper Manufacturing	352 (2.9%)
Cristalerías Toro S.A.I.C.	Glass Manufacturing	228 (1.8%)
Gerdau Aza S.A.	Steel Manufacturing	213 (1.7%)
Soprocal Calerías e Industrias S.A.	Lime and Carbonate Production	179 (1.5%)
Molibdenos y Metales S.A.	Molybdenum Processing	39 (0.7%)
Sociedad Industrial Romeral S.A.	Construction	29 (0.2%)
Industrias Princesa LTDA	Brick Manufacturing	26 (0.2%)
Papeles Industriales S.A.	Paper Manufacturing	17 (0.1%)
10 Largest NO_X Emitters	See above	4,252 (34.8%)
Source: DICTUC (2007)		

To estimate emissions for large emitters, we draw upon emissions inventories, company-specific emissions reports, and emissions standards for the Santiago Metropolitan Region. For eight of the large emitters, data is available in the 2005 emissions inventory. And, all large emitters reported their emissions in 2010 and 2014, as required for sources producing over eight tons of NO_x annually. Finally, we assume compliance with, a mandated emissions standard for major emitters that requires reductions in NO_x emissions from 1997 levels by 33% by 2007 and 50% by 2010 (DS66 2009 MinSegPres, Article 69).

To construct a factual scenario for each large emitter, we linearly interpolate source-specific emissions for years without (a) emissions inventories, (b) declared emissions, or (c) specific regulation on emissions. For the years 1990 through 1996, we assume a flat level of emissions equal to our estimated value in 1997.[20] Similarly, we construct a counterfactual emissions estimate by assuming that no emissions reductions occur after 1997 (i.e., no regulatory actions). However, we allow for counterfactual emissions to change based on reported expansions for each source.[21]

In sum, we capture a significant portion of NO_x emissions by individually modeling the emissions from major sources. For the remaining 65 percent of NO_x emissions, we

[20] There were no major regulations during this time that would have prompted emissions reductions.

[21] These expansions are documented by the Chilean Servicio de Evaluación Ambiental (SEA, Environmental Evaluation Service) in Evaluación de Impacto Ambiental (EIA, Environmental Impact Evaluation), Declaración de Impacto Ambiental (DIA, Environmental Impact Declaration), and other documentation. Reports can be accessed at http://sea.gob.cl/.

employ an aggregate estimation approach in which we select a base year emissions inventory and scale emissions based on annual growth in industrial sector GDP and emissions factors from USEPA's AP-42 Air Pollutant Emissions Factors Database.[22] For a base emissions inventory, we draw upon the Ministry of Health's 2014 emissions database.[23] The inventory provides a comprehensive database of emissions sources and was constructed recently; however, we note that emissions estimates are self-reported. Prior to modeling emissions from small emitters, we remove the 10 large emitters from our dataset to avoid double-counting emissions.

To estimate factual emissions, we divide 2014 NO_x emissions into categories that correspond with AP-42 emissions factors. Generally, these categories cover fuel type (e.g., natural gas or fuel oil), source type (e.g., boiler or oven), and source size (e.g., boiler capacity). MMA industrial sector experts selected emissions factors representative of the control measures implemented since uncontrolled industrial activity in the early 1990s. Notably, the only NO_x controls selected by experts were low NO_x burners on large boilers, i.e., those exceeding 20 MW. Without detailed information on the implementation of NO_x controls, we assume that improvements in emissions factors were linear between 1990 and 2014.[24] We further scale NO_x emissions by industrial sector GDP to reflect growth in both the number of sources between 1990 and 2014 and the activity level of these sources.[25] Finally, we estimate counterfactual NO_x emissions from small emitters by scaling 1990 emissions with industrial sector GDP.

2.4.2 INDUSTRIAL EMISSIONS OF SULFUR OXIDES

We estimate industrial emissions of SO_2 using an identical approach to that of estimating NO_x. We first estimate the emissions of large emitters by drawing upon past emissions inventories, reported emissions, and mandated emissions reductions. We focus on the top six emitters of SO_2, the majority of which derive from one source which processes molybdenum. These emitters are presented in Exhibit 2-8 and represent roughly half of all 2005 SO_2 emissions in Santiago.

[22] AP-42 emissions factors may be accessed at https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emission-factors.

[23] The database is maintained under resolution 15027 of 1994 (see http://bcn.cl/1v1hk).

[24] For example, we calculate NO_x emissions from large natural boilers in 1990 by scaling the 2014 emissions by the ratio of emissions factors for uncontrolled (Pre-NSPS) units (280 lb/106 scf) and those equipped with low NO_x burners (140 lb/106 scf).

[25] We define the industrial sector to include manufacturing industry and commercial activities including wholesale and retail trade, hotels and restaurants. We implicitly assume a one-to-one relationship between emissions and GDP in the industrial sector.

EXHIBIT 2-8. MAJOR SO_2 EMITTERS

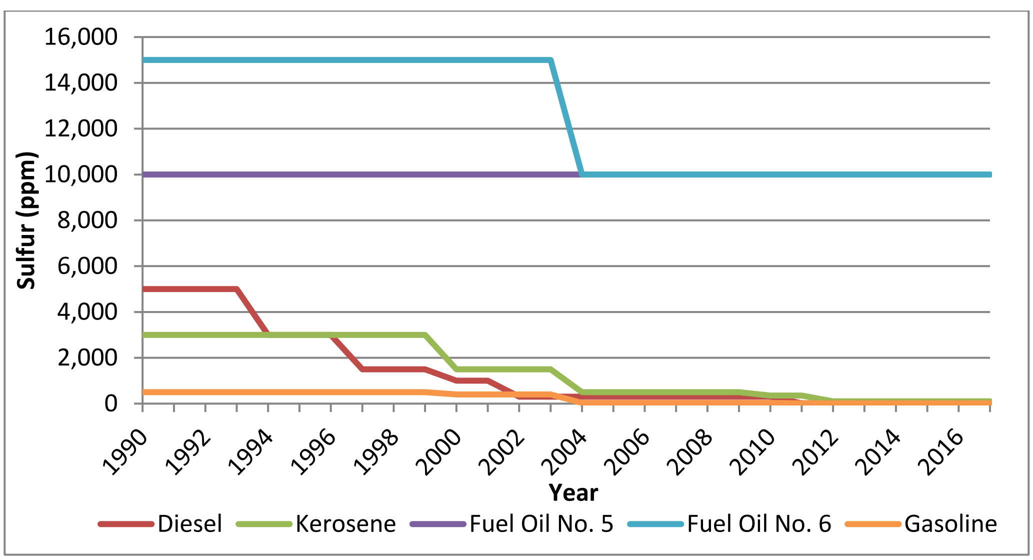
COMPANY	INDUSTRY	2005 SO_2 EMISSIONS, TONS, (% OF TOTAL)
Molibdenos y Metales S.A.	Molybdenum processing	4,612 (36.0%)
Cristalerías de Chile S.A.	Glass manufacturing	801 (6.2%)
Cemento Polpaico S.A.	Cement manufacturing	400 (3.1%)
Cristalerías Toro S.A.I.C.	Glass manufacturing	300 (2.3%)
Soprocal Calerías e Industrias S.A.	Lime and carbonate production	179 (1.4%)
Industrias Princesa LTDA	Brick manufacturing	75 (0.6%)
8 Largest SO_2 Emitters	See above	6,367 (49.6%)

Source: DICTUC (2007)

We supplement our SO_2 emissions modeling of large emitters by employing an aggregate approach to modeling the remaining emissions from smaller sources. In contrast to NO_x emissions factors, the SO_2 emissions factors in the AP-42 database largely reflect the sulfur content of fuel inputs. Emissions of SO_2 are assumed to scale linearly with sulfur content. We are unaware of a comprehensive database of the observed sulfur content in fuels in Santiago (or Chile as a whole) and thus use mandated fuel standards as a proxy for observed sulfur content.

The standard for diesel fuel gradually tightened from 5,000 parts per million (ppm) in 1990 to 15 ppm in 2011. Gasoline observed similar declines in the maximum allowable sulfur content. Exhibit 2-9 illustrates the increasingly stringent standards for sulfur content in fuel over time in the Santiago Metropolitan Region. We thus scale emissions from small sources to follow a one-to-one relationship with sulfur content and economic activity in the industrial sector. The counterfactual scenario for SO_2 assumes that sulfur standards remain at 1990 levels through 2020.

EXHIBIT 2-9. STANDARDS FOR SULFUR CONTENT IN FUEL IN SANTIAGO METROPOLITAN REGION



2.4.3 INDUSTRIAL EMISSIONS OF FINE PARTICULATE MATTER

Industrial emissions of fine particulate matter originate from many, diffuse sources in Santiago. These sources include car painting booths, large cooking ovens, and wheat mills, among a wide variety of sources. As such, modeling direct $PM_{2.5}$ emissions from individual sources over our 30-year timeframe is infeasible. Thus, we employ an aggregate modeling approach in which we assess trends in industrial emissions intensity.

The first phase of this modeling effort included consultation with industrial sector experts at MMA to assess the quality of $PM_{2.5}$ emissions inventories in the region between 1990 and 2020. Ultimately, three inventories were selected with aggregate $PM_{2.5}$ emissions estimates for the industrial sector. These inventories cover the years 1997 (CONAMA, 1997), 2005 (DICTUC 2007), and 2014 (USACH 2014).[26] For each of the three years covered by emissions inventories, we calculate emissions intensity by dividing $PM_{2.5}$ emissions by industrial sector GDP. Next, we assessed the goodness of fit of several trend lines between these emissions intensity units and assessed the trends on three criteria:

- **Monotonic:** Emissions intensity should experience a strictly decreasing pattern over time as environmental regulations become more stringent.
- **Strictly positive:** The selected trend line should never produce negative estimates of emissions intensity.
- **Steepest slope in mid-1990s:** Emissions intensity should decline at a decreasing rate to reflect stringent emissions reductions imposed in the mid-1990s.

Based on these criteria, we fit an exponential function to the three emissions intensity estimates to produce estimates for the period between 1992 and 2020. We assume that emissions intensity was flat for the period between 1990 and 1992, as $PM_{2.5}$ controls had not yet been mandated. To construct the factual scenario, we multiply estimated annual emissions intensity by industrial sector GDP. The counterfactual scenario assumes a constant pre-regulation emissions intensity (i.e., the 1990-1992 value), which is then multiplied by industrial sector GDP in each year.

2.5 WILDFIRES

We estimate emissions of $PM_{2.5}$, NO_x, SO_2, and NH_3 stemming from wildfires in the Santiago Metropolitan Region. Using monthly data on wildfire damages for the period 1985 to 2016, we calculate seasonal and annual damage estimates in hectares.[27] For the years 2017 to 2020, we assume that seasonal and annual wildfire damages are equal to the mean observed values from 1985 to 2016. Based on the results from preliminary regression analysis, we assume that there is no temporal trend in wildfire damages. As expected, we find that wildfires are generally most damaging during the summer months.

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[26] We omitted self-reported emissions inventories per discussion with MMA experts.

[27] Wildfires data are obtained from Corporación Nacional Forestal – Gerencia Protección Contra Incendios Forestales

Because emissions factors differ by land cover type, we evaluate land cover in Santiago in 2014 (Laboratorio Geomática y Ecología de Paisaje) and calculate the coverage of woodland, pasture, and shrub. We assume that wildfires only affect these land cover types and thus assign wildfire damage, in hectares, to each land cover type according to their relative coverage in the region.[28] With wildfire damages split by land cover type, we apply pollutant-specific emissions factors from GreenLabUC (2016).

We estimate that wildfires in Santiago contribute, on average, 364 tons of $PM_{2.5}$, 162 tons of NO_x, 40 tons of NH_3, and 50 tons SO_2 annually. Considerable variation exists in emissions across seasons and years, which we capture in our air quality models described below. Finally, we note that wildfires emissions are unaffected by current environmental regulations and are thus equal across the factual and counterfactual scenarios.

2.6 REGIONAL CONTRIBUTIONS

Regional sources also contribute to ambient $PM_{2.5}$ concentrations in Santiago. Barraza et al. (2017) estimate regional contributions from copper smelters and coastal sources from 1998 to 2012 in a source-apportionment analysis of filter data. As discussed in Chapter 3, we account for these contributions when modeling air quality. These values enter into our analysis as ambient $PM_{2.5}$ concentrations. That is, we do not attempt to model emissions or emissions transport from these sources. Although the authors only assess filter data from 1998 to 2012, we extrapolate these values to span our analytic timeframe. This imputation involves applying 1998 values to the pre-1998 period and the 2012 values to the following period. From 1990 to 1998 we hold the contribution to ambient concentrations from copper smelters constant at the 1998 level; similarly we hold these contributions constant at the 2012 level for the period from 2012 to 2020.

2.7 AGGREGATE EMISSIONS ESTIMATES

The resulting NO_x, $PM_{2.5}$, and SO_2 emissions estimates are summarized in Exhibit 2-10 for the years 1990 and 2017. Emissions are summarized annually. For 1990, the factual and counterfactual scenarios are identical. Differences presented in the exhibit relate to changes between counterfactual and factual emissions in 2017. Exhibits 2-11, 2-12, and 2-13 demonstrate the emissions, in tons per year, for each pollutant and sector for four select years. These exhibits demonstrate both the factual emissions and the additional emissions that would have occurred under the counterfactual scenario.

[28] We also implicitly assume that land cover in Santiago remains unchanged over the past three decades. We also assume that each acre of woodland, shrub, and pasture is equally likely to be affected by wildfires.

EXHIBIT 2-10. SECTOR-SPECIFIC EMISSIONS, 1990 AND 2017

DIRECTLY EMITTED $PM_{2.5}$					
		2017 EMISSIONS			
SECTOR	1990 EMISSIONS	COUNTERFACTUAL	FACTUAL	DIFF.	PCT. DIFF.
Industry	2,732	7,667	549	7,118	-93%
On road	1,595	1,764	908	856	-49%
Non road	861	1,239	1,239	0	0%
Residential	4,698	3,252	1,956	1,296	-40%
Forest fires	95	399	399	0	0%
Total	**9,981**	**14,321**	**5,051**	**9,270**	**-65%**
NITROGEN OXIDES (NO_X)					
		2017 EMISSIONS			
SECTOR	1990 EMISSIONS	COUNTERFACTUAL	FACTUAL	DIFF.	PCT. DIFF.
Industry	6,812	10,843	7,252	3,591	-33%
On road	30,265	29,327	18,900	10,427	-36%
Non road	8,202	10,177	10,177	0	0%
Residential	374	306	182	125	-41%
Forest fires	42	178	178	0	0%
Total	**45,696**	**50,831**	**36,689**	**14,142**	**-28%**
SULFUR DIOXIDES (SO_2)					
		2017 EMISSIONS			
SECTOR	1990 EMISSIONS	COUNTERFACTUAL	FACTUAL	DIFF.	PCT. DIFF.
Industry	11,261	20,439	3,010	17,429	-85%
On road	4,879	9,536	67	9,470	-99%
Non road	16	42	42	0	0%
Residential	58	47	28	19	-41%
Forest fires	13	55	55	0	0%
Total	**16,227**	**30,120**	**3,202**	**26,918**	**-89%**

Notes: Emissions are expressed in tons per year. Diff. = 2017 counterfactual emissions minus 2017 factual emissions. Pct. Diff. = Diff. divided by 2017 counterfactual emissions.

EXHIBIT 2-11. EMISSIONS OF NITROUS OXIDE (TONS/YEAR) FOR THE FACTUAL SCENARIO AND ADDITIONAL EMISSIONS UNDER THE COUNTERFACTUAL SCENARIO

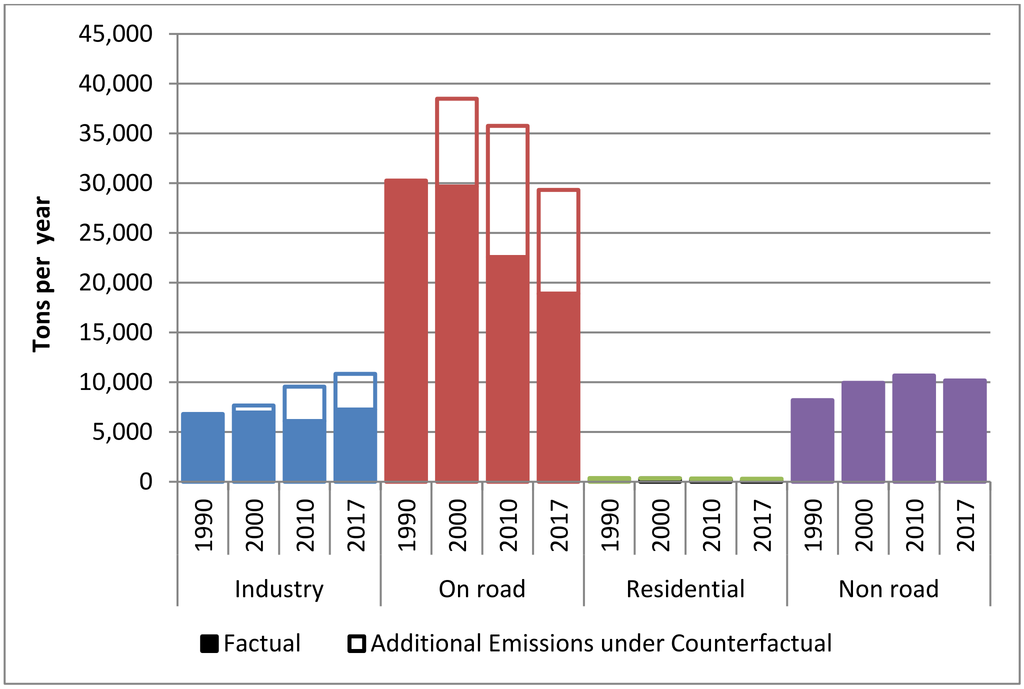


EXHIBIT 2-12. EMISSIONS OF SULFUR DIOXIDE (TONS/YEAR) FOR THE FACTUAL SCENARIO AND ADDITIONAL EMISSIONS UNDER THE COUNTERFACTUAL SCENARIO

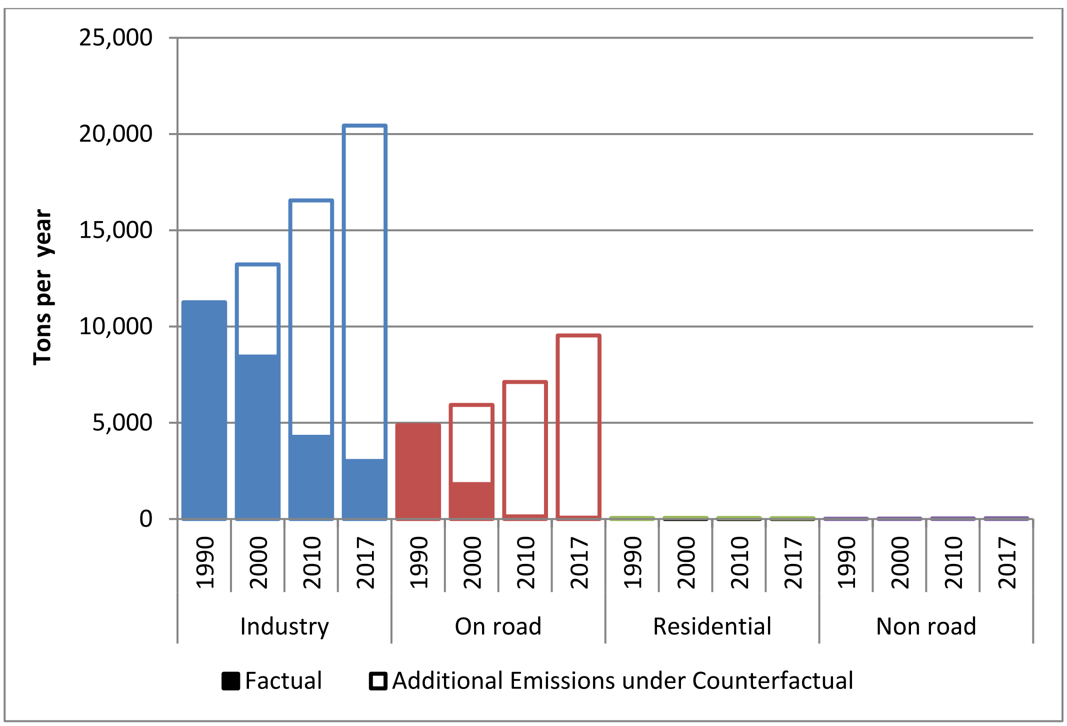
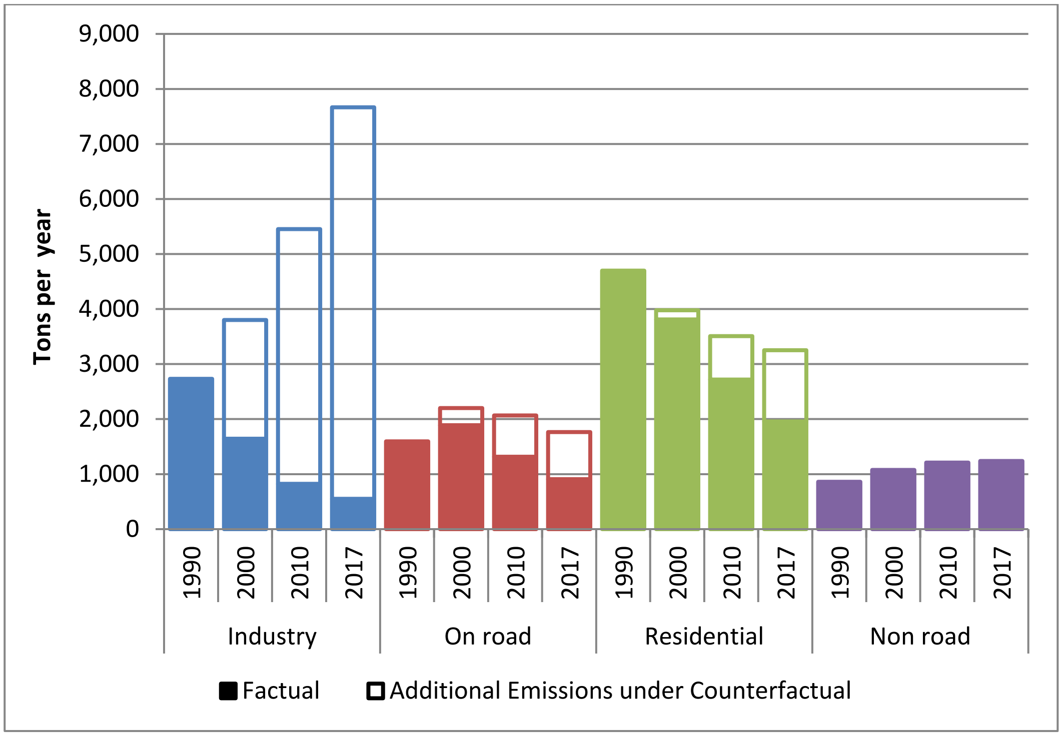


EXHIBIT 2-13. EMISSIONS OF $PM_{2.5}$ (TONS/YEAR) FOR THE FACTUAL SCENARIO AND ADDITIONAL EMISSIONS UNDER THE COUNTERFACTUAL SCENARIO



We find that for each pollutant, total emissions would have increased since 1990 without environmental controls. This pattern is particularly pronounced for SO_2, where emissions would have roughly doubled. However, due to the introduction of controls, the 2017 factual scenario reflects significant emissions reductions for each pollutant. Factual NO_x emissions are roughly 28 percent lower than the counterfactual scenario, due largely to improvements in the industrial and on road sectors. Factual $PM_{2.5}$ emissions are roughly 63 percent lower than the counterfactual value, driven largely by a 93% difference between the scenarios for industrial sources. Finally, SO_2 emissions are 89 percent lower in total between the scenarios, driven by drastic reductions in the sulfur content in fuels. Below, we discuss the costs associated with achieving these emissions reductions.

CHAPTER 3 | DIRECT COSTS

Concurrent with modeling emissions, we estimate the associated costs of emissions controls. Consistent with USEPA (2011), we focus only on the first-order economic costs of environmental controls (i.e., "direct costs"). For example, we consider expenditures to purchase, install, and operate pollution controls (e.g., low NO_x burners). We do not consider indirect economic effects, or those that result from direct costs and benefits.[29] We only estimate costs for sectors where emissions reductions occur. Thus, no costs are associated with wildfires or regional sources, the latter of which are affected by environmental regulations in both our factual and counterfactual scenarios. Below, we outline our methods to estimating direct costs for the onroad, non-road, residential, and industrial sectors.

3.1 ONROAD

Emissions reductions in the onroad sector are attributed to two sets of environmental regulations. First, regulations required that imported vehicles comply with increasingly stringent air emissions standards. Second, national and regional fuel standards greatly reduced sulfur content in transportation fuels. We estimate costs for these regulations separately.

3.1.1 VEHICLE EMISSIONS STANDARDS

We draw upon three sets of cost estimates to assess the costs to automotive manufacturers to produce vehicles meeting varying emissions standards. Each source, summarized in Exhibit 3-1, provides the incremental costs for manufacturers to comply with each "step" of EURO emissions standards. First, ICCT (2012) provides cost estimates for light duty vehicles. ICCT (2016) provides comparable estimates for heavy duty vehicles. Finally, we apply cost estimates from LAT (2005) for motorcycles.[30] We assume that these costs are fully passed through to consumers and businesses in Santiago.

[29] For example, an indirect cost may be the increased price of cement in Santiago because of environmental controls installed by cement producers. Accounting for such indirect effects generally requires economy-wide modeling, which is outside of the scope of this project.

[30] We apply results from Approach #2 summarized in LAT (2005).

EXHIBIT 3-1. INCREMENTAL COSTS TO COMPLY WITH VEHICLE EMISSIONS STANDARDS

EMISSIONS STANDARD	LD GASOLINE VEHICLES (ICCT 2012)	LD DIESEL VEHICLES (ICCT 2012)	HD VEHICLES (ICCT 2016)	MOTORCYCLES (LAT 2005)
No Standard → EURO I	$156	$62	$469*	$31**
EURO I → EURO II	$69	$92	$469*	$100**
EURO II → EURO III	$134	$371	$469	$141**
EURO III → EURO IV	$28	$160	$4,151	-
EURO IV → EURO V	$11	$337	$506	-
EURO V → EURO VI	-	$518	$2,510	-

Notes: All costs are summarized in 2016 USD. Values converted using 2016 Purchasing Power Parity values and country-specific inflation. LD = Light Duty. HD = Heavy Duty. * Incremental costs to comply with EURO I and EURO II standards for heavy duty vehicles are assumed to be equal to the incremental cost of reaching EURO III. ** Incremental costs from LAT (2005) are assumed to be equal to the midpoint of the ranges provided by the authors.

The incremental costs summarized in Exhibit 3-1 are additive. For example, we assume that for light duty vehicles, the added cost of producing a vehicle compliant with EURO IV standards is $231 more than for an equivalent vehicle meeting only the EURO I standard ($69 + $134 + $28 = $231). These costs are applied to emissions reductions by comparing the composition of the vehicle fleet under both the factual and counterfactual scenarios (see Exhibit 2-2).

3.1.2 FUEL STANDARDS

Additionally, we consider fuel standards first issued by the Ministry of Economics and subsequently tightened in MMA PPDAs. These regulations restricted sulfur content in fuels, thus affecting emissions from both onroad and industrial sources. We account for reductions in sulfur content in gasoline and diesel fuels during our study period using incremental refining costs from IEc (2011). Specifically, we apply a diesel-specific cost of 2.0 cents per gallon (2010$) for reductions to 500ppm sulfur and 3.25 cents per gallon (2010$) for reductions to 15ppm sulfur.[31] These costs were adjusted for learning effects (i.e., decreasing costs through experience in the refining process) and reduced sulfur inhibited corrosion of vehicle components, which reduces maintenance costs for consumers. And, we calculate the average gasoline refinery costs for 2010 and 2020 to yield a cost of 1.25 cents per gallon (2010$). These values are converted to 2016$ using the U.S. Consumer Price Index and summarized in Exhibit 3-2 below.

[31] We average the 3.0 cents per gallon estimate for 2010 and the 3.5 cents per gallon estimate for 2020.

EXHIBIT 3-2. PER-GALLON REFINING COSTS

SULFUR CONTENT	GASOLINE	DIESEL
500+ ppm	$0.0167	$0.0267
15+ ppm		$0.0427

Notes: Adapted from IEc (2011). Values expressed in 2016$ per gallon.

For years with sulfur reductions, we calculate total sectoral costs by multiplying factual fuel consumption by the removal costs summarized above. For each year, we ensure that costs correspond to the factual level of sulfur content in fuels. As we explain below, this methodology is also applied to fuel consumption in the industrial sector.

3.2 NON-ROAD

The 2018 PPDA establishes emissions standards for non-road machinery and requires installation of pollutant filters in construction machinery used in governmental construction projects. We apply cost estimates from MMA (2016a) for air emissions standards and estimates from GEASUR (2015a) for construction filters. In both cases operation and investment costs were considered. These cost estimates are summarized in Exhibit 3-3.

EXHIBIT 3-3. NON-ROAD COSTS

PARTICLE FILTERS		
CAPACITY	INVESTMENT	O & M ($/HR)
19 ≤ kW < 37	859	0.64
37 ≤ kW < 56	1,074	1.15
56 ≤ kW < 75	1,074	1.15
75 ≤ kW < 130	1,290	1.58
130 ≤ kW < 300	1,790	2.79
300 ≤ kW < 560	1,790	2.79

ENTRY STANDARDS				
STANDARD	INVESTMENT		O & M ($/YR)	
-	**Stage IIIa**	**Stage IV**	**Stage IIIa**	**Stage IV**
No standard	316	741	-186	-15
Stage I	218	644	-190	-19
Stage II	120	546	-136	35
Stage IIIA	-	426	-	171

Notes: All costs expressed in 2016 USD. The entry standard costs reflect upgrade costs over an existing standard (no standard through Stage IV). Negative O&M costs reflect cost savings from lower fuel consumption and reduced maintenance.

3.3 RESIDENTIAL

We estimate residential sector costs using average cost per ton estimates.[32] To calculate this average cost, we first estimate the unitary emissions reductions stemming from the replacement of an old wood-burning device for a new device. We obtained the proportion of outgoing firewood equipment from CDT (2012) and the proportion of new devices from MMA (2016b).[33] This approach considers investment costs and changes in operational costs based on fuel type, efficiency, and heating demand. These costs and emissions reductions relate to three control measures:

1. Prohibition of firewood in central Santiago.[34]
2. Prohibition of specific firewood devices (e.g., salamandras, braziers, open-fire stoves) in the entire Santiago Metropolitan Region.
3. Prohibition of other firewood devices with emissions exceeding 2.5 grams per hour in the rural part of the region.

These measures require that many households invest in lower-emission replacements for their firewood-burning devices. We annualize these investment costs across the assumed life of the device. We then calculate unitary costs by dividing costs by emissions reductions for each upgraded device. We then calculate an average weighted unitary cost according to the proportion of outgoing and ingoing devices.

We estimate that the average investment cost of reducing $PM_{2.5}$ by replacing old firewood-burning devices is $5,759 per ton of emissions reduced. We also find that the average upgrade produces fuel savings of around $1,740 per ton of emissions. These fuel savings are counted as benefits, as described later in this report. We apply the investment cost to emissions reductions (i.e., the difference between the counterfactual and the factual scenario) for the period from 1990 to 2020. Thus, we assume that the individual cost of upgrading a firewood-burning device has remained relatively constant during this timeframe.

3.4 INDUSTRIAL SOURCES

We estimate industrial sector control costs using pollutant-specific cost per ton estimates largely consistent with MMA (2016b). Where necessary, we adjust these estimates, originally generated by DICTUC (2013) for the period from 2016 to 2026, to reflect the

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[32] For this report, we apply cost per ton estimates to emissions reductions that occur each year throughout the study period. That is, we compare counterfactual to factual emissions in each year to estimate the reduction in emissions and apply our cost per ton estimate to this difference.

[33] The average proportion of outgoing costs are 12.4% for chimneys, wood stoves, and others; 24.3% for the Salamader stove; 6.45% for simple combustion; and 56.8% for double split firewood. The average proportion of incoming costs are 10% for pellets; 40% for kerosene stoves; 48% for liquefied gas stoves; and 2% for electric-powered stoves.

[34] Pellet stoves are permitted in central Santiago.

technology mix of emissions controls dating back to 1990.[35] For SO_2 emissions abatement, we consider costs to refineries of reducing sulfur content in fuels. We summarize this methodology below.

3.4.1 COSTING FOR NO_X EMISSIONS

We generate separate control costs for small and large NO_x emitters (as defined in Section 2-4). For large emitters, we draw upon data from CMM (2016) characterizing emissions controls installed by large emitters as of 2016. Using this information, we construct an average cost per ton of emissions abatement from 1990 to 2015 (i.e., the period in which the controls were implemented), weighted by the prevalence of each technology. We derive a cost per ton estimate of $3,678 per ton. For small emitters with a capacity above 20 MW, we apply a cost per ton estimate reflecting the cost of low NO_x burners, the primary control technology modeled in Section 2-4. The average cost per ton is $3,751 in 2016 USD for the period 1990 to 2020.

3.4.2 COSTING FOR PM EMISSIONS

We apply one cost per ton to all emitters of $PM_{2.5}$, reflecting our aggregated $PM_{2.5}$ emissions modeling. We again identify the control technologies installed prior to 2016 using CMM (2016) and their associated costs per ton from DICTUC (2013). Using these data, we then construct a weighted average cost per ton based on frequency of emissions control technologies. The resulting cost of $PM_{2.5}$ abatement is $220 per ton.

3.4.3 COSTING FOR SO_2 EMISSIONS

For SO_2, we calculate costs of emissions reductions separately for small and large emitters, based on the reduction of sulfur content in fuel, fuel switching toward fuels with lower sulfur content, and relevant abatement technology. The majority of costs for SO_2 emissions reductions are derived from reducing the sulfur content in fuel or switching to fuels that have lower sulfur content, rather than from abatement technology (DICTUC 2013). For large emitters of SO_2, we consider the costs of fuel switching toward fuels like natural gas and the cost of reducing sulfur content in fuel. For cement kilns specifically, we consider the cost of the desulfurization of the exit gases from the kiln (DICTUC 2013). The latter SO_2 control only applies to Cemento Polpaico, a large emitter and cement producer. Based on 2014 SO_2 emissions from each large emitter, we generate a weighted average cost for large emitters of $3,255 per ton. For small emitters, we only consider the cost of reducing the sulfur content in fuels across fuel types. The average cost for these small sources is $2,587 per ton from 1990 to 2020.

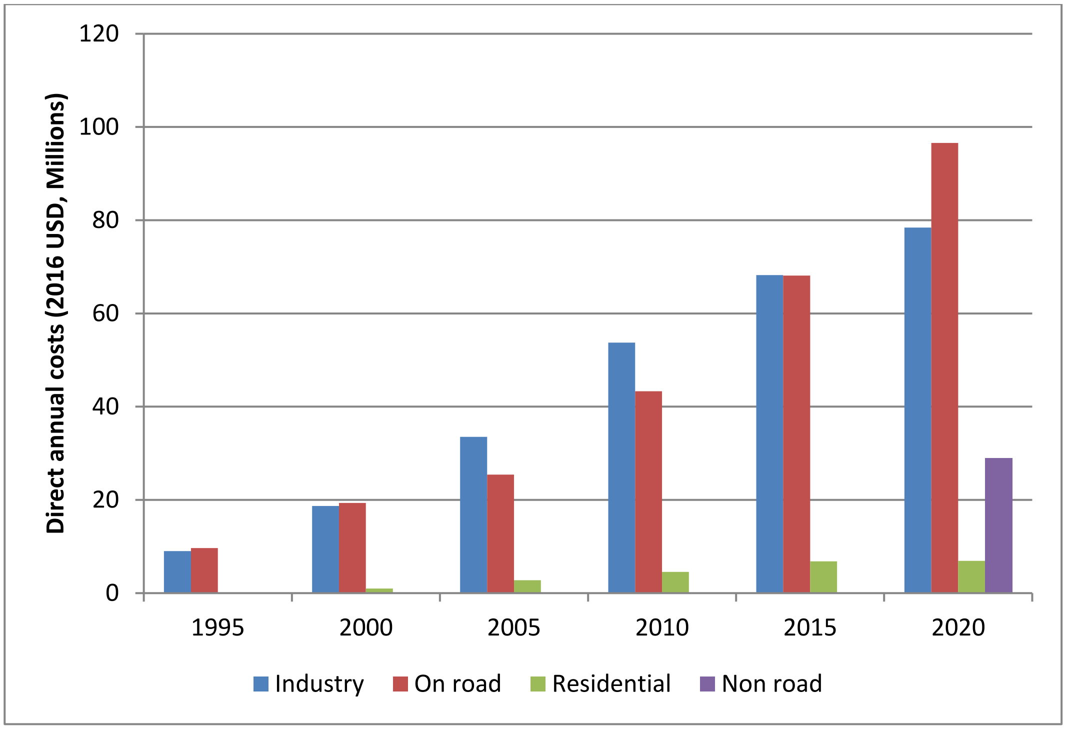
For each of the above pollutants, we apply these cost per ton estimates to the relevant air emissions reductions for the industrial sector. That is, we subtract factual emissions from counterfactual emissions and multiply this difference by the pollutant-specific and source-specific cost per ton estimate.

[35] DICTUC (2013) develops cost estimates for the Metropolitan Region using USEPA's Control Strategy Tool (CoST).

3.5 RESULTS

The resulting sector-specific costs are summarized in Exhibit 3-4 for the select years across our study period.

EXHIBIT 3-4. SECTOR-SPECIFIC COSTS, 1990-2020



Costs steadily increase from 1990 to 2020 as environmental regulations are implemented. Costs in the industrial and onroad sectors are relatively comparable and comprise the majority of the direct costs associated with environmental controls. Annual costs in each of these two sectors increase from roughly $10 million in 1995 to over $75 million in 2020. Residential sector costs are lower, averaging roughly $5 million annually. Finally, non-road sources only incur costs in 2020, when the 2017 PPDA requires environmental controls for these sources. In total, we estimate that direct costs from environmental controls over our study period are $680 million (2016 USD), discounted using a 6% discount rate and a base year of 1990.

CHAPTER 4 | AIR QUALITY MODELING

Using the emissions estimates from Chapter 2, we model pollutant concentrations in Santiago using two reduced form air quality models. First, we generate $PM_{2.5}$ concentration estimates using emissions-concentration factors (ECFs) from MMA's economic analyses (e.g., MMA 2016a). This approach calculates the ratio of emissions and measured ambient concentrations in a target year and assumes that this relationship is constant over time and space. Second, we adapt the 2 x 2 kilometer source-receptor matrix developed for the transportation sector presented in DICTUC (2010) for use in our analysis. These approaches, detailed in further detail below, produce air quality surfaces used for estimating health benefits in Chapter 5.

4.1 MMA APPROACH

First, we apply constant ECFs from MMA (2016b) that equate one ton of emissions with pollutant-specific effects on ambient $PM_{2.5}$ concentrations. The ECFs were developed using recent particulate matter composition in the region (FUDE 2015) and aerosol formation factors from Leeuw (2002). These sources were used to generate equivalences between the pollutants, as displayed in Exhibit 4-1. For example, one ton of NO_x contributes equally to ambient $PM_{2.5}$ as 0.118 tons of directly-emitted $PM_{2.5}$.[36] MMA (2016b) combine these estimates with a 2015 emissions inventory to derive total $PM_{2.5}$-equivalent emissions, which they divide by annual $PM_{2.5}$ concentrations to derive an ECF for each pollutant, also displayed in Exhibit 4-1.[37]

EXHIBIT 4-1. ECF MODELING

VARIABLE	$PM_{2.5}$	SO_2	NO_X	NH_3
$PM_{2.5}$ Emissions Equivalent	1.00	0.341	0.118	0.113
ECF (Ton/µg$PM_{2.5}$/m3)	481	1,410	4,088	4,239

Notes: $PM_{2.5}$ emissions equivalent is the tons of $PM_{2.5}$ that contributes an equal amount to ambient $PM_{2.5}$ as one ton of the pollutant of interest. The ECF is the amount of a pollutant (in tons) that results in one µg/m^3 of ambient $PM_{2.5}$ in the Santiago air shed.

[36] These equivalences are also used for offsetting of emissions for large industrial sources under the 2018 PPDA.

[37] MMA (2016b) generate ECFs using monitor data from one station. The average annual concentrations from all monitor sites was found to be 15% lower than concentrations at the one monitor used by MMA (2016b). Thus, we adjust the ECFs by a factor of 0.85 to reflect concentrations in the entire region.

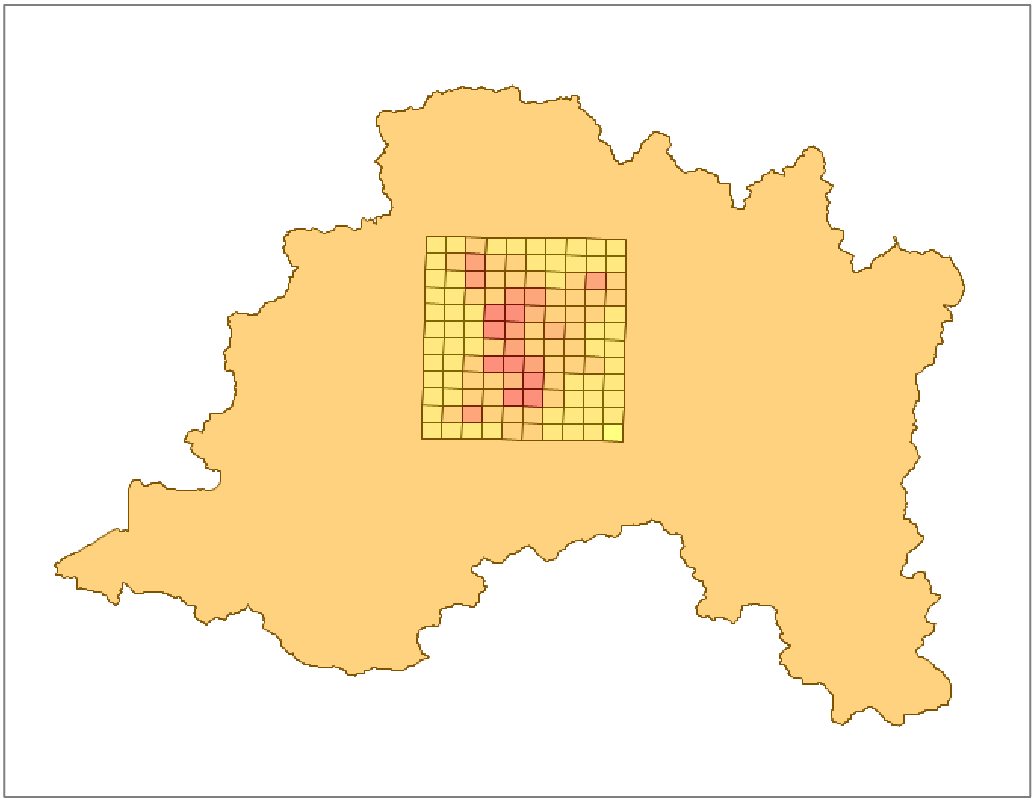
The ECF estimates represent the emissions (in tons) required to contribute one µg/m^3 of ambient $PM_{2.5}$ annually in the Santiago air shed. For example, in the case of NO_x, emitting 4,088 tons during one year within the air shed, from any source, would result in an increase of one µg/m^3 of annual $PM_{2.5}$ across the Santiago air shed.

In estimating the ECFs, we remove regional pollutant contributions from ambient concentrations prior to the calculations outlined above. The resulting ECFs are thus derived from Santiago-sourced air pollutant concentrations. We assume that the resulting ECFs are constant over time; however, we note that meteorological conditions and the presence of other $PM_{2.5}$ precursors may affect the ECFs from year to year. This approach does not differentiate emissions by location. All emissions in the Santiago Metropolitan Region are assumed to contribute equally to ambient concentrations in the region. Thus, the model provides one annual $PM_{2.5}$ concentration for the entirety of Santiago. These estimates are combined with Barraza et al. (2017) estimates of regional contributions from 1998 to 2012. We extrapolate these regional contributions by applying the 1998 values to the pre-1998 period and the 2012 values to the following period.

4.2 SOURCE-RECEPTOR APPROACH

To address some of the shortcomings of the MMA approach—namely, the geographic aggregation—we consider a second approach to estimating $PM_{2.5}$ concentrations. This approach (hereafter, the Jorquera model), summarized in DICTUC (2010) and developed by Dr. Héctor Jorquera, produces geographically disaggregated concentration estimates for the center of the Santiago Metropolitan Region (see Exhibit 4-2). Specifically, the Jorquera model represents a source-receptor matrix with 120 grid cells. Each cell acts as both an emissions source and a receptor of ambient air pollutant concentrations. That is, emissions from each cell contribute to concentrations in all 120 grid cells. The relative contribution of one unit of emissions from a source cell to concentrations in each receptor cell depends upon several factors included in the matrix's underlying dispersion model. These factors include topography, meteorology, and distance between the source and receptor cells. Additionally, the Jorquera model considers the varying meteorological conditions by season and estimates concentrations for spring, summer, fall, and winter.

EXHIBIT 4-2. JORQUERA MODEL GRID WITHIN THE SANTIAGO METROPOLITAN REGION



Note: The shaded grid cells pictured above are an illustrative example of the varying air quality in Santiago.

The Jorquera model was developed to model the impact of transport sector emissions on ambient $PM_{2.5}$.[38] As such, the model does not account for background concentrations in the region. We add a background concentration to each estimated grid cell by drawing upon estimates of regional contributions from copper smelters and coastal sources in Barraza et al. (2017). Further, we expand the limited geographic scope of the matrix by applying the mean concentration in the gridded area to the remaining area.[39]

The Jorquera model further requires that emissions covered by the central grid be mapped to each grid cell. In most cases, our emissions estimates were estimated at the comuna-level.[40] Thus, we allocate these emissions to grid cells using both population and area weighting, depending on the sector of the emissions. For the basic area-weighted approach, we split comuna emissions into its overlapping grid cells by the percentage of

[38] Dr. Jorquera provided useful guidance on adapting this model for use with other sectors.

[39] We note that the nongridded area is likely to have a lower $PM_{2.5}$ concentration; however, the population in this area is roughly one tenth of the total Santiago population.

[40] Comunas are the smallest administrative subdivision in Chile. There are 52 comunas in the Santiago Metropolitan Region.

the comuna area overlapping with each grid cell.[41] We assign emissions in this manner for forest fires and small industrial sources. For the remaining sectors, we allocate emissions using parcel-level population data from 2016 Census, which we use to population-weight the emissions allocation. That is, if 20 percent of population in comuna A lives in grid cell B, we would allocate 20 percent of the comuna's emissions to that grid cell (even if the overlapping area differs). Onroad, non-road, and residential emissions are population weighted from comunas to grid cells across the Metropolitan Region. For large emitters of NO_x and SO_2, we allocate emissions to grid cells using the facilities' precise coordinates. Emissions occurring outside of the region are not accounted for by the Jorquera model; however, our application of the mean gridded concentration implicitly assumes emissions reductions are also occurring in outlying areas.

4.3 BIAS CORRECTION

We adjust the estimated concentrations from each approach to ensure that our modeled factual concentrations match observed concentrations in Santiago from 1990 to 2016.[42] This is done by first generating an adjustment factor equal to observed concentrations divided by predicted concentrations in the factual scenario. This annual bias correction factor is then applied to both the factual and counterfactual modeled concentrations. For both approaches, we only adjust concentrations stemming from modeled emissions. That is, the background concentrations (i.e., regional contributions) are first removed from the above calculations and thus remain unchanged.

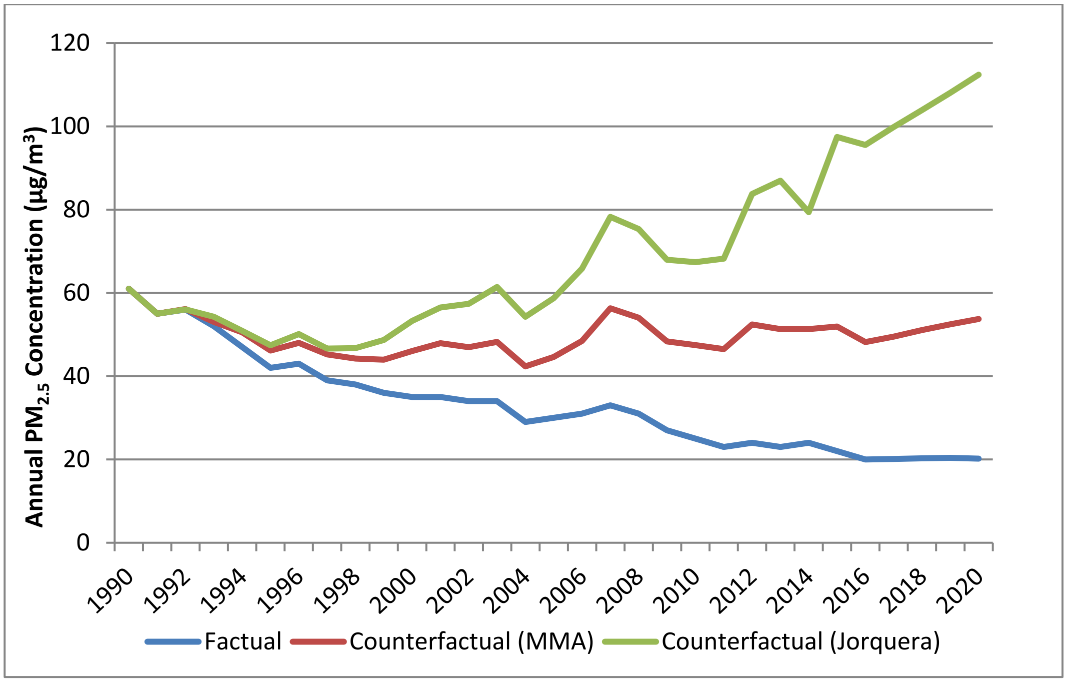
4.4 CONCENTRATION ESTIMATES

The resulting concentration estimates from the MMA (ECF) and Jorquera approaches are summarized in Exhibit 4-3 below.

[41] For example, consider a comuna overlapping two grid cells, as well as the non-gridded area. If 20 percent of the area is in grid cell A, 30 percent is in grid cell B, and 50 percent is outside of the grid, then 20 percent of the comuna's emissions would be allocated to grid cell A and 30 percent would be allocated to grid cell B.

[42] Observed air quality data is obtained from MMA.

EXHIBIT 4-3. MODELED $PM_{2.5}$ CONCENTRATIONS



Under the factual scenario, $PM_{2.5}$ concentrations have declined from a high of 61 µg/m^3 in 1990 to 20 µg/m^3 in 2017.[43] Under the counterfactual scenario, pollutant concentrations vary considerably between the MMA and Jorquera models. For the MMA approach, concentrations declined from 1990 to 2017, although to a lesser extent than the factual scenario. Compared to 2017 annual concentrations of 20 µg/m^3 in the factual scenario, counterfactual concentrations would be roughly 150 percent higher (50 µg/m^3) using MMA approach and 400 percent higher (100 µg/m^3) using the Jorquera approach.[44]

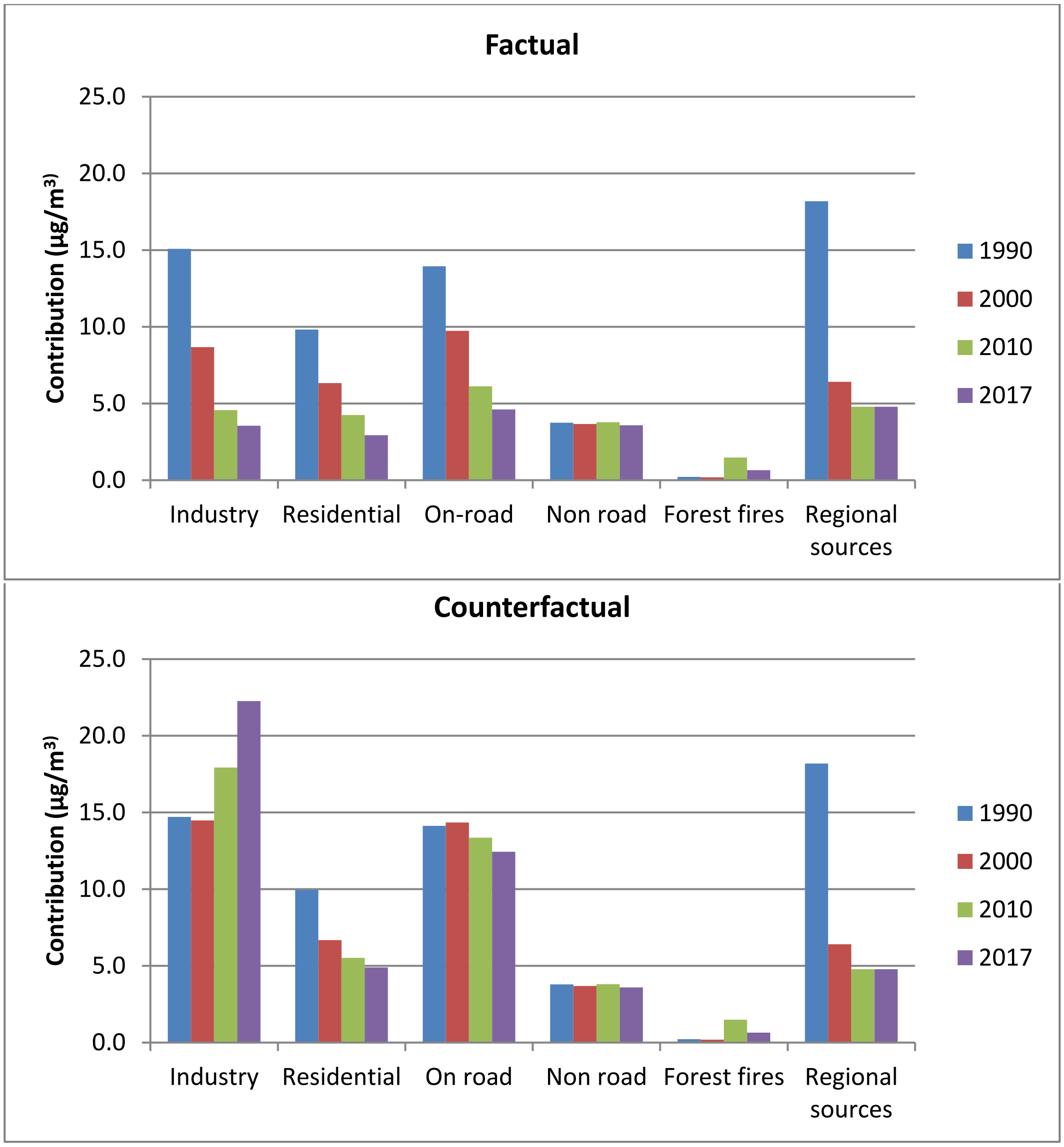
The estimated concentrations are all influenced by environmental controls outside of Santiago. Notably, regional contributions from copper smelters and coastal sources declined from over 18 µg/m^3 in the early 1990s to less than 5 µg/m^3 in recent years.[45] This improvement, highlighted in the right panel of Exhibit 4-4, is reflected in both the factual and counterfactual scenario. Contributions from the remaining sectors are also presented in Exhibit 4-4, which draws upon results from the MMA model.

[43] The factual data represents an average across multiple monitoring stations. Because some stations still exceed 30 µg/m^3, the region is still considered saturated.

[44] The high ambient $PM_{2.5}$ estimates stemming from the Jorquera model are not without precedent: $PM_{2.5}$ levels in Delhi, India regularly exceed 100 µg/m3 annually (see WHO Global Urban Ambient Air Pollution Database, available at http://www.who.int/phe/health_topics/outdoorair/databases/cities/en/). This counterfactual scenario represents what Santiago would look like with no environmental controls. A worsening from 1990 levels is plausible.

[45] Coastal sources represent various industrial processes on the Chilean coast near Santiago.

EXHIBIT 4-4. SECTORAL $PM_{2.5}$ CONTRIBUTIONS, MMA APPROACH



We attribute 2017 ambient $PM_{2.5}$ concentrations in Santiago roughly equally between industrial, residential, onroad, non-road, and regional sources.[46] However, contributions have declined more rapidly for industrial sources, including those outside of Santiago (i.e., regional sources). And, industry is the only sector with increasing emissions in the counterfactual scenario, largely due to exogenous changes in the residential and onroad sectors, where shifts towards cleaner cooking and heating units and cleaner vehicles would have occurred in the counterfactual scenario, albeit at a slower pace.

The decrease in contributions from regional sources significantly contributed to air quality improvements in both factual and counterfactual scenarios. In total, contributions from *within* Santiago (i.e., excluding regional sources) have declined over 50 percent since 1990. Under the counterfactual scenario, concentrations from Santiago sources would have increased by roughly five percent (43 $\mu g/m^3$ to 45 $\mu g/m^3$) using the MMA approach.[47] The counterfactual estimates are much higher using the Jorquera approach, as displayed above in Exhibit 4-3.

[46] Notably, regional sources largely represent industry outside of Santiago, but in close enough proximity to affect the air quality within Santiago.

[47] This increase is not monotonic, as concentrations fluctuate over the study period.

CHAPTER 5 | BENEFITS ASSESSMENT

Human health benefits comprise a large portion of the benefits of air quality management in the Santiago Metropolitan Region. While other benefits of air quality management exist (e.g., improved visibility, reductions in greenhouse gas emissions), improvements in human health are the primary focus of economic analyses of environmental regulations in Chile and many regulatory impact analyses more broadly. We express these health benefits as avoided cases of air pollution-related health outcomes, such as premature mortality. For the retrospective benefit-cost analysis, we focus on premature mortality, which comprises the majority of benefits from environmental regulations in Santiago (MMA 2016b). Additionally, we consider fuel savings resulting from the vehicle and non-road emissions standards discussed in Chapter 2. The critical episode analysis presented in Chapter 7 further evaluates morbidity endpoints (i.e., nonfatal health outcomes). In addition to estimating the number of premature deaths avoided, we assign a monetary value to each case using an estimate of value per statistical life (VSL). By monetizing health-related outcomes, we can more easily compare the benefits of policy interventions with the relevant costs.

This chapter provides an overview of our approach, including details on USEPA's Environmental Benefits Mapping and Analysis Program (BenMAP-CE). We also present our data sources for key inputs such as population, baseline incidence rates, and concentration-response functions from the epidemiological literature. Finally, we provide an overview of our valuation approach and summarize our findings

5.1 OVERVIEW OF APPROACH

We estimate the impact of environmental regulations on premature mortality by assessing the difference in the risk of death under the factual and counterfactual scenarios. For this analysis, we use BenMAP-CE, an open-source program employed by USEPA for their regulatory impact analyses.[48] USEPA relies on health impact functions to quantify the change in incidence of adverse health impacts stemming from changes in ambient pollutant concentrations:

$$\Delta y = y_o \cdot \left(1 - e^{-\beta \cdot \Delta PM}\right) \cdot Pop$$

[48] This analysis was also conducted using Analytica. The Analytica model generated comparable benefits estimates. Differences were consistently less than five percent.

where Δy is the change in the incidence of the adverse health effect, y_o is the baseline incidence rate for the health effect, beta (β) is a coefficient derived from a relative risk (RR) estimate associated with a change in exposure (i.e., pollutant concentration) as expressed in concentration-response functions, ΔPM is the change in concentrations of fine particulate matter, and *Pop* is the exposed population.[49]

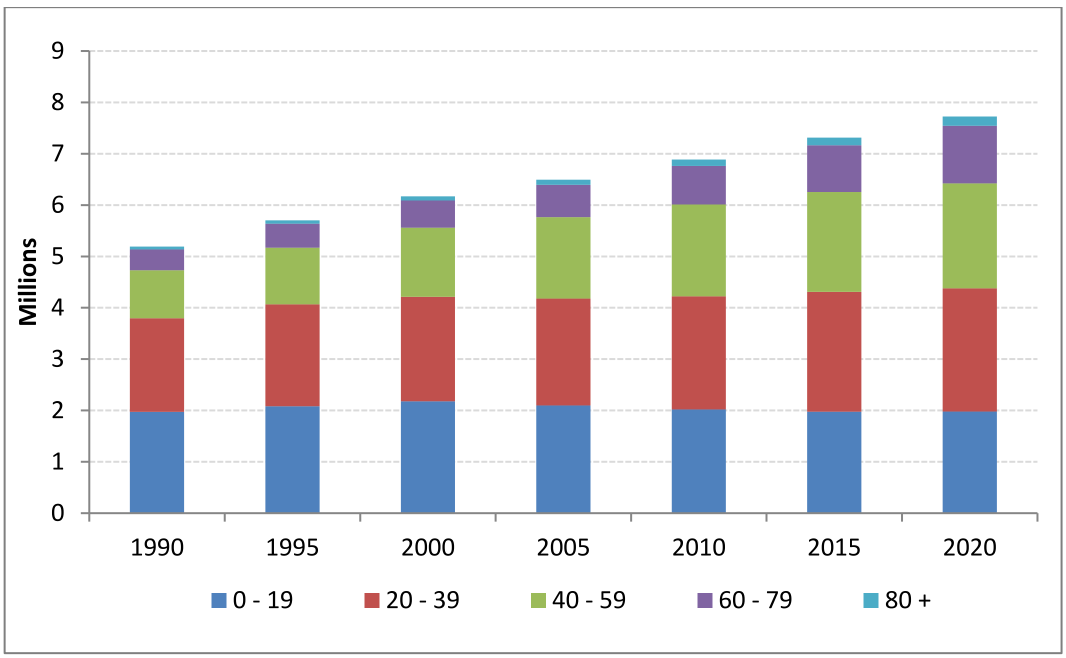
5.1.1 DATA INPUTS

We draw upon multiple data sources to parameterize and implement the generic health impact function presented above. These data sources are described below.

Population

We combine two population datasets from the National Institute of Statistics (INE) to generate comuna-level estimates stratified by gender and age for the years 1990 to 2020. First, we generate the fraction of the total Santiago population in each age and gender category for each year. We then apply this demographic profile to comuna-level population estimates. Thus, we assume that the age and gender profile is constant across comunas. The comuna-level populations are summarized in Exhibit 5-1 for 2017.

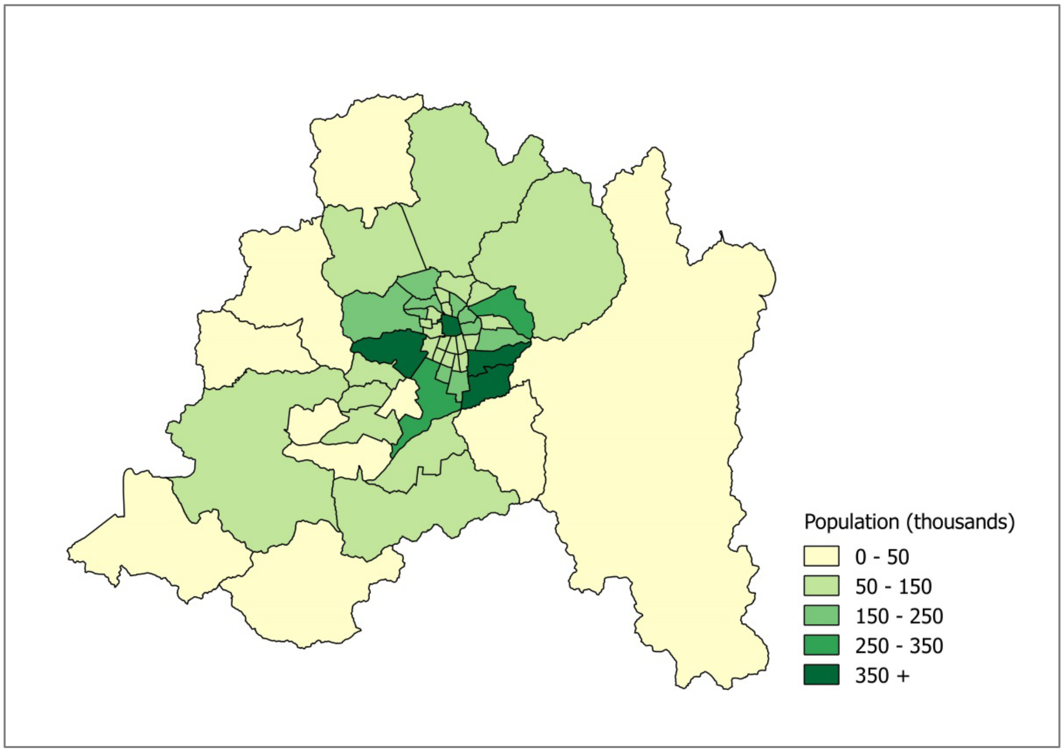
EXHIBIT 5-1. METROPOLITAN REGION POPULATION



[49] Based upon the functional form of the underlying concentration-response function, the functional form of the health impact function may differ. ΔPM may also be replaced by concentrations of other pollutants (e.g., ozone) or conditions (e.g., temperature).

Compared to a population of 5.2 million residents in 1990, the population for the Santiago Metropolitan Region now approaches 7.5 million. Notably, the majority of the Santiago population resides in the center of the Metropolitan Region (see Exhibit 5-2).

EXHIBIT 5-2. SANTIAGO POPULATION BY COMUNA (2017)



Baseline Incidence

Baseline incidence rates were calculated using 1990 – 2015 mortality data from the Ministry of Health's Department of Health Statistics and Information.[50] We calculate incidence rates using five-year bins to reduce annual variability.[51] We assume that incidence rates for the post-2015 period are equal to rates from 2010 to 2015.[52] The resulting all-cause mortality rates are presented in Exhibit 5-3.

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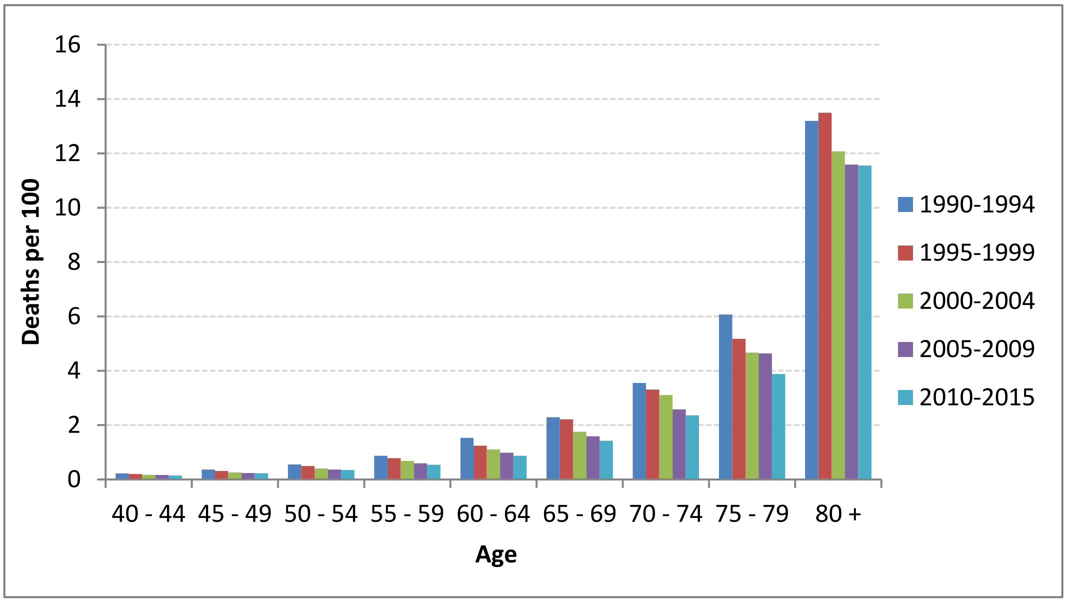
[50] These data are available at http://www.deis.cl/bases-de-datos-defunciones/.

[51] We use a six-year bin for the years 2010 to 2015.

[52] Beginning in 1997, mortality was summarized using medical codes from the International Classification of Diseases (ICD). We map ICD codes to mortality categories (e.g., all cause, non-accidental) using Table D-2 in the BenMAP-CE User's Manual Appendices, available at https://www.epa.gov/sites/production/files/2017-04/documents/benmap_ce_um_appendices_april_2017.pdf.

EXHIBIT 5-3. INCIDENCE RATES FOR TOTAL MORTALITY



For most age groups, all-cause mortality rates in Santiago have steadily declined since 1990. As expected, mortality rates increase with age. For the oldest age group (80 plus), 2015 incidence rates are roughly 12 deaths per 100 individuals annually. Although not shown in Exhibit 5-3, we stratify incidence rates by gender.

Concentration-Response Functions

We estimate premature mortality using concentration-response functions from three epidemiological studies (Laden et al. 2006, Krewski et al. 2009, Burnett et al. 2017). Laden et al. (2006) and Krewski et al. (2009) are adult cohort studies from the United States that relate $PM_{2.5}$ changes with all-cause mortality. Both studies estimate a linear relationship between $PM_{2.5}$ changes and premature mortality. Burnett et al. (2017) represents a global meta-analytic mortality risk function dependent only on cohort studies of long-term exposure to outdoor $PM_{2.5}$. The currently unpublished study incorporates data from a large number of studies (41 in total), including several at higher $PM_{2.5}$ concentrations (like those assessed in the counterfactual case of our analysis). The authors estimate a non-linear relationship between $PM_{2.5}$ concentrations and non-accidental mortality, which we apply using their 12 age-specific functions.

5.1.2 VALUATION

We apply the central VSL estimate from DICTUC (2014) to monetize benefits associated with avoided premature mortality. DICTUC developed and administered a stated preference study to estimate individual willingness to pay for cardiorespiratory mortality risk reductions. The sample was representative of the adult population in Santiago and thus provides a local value for our benefits analysis. We adjust the VSL estimate ($1.1

million, in 2016 USD) for per capita income growth in each year using Chilean GDP per capita from 1990 to 2016.[53] We assume a longitudinal income elasticity equal to 1.0 to maintain consistency with MMA (2016b). Thus, change in VSL over time is strictly proportional to the time series change of aggregate population-level income per capita for the Santiago region in our analysis. The income elasticity, however, is not used for cross-sectional applications - that is, changes in mortality risk are valued the same across all age and income categories.

5.1.3 BENMAP-CE METHODOLOGY

We estimate changes in premature mortality due to reductions in ambient $PM_{2.5}$ for each year from 1990 to 2020 using the command-line version of BenMAP-CE.[54] For each year, we estimate the change in premature mortality by calculating difference in concentrations between the counterfactual to factual scenarios (ΔPM). This analysis is done using modeled concentrations from both the MMA and Jorquera approaches.

5.1.4 FUEL SAVINGS

In addition to the human health benefits outlined above, we also estimate fuel savings benefits stemming from the air emissions standards described in Chapter 2. We calculate the difference between factual and counterfactual fuel consumption to estimate fuel savings resulting from the air emissions standards. The difference between these scenarios gives us the corresponding fuel savings in gallons. We multiply this value by annual average fuel sales prices observed in Santiago from INE to obtain monetized fuel savings.[55]

5.2 RESULTS

The results of our analysis suggest that environmental regulations have significantly reduced the number of premature deaths in Santiago throughout our study period. The non-monetized benefits are summarized in Exhibit 5-4 using the three epidemiological studies summarized above and the MMA air quality modeling approach detailed in Chapter 4. These benefits result from an improvement in air quality from the counterfactual to the factual scenario.

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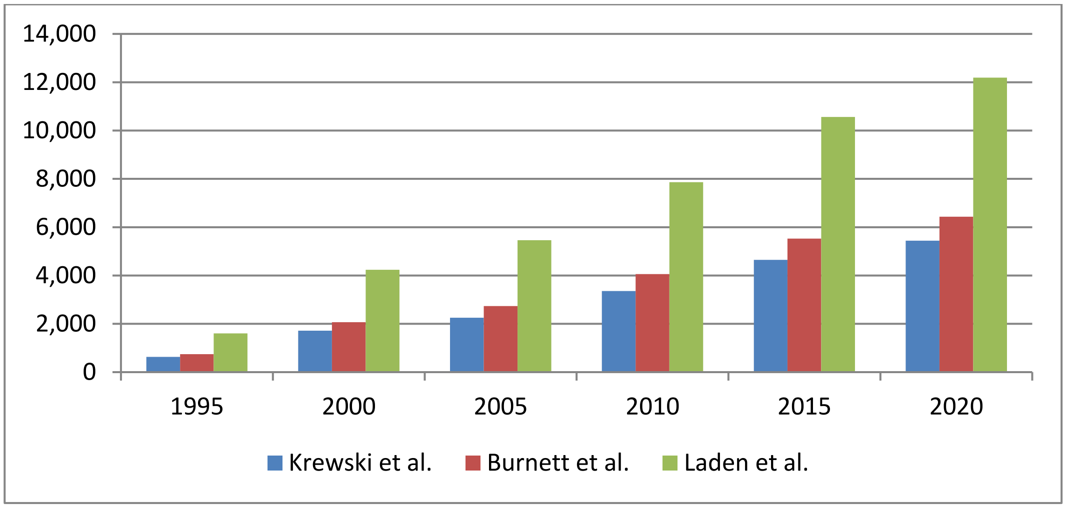
[53] We assume that the rate of income growth from 2011 to 2016 is maintained through 2020.

[54] The analysis was completed using BenMAP-CE version 1.4.11.1. Command line allows for the batch processing of BenMAP-CE files.

[55] We computed an annual average fuel price using data obtained at https://www.cne.cl/estadisticas/hidrocarburo/.

EXHIBIT 5-4. ANNUAL PREMATURE DEATHS AVOIDED, 1995-2020



The number of avoided premature deaths from environmental regulations has steadily increased since 1990, when the factual and counterfactual scenarios were identical. In 2017, roughly 5,000 premature deaths avoided are attributable to environmental regulations imposed since 1990 (using Krewski et al. function). The three studies provide a range of estimates that vary substantially. Krewski et al. (2009) and Burnett et al. (2017) are relatively comparable, while Laden et al. (2005) provides an upper estimate roughly twice as high. Another important source of uncertainty is the choice of air quality modeling approach – the impact of using of the Jorquera model versus the MMA ECF approach is summarized in Exhibit 5-5 for select years.

EXHIBIT 5-5. MODEL COMPARISON, SELECT YEARS - ANNUAL MORTALITY RISK

C-R FUNCTION	2000		2010		2017	
	MMA	JORQUERA	MMA	JORQUERA	MMA	JORQUERA
Burnett et al. (2017)	2,068	2,448	4,059	5,238	5,640	8,637
Krewski et al. (2009)	1,719	2,985	3,356	6,100	4,680	10,535
Laden et al. (2005)	4,234	6,648	7,866	11,956	10,661	18,117

Overall, we find that the Jorquera model predicts a greater reduction in premature deaths. Using the Krewski et al. function, this difference ranges from approximately 20 percent in 1994 to greater than 55 percent in 2017. This result is consistent with our finding that the Jorquera model produces higher $PM_{2.5}$ estimates under the counterfactual scenario (see Exhibit 4-3). For the remainder of the study, we present the lower range of estimates from our analysis (i.e., Krewski and MMA approach). Summed across the 31-year study period, results using the Krewski et al. (2009) function suggest that over 80,000 premature deaths have been avoided due to implementation of environmental controls. As we describe in greater detail below, the monetized benefits of avoided premature mortality increase from roughly $670 million in 1995 to almost $5 billion in 2017.

CHAPTER 6 | COMPARISON OF BENEFITS AND COSTS

In the previous chapters, we presented our methods for estimating monetized benefits and costs associated with environmental controls in Santiago from 1990 to 2020. Below, we compare our estimates of benefits and costs to assess the net economic effect of these controls. Further, we discuss key sources of uncertainties in our analysis.

6.1 METHODOLOGY

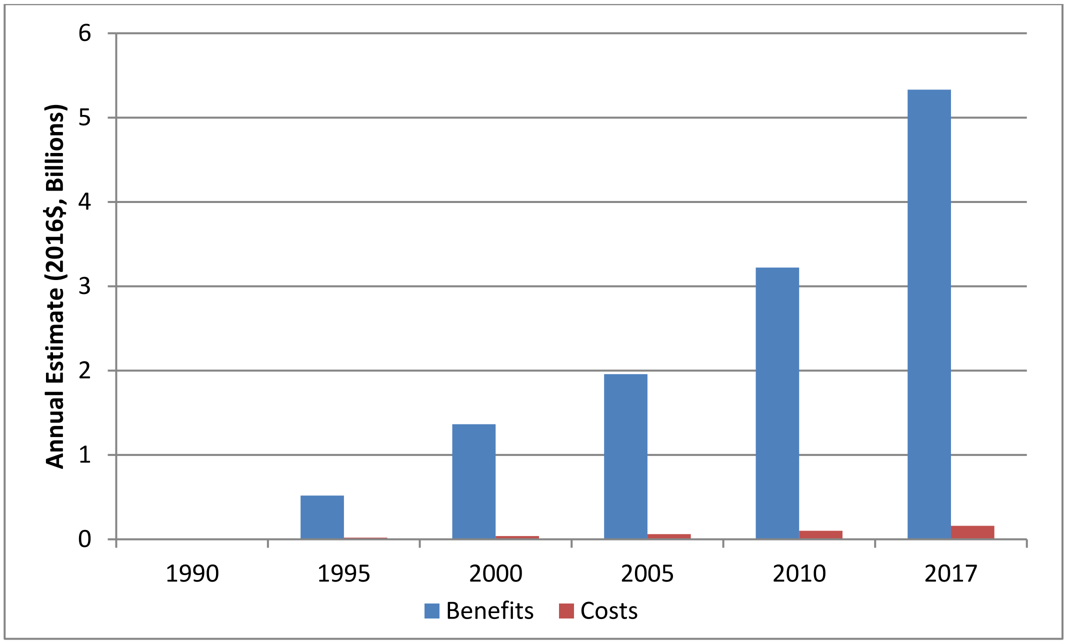
The results summarized below reflect our preferred estimates among a range of values derived using three concentration-response functions from the epidemiological literature and two air quality models. As discussed above, we focus on the Krewski et al. (2009) function, which is commonly employed in international benefits assessments, including those conducted by MMA. Further, we present results primarily using the MMA air quality modeling approach. These analytic choices are consistent with past MMA economic analyses that have undergone substantial internal and external review (e.g., MMA 2016b). Further, consistency with MMA methods facilitates direct comparisons with existing prospective economic analyses. For results aggregated across years, we discount benefits and costs equally using a 6% discount rate and a base year of 1990, still presenting values in 2016 USD.[56] Thus, these findings are framed such that a policy-maker in 1990 could determine whether the regulations under consideration would result in net economic benefits.

6.2 RESULTS

We find strong evidence that environmental regulations in Santiago have been economically beneficial in the aggregate over the past three decades. Our preferred estimates are summarized in Exhibit 6-1 for select years.

[56] We choose 6% as a discount rate to maintain consistency with MMA economic analyses (see MMA 2016). This value also falls between the 3% and 7% rates used in economic analyses by U.S. Federal agencies (see U.S. Office of Management Budget 2003, Circular A-4).

EXHIBIT 6-1. COMPARISON OF ANNUAL BENEFITS AND COSTS, SELECT YEARS



The economic costs and benefits of environmental controls have steadily increased since the early 1990s. Both values have increased roughly tenfold since 1995, with benefits now exceeding $5 billion and costs exceeding $150 million. In each year, benefits exceed costs by a factor of roughly 30. Each component is separately summarized in Exhibits 6-2 (benefits) and 6-3 (costs) by sector.

EXHIBIT 6-2. SECTOR-SPECIFIC BENEFITS, SELECT YEARS

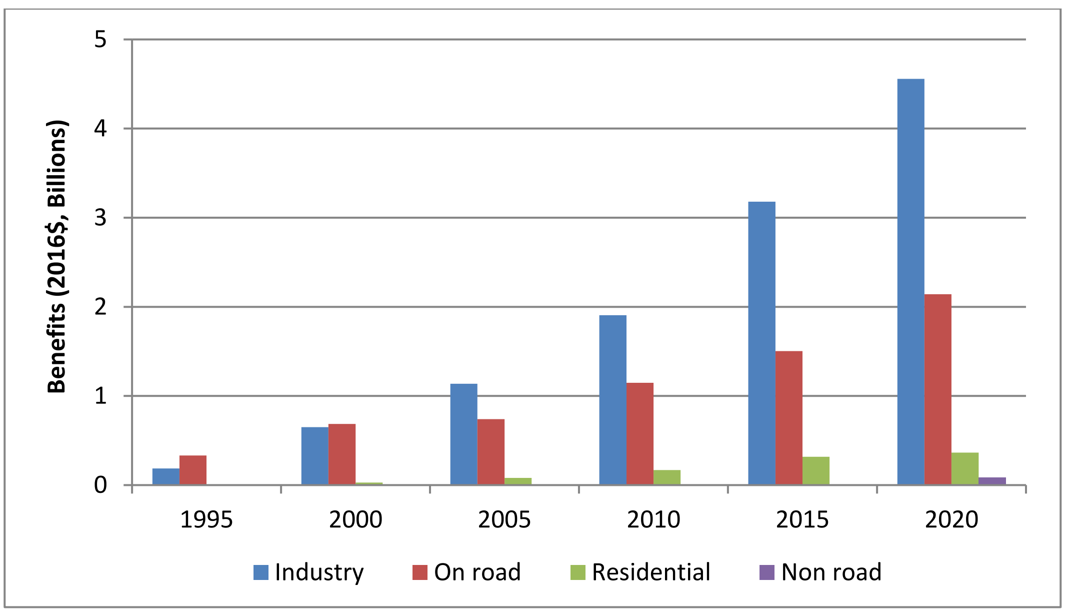
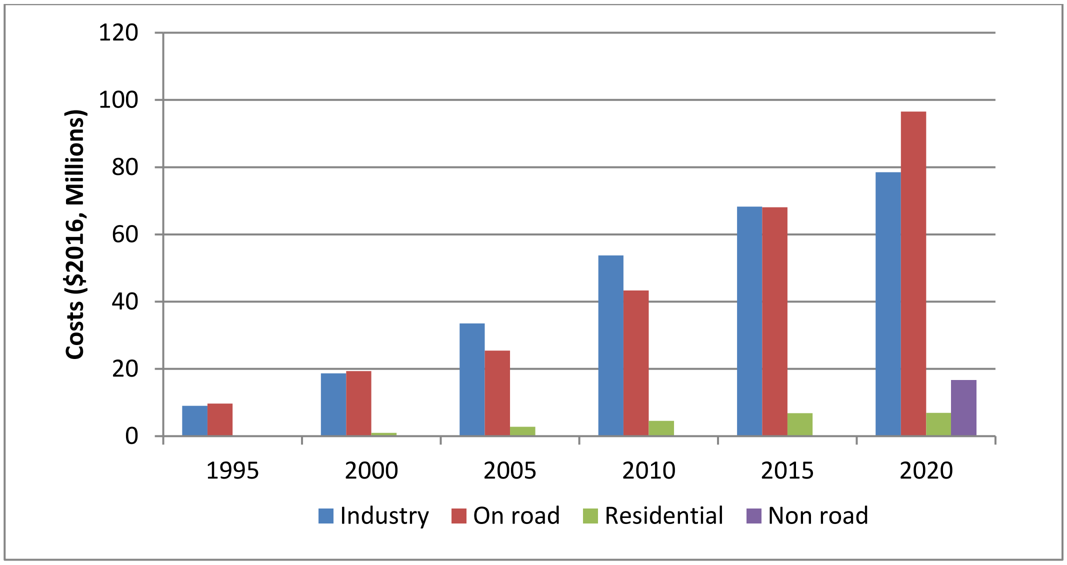


EXHIBIT 6-3. SECTOR-SPECIFIC COSTS, SELECT YEARS



The industrial and onroad sectors account for the majority of both the benefits and costs of environmental regulations in Santiago. Whereas industrial sources have comprised an increasing share of the benefits over time, onroad sources have comprised an increasing share of costs. We estimate that emissions reductions from industrial sources resulted in over $3 billion in benefits, compared with roughly $70 million in costs. In comparison, 2017 benefits and costs for the onroad sector are approximately $1.5 billion and $80 million, respectively. We further find that the air pollution controls for residential and nonroad sectors provide net benefits to the region; however, the relative magnitude of these sectors is significantly smaller, with total annual benefits peaking around $450 million in 2020.

6.3 UNCERTAINTIES

The results presented above are accompanied by numerous sources of uncertainty, of which the net effect on our estimates is ambiguous. We attempt to catalogue the major sources of uncertainty in Exhibit 6-4.

EXHIBIT 6-4. KEY UNCERTAINTIES WITH BENEFIT-COST ANALYSIS

POTENTIAL SOURCE OF ERROR	DIRECTION OF POTENTIAL BIAS FOR NET BENEFITS
UNCERTAINTIES RELATED TO EMISSIONS ESTIMATION	
Sulfur standards used in lieu of data on sulfur content in fuels.	Overestimate. If sulfur content in the early factual case was actually below the initial standards, by a wider margin than in the later years, then reductions in content may be overestimated.
Assume clean vehicle technology adoption would occur exogenously under the counterfactual scenario (albeit with a five-year delay).	Underestimate. If manufacturers continued to sell cars failing to comply with international emissions standards, the motor vehicle fleet would not see declines in emissions under the counterfactual scenario.
The residential sector counterfactual scenario uses firewood use growth from Valparaiso.	Unable to determine based on current information. Santiago may have shifted away from firewood use faster, or more slowly, than surrounding regions.
The peak of emissions from individual, large industrial sources of NO_x and SO_2 are assumed to equal the long-run emissions level under the counterfactual scenario.	Unable to determine based on current information. Sources may have increased or decreased emissions, independent of air environmental regulations.
Counterfactual $PM_{2.5}$ emissions intensity for 1993-2020 in industrial sector assumed to stay at 1990-1992 levels.	Possible overestimate. Emissions intensity more likely to have declined than increased without environmental regulation, for example because of likely decreases in energy intensity over time as new technology replaces older technology.
Emissions from many industrial sources are assumed to scale proportionally to industrial sector GDP.	Unable to determine based on current information. Relationship between emissions and sectoral GDP may be greater than, or less than one.
UNCERTAINTIES RELATED TO COST ESTIMATION	
Analysis focuses only on direct costs. Indirect costs include welfare effects (restrictions during critical episodes, switch to less-preferred vehicles and heating sources) and broader economic results (e.g., higher costs of goods and services, such as concrete).	Overestimate. Accounting for additional costs will reduce net benefits estimates.
Use of cost data from United States for refineries and industry.	Unable to determine based on current information.
UNCERTAINTIES RELATED TO AIR QUALITY MODELING	
MMA approach does not spatially disaggregate ambient $PM_{2.5}$ concentrations.	Underestimate. Monitor data suggests that concentrations are highest in central Santiago, where the majority of the population resides.
Jorquera model produces significantly higher $PM_{2.5}$ concentration estimates under counterfactual scenario.	Unable to determine based on current information. Future work may examine seasonal bias correction for the Jorquera model.

POTENTIAL SOURCE OF ERROR	DIRECTION OF POTENTIAL BIAS FOR NET BENEFITS
BENEFITS ASSESSMENT	
Analysis assumes a causal relationship between PM exposure and premature mortality from Krewski et al. (2009).	Unable to determine based on current information. Potentially major overestimate if assumption of causality is incorrect. Possible underestimate if relationship is closer to Laden et al. (2005) findings.
Analysis does not include morbidity estimation, estimation of health effects from other pollutants (e.g., ozone), or other benefits not related to human health (e.g., visibility, agricultural effects)	Underestimate.
No cessation lag used for premature mortality.	Overestimate. If there is a time lag between $PM_{2.5}$ changes and premature mortality, then benefits occurring in the future should be discounted.
Valuation approach applies VSL estimate from DICTUC (2014).	Unable to determine based on current information. Mortality values comprise the majority of monetized benefits, so accurately estimating and applying VSL is critically important.
Valuation approach assumes income elasticity of VSL equal to one.	Unable to determine based on current information. Possible underestimate if elasticity is less than one; possible overestimate if elasticity is greater than one.

Addressing specific uncertainties, where possible, is an important next step for MMA economists and academic researchers. We present our recommended topics for future research in Chapter 9. In several instances, the uncertainties presented in Exhibit 6-4 stem from our aggregate analytic approach (e.g., emissions intensity for industrial sector $PM_{2.5}$ emissions). Below, we take a closer look at a specific set of environmental controls: the Santiago critical episode management program.

CHAPTER 7 | FORECASTING CRITICAL EPISODES

The most prominent policy employed by MMA to address spikes in PM air pollution involves the forecasting of critical air pollution episodes for the Santiago Metropolitan Region, and the air pollution control measures triggered by the declaration of a critical episode. Declarations, if required, are made and communicated to the public in the evening for the following day, as declaration of a critical episode entails restrictions that affect the next day's commute and, for severe events, may compel large emitters across a number of source sectors within the region to halt or decrease activity. Forecasts are based on a wide range of measured and modeled data describing meteorological and air quality conditions collected each day in an effort to accurately predict the occurrence and magnitude of these episodes. However, because the decision to declare an episode must be made in advance and because Santiago is located in a notoriously challenging atmosphere for forecasting meteorology, the SEREMI may at times either forecast a critical episode for a day that does not ultimately meet that threshold, imposing costs on those forced to decrease or change their activity if an episode is declaraed, or may fail to forecast an episode for a day that does meet the threshold. In this analysis, we explore using statistical modeling the set of factors and data that are most predictive of a critical episode occurrence to assist the SEREMI in their critical episode forecast process.

7.1 METHODS

7.1.1 EPISODE FORECASTING PROCEDURE

The SEREMI currently suggests declaration for the next day's episode status before 21:00 every evening during the winter season based on predicted PM concentrations. The SEREMI then verifies whether a critical episode has occurred based on $PM_{2.5}$ or PM_{10} concentrations measured at SINCA air quality monitors across the city for that day. Due to its greater impact on human health, in this analysis, we focus on predictions and episodes involving the $PM_{2.5}$ fraction only. To verify whether an episode has occurred, the maximum 24-hour moving average $PM_{2.5}$ concentration measured between 0:00 and 23:00 on the day of interest at any monitor determines episode status. Critical episodes are broken into three types, including Alert (Alerta), Pre-emergency (Preemergencia), and Emergency (Emergencia), with a non-episode day defined as Good or Regular (Bueno o Regular). Each episode status is defined by a range of $PM_{2.5}$ concentrations measured during the hours of 0:00-23:00, shown in Exhibit 7-1.

EXHIBIT 7-1. THRESHOLD $PM_{2.5}$ MOVING AVERAGE CONCENTRATIONS (µG/M³) FOR AIR QUALITY EPISODE STATUS

AIR QUALITY STATUS	$PM_{2.5}$ CONCENTRATION (UG/M³)
Good or Regular (Bueno o Regular)	0-79
Alert (Alerta)	80-109
Pre-emergency (Preemergencia)	110-169
Emergency (Emergencia)	>170

If $PM_{2.5}$ concentrations are forecasted to reach Alert, Pre-emergency, or Emergency levels, the SEREMI communicates various restrictions on activities in Santiago, shown in Exhibit 7-2.

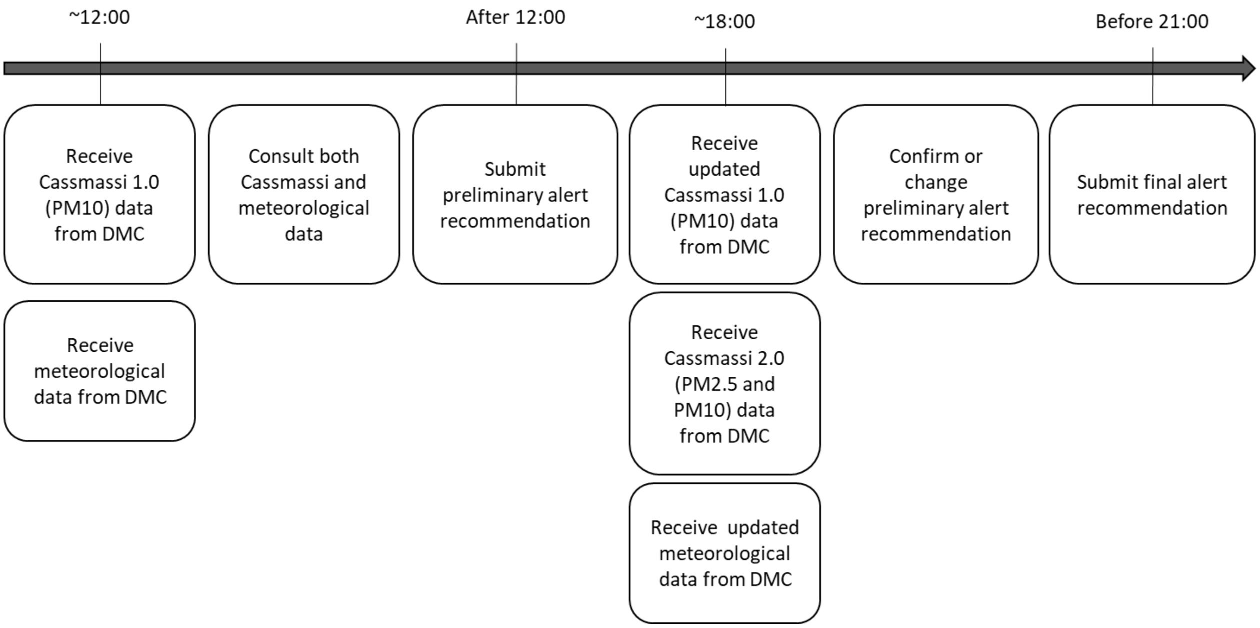
EXHIBIT 7-2. ACTIONS TAKEN BY MMA AND SEREMI FOR EACH CRITICAL EPISODE STATUS

CRITICAL EPISODE STATUS	RESTRICTIONS
Alert	• Restriction on vehicles without seal, with license plates that end in any of 4 specified digits on weekdays and any of 2 specified digits on weekends.*
Pre-emergency	• Restrictions on vehicles without seal, with license plates that end in any of 6 specified digits, Monday-Sunday* • Restrictions on vehicles with green seal, with license plates that end in any of 2 specified digits, Monday-Sunday* • Shut down of specific industrial sources • Some roads become exclusively bus routes during rush hours
Emergency	• Restrictions on vehicles without seal, with license plates that end in any of 8 specified digits, Monday-Sunday* • Restrictions on vehicles with green seal, with license plates that end in any of 4 specified digits, Monday-Sunday* • Shut down of specific industrial sources, with more businesses shut down than in the Pre-emergency case • Some roads become exclusively bus routes during rush hours
All episode restrictions	• Prohibit the burning of wood in the whole Santiago Metropolitan Region • Recommend that schools suspend physical education classes

*Note: these digits range from 0 to 9 and are rotated with each subsequent critical episode

The critical episode decision making process involves a variety of empirical and non-empirical factors that must be collected, analyzed and discussed with the government authorities in order to reach a decision before 21:00 each day. The statistical regression model we describe in the next section evaluates the importance of the various types of data and information considered by the SEREMI in making its recommendation to key governmental decision makers. Exhibit 7-3 shows the process currently employed and information currently considered by the SEREMI.

EXHIBIT 7-3. CRITICAL EPISODE PREDICTION PROCESS



7.1.2 REGRESSION MODELING

We performed a regression analysis to understand which combination of variables is most predictive of a critical air quality episode within the Santiago Metropolitan Region. From internal communication with the SEREMI and MMA staff and stakeholders, we identified meteorological and air quality parameters associated with oncoming critical episodes and defined a suite of independent variables from raw data sources. Because the SEREMI forecasts and communicates the declaration of episodes in advance for the following day by 21:00 each evening, we focused only on data that are measured and accessible prior to the episode declaration deadline, which we define as prior to 20:00. Meteorological data are reviewed by Ministry staff between 17:00 and 20:00 hours to look for late-day changes in key meteorological variables that could indicate a critical episode is likely the next day. Cassmassi 1.0 report variables, which are related to the Cassmassi 1.0 PM_{10} prediction model, are available to the SEREMI at 18:00 every evening; monitor data are available within one hour of having obtained data.

We restricted the outcome variable of our regression analysis to be binary—every day in the sample is either a critical episode day or not, based not on the forecasted status, but on measured PM concentrations (i.e., the maximum moving average of $PM_{2.5}$ concentration ($\mu g/m^3$) measured at any monitor in the SINCA network between 0:00 and 23:00 on a specific day). Because our outcome variable is binary, we employed logistic regression modeling to determine the most predictive independent variables of critical episode occurrence. In our analysis, we assigned the outcome variable 1 if an episode occurred ($PM_{2.5}$ threshold was reached) and 0 if an episode did not occur ($PM_{2.5}$ threshold was not reached). If the maximum measured concentration is above the concentration threshold for an "Alert", "Pre-emergency", or "Emergency", then that day is defined as a critical episode.

7.1.3 VARIABLE CREATION AND DATA SOURCES

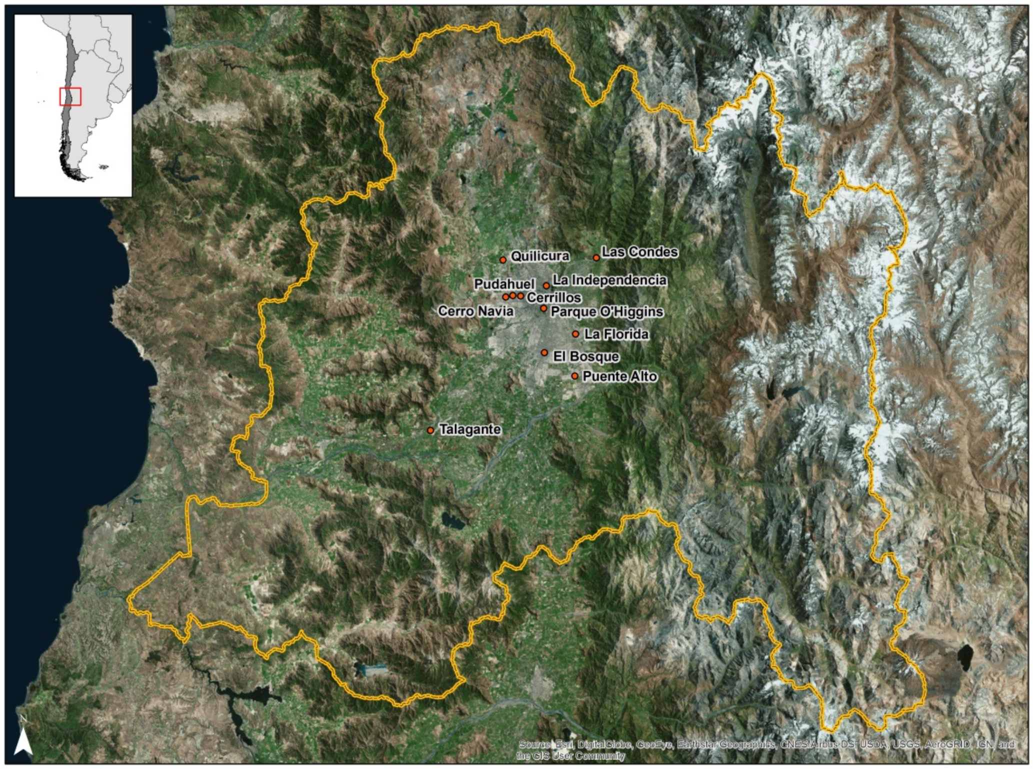
After defining the binary outcome variable for the model, we created and tested a suite of independent variables to understand which factors contribute to predicting an air quality episode. We defined variables from raw data sources. All variables span the study period and can be grouped into three main categories—meteorological data, $PM_{2.5}$ concentrations from SINCA monitors, and model data. The study period includes the 2015 and 2016 winter seasons (April 1-August 31) to build the regression model and the 2017 winter season to test the regression models. For meteorological data, we used MeteoChile as the primary source for temperature, relative humidity, pressure, wind speed, and wind direction. MeteoChile continuously monitors these conditions at various meteorological monitoring stations around Santiago, as seen in Exhibit 7-4.

EXHIBIT 7-4. METEOCHILE METEOROLOGICAL MONITORING STATIONS

Source: MeteoChile http://www.meteochile.gob.cl/PortalDMC-web/index.xhtml

In addition to quantitative minute-resolved MeteoChile data, we supplement meteorological data with qualitative meteorological conditions from Cassmassi 1.0 reports. Next, we utilize $PM_{2.5}$ concentrations measured at eleven monitors around the Santiago Metropolitan Region as part of the SINCA network. The SEREMI provided hourly concentration averages for each monitor throughout 2015, 2016, and 2017. Exhibit 7-5 shows the locations of the $PM_{2.5}$ monitors.

EXHIBIT 7-5. SINCA NETWORK OF AIR QUALITY MONITORING STATIONS IN SANTIAGO



Lastly, we used IOWA/WrfChem and Meteodata model forecasts for the 2015, 2016, and 2017winter seasons. These models are predictive $PM_{2.5}$ models, and provide 24-, 48-, and 72- hour forecasts for $PM_{2.5}$ concentrations within Santiago.

The models use a combination of meteorological conditions, historical, and current $PM_{2.5}$ concentrations to predict future trends of $PM_{2.5}$ in the metropolitan area. Appendix A provides a comprehensive list of all of the variables we tested in our regression model.

Temperature

In Santiago, a positive maximum temperature differential between the Lo Prado (higher elevation) and San Pablo (lower elevation) monitoring stations indicates a thermal inversion in the atmosphere, which increases the potential for critical episodes. We created a binary temperature variable, which equals 1 when the maximum temperature differential between Lo Prado and San Pablo between 17:00-20:00 (by minute) is positive or zero and 0 when the temperature differential between the stations is negative.

Humidity

Precipitation cleanses the air by capturing PM particles as it falls through the atmosphere, and as such, air quality is expected to worsen as humidity decreases. We converted raw relative humidity data from the Lo Prado station to specific humidity. We calculated the average humidity (g vapor/kg of air) between the 17:00-20:00 time period and defined the humidity variable as continuous.

Wind speed

High wind speeds tend to clear out PM while low wind speeds allow particles to settle within the valley. We defined the wind speed variable as the average wind speed between 17:00-20:00 measured in m/s at the San Jose meteorological station (based on internal communication with MMA and SEREMI meteorologists). The San Jose station is on the east side of Santiago, where the meteorological service closely monitors wind speed and weather fronts as eastern conditions can be particularly indicative of changing meteorological conditions that can produce a critical episode.

"Tipo A"

We collected and analyzed qualitative meteorological conditions from the Cassmassi 1.0 report. Descriptive phrases of conditions on the surface and higher in the atmosphere indicate the presence of a "Tipo A" weather front. We define "Tipo A" as a binary variable, which is set to 1 when the Cassmassi 1.0 report indicates a "vaguada" or "trough" condition in the surface level atmosphere and "dorsal" condition in the high altitude atmosphere.

Maximum $PM_{2.5}$ monitored concentration

From the air quality monitor dataset, we created variables that capture monitor concentrations the evening before an episode, because substantial increases in PM concentrations in this period can be an indicator of forthcoming stagnant conditions that lead to critical episodes. We defined a continuous variable that captured the maximum 24-hour moving average concentration measured at any monitor between 17:00-20:00 the night before.

Slope of monitored $PM_{2.5}$ concentrations

We calculated and defined the slope of $PM_{2.5}$ monitor concentrations as the rate of change in maximum 24-hour moving average across all stations measured at 17:00 and the maximum 24-hour moving average across all station measured at 20:00. The slope indicates how rapidly $PM_{2.5}$ concentrations are changing within this time period the night before a potential critical episode. The directionality and magnitude of the slope can display a trend in $PM_{2.5}$ concentrations relevant for the coming day.

Probability of Coastal Advection

The Cassmassi 1.0 PM reports include a qualitative phrase that describes the likelihood of whether a coastal advection (Adveccion Costera) is likely to occur. We defined the probability of Adveccion Costera as 1 if there is a non-zero probability and a 0 if there is not a probability of this weather pattern.

Air quality model variables

Lastly, we constructed binary variables from the IOWA/WrfChm and Meteodata 24-hour $PM_{2.5}$ air quality models. Similar to the outcome variable definition, we defined the model variables as 1 if the concentrations forecasted reached the critical episode threshold and 0 if they did not. For the IOWA/WrfChem model, if the 24-hour predicted concentration reaches a critical episode threshold, we define the variable as 1 and 0 otherwise. We defined the Meteodata variable as a binary variable equal to 1 if the 24-hour predicted concentration surpasses the critical episode threshold and 0 if not.

7.1.4 MODEL SELECTION

After finalizing the set of independent variables for testing, we conducted stepwise regression analyses to statistically narrow the model to include only the most predictive variables. Stepwise regression systematically removes or adds variables to a model based on a specified significance threshold. For our analysis, we employed a backward stepwise regression with a significance threshold of $p<0.05$. The backward stepwise regression starts with all of the desired independent variables in one model. The model is run with all of the variables, and the least significant variable is removed. After removal, the model is run again, and the least significant variable is removed. This iterative process continues until all of the variables left in the model reach the significance threshold. At the end of the stepwise process, we added scientifically viable but not necessarily statistically significant variables back into the final regression model with discretion to produce the final model.

7.2. RESULTS

7.2.1 EPISODE FORECASTING REGRESSION RESULTS: SUMMARY RESULTS

Although we have data for April – August of 2015, 2016 and 2017, we chose to run our regressions on the 2015 and 2016 datasets as 2017 was an anomalous year for critical episode prediction. There are 306 days in our study time frame of April-August 2015 and 2016. However, we were only able to include, at most, 297 of these days largely due to missing data across variables. In the full 306 day sample for 2015 and 2016, there were 46 Alert critical episodes, 26 Pre-emergency episodes, and 4 Emergency episodes that occurred, compared with 25 Alert episodes and 1 Pre-emergency episode that occurred in 2017. While this anomalous year does not provide a perfect dataset on which the model can be tested and applied, it allows us to take advantage of the two previous more typical years to build the model. Exhibit 7-6 demonstrates the breakdown of these episodes by year and type.

EXHIBIT 7-6. NUMBER OF CRITICAL EPISODES PER YEAR BY TYPE OF EPISODE INCLUDED IN ANALYSIS

TYPE OF EPISODE	NUMBER OF EPISODES BY YEAR		
	2015	2016	2017
Alert	22	24	25
Pre-emergency	15	11	1
Emergency	1	3	0

7.2.2 REGRESSION RESULTS

The results of the regression analysis indicate what meteorological and modelled factors are most predictive of a critical episode occurring on a given day. For the results, we take a bifurcated approach to examine two different outcomes: (1) all episode types (including Alert) together and (2) just Pre-emergency or Emergency episodes Both of these outcome variables are a binary variable equal to 1 if the episode occurs between 0:00 and 23:00 on a given day and 0 if no episode occurs on a given day. We summed Pre-emergency and Emergency episodes because the sample size of Emergency days in 2015-2016 was insufficient to examine on its own. We examine a variety of explanatory variables as described above through many iterations of the regression analysis. We omit explanatory variables that are highly correlated with other explanatory variables to avoid multicollinearity. For example, we do not include wind speed from both San Pablo and San José stations as they are highly correlated. For the second set of regressions where the outcome variable is defined as whether a Pre-emergency or Emergency occurs, we modify the IOWA/WrfChem model variable and Meteodata model variable to be 1 when a Pre-emergency or Emergency is predicted and 0 otherwise. This modification allows us to understand each model's accuracy when predicting a Pre-emergency or Emergency.

Exhibit 7-7 presents the independent variables in our analysis that represent the most relevant predictors of a critical episode in 2015-2016. This table represents the full range of variables across all final regression models.

EXHIBIT 7-7. FINAL EXPLANATORY VARIABLES INCLUDED IN REGRESSION ANALYSIS

VARIABLE NAME	DESCRIPTION
IOWA/WrfChem Model	Binary variable, based on prediction of episode from IOWA/WrfChem Model from 24 hours before. (1 = episode threshold exceeded)
Meteodata Model	Binary variable, based on prediction of episode from Meteodata Model from 24 hours before. (1 = episode threshold exceeded)
Specific Humidity	Continuous variable, the average specific humidity from 17:00-20:00 the day before.
Temperature Differential	Binary variable, based on maximum temperature differential between Lo Prado and San Pablo station from 17:00-20:00 the day the before. (1 = temperature differential is greater than or equal to zero degrees Celsius)
Wind Speed	Continuous variable, the wind speed at San Pablo station from 17:00-20:00 the day before, in meters per second.

VARIABLE NAME	DESCRIPTION
Maximum Monitored $PM_{2.5}$ Concentration	Continuous, the maximum 24-hour moving average $PM_{2.5}$ concentration from 17:00-20:00 the day before.
Slope of Monitored $PM_{2.5}$ Concentration	Continuous variable, the rate of change calculated from the maximum 24-hour moving average $PM_{2.5}$ concentration at 17:00 and the maximum 24-hour moving average $PM_{2.5}$ concentration at 20:00.
Tipo A	Binary variable, based on the presence of a Tipo A weather front as reported in Cassmassi 1.0 PM (1 = Tipo A present, 0 = Tipo A absent).
Probability of Adveccion Costera	Binary variable, based on the probability of a coastal advection as reported in Cassmassi 1.0 PM (1 = there is a probability, 0 = there is no probability)

We consider two subsets of regressions based on the explanatory variables above: (1) those that include the maximum monitored $PM_{2.5}$ concentration from the night before and (2) those that do not. While the maximum monitored $PM_{2.5}$ concentration is highly predictive of an episode occurring the next day, we are concerned about collinearity of this variable with other variables included. For example, we are concerned that both the Meteodata and IOWA/WrfChem model in some way consider monitor concentration from the day before, leading to multicollinearity with the maximum monitor concentration. In total, we report four alternative sets of results to encompass all possible combinations of outcome variables and inclusion versus exclusion of the maximum monitored $PM_{2.5}$ concentration. Exhibit 7-8 below highlights what is unique about each part of the results and explains the combinations of explanatory and outcome variables.

EXHIBIT 7-8. FINAL EXPLANATORY VARIABLES INCLUDED IN REGRESSION ANALYSIS

RESULTS	DESCRIPTION OF UNIQUE VARIABLES INCLUDED
Alternative 1	• Outcome Variable: Any type of $PM_{2.5}$ Critical Episode occurs • DOES contain maximum monitor concentration variable
Alternative 2	• Outcome Variable: Any type of $PM_{2.5}$ Critical Episode occurs • DOES NOT contain maximum monitor concentration variable
Alternative 3	• Outcome Variable: Alert Critical Episode occurs • DOES NOT contain maximum monitor concentration variable
Alternative 4	• Outcome Variable: Pre-emergency or Emergency $PM_{2.5}$ Critical Episode occurs • DOES contain maximum monitor concentration variable
Alternative 5	• Outcome Variable: Pre-emergency or Emergency $PM_{2.5}$ Critical Episode occurs • DOES NOT contain maximum monitor concentration variable

7.2.3 RESULTS: ALTERNATIVE 1

The first regression model includes four explanatory variables (maximum monitor concentration, IOWA/WrfChem ouput, Meteodata model output, Wind speed at San Pablo, probability of coastal advection, and slope of monitor concentrations) and the outcome variable of a binary variable equal to one if any type of $PM_{2.5}$ episode occurs. The results for the logistic regression are reported as an odds ratio and are summarized in Exhibit 7-9 below. An odds ratio greater than one for a binary explanatory variable can be interpreted as follows: when that binary variable is equal to one, the outcome is as many times more likely to occur as the value of the odds ratio. For example, when specific humidity falls to six gram of vapor per kilogram of air or less between 17:00 and 20:00 (binary variable equal to one), a critical episode of any type (the outcome variable) is over 3 times more likely to occur. For an odds ratio less than one, the result can be interpreted as the outcome being less likely as the value of the explanatory variable increases. For example, since the odds ratio of the wind speed is less than one, when the wind speed is higher, a critical episode is less likely. Higher maximum monitor concentration the day before suggests a statistically significant, but only slightly increased likelihood of critical episode. Positive prediction of a critical episode by the Meteodata model increases the likelihood of a critical episode by 7.5 times.

EXHIBIT 7-9. ALTERNATIVE 1: IMPACT OF VARIABLES ON LIKELIHOOD OF ALL CRITICAL EPISODE TYPES

EXPLANATORY VARIABLES	ODDS RATIO	STANDARD ERROR
Maximum Monitor Concentration	1.011***	(0.004)
IOWA/WrfChem Model	3.246**	(1.597)
Meteodata Model	7.481***	(3.334)
Wind Speed (San Pablo)	0.701**	(0.109)
Probability of Coastal Advection	0.179**	(0.142)
Slope of $PM_{2.5}$ Concentrations	1.636**	(0.364)
Constant	.114***	(0.084)
Observations	**257**	

Standard errors in parentheses, ***p<0.01, ** p<0.05, * p<0.1

7.2.4 RESULTS: ALTERNATIVE 2

Exhibit 7-10 shows Alternative 2 model results, where the most important explanatory variables are wind speed, probability of coastal advection, slope of monitor concentration, the IOWA/WrfChem model, and the Meteodata model; maximum monitor concentration is not included. When the IOWA/WrfChem and Meteodata models predict a critical episode, a critical episode is more likely, with a slightly larger coefficient for the Meteodata model in this context. Consistent with Alternative 1, as the slope increases, the likelihood of a critical episode increases while higher wind speed decreases critical episode likelihood.

EXHIBIT 7-10. ALTERNATIVE 2: IMPACT OF VARIABLES ON LIKELIHOOD OF ALL CRITICAL EPISODE TYPES

EXPLANATORY VARIABLES	ODDS RATIO	STANDARD ERROR
Wind Speed (San Pablo)	0.659***	(0.091)
Probability of Coastal Advection	0.189**	(0.151)
Slope of $PM_{2.5}$ Concentrations	1.434**	(0.259)
IOWA/WrfChem Model	6.171***	(2.732)
Meteodata Model	7.862***	(3.359)
Constant	0.391*	(0.217)
Observations	**257**	
Standard errors in parentheses, ***p<0.01, ** p<0.05, * p<0.1		

7.2.5 RESULTS: ALTERNATIVE 3

Exhibit 7-11 shows Alternative 3 regression results where the outcome variable equals 1 when an Alert occurs and 0 otherwise. The final variables included in the regression model are wind speed, Meteodata model data, and humidity. The Meteodata model data is defined for days when the model predicts a concentration that falls within the Alert range. Consistent with results presented in Alternatives 1 and 2, we see a negative relationship with humidity and episode declaration. The IOWA/WrfChem model is not included in the regression results; however the Meteodata model variable shows that an Alert episode is 4 times more likely to occur if the Meteodata model predicts an Alert. The regression results suggest that humidity is important in predicting Alert episodes, where a lower humidity is associated with a higher chance of Alert episode declaration.

EXHIBIT 7-11. ALTERNATIVE 3: IMPACT OF VARIABLES ON LIKELIHOOD OF ALERT CRITICAL EPISODE

EXPLANATORY VARIABLES	ODDS RATIO	STANDARD ERROR
Wind Speed (San Pablo)	0.719***	(0.083)
Meteodata Model (Alert Only)	4.188***	(1.532)
Humidity (Lo Prado)	0.835*	(0.086)
Constant	1.286	(0.776)
Observations	**270**	
Standard errors in parentheses, ***p<0.01, ** p<0.05, * p<0.1		

7.2.6 RESULTS: ALTERNATIVE 4

Exhibit 7-12 shows the results of Alternative 4 regression model, including maximum monitor concentration, IOWA/WrfChem model predicting Pre-emergency or Emergency, slope of monitor concentrations, and humidity; the outcome variable is restricted to Pre-emergency and Emergency episodes only. The IOWA/WrfChem model predicts monitor concentrations for the next day and the IOWA/WrfChem variable included in this model is set equal to 1 when the concentration predicted reaches a Pre-emergency or Emergency threshold and 0 if otherwise. Consistent with Alternative 1, when the maximum monitor concentrations are higher the night before, a Pre-emergency or Emergency episode is slightly more likely. The relationship between the IOWA/WrfChem model, slope of monitor concentrations, and episode occurrence remains consistent across Alternatives 1, 2 and 4.

EXHIBIT 7-12. ALTERNATIVE 4: IMPACT OF VARIABLES ON LIKELIHOOD OF EMERGENCY OR PRE-EMERGENCY CRITICAL EPISODE

EXPLANATORY VARIABLES	ODDS RATIO	STANDARD ERROR
Maximum Monitor Concentration	1.011***	(0.003)
IOWA/WrfChem Model (Pre-emergency or Emergency)	7.354***	(5.020)
Slope of monitor concentrations	1.961***	(0.481)
Humidity (Lo Prado)	0.466***	(0.118)
Constant	0.165	(0.203)
Observations	**297**	
Standard errors in parentheses, ***p<0.01, ** p<0.05, * p<0.1		

7.2.7 RESULTS: ALTERNATIVE 5

Exhibit 7-13 shows the results of Alternative 5 regression model, excludes maximum monitor concentration. In this regression, compared to that of Alternative 4, the temperature differential variable is included in the model. If the maximum temperature differential between Lo Prado and San Pablo is greater than zero, it is almost five times more likely that a Pre-emergency or Emergency episode will occur the next day. Similar to the result in Alternative 4, the average humidity is associated with a lower likelihood of episode occurrence. This regression affirms that lower levels of humidity the day before is a consistent predictor of a Pre-emergency or Emergency episode. Also consistent with Alternative 4, the IOWA/WrfChem model significantly predicts a Pre-emergency or Emergency the next day. This is in contrast to results presented in Alternative 3 that show Meteodata model significantly predicts Alert episodes for the next day. These results, along with the results from Alternative 2, suggest that model data are important to consider in the absence of maximum monitor concentration.

EXHIBIT 7-13. ALTERNATIVE 5: IMPACT OF VARIABLES ON LIKELIHOOD OF EMERGENCY OR PRE-EMERGENCY CRITICAL EPISODE

EXPLANATORY VARIABLES	ODDS RATIO	STANDARD ERROR
Humidity (Lo Prado)	0.628**	(0.134)
IOWA/WrfChem Model (Pre-emergency or Emergency Only)	11.788***	(7.721)
Max temperature differential	4.705**	(2.863)
Constant	0.143	(0.173)
Observations	**270**	
Standard errors in parentheses, ***p<0.01, ** p<0.05, * p<0.1		

7.3 DISCUSSION

7.3.1 IMPLICATIONS OF REGRESSION RESULTS

The results from our regressions suggest several key takeaways for the critical episode forecasting process in the Santiago Metropolitan region. First, the results provide insight as to which meteorological variables are most important to consider in the 17:00-20:00 time frame. Next, both meteorological data and monitor data should be considered in the episode forecasting process. Regression model results can be used to update the internal daily minutes that are currently used to inform the forecasting process to ensure consistent, systematic reporting of key predictive variables in addition to other relevant information. Finally, the regression process provides a potential framework for future prediction and retrospective analysis of critical episodes.

For all critical episodes together, regardless of whether the maximum monitor concentration is considered, the degree of change in PM monitor concentrations, probability of coastal advection, and average wind speed at San Pablo station are important variables to consider. However, the wind speed during this specific time is not systematically used for the critical declaration forecasting process. All of the data is publicly available from the Chilean Meteorological services, but can only be downloaded in minute-by-minute data at the current time. If this data could readily be processed during the 17:00 to 20:00 period each day, it can help inform critical episode forecasting.

Similarly, the humidity variable between 17:00 and 20:00 is a strong predictor of a Pre-emergency or Emergency episode the next day. While this variable is identified as important by key decision makers in the SEREMI, it is not well-documented in the critical episode decision-making process at this time. Furthermore, publicly available meteorological data does not specifically report the temperature differential between Lo Prado and San Pablo station in real time, which may provide decision-makers a key source of information.

The results also suggest that modeled $PM_{2.5}$ concentrations are an important predictor of a critical episode in the absence of monitored $PM_{2.5}$ concentrations. Overall, the regression results suggest that both the Meteodata and IOWA/WrfChem models, particularly the latter, should be seriously considered when deciding whether or not to declare a critical episode. Moreover, the IOWA/WrfChem model more accurately predicts a Pre-emergency or Emergency episode than an Alert or any critical episode type. While the SEREMI should be mindful of mitigating factors on the day of episode declaration (high wind speed, high humidity, negative temperature differential), the IOWA/WrfChem and Meteodata models can provide advice on what choice to make for the episode declaration.

We are confident from the regression results that higher maximum monitor concentration the day before is related to an episode the next day. However, this may simply be a factor of multi-day weather conditions that lead to a series of critical episodes in a row. If the concentration is already elevated because there was an episode that day, then it may be very likely there will also be an episode the next day as well. Given this, the maximum monitor concentration could be used as a sign to see if the episode status will change for the next day. For example, if the given day has an Alert and, in the 17:00 to 20:00 window, the concentrations are still at the higher end of the Alert range (close to Pre-emergency); this could potentially motivate the SEREMI to forecast a Pre-emergency the next day.

Overall, this regression analysis should provide the SEREMI confidence in their air quality models of predicted $PM_{2.5}$, while highlighting potential additions to the critical episode forecasting process. First, to consider meteorological data in the 17:00-20:00 period on the day of prediction, the SEREMI will need to formalize a procedure to make sure these data are analyzed each day. This could be done by having a staff member download the appropriate data and process it into the most influential weather variables: average wind speed, specific humidity, and maximum temperature differential between Lo Prado and San Pablo stations. This approach could be automated to display real time processing of data to create necessarily variable formats. Moreover, the SEREMI could incorporate information gained from this analysis into a standardized electronic version of the "Minutas Internas Diarias".

7.4 MODEL VALIDATION

In addition to strengthening the current episode prediction process, this regression model provides a framework to analyze past and present years of information about critical episodes. Using the models presented in Section 7.3 and data collected in 2017, we calculated the probability of an episode occurring for every day in the 2017 winter season by regression model. We analyzed each model's predicted probability of an episode occurring and the actual data of whether an episode occurs to better understand the error associated with each model.

Below, we present the results of this validation analysis by demonstrating the Type 1 and Type 2 error at thresholds starting at 10% likelihood of the outcome variable occurring and increasing in likelihood from there. For each threshold presented we assume that any day the model produces a percentage above that threshold likelihood, that type of episode is declared. Type 1 error occurs when an episode is declared for that day ,but did not actually occur. Type 2 error is when the model predicts a percentage less than the threshold but an episode actually does occur. In order to balance Type 1 and Type 2 error, the model threshold must be set high enough to reduce the number of false alarms (Type 1 error) but miss as few episodes as possible to protect the public from poor air quality (Type 2 error). As shown in exhibits 7.14 through 7.18 below, the regression models in this study make it difficult to balance Type 1 and Type 2 error.

For predicting all episodes, Alternative 2 is better able to minimize Type 1 and Type 2 error when the percentage threshold is set at 10% than Alternative 1. For predicting Alerts, Alternative 3 does not provide much predictive power; the Type 1 and Type 2 error are less than 50% only at the 15% threshold (not shown in Exhibit 7-16). Even at the 15% threshold, Type 1 and Type 2 error are still high, at 30% and 43%, respectively. For Pre-emergency and Emergency prediction, Alternative 5 in Exhibit 7-18 shows the best predictive power of any of the models. At the 50% threshold of prediction, the model has only 5% Type 1 error and 0% Type 2 error. This suggests that Alternative 5 could potentially be used in the prediction of Pre-emergency and Emergency episodes. However, as noted above, 2017had an unusually low number of Pre-Emergency and Emergency episodes.

Overall, all of the model alternatives should be tested on more data to better understand the threshold of each model at which an episode should be declared. Furthermore, with the models shown in the Exhibits 7-14 to 7-18, the MMA whether it is their priority to avoid calling too many episodes (Type 1 error) or avoid calling too few episodes (Type 2 error).

EXHIBIT 7-14. ALTERNATIVE 1: MODEL VALIDATION FOR ALL EPISODES

PERCENTAGE THRESHOLD	CALLED, NOT OCCURRED	NOT CALLED, OCCURRED	TYPE 1 ERROR	TYPE 2 ERROR
10%	87	0	84%	0%
20%	39	17	38%	74%
30%	0	23	0%	100%
40%	0	23	0%	100%
50%	0	23	0%	100%
60%	0	23	0%	100%
70%	0	23	0%	100%
80%	0	23	0%	100%
90%	0	23	0%	100%
100%	0	23	0%	100%

EXHIBIT 7-15. ALTERNATIVE 2: MODEL VALIDATION FOR ALL EPISODES

PERCENTAGE THRESHOLD	CALLED, NOT OCCURRED	NOT CALLED, OCCURRED	TYPE 1 ERROR	TYPE 2 ERROR
10%	39	2	38%	9%
20%	23	5	22%	22%
30%	20	7	19%	30%
40%	16	9	16%	39%
50%	10	11	10%	48%
60%	9	13	9%	57%
70%	5	15	5%	65%
80%	5	18	5%	78%
90%	2	21	2%	91%
100%	0	23	0%	100%

EXHIBIT 7-16. ALTERNATIVE 3: MODEL VALIDATION FOR ALERT CRITICAL EPISODE

PERCENTAGE THRESHOLD	CALLED, NOT OCCURRED	NOT CALLED, OCCURRED	TYPE 1 ERROR	TYPE 2 ERROR
10%	57	2	54%	10%
20%	22	11	21%	52%
30%	8	14	8%	67%
40%	5	16	5%	76%
50%	3	17	3%	81%
60%	0	19	0%	90%
70%	0	21	0%	100%
80%	0	21	0%	100%
90%	0	21	0%	100%
100%	0	21	0%	100%

EXHIBIT 7-17. ALTERNATIVE 4: MODEL VALIDATION FOR PRE-EMERGENCY/EMERGENCY CRITICAL EPISODES

PERCENTAGE THRESHOLD	CALLED, NOT OCCURRED	NOT CALLED, OCCURRED	TYPE 1 ERROR	TYPE 2 ERROR
10%	8	1	6%	50%
20%	4	1	3%	50%
30%	2	1	2%	50%
40%	2	1	2%	50%
50%	2	2	2%	100%
60%	1	2	1%	100%
70%	0	2	0%	100%
80%	0	2	0%	100%
90%	0	2	0%	100%
100%	0	2	0%	100%

EXHIBIT 7-18. ALTERNATIVE 5: MODEL VALIDATION FOR PRE-EMERGENCY/EMERGENCY CRITICAL EPISODES

PERCENTAGE THRESHOLD	CALLED, NOT OCCURRED	NOT CALLED, OCCURRED	TYPE 1 ERROR	TYPE 2 ERROR
10%	19	0	15%	0%
20%	12	0	10%	0%
30%	8	0	6%	0%
40%	7	0	6%	0%
50%	6	0	5%	0%
60%	2	1	2%	50%
70%	2	2	2%	100%
80%	1	2	1%	100%
90%	0	2	0%	100%
100%	0	2	0%	100%

CHAPTER 8 | CRITICAL EPISODE BENEFIT COST ANALYSIS

We perform a benefit-cost analysis of the critical episode management system within the larger retrospective benefit cost analysis in this report. This analysis is based on critical episode data provided to us by the SEREMI for 2015 – 2017. Because critical episodes are called for a single day at a time, we calculate benefits and costs associated with episode declaration on a daily basis and aggregate across the year. Below, we describe the approach for quantifying benefits and costs associated with critical episode declaration.

8.1 BENEFITS ASSESSMENT

8.1.1 OVERVIEW AND MOTIVATION FOR ASSESSMENT

To fully illustrate the SEREMI's critical episode forecasting process and management, we conducted a benefits assessment to quantify health benefits associated with critical episode declarations. Depending on the severity of the episode status, the city of Santiago initiates various actions of increasing stringency to reduce air pollution concentrations and exposure, and in turn, reduce negative health outcomes, such as premature mortality, asthma, and cardiovascular disease incidence. We describe below how we estimate health benefits associated with improved air quality resulting from these actions.

8.1.2 BENEFITS ASSESSMENT METHODS

We used the BenMAP-CE program to conduct a screening-level benefits assessment of the specific benefits associated with the decrease in air pollution that occurs when declaring a critical episode. Different actions are taken based on the severity of the episode status; a more severe air quality episode will result in more regulated activities within the city and higher reductions in $PM_{2.5}$ concentrations. The specific restrictions associated with each episode status can be found in Exhibit 7-2. We model two relevant policy scenarios: (1) air pollution reductions associated with Alert status and (2) air pollution reductions associated with Pre-emergency/ Emergency statuses together. The two scenarios modelled are presented in Exhibit 8-1.

Within BenMAP-CE, the baseline air quality scenario is representative of days when $PM_{2.5}$ concentrations measured are higher than the declared episode threshold, at one or more monitors throughout the Santiago Metropolitan Region. We modeled the baseline air quality scenario to capture days where the air quality is worse than expected and the necessary restrictions are not in place. The days in the baseline sample will have adverse health impacts due to increased exposure to $PM_{2.5}$.

We modeled the control air quality scenario to be representative of days when the declared episode status matches or has better air quality than the measured episode status. Because the control scenario is characterized by days where more stringent action was taken to reduce $PM_{2.5}$ concentrations, we expect better air quality and positive health benefits. Air quality changes for control scenarios are calculated as a percent reduction of the baseline scenario. This percent reduction is then applied to the baseline air quality surface measured across Santiago air quality monitors. This represents an imperfect measure of the impact of the critical episode designations, because we are unable to control for other factors that may influence concentrations across these two sets of days, such as meteorological conditions or unusual emissions activities associated with a large sporting event or concert.[57] As such we are limited in our ability to characterize the true counterfactual concentrations and the full reduction achieved.

To determine the percent reduction in air quality applicable for the two analysis scenarios, we considered difference-in-means t-tests between the following two groups: (1) the maximum monitor concentrations on days when an episode was declared and the actual air quality matched or was better than the episode declared versus (2) the maximum monitor concentrations on days when the air quality that occurred was at a worse critical episode level than what was declared, when considering Good and Regular as the same category. These t-tests were conducted separately for Alert and Pre-emergency/Emergency status across the Santiago Metropolitan Region. We found the difference in mean of the maximum 24-hour $PM_{2.5}$ monitor concentrations across the city to be statistically significantly lower for both declared Alert days (6% lower) and declared Pre-emergency/Emergency days (9% lower). We use the resulting percent decrease in monitor concentrations as the monitor rollback in BenMAP.

Changes in $PM_{2.5}$ concentrations over short timeframes (e.g., daily exposures) have different relationships to health outcomes than long-term exposure to air pollution. As a result, the benefits of the critical episode program are not easily isolated from the more comprehensive cost-benefit analysis of long-term PM reductions presented earlier in this report. As a complement to our regression modelling in Chapter 7, which focuses on improving daily air quality management decision making, this benefits analysis more specifically captures health impacts of changes in short-term spikes in $PM_{2.5}$ concentrations.

[57] During these celebratory events, Chileans often use barbacoa grills to cook meat. These ovens produce emissions associated with incomplete combustion of biomass fuels.

EXHIBIT 8-1. DESCRIPTION OF SCENARIOS ANALYZED IN BENMAP-CE

SCENARIO	BASELINE SCENARIO	CONTROL SCENARIO
Alert Declaration	Monitor concentrations are taken as the maximum 24 hour moving average at a station across all days where either: 1) No action was taken (Good or Regular air quality was declared) but an Alert did occur 2) An Alert was called an Alert occurred, adjusting for reduction caused by Alert declaration	Monitor concentrations from baseline scenario are rolled back by a specific percentage based on t-test results. The monitor rollback is used to model the potential health benefits of declaring an Alert episode when an Alert is measured.
Pre-emergency and Emergency Declaration	Monitor concentrations are taken as the maximum 24 hour moving average at a station across all days where either: 1) Action for a less severe critical episode was taken (Alert declared and Pre-emergency occurred, or Pre-emergency declared and Emergency occurred) 2) Episode that was called actually occurred (Pre-emergency declared and occurred or Emergency declared and occurred), adjusting for reduction caused by Pre-emergency/Emergency declaration	Monitor concentrations from baseline scenario are rolled back by a specific percentage based on t-test results. The monitor rollback is used to model the potential health benefits of declaring a Pre-emergency or Emergency episode when a Pre-emergency or Emergency is measured.

8.1.3 BENMAP-CE INPUTS

To calculate health impacts, we used BenMAP-CE to apply scenario-specific air quality changes to the exposed population and use health impact functions to relate air pollution exposure to health impacts. BenMAP-CE uses monitor concentrations and locations, population, baseline incidence rates for health endpoints of interest, health impact functions that relate change in air quality and those health endpoints, and valuation functions that quantify economic benefits of avoided negative health outcomes. These methods are described further in Chapter 5.

Population

We used the 2016 population dataset for the Santiago Metropolitan Region as described in Chapter 5, disaggregated by gender and age.

Baseline Monitor Concentrations

The monitor data used in this analysis is a subset of the monitor dataset used in the regression modelling described in Chapter 7 above. The original dataset spans 11 monitor sites and provides average hourly values for every day in our sample. The monitor concentration is calculated as the maximum 24-hour moving average concentration at each monitor on a given day.

Alert Scenario. For the Alert scenario, the days included in the baseline monitor concentrations calculations are 1) days when no action was taken (Good or Regular air quality was declared) but an Alert did occur or 2) days when an Alert was called an Alert occurred.

Pre-Emergency/Emergency Scenario. For the Pre-emergency/Emergency scenario, the days included in the baseline are 1) days where action for a less severe critical episode was taken and a Pre-emergency or Emergency occurred, or 2) days when the episode that was called actually occurred (Pre-emergency declared and occurred or Emergency declared and occurred).

In both scenarios above, in order to take into account the reduction in concentration caused by the declaration of a critical episode, we adjust baseline monitor concentrations accordingly. For example, for the Alert scenario, we adjust the monitor concentrations in group 2 by one plus the percent reduction in concentration caused by declaring an Alert. We used a t-test to estimate the average percent reduction in the maximum concentration between days when an Alert was declared and an Alert or Good/Regular day occurred, and those days where an Alert occurred but Good/Regular was declared. We employed a similar process to adjust for episodes declared under the Pre-emergency/Emergency scenario.

Incidence Rates

We adapted baseline incidence rates from yearly incidence data provided by MMA. The incidence rates are based on two studies conducted to determine baseline incidence rates for the Santiago Metropolitan Region and the country as a whole (DICTUC 2011, DICTUC 2015). To calculate daily baseline incidence for use with daily health impact functions, we adjust these annual baseline incidence rates to daily baseline incidence rates by a factor of 0.002739 (1/365 days).

Health Impact Functions

We utilized mortality and morbidity health impact functions for our benefits analysis, including a short-term $PM_{2.5}$ mortality function from a review article of global studies and a subset of the EPA Standard morbidity functions pre-loaded to BenMAP-CE that have been previously used in analyses conducted by the MMA. For daily mortality impacts, we used the results of a meta-analysis of daily time series studies in the Latin and South American regions by Atkinson et al., 2014, where one of the underlying studies was conducted in the city of Santiago. We supplement this with specific morbidity health impact functions (shown in Exhibit 8-2) to be consistent with the health endpoints analyzed in MMA's Análisis General de Impacto Económico y Social (AGIES), or general analysis of economic and social impacts.

EXHIBIT 8-2. HEALTH IMPACT FUNCTIONS

AUTHOR	YEAR	ENDPOINT GROUP	AGE RANGE
Atkinson	2014	Short-Term Mortality, All Cause	0-99
Ito	2003	Hospital Admissions, Chronic Lung Disease	65-99
Ito	2003	Hospital Admissions, Pneumonia	65-99
Moolgavkar	2000	Hospital Admissions, Cardiovascular (less myocardial infarction)	18-64

AUTHOR	YEAR	ENDPOINT GROUP	AGE RANGE
Moolgavkar	2003	Hospital Admissions, Cardiovascular (less myocardial infarction)	65-99
Moolgavkar	2000	Hospital Admissions, Chronic lung disease	18-64
Moolgavkar	2003	Hospital Admissions, Chronic lung disease	65-99
Ostro	1987	Work Loss Days	18-64
Sheppard	2003	Hospital Admissions, Asthma	0-64

Valuation

The VSL function used in our analysis is consistent with the VSL used in the retrospective benefit cost analysis, outlined in Chapter 5. Valuation functions for each of the morbidity endpoints shown in Exhibit 8-2 are provided in Exhibit 8-3. These morbidity valuation estimates are consistent with the AGIES analysis performed by MMA.

EXHIBIT 8-3. MORBIDITY VALUATION FUNCTIONS

HEALTH ENDPOINT GROUP	AGE RANGE	VALUATION, COST PER CASE (2016 USD)
Short-Term Mortality, All Cause	0-99	$1,100,000
Hospital Admissions, Cardiovascular (less myocardial infarction)	18-99	$3,800
Hospital Admissions, Pneumonia	65-99	$2,700
Hospital Admissions, Asthma	0-17	$1,700
Hospital Admissions, Asthma	18-64	$1,900
Hospital Admissions, Chronic lung disease	18-64	$2,400
Hospital Admissions, Chronic lung disease	65-99	$2,500
Work Loss Days	18-64	$60

8.2 BENEFITS ASSESSMENT RESULTS

We estimate health benefits associated with declaring (1) Alert critical episodes and (2) Pre-emergency and Emergency episodes. We present the health benefits as a yearly average for both incidence and valuation. According to the MMA, there have been, on average from 2000 to 2017, 30 Alert episodes per year and 11 Pre-Emergencies and Emergencies per year. We use these numbers to calculate the incidence and valuation for the year in Exhibits 8-4 and 8-5, below.

We analyze the benefits associated with declaring Alert critical episodes during the winters of 2015 through 2017. These results of this screening assessment, as a yearly average, are shown in Exhibit 8-4. When $PM_{2.5}$ concentrations exceeded the Alert threshold of 80 $\mu g/m^3$, declaring an Alert episode reduced premature mortality on average by 22 persons per year, creating a benefit of $23M USD per year. Morbidity-related benefits for the endpoints shown in Exhibit 8-4 below total $540,000 USD per year for work loss days and $91,000 for hospital admissions.

EXHIBIT 8-4. ALERT CRITICAL EPISODE DECLARATION BENEFITS PER YEAR (2016$)

ENDPOINT GROUP	AGE RANGE	INCIDENCE	VALUATION
Short-Term Mortality, All Cause	0-99	21.6	$23,100,000
Hospital Admissions, Cardiovascular (less myocardial infarction)	18-99	14.7	$57,000
Hospital Admissions, Pneumonia	65-99	9.0	$2,700
Hospital Admissions, Asthma	0-64	1.8	$3,900
Hospital Admissions, Chronic lung disease	18-64	1.2	$2,700
Hospital Admissions, Chronic lung disease	65-99	1.5	$3,600
Work Loss Days	18-64	9,300	$540,000

We analyze the benefits associated with declaring Pre-emergency and Emergency episodes during the winters of 2015 through 2017. These results of this screening assessment, as a yearly average, are shown in Exhibit 8-5. When $PM_{2.5}$ concentrations exceeded the Pre-emergency threshold of 110 $\mu g/m^3$ or the Emergency threshold of 180 $\mu g/m^3$, declaring a Pre-emergency or Emergency episode reduced premature mortality on average by 14 persons per year, creating a benefit of $15.4M USD. Morbidity-related benefits for the endpoints shown in Exhibit 8-4 below total over $360,000 USD per year for work loss days and $61,000 for hospital admissions. Although the daily impacts of a Pre-emergency or Emergency are larger than for Alert, there are approximately one-third as many Pre-emergencies and Emergencies as there are Alerts. Therefore, the total valuation and incidence estimates in Exhibit 8-5 are smaller than those in Exhibit 8-4.

EXHIBIT 8-5. PRE-EMERGENCY AND EMERGENCY CRITICAL EPISODE DECLARATION BENEFITS PER YEAR (2016$)

ENDPOINT GROUP	AGE RANGE	INCIDENCE	VALUATION
Short-Term Mortality, All Cause	0-99	14.3	$15,400,000
Hospital Admissions, Cardiovascular (less myocardial infarction)	18-99	9.9	$37,400
Hospital Admissions, Pneumonia	65-99	6.1	$16,500
Hospital Admissions, Asthma	0-64	1.5	$2,750
Hospital Admissions, Chronic lung disease	18-64	0.8	$1,870
Hospital Admissions, Chronic lung disease	65-99	1.0	$2,310
Work Loss Days	0-64	6,270	$363,000

8.3 COSTS OF DECLARING A CRITICAL EPISODE

Declaration of a critical episode triggers a number of air quality control measures in the Santiago Metropolitan Region. These include:[58]

- A recommendation to suspend physical education classes (Alert, Pre-emergency, and Emergency)
- Vehicle restrictions (increasing stringency from Alert to Pre-emergency to Emergency)
- Curtailment of the most-polluting industrial sources (increasing number of sources from Pre-emergency to Emergency)
- A prohibition on using wood-burning heaters (Alert, Pre-emergency, and Emergency)

We considered four categories of impacts in our analysis of the costs associated with these control measures: transportation impacts, industrial sector costs, residential sector costs, enforcement costs. The analysis does not consider costs or benefits associated with the recommendation to suspend physical education classes because information on the degree to which this voluntary restriction is adopted is not available.

8.3.1 TRANSPORTATION IMPACTS

Our assessment of transportation impacts is based on a system modeling analysis of critical episodes conducted by SECTRA, Chile's Office of the Secretary of Transportation Planning.[59] According to SECTRA's analysis, the most significant transportation-related impact of declaring a Pre-emergency or Emergency is a reduction in roadway congestion. SECTRA estimates that system-wide travel time (i.e., travel time on public transportation and in private vehicles) decreases substantially when an episode is declared. SECTRA assumes that all trips for work or school purposes will continue, although travelers may need to switch from private vehicles to public transportation, and most trips for "other" purposes will also continue; only 11 percent of "other" trips for households with one car will not happen, and seven percent of "other" trips for households with two or more cars will not happen. We use SECTRA's estimated final travel demand for the morning peak period during critical episodes to estimate the daily system wide travel time. We converted SECTRA's morning peak values to daily values using SECTRA's assumed expansion factor of 7.10 hours per day (2,593 hours per year) and applying social cost of time values from the Ministry of Social Development. These social cost of time values include weighting factors for the different stages of public transportation travel, as shown in Exhibit 8-6. The final values of time consumption for a single day are shown in Exhibit 8-7.

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[58] Ministerio del Medio Ambiente. http://portal.mma.gob.cl/pronostico-rm

[59] SECTRA. "Plan de descontaminación ambiental: Modelación y Análisis del Plan de Movilidad del Transporte Público para Episodios de Contaminación Ambiental." Undated.

EXHIBIT 8-6. SYSTEMWIDE TRAVEL TIME FOR SINGLE DAY (SECTRA ANALYSIS)

SCENARIO	PUBLIC TRANSIT TIME					TOTAL PRIVATE TRAVEL TIME (HR)	SYSTEMWIDE TRAVEL TIME (HR)
	ACCESS TIME (HR)	TRANSFER TIME (HR)	WAITING TIME (HR)	TRANSIT TIME (HR)	TOTAL PUBLIC TRANSIT TRAVEL TIME (HR)		
No episode	850,554	36,686	449,186	2,354,096	3,690,528	2,597,575	6,288,103
Pre-emergency	856,393	30,434	394,619	2,119,461	3,400,908	1,308,279	4,709,186
Emergency	917,617	29,212	431,681	2,171,989	3,550,499	913,326	4,463,825

We converted these estimates from morning peak to daily values using SECTRA's assumed expansion factor (2,593 hours per year, or 7.10 hours per day), and then applied social cost of time values from the Ministry of Social Development. These social cost of time values include weighting factors for the different stages of public transportation travel, as shown in Exhibit 8-7.[60]

EXHIBIT 8-7. SOCIAL COST OF TIME VALUES

TRAVEL STAGE (CATEGORIES OF PUBLIC TRANSIT TIME)	WEIGHTING FACTOR	CLP/HR	USD/HR*
Travel, private or public (Transit)	1	1,688	$2.53
Waiting (Waiting)	2	3,376	$5.06
Walking (Access, Transfer)	3	5,064	$7.59
* Assumes exchange rate of 667.3 CLP/USD (December 30, 2016), consistent with SECTRA analysis.			

The final results of this analysis are shown in Exhibit 8-8 below. Because of the substantial reduction in system-wide travel time, the declaration of Pre-emergencies and Emergencies is associated with a net economic benefit.

EXHIBIT 8-8. INCREMENTAL BENEFITS ASSOCIATED WITH TRAVEL TIME

SCENARIO	SOCIAL COST OF TIME CONSUMPTION (USD)	INCREMENTAL BENEFIT (USD)
No episode	$21,500,000	$0
Pre-emergency	$17,400,000	$4,100,000
Emergency	$17,200,000	$4,400,000

In addition to overall reductions in travel time, the reduction in congestion associated with the declaration of a critical episode also reduces greenhouse gas emissions from vehicles. The SECTRA analysis provides an estimate of CO_2 reductions for pre-emergencies and emergencies relative to no-episode days. We valued these reductions using the recommended social cost of carbon from the Ministry of Social Development

[60] Ministerio de Desarrollo Social. "Precios Sociales 2017." February 2017.

($32.50 USD), as shown in Exhibit 8-9. Total benefits to the transportation sector (the sum of travel time benefits and avoided CO_2 emissions) are shown in Exhibit 8-10.

EXHIBIT 8-9. CO_2 REDUCTIONS ASSOCIATED WITH TRAVEL RESTRICTIONS DURING CRITICAL EPISODES

SCENARIO	CO_2 EMISSIONS (TONS/DAY)	CO_2 REDUCTION (TONS/DAY)	INCREMENTAL BENEFIT (USD)
No episode	25,902	0	$0
Pre-emergency	19,116	6,800	$220,000
Emergency	16,187	9,700	$320,000

EXHIBIT 8-10. TOTAL TRANSPORTATION SECTOR BENEFITS (2016 USD$)

SCENARIO	INCREMENTAL BENEFIT (USD)
No episode	$0
Pre-emergency	$4,300,000
Emergency	$4,600,000

Of note, these quantified benefits excluded a number of potential impacts, including the loss of utility (happiness) by those who do not travel. Data are not available to value that loss; however, SECTRA assumes that only a small percentage of the population would choose to cancel or postpone their trips (11 percent of non-school or work trips for households with one car, and seven percent of non-school or work trips for households with two or more cars). Because SECTRA assumes all school and work trips will continue, there is not likely to be a substantial cost associated with lost wages or reduced economic activity, other than the industrial sector costs described in the following section.

The SECTRA analysis notes potential cost savings associated with reduced fuel consumption and reduced public transit operating costs (e.g., reduced wear and tear on buses, if fewer buses are needed to maintain route frequencies due to reduced traffic congestion). We excluded these cost savings because of concern that fuel and operating costs may already be factored into the willingness-to-pay estimates used by the Ministry of Social Development to value travel time. Regardless, as estimated by SECTRA, these cost savings are minimal and would not affect the overall magnitude of benefits.

8.3.2 INDUSTRIAL SECTOR COSTS

During Pre-emergencies and Emergencies, the most-polluting industrial sources in the Santiago Metropolitan Region must cease operation. We approximated the costs associated with shutting down these industries based on estimates of their daily revenues (gross domestic product, or GDP).

According to the 2016 Operating Plan for critical episode management, 1,237 of the 11,588 industrial sources in the region may have to shut down during a Pre-emergency, and 2,617 sources may have to shut down during an Emergency.[61] For any Pre-emergency or Emergency, only approximately one-third of this total number of sources are actually required to shut down, following Resolución 9222 of the Ministry of Health.[62] The Banco Central de Chile reports GDP for the manufacturing sector in the metropolitan region of approximately $12.2 billion USD (2016 currency) for 2014, the most recent year available.[63] We assumed that the manufacturing sector encompasses the most-polluting industrial sources that would be required to shut down during critical episodes.

To estimate daily costs, we divided annual GDP for the manufacturing sector by 365 days, and multiply by the proportion of industrial sources that would be required to shut down (412 of 11,588 in a Pre-emergency; 872 of 11,588 in an Emergency). The results of this calculation are shown in Exhibit 8-11. This calculation is intended to be a screening-level approximation of possible costs, and thus depends on a number of assumptions about the facilities needing to shut down. Costs could be overstated if, for example, businesses make up for lost production by working overtime or by running additional manufacturing lines on non-episode days. On the other hand, costs could be understated if suppliers of curtailed businesses are affected (e.g., because businesses reduce their purchases of input materials), or if employees lose wages and reduce their spending accordingly. Finally, the use of regional GDP to estimate daily revenues assumes that the curtailed businesses are representative of the industry as a whole. Because revenue data are not readily available for the specific businesses that would be curtailed, we adopted this screening-level approach, recognizing the inherent uncertainty in the estimates.

EXHIBIT 8-11. TOTAL INDUSTRIAL SECTOR COSTS PER EPISODE (2016$)

SCENARIO	INDUSTRIAL SOURCES CURTAILED	LOST REVENUES (USD)
No episode	0	$0
Pre-emergency	410	$1,200,000
Emergency	870	$2,500,000

8.3.3 RESIDENTIAL SECTOR COSTS

During critical episodes, households in the metropolitan region are prohibited from burning wood as a heating source. To estimate the cost associated with this restriction, we relied on data from the 2016 AGIES. These analyses assume that all households with

[61] SEREMI del Medio Ambiente, Región Metropolitana de Santiago. "Plan Operacional Para la Gestión de Episodios Críticos de Contaminación Atmosférica por Material Particulado Respirable (MP10) en la Región Metropolitana, Año 2016." 2016.

[62] Ordena Paralización de Fuentes Estacionarias en Condiciones que Indica e Imparte Instrucciones, Ministerio de Salud Resolución 9222 (2016). Available at: https://www.leychile.cl/Navegar?idNorma=1090320

[63] Throughout IEc's analysis, values are inflated to 2017 currency using the GDP deflator for Chile from OECD Statistics. Chilean pesos are converted to U.S. dollars using an exchange rate of 667.3 CLP/USD, from the Ministerio de Dessarrollo Social.

wood-burning heaters would need to purchase and operate an alternative heating source to ensure access to heat during the winter season, April through August. Lacking additional information, these assumptions provide a conservative upper bound value. The purchase and operating costs associated with each heating source are shown in Exhibit 8-12. For the firewood fuel source in Exhibit 8-12, we used the average fuel consumption across chiminea, salamandra, simple combustion, and basic double consumption stoves.

EXHIBIT 8-12. COSTS OF RESIDENTIAL HEATING BY FUEL SOURCE[64]

FUEL SOURCE	PRICE OF EQUIPMENT (CLP)	CONSUMPTION	PRICE OF FUEL (CLP)
Firewood	0	1603 (kg/year/home)	166 (CLP/kg)
Kerosene	640,000	299 (kg/year/home)	600 (CLP/ kg)
Liquefied gas	681,000	282 (kg/year/home)	876 (CLP/kg)
Pellets	775,000	743 (kg/year/home)	236 (CLP/kg)
Electric Power	424,500	3093 (KWH/year/home)	95 (CLP/KWH)

According to the AGIES, approximately six percent of the population in the metropolitan region currently uses firewood for heating and cooking. Assuming an average household size of 3.5 people[65] and an overall population of 7.3 million,[66] an estimated 125,000 households will need to switch heating sources. Based on assumptions used in the AGIES, we estimated that approximately 40 percent of these households will switch to kerosene, 48 percent to gas, 10 percent to pellets, and two percent to electric sources.[67]

To quantify the costs associated with switching, we first annualized equipment costs over an assumed equipment lifetime of eight years using a six percent social discount rate, per AGIES. We then calculated expected annual fuel costs based on the fuel consumption rates and price of fuel shown in Exhibit 8-9. We then calculated the incremental cost of each alternative heating source compared to firewood.

To quantify per-critical episode costs associated with a switch in heating fuels, the analysis would ideally divide the incremental annual cost of each alternative heating source by the average number of critical episodes per year, over the lifetime of the equipment. This is difficult to do because the number of critical episodes varies substantially by year—for example, in 2013 there were 15 critical episodes for $PM_{2.5}$,

[64] Villena, Mauricio, Marcelo Villena, and Carlos Chavez. "Análisis General de Impacto Económico y Social del Rediseño del Plan Operacional para Enfrentar Episodios Críticos de Contaminación Atmosférica por Material Particulado Respirable (PM10) en la Región Metropolitana." March 2007.

[65] World Data Atlas. 2010. https://knoema.com/atlas/Chile/Metropolitana-de-Santiago/Average-Household-Size

[66] World Population Review. http://worldpopulationreview.com/world-cities/santiago-population/

[67] These numbers are scaled from the AGIES assumptions (10 percent pellet, 40 percent kerosene, 48 percent gas, and two percent electric) because cost data were not available for pellet heaters.

while in 2015 there were 51.[68] Consistent with the critical episode analysis in Chapter 7, we assumed an average of 34 critical episodes per year, based on 2016 data (42 critical episodes) and 2017 data (26 critical episodes).

Finally, we multiplied the per-household incremental cost by the number of households assumed to switch to each alternative source. The overall cost associated with switching residential heating sources is estimated at $ 220,000 per episode in 2016 currency, as shown in Exhibit 8-13. Negative values represent net cost savings. Importantly, however, these cost estimates assume that households will be able to and will choose to purchase alternative heating equipment. If households lack access to the financial capital necessary to purchase the equipment upfront, they may have no option but to forego heating. In that case, costs would reflect the social welfare loss to those households rather than direct purchase costs.

EXHIBIT 8-13. TOTAL RESIDENTIAL SECTOR COSTS (2016$)

FUEL SOURCE	PER-CRITICAL EPISODE COST (USD)	
	INCREMENTAL COST PER HOUSEHOLD PER EPISODE	INCREMENTAL COST PER EPISODE FOR SANTIAGO RM
Kerosene	$0.01	$730
Liquefied gas	$3.24	$200,000
Pellets	$0.64	$8,200
Electric power	$3.77	$9,600
	Total	**$220,000**
Note: Sum of incremental costs may not add up to $220,000 due to rounding.		

8.3.4 ADMINISTRATIVE COSTS

The government of Chile incurs costs associated with declaring critical episodes, primarily through staff time required to enforce travel restrictions. When travelers are stopped for violating the critical episode vehicle restriction, they are required to pay a fine. This fine, which is set at a flat fee for all violations, represents a transfer payment between drivers and the government. Presumably, this fee offsets some, if not all, of the administrative costs of enforcement. For that reason, we do not include enforcement costs in this screening-level analysis.

8.3.5 TOTAL COSTS

Total yearly costs associated with the declaration of critical episodes are presented in Exhibit 8-14 below. On average, there are 30 Alerts per year, 10 Pre-emergencies, and approximately one Emergency. The yearly cost from Alerts is over $6M. For Pre-emergencies and Emergencies combined, the yearly benefits are over $30M. Because

[68] SEREMI del Medio Ambiente, Región Metropolitana de Santiago. "Informe Final para la Gestión de Episodios Críticos de Contaminación Atmosférica por Material Particulado Respirable (MP10)." 2016.

industrial sector restrictions do not apply during Alerts and transportation restrictions only apply to vehicles without catalytic converters during Alerts, Alert costs are wholly attributed to the need for households to adopt alternative heating sources. For both the Pre-emergency and Emergency episode declaration, the transportation benefits are greater than the costs to the industrial and residential sectors.

EXHIBIT 8-14. TOTAL YEARLY COSTS PER CRITICAL EPISODE TYPE (2016$)

SECTOR	CRITICAL EPISODE COST (USD)		
	ALERT	PRE-EMERGENCY	EMERGENCY
Transportation		($43,000,000)	($4,600,000)
Industrial		$12,000,000	$2,500,000
Residential	$6,400,000	$2,200,000	$220,000
Total	**$6,400,000**	**($28,800,000)**	**($1,880,000)**

CHAPTER 9 | DISCUSSION AND NEXT STEPS

In the previous chapters, we describe our analytic approach and findings in detail. In this chapter, we summarize our findings and discuss their implications. We also suggest possible next steps for researchers and SEREMI and MMA staff.

9.1 SUMMARY OF FINDINGS

Our retrospective benefit-cost analysis provides evidence that environmental regulations in the Santiago Metropolitan Region over the past three decades have proven overwhelmingly beneficial from an economic perspective. Annual benefits over the period consistently exceed costs by an order of magnitude. This result holds true when assessing individual sectors. The benefits largely reflect reductions in premature deaths among Santiago residents: we find that roughly 80,000 premature deaths have been avoided since 1990 due to improved air quality stemming from environmental regulations. These results may be conservative estimates, as sensitivity analyses using alternative epidemiological literature and air quality models yield greater estimated benefits. In total, we estimate benefits of $25 billion across the period compared with $720 million in costs.[69]

We expand upon these findings by closely assessing one air quality management policy in greater detail: the critical episode management program. We first evaluate the factors influencing episode declarations and assess which factors exert the greatest influence on the likelihood of an air quality episode. We find that MMA staff can enhance and streamline their declaration decisions by focusing on several key data sources and parameters: IOWA/WrfChem model predictions, maximum $PM_{2.5}$ monitor concentrations, and meteorological indicators (average wind speed at San Pablo station, afternoon specific humidity at the Lo Prado Station, and the afternoon temperature differential at stations with different elevation). Further, we find evidence that critical episode declarations improve air quality by six percent on average across the metropolitan area for Alert episodes and by nine percent on average for Pre-emergency and Emergency episodes together. This finding, coupled with the increasing effects for more severe declarations, suggests that the SEREMI critical episode program is effective. Using these results, we estimate the benefits and costs of episode declaration and find that on average for the year, declaring an Alert episode yields $24M in benefits compared

[69] Total benefits and costs reflect net present value calculations using a base year of 1990 and a discount rate of 6%. Undiscounted, these values are $80 billion in benefits and $2.4 billion in costs.

with $6M in costs, and declaring a Pre-emergency or Emergency episode yields approximately $16M in health-related benefits and $46M in total benefits . Cost for both Pre-emergency and Emergency episodes are exceeded by avoided health impacts and the beneficial value-of-time impacts from transportation restrictions for the episode itself.

9.2 FUTURE RESEARCH NEEDS

9.2.1 RETROSPECTIVE BENEFIT COST ANALYSIS

These results are not without limitations. As discussed in Chapter 6 for the retrospective benefit-cost analysis, the results are accompanied by significant uncertainties in key assumptions, many of which are inherent in attempting to characterize a hypothetical scenario without environmental controls. However, researchers may improve upon our analysis by using more detailed data sources or other evidence from the academic literature. In particular, the results suggest a high sensitivity to the air quality model employed. Due to the concentrated population in central Santiago, we recommend improving upon the MMA modeling approach by developing a model with greater spatial disaggregation. Further, researchers may incorporate many of the benefits and costs not included in our analysis, such as morbidity benefits and indirect costs.

Future work may be aided by comparisons between our results and prospective analyses previously conducted by MMA. Such a comparison may highlight key uncertainties in the analyses and provide MMA economists with an opportunity to improve their methods for conducting future prospective analyses. Finally, we hope that this report serves as a valuable example for MMA economists who wish to conduct retrospective analyses in the future. More specifically, economists may wish to undertake targeted evaluations of specific programs, such as our analysis of the critical episode management program.

9.2.2 CRITICAL EPISODE ANALYSIS: FORECASTING CRITICAL EPISODES

Limitations associated with understanding the most predictive factors of a critical episode are described in Chapter 7. Regression models were built using three years of data, but could be refined by increasing sample size through including additional years' data. Possible next steps in this analysis include applying the final regression models with raw data from the an upcoming winter season to predict critical episode status and comparing those predictions with the air quality conditions that actually occurred. This analysis will allow the SEREMI to assess the practicality of using these regression models as part of their critical episode declaration process. Qualitatively, including the predictive variables identified through the regression analysis consistently in the SEREMI's internal minutes will provide empirically-derived important information to aid in their decision-making process going forward and in future re-evaluations of the forecasting methodology.

9.2.3 CRITICAL EPISODE ANALYSIS: BENEFIT COST ANALYSIS

The screening-level critical episode benefit cost analysis suffers from limited sample size due to the small number of more extreme episodes that occurred between the winters of 2015 and 2017. However, even with limited data and in the absence of quantifying welfare costs, we find that for Alert episodes, public health benefits appear to outweigh costs of implementing critical episode policies by more than a factor of 3 ($24M USD in benefits per year versus $7M in costs per year). Because we needed to pool Pre-emergency and Emergency episodes due to the small sample size, specifying the benefits and costs for each of these more severe episodes individually is difficult; however, the total benefits on average for these two more significant episodes totals approximately $46M USD per year, even after factoring in industrial and residential sector costs. This benefit-cost analysis can be updated each year to include additional data points to better estimate the incremental impacts of the declaration-related controls and to understand how critical episode declaration policies may be impacted by changing costs and benefits over time. In addition, MMA could consider adding additional health endpoints not included in our analysis, including non-fatal myocardial infarctions and non-fatal strokes. Additional efforts to refine the estimates of the impacts on $PM_{2.5}$ concentrations of declaring each type of episode would also be useful, either by employing a larger data set and/or analyzing PM levels of paired days with similar characteristics other than the episode declaration.

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APPENDIX A | CRITICAL EPISODE REGRESSION MODEL VARIABLES TESTED

VARIABLE	SPECIFICATION
Actual $PM_{2.5}$ Episode	Binary variable for episode or no episode based on episode status from max monitor concentration for date between 0:00-23:00
Actual $PM_{2.5}$ Episode	Binary variable for episode or no episode based on episode status from max monitor concentration for date between 0:00-17:00
Actual $PM_{2.5}$ Alert Episode	Binary variable for Alert or no Alert based on episode status from max monitor concentration for date between 0:00-23:00
Actual $PM_{2.5}$ Alert Episode	Binary variable for Alert or no Alert based on episode status from max monitor concentration for date between 0:00-17:00
Actual $PM_{2.5}$ Pre-emergency Episode	Binary variable for Pre-emergency or no Pre-emergency based on episode status from max monitor concentration for date between 0:00-23:00
Actual $PM_{2.5}$ Pre-emergency Episode	Binary variable for Pre-emergency or no Pre-emergency based on episode status from max monitor concentration for date between 0:00-17:00
Actual $PM_{2.5}$ Emergency Episode	Binary variable for Emergency or no Emergency based on episode status from max monitor concentration for date between 0:00-23:00
Actual $PM_{2.5}$ Emergency Episode	Binary variable for Emergency or no Emergency based on episode status from max monitor concentration for date between 0:00-17:00
Actual Episode Day Before	Binary variable for episode or no episode the day before based on max monitor concentrations from the day before from 0:00-17:00
IOWA/WrfChem Prediction 24 Hrs	Binary variable for episode or no episode based on IOWA/WrfChem prediction from 24 hours before
IOWA/WrfChem Prediction Alert 24 Hrs	Binary variable for Alert or no Alert based on IOWA/WrfChem prediction from 24 hours before
IOWA/WrfChem Prediction Pre-emergency 24 Hrs	Binary variable for Pre-emergency or no Pre-emergency based on IOWA/WrfChem prediction from 24 hours before
IOWA/WrfChem Prediction Emergency 24 Hrs	Binary variable for Emergency or no Emergency based on IOWA/WrfChem prediction from 24 hours before
Meteodata MOSA 24 Hrs	Binary variable for episode or no episode from the Meteodata MOSA concentration prediction
Meteodata MOSA 24 Hrs Alert	Binary variable for Alert or no Alert from the Meteodata MOSA concentration prediction
Meteodata MOSA 24 Hrs Pre-emergency	Binary variable for Pre-emergency or no Pre-emergency from the Meteodata MOSA concentration prediction
Meteodata MOSA Hrs Emergency	Binary variable for Emergency or no Emergency from the Meteodata MOSA concentration prediction
Meteodata Perc 24 Hrs	Binary variable for episode or no episode based on the episode status from the percentages in Meteodata. If the percent chance that episode is Bueno is > 50%, prediction is coded as no episode. If it is < 50 %, prediction is coded as episode.
Meteodata Perc 24 Hrs Alert	Binary variable for Alert or no Alert based on the episode status from the percentages in Meteodata. If the percent chance that episode is Bueno is < 50, and the percent chance of Alert is greater than the % chance of Pre-emergency or Emergency, the day is coded as Alert.

VARIABLE	SPECIFICATION
Meteodata Perc 24 Hrs Pre-emergency	Binary variable for Pre-emergency or no Pre-emergency based on the episode status from the percentages in Meteodata. If the percent chance that episode is Bueno is < 50, and the percent chance of Pre-emergency is greater than the % chance of Alert or Emergency, the day is coded as Pre-emergency.
Meteodata Perc Hrs Emergency	Binary variable for Emergency or no Emergency based on the episode status from the percentages in Meteodata. If the percent chance that episode is Bueno is < 50, and the percent chance of Emergency is greater than the % chance of Alert or Pre-emergency, the day is coded as Emergency.
Combined Model IOWA/WrfChem and Meteodata MOSA	Binary variable for when both IOWA/WrfChem prediction 24 hrs and Meteodata MOSA 24 hrs predict an episode.
Combined Model IOWA/WrfChem and Meteodata Perc	Binary variable for when both IOWA/WrfChem prediction 24 hrs and Meteodata % 24 hrs predict an episode.
IOWA/WrfChem prediction 48 hours	Binary variable for episode or no episode based on IOWA/WrfChem prediction from 48 hours before
IOWA/WrfChem prediction 72 hours	Binary variable for episode or no episode based on IOWA/WrfChem prediction from 72 hours before
Tipo A AM	Binary variable for whether Tipo A weather front is reported in Cassamassi 1.0 AM, (vaguada en superficie y dorsal en altura)
Tipo A PM	Binary variable for whether Tipo A weather front is reported in Cassamassi 1.0 PM, (vaguada en superficie y dorsal en altura)
Tipo A AM Update	Binary variable for whether Tipo A weather front is reported in Cassamassi 1.0 AM, updated with Chileans' suggestion
Tipo A PM Update	Binary, for whether Tipo A weather front is reported in Cassamassi 1.0 PM, updated with Chileans' suggestion
Capa Mezcla AM	Continuous, mixing height reported in Cassmassi 1.0 AM
Capa Mezcla PM	Continuous, mixing height reported in Cassmassi 1.0 PM
Adveccion Costera	Binary variable for probability of coastal advection reported in Cassmassi 1.0 PM
Daily Max Temp Differential	Continuous, of the maximum temperature difference between Lo Prado and San Pablo stations, from 0:00-23:00
Daily Max Temp Differential >= 8	Binary variable equal to one if the daily maximum temperature differential is greater than or equal to 8 degrees Celsius
Daily Max Temp Differential >= 7	Binary variable equal to one if the daily maximum temperature difference is greater than or equal to 7 degrees Celsius
Daily Max Temp Differential >= 6	Binary variable equal to one if the daily maximum temperature differential is greater than or equal to 6 degrees Celsius
Daily Max Temp Differential >= 9	Binary variable equal to one if the daily maximum temperature differential is greater than or equal to 9 degrees Celsius
Daily Max Temp Differential >= 10	Binary variable equal to one if the daily maximum temperature differential is greater than or equal to 10 degrees Celsius
Daily average wind speed	Continuous, Average daily wind speed at San Jose station, in m/s
Percent of wind from East	Continuous, percent of time during the day that the wind is blowing from the East at San Jose station (East defined as 45-90 degrees)
Daily average humidity	Continuous, Average daily specific humidity at Lo Prado station, in g of vapor/kg of air from 0:00-23:00. Calculated using temperature, relative humidity and pressure at Lo Prado station.

VARIABLE	SPECIFICATION
Morning AND night before hourly max wind direction from east > 25%	Binary variable equal to 1 if the percent of time the wind is blowing from the east at San Jose station is greater than 25% for the hours of 20:00-23:00 the night before AND 0:00-5:00 the day of.
Morning OR night before hourly max wind direction from east > 25%	Binary variable equal to 1 if the percent of time the wind is blowing from the east at San Jose station is greater than 25% for the hours of 20:00-23:00 the night before OR 0:00-5:00 the day of.
Average specific humidity, day of	Continuous variable, average daily specific humidity at Lo Prado station, in g of vapor/kg of air from 0:00-17:00. Calculated using temperature, relative humidity and pressure at Lo Prado station.
Average specific humidity, night before	Continuous variable, average daily specific humidity at Lo Prado station, in g of vapor/kg of air from 17:00-20:00
Specific humidity <= 6, day of	Binary variable equal to one when average humidity from 0:00-17:00 < 6
Specific humidity <= 6, night before	Binary variable equal to one when average humidity from 17:00-20:00 < 6
Max temperature differential > =8, day of	Binary variable equal to one if the maximum temperature differential is greater than or equal to 8 degrees Celsius at between 0:00-17:00
Max temperature differential >= 8, night before	Binary variable equal to one if the maximum temperature differential is greater than or equal to 9 degrees Celsius between 17:00-20:00
Max temperature differential >= 9, day of	Binary variable equal to one if the maximum temperature differential is greater than or equal to 9 degrees Celsius between 0:00-17:00
Max temperature differential > =9, night before	Binary variable equal to one if the maximum temperature differential is greater than or equal to 8 degrees Celsius between 17:00-20:00
Interaction term between max temperature differential >= 8 and specific humidity <=6, day of	Binary variable equal to one when both max temperature differential > 8 and specific humidity < 6 between 0:00-17:00
Interaction term between max temperature differential >= 8 and specific humidity <= 6, night before	Binary variable equal to one when both max temperature differential > 8 and specific humidity < 6 between 17:00-20:00
Interaction term between max temperature differential > 9 and specific humidity, day of	Binary variable equal to one when both max temperature differential > 9 and specific humidity < 6 between 0:00-17:00
Interaction term between max temperature differential > 9 and specific humidity, night before	Binary variable equal to one when both max temperature differential > 9 and specific humidity < 6 between 17:00-20:00
Percent time wind direction from San Jose, day of	Continuous, percent of the time between 0:00 and 17:00, calculated by minute, that the wind at San Jose station is blowing from the Northeast (defined as 45 to 90 degrees)
Percent time wind direction from San Jose, night before	Continuous, percent of the time between 17:00 and 20:00 the day before, calculated by minute, that the wind at San Jose station is blowing from the Northeast (defined as 45 to 90 degrees)
Percent time wind direction from San Jose > 15, day of	Binary variable equal to one when percent of time wind direction from East is > 15% of the time from 0:00-17:00
Percent time wind direction from San Jose > 15, night before	Binary variable equal to one when percent of time wind direction from East is > 15% of the time from 17:00-20:00
Wind speed, day of	Continuous, Average daily wind speed at San Jose station, in m/s from 0:00-17:00
Wind speed, night before	Continuous, Average daily wind speed at San Jose station, in m/s from 17:00-20:00
Wind speed < 2, day of	Binary variable equal to one when wind speed < 2 m/s between 0:00-17:00
Wind speed < 2, night before	Binary variable equal to one when wind speed < 2 m/s between 17:00-20:00
Max Monitor concentration from night before	Continuous, maximum monitor concentration from 17:00-20:00

VARIABLE	SPECIFICATION
Slope of max monitor concentration, from night before	Continuous, slope of monitor concentrations at 17:00 and 20:00
Slope of specific humidity, from night before	Continuous, slope of specific humidity at 17:00 and 20:00
Percent Change in monitor concentration, from night before	Continuous, percent change in monitor concentrations between 17:00-20:00
Percent change in specific humidity, from night before	Continuous, percent change in specific humidity between 17:00-20:00