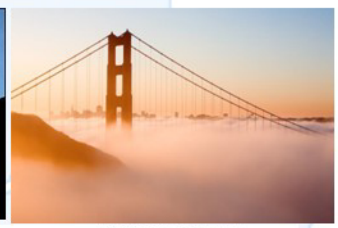
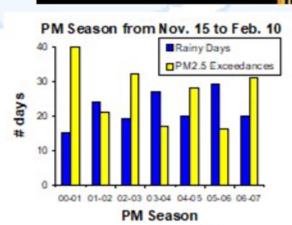
BAY AREA AIR QUALITY MANAGEMENT DISTRICT
375 Beale Street, San Francisco, CA 94105

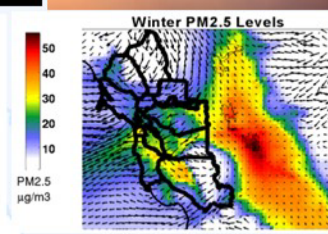
Air Quality Modeling and Analysis Section Publication No. 202212-025-PM

Assessing Ambient Air Quality and Health Impacts from Natural Gas Building Appliances in the Bay Area: Supplemental Information for Proposed Amendments to Regulation 9, Rule 4 and Rule 6

December 2022







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Assessing Ambient Air Quality and Health Impacts from Natural Gas Building Appliances in the Bay Area: Supplemental Information for Proposed Amendments to Regulation 9, Rule 4 and Rule 6

Executive Summary

Introduction

This assessment evaluates ambient air quality and health impacts from commercial and residential natural gas combustion emissions to provide supplemental information for proposed amendments to Bay Area Air Quality Management District (Air District or BAAQMD) Rules 9-4 and 9-6. These proposed rule amendments (Elwell, 2022) limit emissions of oxides of nitrogen (NO and NO_2, together referred to as NO_x) from natural gas-fired furnaces (9-4) and water heaters and boilers (9-6). They impose a zero-NO_x standard on natural gas-fired commercial and residential building space and water heating appliances.

Natural gas-fired furnaces, water heaters, and boilers emit NO_x, fine particulate matter ($PM_{2.5}$), and other pollutants directly into the air. Once emitted to the atmosphere, NO_x further reacts with other pollutants to form *secondary $PM_{2.5}$*. *Total $PM_{2.5}$* is the combination of directly emitted, or *primary $PM_{2.5}$*, and secondary $PM_{2.5}$.

This assessment focuses on the impact of reductions in emissions from natural gas-fired building appliances to be expected should the proposed rule amendments be fully implemented, with emissions reductions from current versions of the rules being excluded from benefit analyses. The proposed amendments do not specify what technology to use, but one way to meet the zero-NO_x requirement is with electric appliances, which are currently available on the market. Because the adoption of electric equipment would eliminate all combustion-related emissions, this assessment evaluates reduced impacts with electric appliances that emit no NO_x—and so contribute no secondary $PM_{2.5}$—and also emit no primary $PM_{2.5}$.

Should zero-NO_x natural-gas fired appliances be developed in response to the proposed rules, the rules would achieve the described reductions in secondary $PM_{2.5}$ but may or may not achieve the reduction in impacts ascribed to reductions in primary $PM_{2.5}$, depending on how the appliances are designed and how many consumers choose to purchase natural-gas fired versus electric appliances.

Analysis Methods

Using the U.S. EPA's Community Multiscale Air Quality (CMAQ) model, staff conducted a year-long simulation to estimate ambient NO_x and $PM_{2.5}$ contributions from commercial and residential building appliances. Using the U.S. EPA's Environmental Benefits Mapping and Analysis Program – Community Edition (BenMAP-CE), staff also estimated the health impacts of simulated $PM_{2.5}$. BenMAP-CE provides many health impact functions to estimate health impacts of $PM_{2.5}$ and ozone. This assessment focused on estimating the health impacts of $PM_{2.5}$. Numerous scientific studies (U.S. EPA, 2019) have linked $PM_{2.5}$ exposure to adverse human health effects, including but not limited to premature death, non-fatal heart attacks, and asthma. The contribution of NO_x emissions to ambient ozone levels in this context is relatively small, and the health effects of these small changes in ozone levels are minimal.

This modeling analysis featured two annual simulations for 2018: (1) a baseline scenario that included the Air District's latest emissions estimates from all inventoried sources and (2) a control scenario that removed emissions from space heating and water heating appliances subject to the proposed rules. Differences between these two simulations provided an estimate of the air quality impacts of these *targeted building appliances*. Because these modeled impacts include post-2018 NO_x emission reductions associated with the current version of Rule 9-6, modeling results were adjusted so that the control scenario is representative solely of emissions reductions resulting from full implementation of the proposed updates to Rules 9-4 and 9-6, under the scenario that no zero-NO_x natural-gas fired appliances are developed. Should zero-NO_x natural-gas fired appliances be developed in response to the proposed rules, the rules would achieve the described reductions in secondary $PM_{2.5}$ but may or may not achieve the reductions ascribed to reductions in primary $PM_{2.5}$.

CMAQ simulation results were analyzed for two cases: (1) an estimate of chemically produced (secondary) $PM_{2.5}$ impact from the targeted building appliances and (2) an estimate of total $PM_{2.5}$ impact from the targeted building appliances. Changes in secondary $PM_{2.5}$ level were attributed to NO_x emissions from the targeted building appliances. The estimated total $PM_{2.5}$ impact includes impacts from both the secondary $PM_{2.5}$ and from primary $PM_{2.5}$ that is directly emitted from the targeted building appliances. BenMAP-CE was applied for changes in both secondary and total $PM_{2.5}$ levels.

In addition to an evaluation of air quality and health impacts of $PM_{2.5}$, this assessment also includes an examination of modeled changes to levels of 24-hour-average $PM_{2.5}$ and 8-hour-average ozone at air quality monitoring stations when observed concentrations were near the level of the national ambient air quality standards. Understanding how peak air pollution levels are influenced by reduction in emissions from targeted building appliances provides insight into how proposed amendments to Rules 9-4 and 9-6 might influence achieving and maintaining state and federal ambient air quality standards should the proposed rules be fully implemented.

Emissions from the Appliances Covered by Proposed Rule Amendments
Table E.1 summarizes emissions from applicable commercial and residential natural gas combustion in the Bay Area from the 2018 baseline scenario that would be targeted by the proposed rule amendments.[1] Air quality and health impacts were evaluated based on a 3,690 tons per year (ton/yr) reduction in NO_x emissions and a 458 ton/yr reduction in primary $PM_{2.5}$ emissions, along with reductions in emissions of other pollutants shown in Table E.1. Note that for 2018, NO_x emissions from these targeted appliances totaled 4,267 tons; however, it is estimated that full implementation of existing Rule 9-6 will reduce NO_x emissions from commercial and residential water heating by 576 tons relative to 2018. That leaves 3,690 tons of NO_x emissions to be addressed by the proposed rule amendments. For the remaining pollutants, all emissions reductions from 2018 levels are associated only with the proposed rule amendments. Additional details on emissions reduction estimates and how emissions were treated in the modeling analyses are provided in Appendix A.1.

[1] Natural gas combustion emissions represent the Air District's latest estimates for residential (2019) and commercial (2018) sources. These estimates are considered representative of 2018 conditions for modeling purposes.

Table E.1: Bay Area emissions targeted by proposed rule amendments.

Description	Annual Emissions (ton/yr)				
	NO_x	$PM_{2.5}$	SO_x	ROG	CO
Commercial – space heating	553	45	4	29	238
Commercial – water heating	240	55	4	35	291
Residential – space heating	2,410	197	16	125	1,037
Residential – water heating	487	161	13	103	847
Total[a]	**3,690**	**458**	**36**	**292**	**2,413**

[a] Totals may not match column summations due to rounding. Values rounded to nearest ton per year.

Simulated $PM_{2.5}$ Impacts

Figure E.1 shows secondary and total $PM_{2.5}$ contributions from targeted building appliance emissions to ambient $PM_{2.5}$ concentrations. Secondary $PM_{2.5}$ contributions are the highest (exceeding 0.15 μg/m^3) in southwestern San José, Figure E.1 (left panel). Secondary $PM_{2.5}$ contributions between 0.12 μg/m^3 and 0.15 μg/m^3 are seen over the entire metropolitan San José region surrounding the highest $PM_{2.5}$ reduction areas and over relatively small areas in downtown San Francisco and downtown Oakland. Contributions between 0.09 μg/m^3 and 0.12 μg/m^3 extend from Oakland to Gilroy and from San Mateo to San José following the Interstate 880 and 101 corridors. The same level of contributions also extends from San Ramon to Livermore following the Interstate 680 and 580 corridors, respectively. Contributions between 0.04 μg/m^3 and 0.09 μg/m^3 extend over much of the residential areas of the Bay Area and beyond. This spread of contributions across a wide area is due to diffusion and dispersion of pollutants in the atmosphere while forming secondary $PM_{2.5}$.

Total $PM_{2.5}$ contributions from targeted building appliance emissions to annual average $PM_{2.5}$ concentrations exceed 0.30 μg/m^3 in San Francisco and Oakland, Figure E.1 (right panel). Contributions between 0.21 μg/m^3 and 0.30 μg/m^3 are seen in areas surrounding those with concentrations above 0.30 μg/m^3 as well as in San José. $PM_{2.5}$ contributions between 0.09 μg/m^3 and 0.21 μg/m^3 cover residential areas along the major freeways of the Bay Area from Richmond/San Pablo to Gilroy, from San José to San Francisco, and from Concord to Livermore. The same level of $PM_{2.5}$ contributions is found over Napa, Santa Rosa, and Brentwood. The rest of the Bay Area has contributions less than 0.09 μg/m^3.

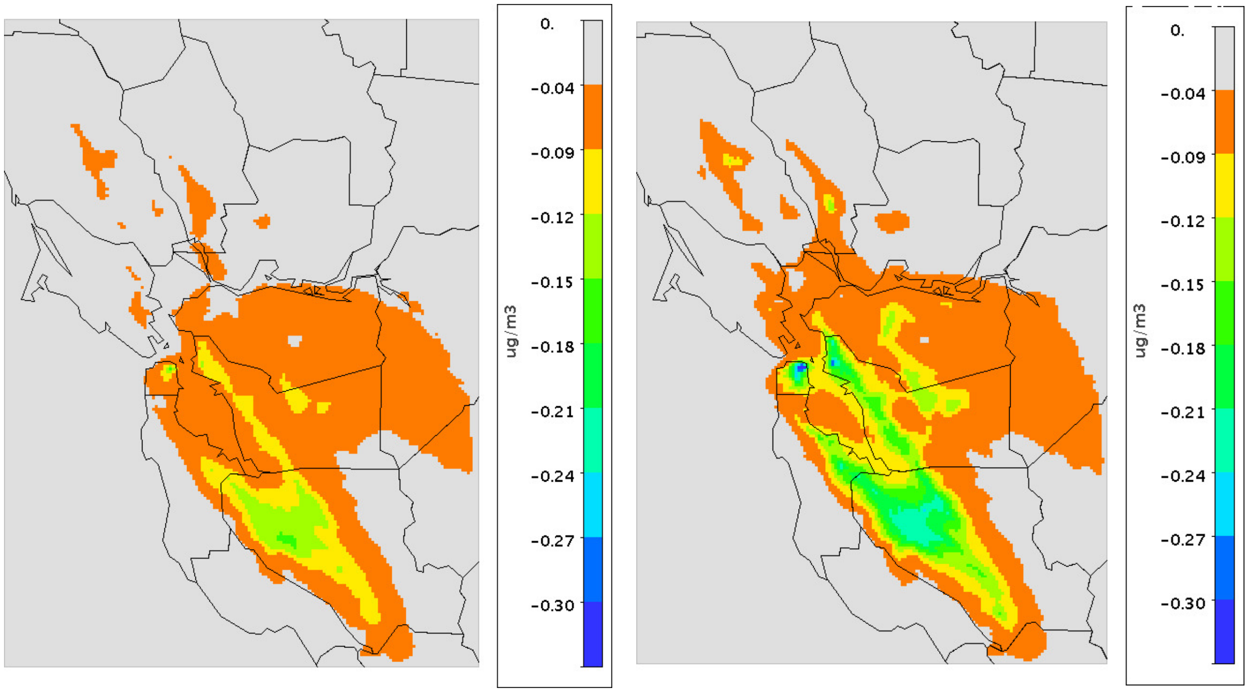

Figure E.1: Simulated reductions in annual average ambient secondary (left) and total (right) $PM_{2.5}$ concentrations with controlled emissions from building appliances covered by proposed amendments to Rules 9-4 and 9-6.

Estimated Health Impacts

Aggregated BenMAP-CE results (Tables E.2 and E.3) show that reductions in secondary $PM_{2.5}$ would reduce the incidence of premature mortality within the Air District's jurisdiction by 23 to 52 cases per year. Similarly, reductions in total $PM_{2.5}$ concentrations would reduce the incidence of premature mortality by 37 to 85 cases per year. The ranges in these estimates reflect different epidemiological studies. The valuations[2] assigned to premature death cases range from 230 to 530 million U.S. dollars for secondary $PM_{2.5}$ and from 380 to 870 million U.S. dollars for total $PM_{2.5}$.

The other health impacts in the EPA's recommended BenMAP-CE configuration include selected chronic/severe illnesses, hospital admissions/emergency room visits due to respiratory and cardiovascular diseases, selected minor health effects, and asthma-related effects. The health impacts evaluated showed decreased annual incidence as a result of reductions in $PM_{2.5}$ levels with elimination of emissions from applicable commercial and residential space and water heating appliances. For example, for a 2020 population, 2.6 to 24 non-fatal heart attacks would be prevented with the modeled reductions in secondary $PM_{2.5}$ and 4.2 to 39 non-fatal heart attacks would be prevented with the modeled reductions in total $PM_{2.5}$. The associated valuations are estimated to be 0.23 to 2.1 million U.S. dollars and 0.38 to 3.5 million U.S. dollars, respectively. Another example is the benefit of 4,100 and 6,700 fewer lost days of work, valued at 1.1 million U.S. dollars and 1.8 million U.S. dollars, respectively.

[2] Valuations are not identical to cost savings. Some valuations are based on cost savings, but the most highly valued component (mortality) is based on an estimate of willingness-to-pay (WTP).

Table E.2: Estimated health impacts avoided with decreased $PM_{2.5}$ from elimination of emissions from applicable commercial and residential space and water heating appliances in the Bay Area.

Health Impact[a]	Avoided Incidence, Per Year	
	Secondary $PM_{2.5}$	**Total $PM_{2.5}$**
Premature mortality		
All causes[b]	23–52	37–85
Chronic/severe illness		
Non-fatal acute myocardial infarction (heart attack)	2.6–24	4.2–39
Hospital admission, neurological[c]	7.7	13
Incidence, out of hospital cardiac arrest	0.45	0.73
Incidence, stroke	1.5	2.4
Incidence, lung cancer	1.9	3.1
Hospital admissions[d]		
Respiratory[e]	2.4	3.9
Cardiovascular[f]	3.0	4.9
ER visits		
Respiratory[g]	13	20
Cardiovascular[h]	6.2	10
Other effects		
Restricted activity days	24,000	39,000
Work loss days	4,100	6,700
Hay fever/allergic rhinitis	440	710
Asthma-related effects		
Asthma symptoms/albuterol use	9,200	15,000
Onset of asthma	71	110

[a] Each health impact is associated with one or more unique International Classification of Diseases-9-Clinical Modification (ICD-9-CM) code(s) (Medicode, 1996).

[b] Includes all ICD-9 codes.

[c] First hospital admission (cause-specific, to indicate onset of the chronic disease) for dementia, Alzheimer's disease, or Parkinson's disease (ICD-9 codes 290, 331.0, or 332, respectively), and other neurological morbidities.

[d] Hospital admissions due to acute exposure to air pollution are assumed to pass through the emergency room; however, the calculated value of hospital admissions does not account for the cost incurred in the emergency room visit. This strategy avoids double-counting.

[e] Includes all respiratory diseases (ICD-9 codes 460–519).

[f] Includes cardio-, cerebro-, and peripheral vascular diseases (ICD-9 codes 410, omitting 410.x2; 410–414; 426–427; 428; 429; 430–438; 440–448).

[g] Includes respiratory diseases (ICD-9 codes 480–486, 491, 492, 496, 460–465, 466, 477, 493, 786.07).

[h] Includes all cardiac outcomes (ICD-9 codes 390–549).

Table E.3: Valuations of avoided health impacts with decreased $PM_{2.5}$ from elimination of emissions from applicable commercial and residential space and water heating appliances in the Bay Area.

Health Impact[a]	Total Valuation in 2020 U.S. Dollars, Million Dollars Per Year	
	Secondary $PM_{2.5}$	Total $PM_{2.5}$
Premature mortality		
All causes[b]	230–530	380–870
Chronic/severe illness		
Non-fatal acute myocardial infarction (heart attack)	0.23–2.1	0.38–3.5
Hospital admission, neurological[c]	0.11	0.19
Incidence, out of hospital cardiac arrest	0.019	0.03
Incidence, stroke	0.059	0.096
Incidence, lung cancer	0.056	0.091
Hospital admissions[d]		
Respiratory[e]	0.028	0.045
Cardiovascular[f]	0.055	0.090
ER visits		
Respiratory[g]	0.013	0.021
Cardiovascular[h]	0.0084	0.014
Other effects		
Restricted activity days	1.9	3.2
Work loss days	1.1	1.8
Hay fever/allergic rhinitis	0.31	0.52
Asthma-related effects		
Asthma symptoms/albuterol use	0.0037	0.0059
Onset of asthma	3.6	5.8
Sum		
All health impacts included	240–540	400–890

[a] Each health impact is associated with one or more unique International Classification of Diseases-9-Clinical Modification (ICD-9-CM) code(s).

[b] Includes all ICD-9 codes.

[c] First hospital admission (cause-specific, to indicate onset of the chronic disease) for dementia, Alzheimer's disease, or Parkinson's disease (ICD-9 codes 290, 331.0, or 332, respectively), and other neurological morbidities.

[d] Hospital admissions due to acute exposure to air pollution are assumed to pass through the emergency room; however, the calculated value of hospital admissions does not account for the cost incurred in the emergency room visit. This strategy avoids double-counting.

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[g] Includes respiratory diseases (ICD-9 codes 480–486, 491, 492, 496, 460–465, 466, 477, 493, 786.07).

[h] Includes all cardiac outcomes (ICD-9 codes 390–549).

Simulated Changes in 24-hour $PM_{2.5}$ and 8-hour Ozone Levels

In addition to evaluating air quality and health impacts from contributions to annual average $PM_{2.5}$, in this assessment staff also examined modeled changes to levels of 24-hour-average $PM_{2.5}$ and 8-hour-average ozone at air quality monitoring stations when observed concentrations were near the level of the national ambient air quality standards. While this assessment did not include a formal modeling attainment demonstration for these pollutants, it did include an examination of how peak levels are influenced by reduced emissions from commercial and residential space and water heating emissions, providing insights into how proposed amendments to Rules 9-4 and 9-6 might influence achieving and maintaining state and federal ambient air quality standards should the proposed rule amendments be fully implemented.

For 24-hour $PM_{2.5}$, comparison of the control scenario to the baseline scenario showed a mean modeled reduction of about 0.7 $\mu g/m^3$ for peak levels at the locations of monitoring sites when levels of at least 30 $\mu g/m^3$ were observed. For 8-hour ozone, the mean modeled reduction was less than 0.1 ppb for peak levels when levels of at least 65 ppb were observed.[3]

[3] For context, the current federal standard for 24-hour $PM_{2.5}$ is 35 $\mu g/m^3$ and the federal standard for 8-hour ozone is 70 ppb.

List of Acronyms

AB 617	Assembly Bill 617
BAAQMD	Bay Area Air Quality Management District
BenMAP-CE	Environmental Benefits Mapping and Analysis Program – Community Edition
CARB	California Air Resources Board
CDC	Centers for Disease Control and Prevention
CEC	California Energy Commission
CEIDARS	California Emission Inventory Development and Reporting System
CEPAM	California Emission Projection and Analysis Model
CMAQ	Community Multiscale Air Quality (model)
CO	Carbon monoxide
E&CEA	Emissions and Community Exposure Assessment (Section)
EGU	Electric generating unit
EIC	Emission Inventory Codes
EMFAC2017	Emission FACtor 2017
ICD-9-CM	International Classification of Diseases-9-Clinical Modification
mscf	Million standard cubic feet
NAICS	North American Industrial Classification System
NO	Nitrogen oxide
NO_2	Nitrogen dioxide
NO_x	Oxides of nitrogen (NO and NO_2)
PG&E	Pacific Gas and Electricity (Company)
$PM_{2.5}$	Particulate matter ≤2.5 µm in aerodynamic diameter
ppb	Parts per billion
ROG	Reactive organic gases
SIP	State Implementation Plan
SMOKE	Sparse Matrix Operator Kernel Emissions (model)
SO_x	Oxides of sulfur
ton/yr-km^2	Tons per year per 1-km grid square
tpd	Tons per day
Ton/yr	Tons per year
U.S. EPA	United States Environmental Protection Agency
WRF	Weather Research and Forecasting (model)
WTP	Willingness to pay (to avoid risk)

Assessing Ambient Air Quality and Health Impacts from Natural Gas Building Appliances in the Bay Area: Supplemental Information for Proposed Amendments to Regulation 9, Rule 4 and Rule 6

1. Introduction

1.1 Background and Purpose

This assessment evaluates ambient air quality and health impacts from commercial and residential natural gas combustion emissions to provide supplemental information for proposed amendments to Bay Area Air Quality Management District (Air District or BAAQMD) Rules 9-4 and 9-6. These proposed rule amendments (Elwell, 2022) limit emissions of oxides of nitrogen (NO and NO_2, together referred to as NO_x) from natural gas-fired furnaces (9-4) and water heaters and boilers (9-6). They impose a zero-NO_x standard on natural gas-fired commercial and residential building space and water heating appliances.

Natural gas-fired furnaces, water heaters, and boilers emit NO_x, fine particulate matter ($PM_{2.5}$), and other pollutants directly into the air. NO_x forms when fuels like natural gas are burned at high temperatures. Once emitted to the atmosphere, NO_x further reacts with other pollutants to form *secondary $PM_{2.5}$*. *Total $PM_{2.5}$* is the combination of directly emitted, or *primary $PM_{2.5}$*, and secondary $PM_{2.5}$.

Numerous scientific studies (U.S. EPA, 2019) have linked $PM_{2.5}$ exposure, to many adverse human health effects, including premature death, non-fatal heart attacks, and asthma.[4] NO has no known adverse health effects, but NO_2 can cause a range of harmful effects and is one of six criteria pollutants for which national ambient air quality standards are set.

This assessment focuses on the difference between current emissions from natural gas-fired building appliances and the emissions to be expected should the proposed rule amendments be fully implemented. The proposed amendments do not specify what technology to use, but one way to meet the zero-NO_x requirement is with electric appliances, which are currently available on the market. Because the adoption of electric equipment would eliminate all combustion-related emissions, this assessment evaluates reduced impacts with electric appliances that emit no NO_x—and so contribute no secondary $PM_{2.5}$—and also emit no primary $PM_{2.5}$.

Should zero-NO_x natural-gas fired appliances be developed in response to the proposed rules, the rules would achieve the described reductions in secondary $PM_{2.5}$ but may or may not achieve the reduction in impacts ascribed to reductions in primary $PM_{2.5}$, depending on how the appliances are designed and how many consumers choose to purchase natural-gas fired versus electric appliances.

The rest of this document provides an overview of the analysis methods (Sections 1.2 and 1.3) and emissions inputs (Section 2), modeled air quality (Section 3), $PM_{2.5}$ health impacts findings

[4] Natural gas combustion is also a significant contributor to ultrafine PM (UFP) emissions in the Bay Area (Yu et al., 2019). Current regulations do not specifically target UFP, though evidence of health effects associated with UFP exposures is growing (Tanrikulu et al., 2014).

(Section 4), modeled changes to peak air pollution levels (Section 5), and a summary of key findings (Section 6).

1.2 Analysis Methods

The analysis method applied for this assessment parallels that of prior studies on the effects of natural gas appliances on outdoor $PM_{2.5}$ and health for the U.S. (Dennison et al., 2021) and for California (Zhu et al., 2020). This Bay Area assessment, however, applied a full-chemistry model to estimate $PM_{2.5}$ concentration increments, residential exposures, and health impacts.

For years, staff have been applying the U.S. EPA's Community Multiscale Air Quality (CMAQ) modeling platform to estimate regional ambient levels of $PM_{2.5}$ in the Bay Area. The CMAQ model includes detailed atmospheric chemical reactions to estimate ambient levels of particle concentrations and other pollutants, such as ozone. Staff initially applied the CMAQ model to simulate $PM_{2.5}$ concentrations at a one kilometer (1-km) horizontal resolution over the entire Bay Area for 2016 (Tanrikulu et al., 2019). This work supported the Air District's activities under Assembly Bill 617 (AB 617), providing assessments of $PM_{2.5}$ concentrations in the West Oakland AB 617 community. Subsequently, annual simulations were conducted for three years (2016–2018) using updated emissions inventories and other model improvements. Results from these simulations are being used to support the Air District's ongoing AB 617 and rulemaking efforts.

For this assessment, staff employed the same modeling platform to complete a year-long CMAQ simulation for 2018 and estimate $PM_{2.5}$-related air quality and health impacts from commercial and residential space and water heating emissions. Meteorological inputs to the CMAQ modeling were prepared using the Weather Research and Forecasting (WRF) model. The application and performance of this model were documented by Tanrikulu et al., 2019.

This modeling analysis featured two annual simulations for 2018: (1) a baseline scenario that included the Air District's latest emissions estimates for all inventoried sources, and (2) a control scenario that removed commercial and residential natural gas combustion emissions associated with space heating and water heating equipment subject to the proposed rules. Differences between these two simulations provided an estimate of the air quality impacts of these *targeted building appliances*. Because the modeled impacts include post-2018 NOx emission reductions associated with the current version of Rule 9-6, modeling results were adjusted so that the control scenario is representative solely of emissions reductions resulting from full implementation of the proposed updates to Rules 9-4 and 9-6, under the scenario that no zero-NO_x natural-gas fired appliances are developed. Should zero-NO_x natural-gas fired appliances be developed in response to the proposed rules, the rules would achieve the described reductions in secondary $PM_{2.5}$ but may or may not achieve the reductions ascribed to reductions in primary $PM_{2.5}$.

CMAQ simulations were analyzed to produce two main results: (1) an estimate of chemically produced (secondary) $PM_{2.5}$ impact from the targeted building appliances and (2) an estimate of total $PM_{2.5}$ impact from the targeted building appliances. The secondary $PM_{2.5}$ consists of ammonium nitrate (originating from NO_x emissions), ammonium sulfate, and organic particles. The contributions of oxides of sulfur (SO_x) and reactive organic gases (ROG) to secondary $PM_{2.5}$ in this context are minimal because their emissions from the targeted building appliances are relatively small. Changes in secondary $PM_{2.5}$ level are therefore attributed to NO_x emissions from the targeted building appliances. The estimated total $PM_{2.5}$ impact includes impacts from both the secondary $PM_{2.5}$ and from primary $PM_{2.5}$ directly emitted from the building appliances.

Using the U.S. EPA's Environmental Benefits Mapping and Analysis Program – Community Edition (BenMAP-CE), staff also estimated the health impacts of simulated $PM_{2.5}$. BenMAP-CE received inputs from the CMAQ control and baseline simulation results to estimate the health impacts associated with the simulated changes in ambient pollutant levels. BenMAP-CE provides many health impact functions to estimate health impacts of $PM_{2.5}$ and ozone. This assessment focused on estimating the health impacts of $PM_{2.5}$. The contribution of NO_x emissions to ambient ozone levels in this context is relatively small, and the health effects of small changes in ozone levels are minimal. There are no known readily available methods or tools for estimating the health impacts of NO_2. BenMAP-CE was applied for changes in both secondary and total (secondary plus directly emitted) $PM_{2.5}$ levels. In addition to determining health impacts, BenMAP-CE was also used to determine conventional health impact valuations, expressed in 2020 U.S. dollars.

1.3 Study Setting

Two nested domains were used in the CMAQ simulations. The outer domain covered the Bay Area, San Joaquin Valley, and Sacramento Valley, as well as portions of the Pacific Ocean and the Sierra Nevada Mountains at 4-km horizontal resolution. The inner domain covered the Bay Area and surrounding regions at 1-km horizontal resolution, as shown in Figure 1.1. The outer domain provided initial conditions and hourly boundary conditions to the 1-km inner domain.

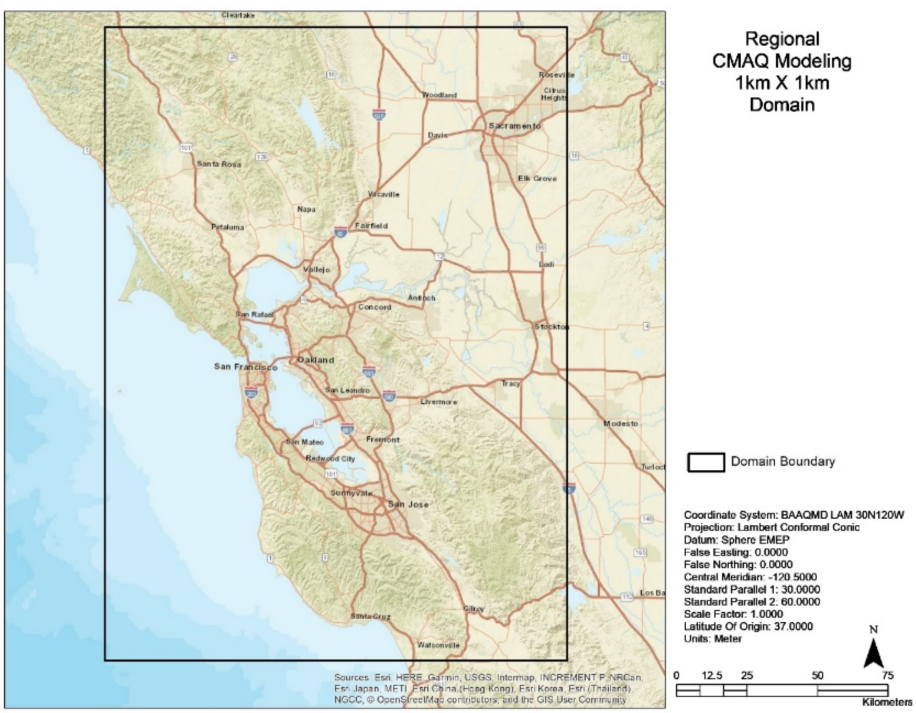

Figure 1.1: The regional 1-km modeling domain used for CMAQ simulations.

2. Emissions Inventory Preparation

Emissions inputs for the 2018 CMAQ simulations were prepared using the U.S. EPA's Sparse Matrix Operator Kernel Emissions (SMOKE) modeling system, which ingests annualized county- or facility-level emissions data and performs several processing steps to convert the data to the spatial, temporal, and chemical resolution required by CMAQ. The anthropogenic emissions data used in SMOKE cover four main source sectors (point, area, on-road mobile, and off-road mobile) and were assembled from a variety of data sources, as described below:

- **Point (permitted stationary sources)** – emissions data from the Air District's California Emission Inventory Development and Reporting System (CEIDARS), which is updated annually and submitted to the California Air Resources Board (CARB).
- **Area (non-permitted stationary sources)** – emissions data from CARB's California Emission Projection and Analysis Model (CEPAM). Specifically, county-level emissions for 2018 were downloaded from the CEPAM 2016 State Implementation Plan (SIP) Inventory, version 1.05.
- **On-road mobile sources** – emissions data by county and month were developed using outputs from CARB's Emission FACtor 2017 (EMFAC2017) model, which reports emissions by vehicle type and emissions process (e.g., idling, running exhaust, brake wear, tire wear).
- **Off-road mobile sources** – county-level emissions data from the CEPAM 2016 SIP Inventory, version 1.05 (same as area sources).

Commercial and residential natural gas combustion sources covered by Rules 9-4 and 9-6 are included in the area source portion of the inventory, and staff have recently prepared updated emission estimates for those sources. These estimates were based on natural gas consumption data from the California Energy Commission (CEC; California Energy Commission, 2019), which are reported by county and end use (e.g., industrial, commercial, and residential). For industrial and commercial sources, these data are reconciled against the Air District's point source inventory to avoid double-counting, and the fraction of natural gas consumption not covered by the point source inventory is assigned to the area source inventory. Emission factors that represent the mass of a pollutant released per million standard cubic feet (mscf) of natural gas burned were then applied to the activity data to develop county-level emissions estimates. These emission estimates were then disaggregated to subsectors (space heating, water heating, other) based on information from the Pacific Gas and Electricity (PG&E) Company (Dickerson, 2003). Additional details on emission estimation methods are provided in Appendix A.1.

Table 2.1 summarizes emissions from area-source commercial and residential natural gas-fired appliances in the Bay Area for the 2018 baseline scenario.[5] These area source emissions are categorized by CARB-assigned emission inventory codes (EIC). They do not include emissions from larger appliances that require registration or permits from the Air District.

[5] Natural gas combustion emissions represent the Air District's latest estimates for residential (2019) and commercial (2017) sources. These estimates were considered representative of 2018 conditions for modeling purposes.

Emissions values shown in bold font in Table 2.1 are covered by the proposed rule amendments. It is estimated that these amendments would reduce baseline NO_x emissions by 3,690 tons per year (ton/yr) and baseline PM2.5 emissions by 458 ton/yr. Note that baseline NO_x emission levels are also impacted by the existing form of Rule 9-6, which, when fully implemented, is anticipated to reduce NO_x emissions from commercial and residential water heating by 235 tpy and 341 tpy, respectively (see Table 2.1). As a result, NO_x emissions from targeted appliances will be reduced by 4,267 ton/yr relative to the 2018 baseline scenario, representing a reduction of about 6% of total annual NO_x emissions in the Bay Area (69,740 ton/yr) as shown in Figure 2.1. However, for the air quality and health impacts analyses described in this report, only the portion of the NO_x reduction attributable to the proposed rule amendments are evaluated. This reduction of 3,690 ton/yr represents a 5.3% decrease in total annual NO_x emissions in the Bay Area.

If electric appliances are adopted to meet the zero-NO_x requirement, $PM_{2.5}$ emissions from targeted appliances will be reduced by 458 ton/yr, which represents a reduction of about 4% of total $PM_{2.5}$ emissions in the Bay Area (12,530 ton/yr). Similarly, if electric appliances are adopted, other pollutants (in addition to NO_x and $PM_{2.5}$) shown in bold in Table 2.1 will be reduced as well. For pollutants other than NO_x, emissions reductions are entirely associated with the proposed rule amendments (under the assumption of electric appliances) rather than the existing forms of Rules 9-4 and 9-6. Appendix A.1 provides emissions estimates for more pollutants and from all sources of natural gas combustion in the Bay Area.

Table 2.1: Bay Area emissions (2018) from area-source building appliances. Emissions targeted by proposed amendments to Rules 9-4 and 9-6 are shown in bold font. Baseline emissions estimated to be addressed by existing Rule 9-6 are shown in italicized font.

Emission Inventory Codes	Description	Annual Emissions (ton/yr)				
		NO_x	$PM_{2.5}$	SO_x	ROG	CO
060-020-0110-0000	**Commercial – space heating**	**553**	**45**	**4**	**29**	**238**
060-030-0110-0000	**Commercial – water heating**	**240**	**55**	**4**	**35**	**291**
610-606-0110-0000	**Residential – space heating**	**2,410**	**197**	**16**	**125**	**1,037**
610-608-0110-0000	**Residential – water heating**	**487**	**161**	**13**	**103**	**847**
	Total – targeted emissions[a]	**3,690**	**458**	**36**	**292**	**2,413**
060-030-0110-0000	*Commercial – water heating (covered by existing Rule 9-6)*	*235*	--	--	--	--
610-608-0110-0000	*Residential – water heating (covered by existing Rule 9-6)*	*341*	--	--	--	--
060-995-0110-0000	Commercial – other	553	45	4	29	238
610-610-0110-0000	Residential – cooking	214	17	1	11	92
610-995-0110-0000	Residential – other	193	16	1	10	83
	Total – other area source appliances[a]	960	78	6	50	413

[a] Totals may not match the column summation due to rounding. Values rounded to nearest ton per year.

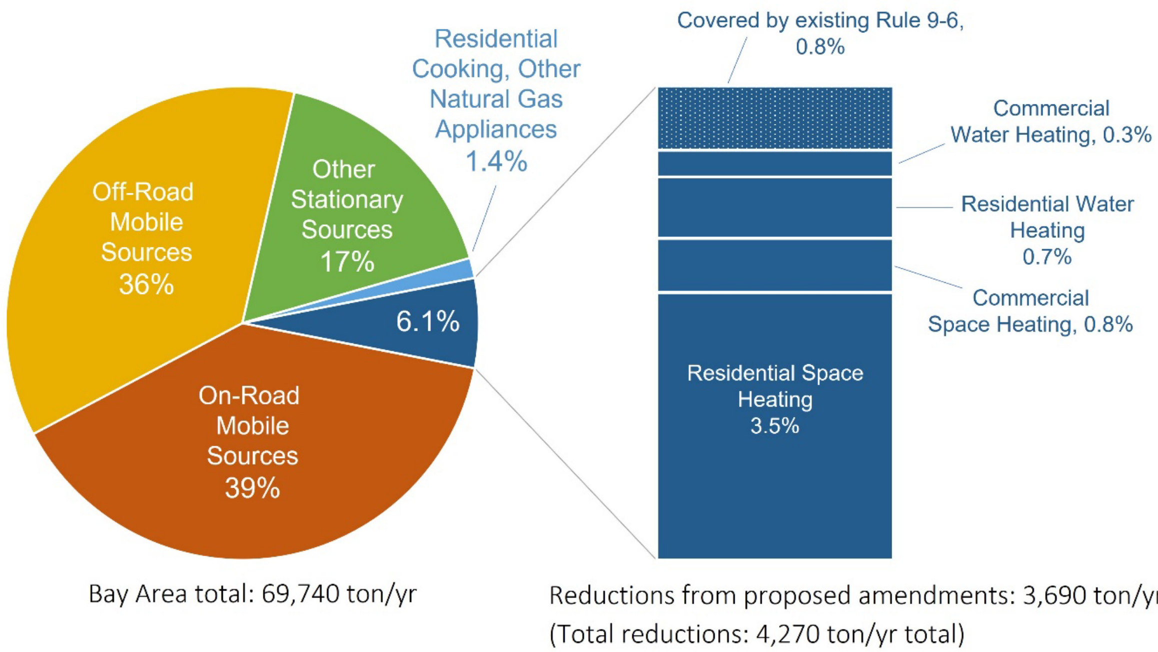

Figure 2.1. The pie chart (left) shows source contributions to total 2018 NO_x emissions in the Bay Area. The bar chart (right) shows NO_x emissions associated with targeted appliances.

Maps of NO_x emissions for the baseline scenario and the difference between the control and baseline scenarios are shown in Figure 2.2. The difference map (right panel) plots NO_x emissions from commercial and residential space and water heating appliances covered by proposed amendments to Rules 9-4 and 9-6.

The largest decrease in NO_x emissions (more than 10 tons per year per 1-km grid square, ton/yr-km^2) is in downtown areas of San Francisco and Oakland, surrounded by areas with a decrease between 6 ton/yr-km^2 and 10 ton/yr-km^2 (right panel). Areas with a decrease between 1 ton/yr-km^2 and 6 ton/yr-km^2 are seen over most of the rest of the San Francisco Peninsula and along a corridor from Richmond/San Pablo to San Leandro, following the Interstate 580 and 80 corridors in the north and the Interstate 880 corridor in the south. Areas with a similar decrease are also seen from the San Francisco Airport to San José, following the Interstate 101 corridor. Most other residential areas of the Bay Area show a decrease between 0.2 ton/yr-km^2 and 1 ton/yr-km^2. Grid squares with a decrease in NO_x emissions less than 0.2 ton/yr-km^2 are not shown.

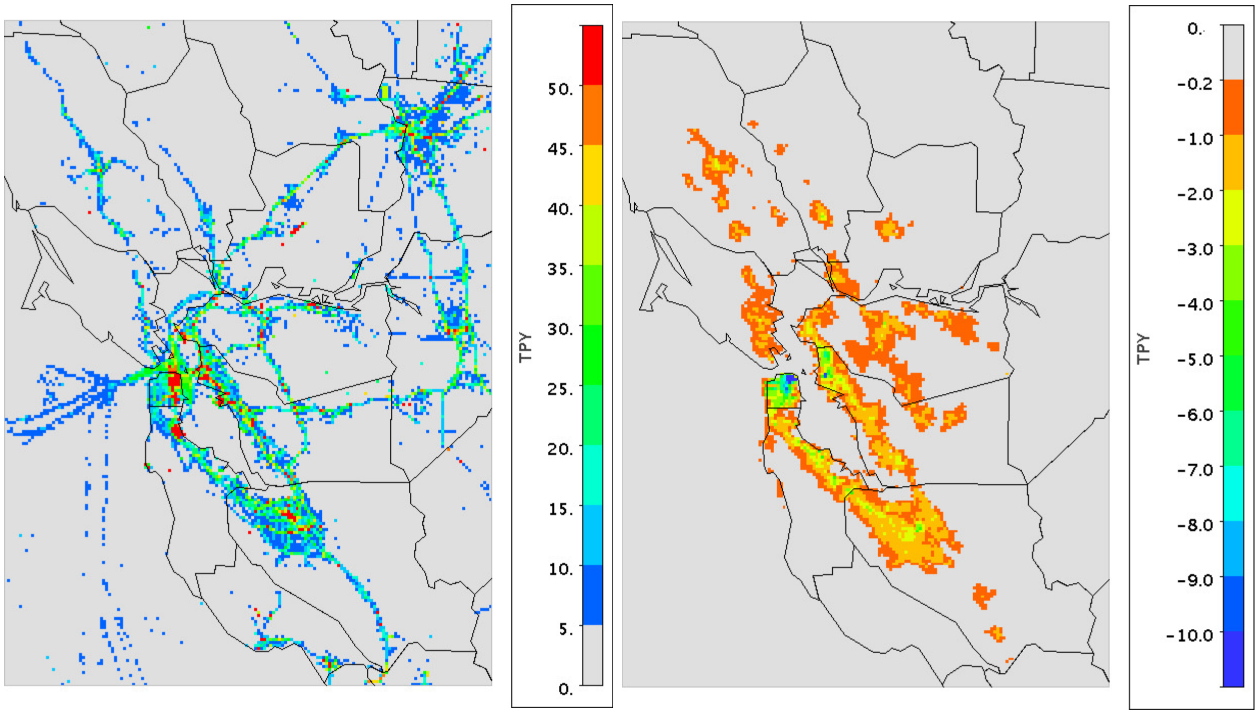

Figure 2.2: NO_x emissions for 2018 baseline scenario (left) and reductions in NO_x emissions (control – baseline) from targeted building appliances with full implementation of proposed rule amendments (right).

Maps of $PM_{2.5}$ emissions for the baseline scenario and the difference between the control and baseline scenarios are shown in Figure 2.3. The difference map (right panel) plots $PM_{2.5}$ emissions from commercial and residential space and water heating appliances covered by proposed amendments to Rules 9-4 and 9-6.

The largest decrease in $PM_{2.5}$ emissions (more than 1.0 ton/yr-km^2) is in downtown San Francisco, surrounded by areas with a decrease between 0.6 ton/yr-km^2 and 1.0 ton/yr-km^2 (right panel). A decrease between 0.6 ton/yr-km^2 and 1.0 ton/yr-km^2 is also in downtown Oakland. A decrease between 0.3 ton/yr-km^2 and 0.6 ton/yr-km^2 is in El Cerrito, downtown San José and at several small towns between the San Francisco Airport and San José, mostly in the vicinity of Interstate 101. A decrease between 0.1 ton/yr-km^2 and 0.3 ton/yr-km^2 is seen at residential areas along many freeways in other parts of the Bay Area, in a pattern similar to the one for NO_x emissions.

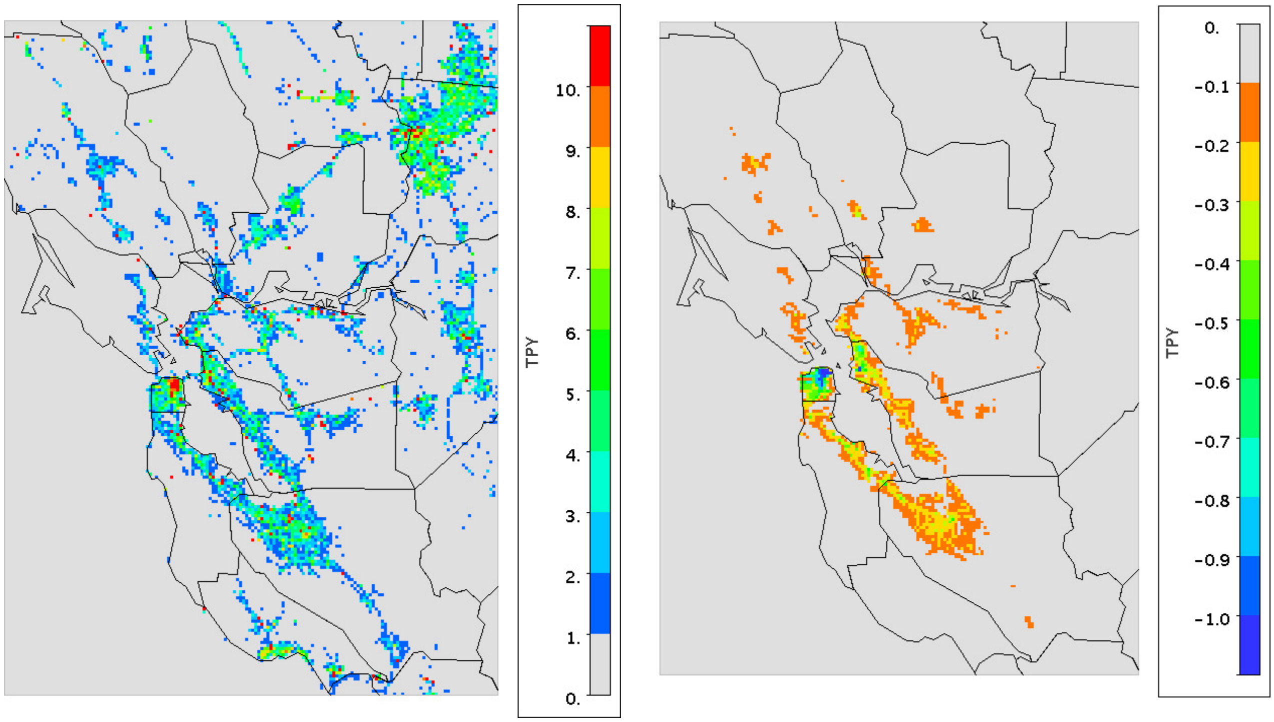

Figure 2.3: $PM_{2.5}$ emissions for 2018 baseline scenario (left) and reductions in $PM_{2.5}$ emissions (control – baseline) from targeted building appliances with full implementation of proposed rule amendments (right).

3. Simulations

As noted in Section 1, results from CMAQ modeling simulations conducted for the year 2018 were used to develop a control scenario that estimated the benefits of proposed amendments to Rules 9-4 and 9-6, which would reduce commercial and residential natural gas combustion emissions from space and water heating appliances.

The CMAQ model provides hourly average concentrations, which were used to estimate annual average concentrations. In the next subsections, we briefly discuss the formation of secondary $PM_{2.5}$ (Section 3.1), Bay Area annual average concentrations, and the contributions of commercial and residential natural gas combustion emissions to ambient NO_x and $PM_{2.5}$ levels (Sections 3.2 and 3.3, respectively).

3.1 Formation of Secondary $PM_{2.5}$

$PM_{2.5}$ consists of two major components: primary and secondary. Primary $PM_{2.5}$ is directly emitted to the atmosphere, while secondary $PM_{2.5}$ is a byproduct of chemical reactions of gaseous pollutants such as NO_x and ammonia (NH_3) in the atmosphere.

NO_x emitted from commercial and residential natural gas combustion, along with NO_x emitted from other sources, contributes to the formation of ammonium nitrate (NH_4NO_3). To form ammonium nitrate, oxides of nitrogen go through an atmospheric oxidation cycle several times, become aged NO_x, and then convert to nitric acid. Nitric acid is a relatively heavy and sticky gas, one that remains near the ground and can combine with ammonia, forming ammonium nitrate.

Conversion of NO_x to nitric acid is a time-consuming process and can take 2 hours to 10 hours in the Bay Area, largely depending on the rate of atmospheric oxidation processes. During this time, oxides of nitrogen diffuse and disperse in the atmosphere and travel away from the original emission sources.

In the Bay Area, key sources of ammonia emissions include agricultural operations, gas-powered automobiles, domestic sources (e.g., household products and pet waste), and some industrial facilities. Ammonia emitted from these sources also diffuses, disperses, and travels in the atmosphere, encountering nitric acid in some locations, depending upon meteorological conditions. As a result, the formation of secondary $PM_{2.5}$ depends on both time and location (i.e., higher levels can occur at locations away from the sources).

Ammonium nitrate can exist in particulate or gaseous form depending on the ambient temperature. For example, at 60 degrees Fahrenheit, ammonium nitrate can be roughly equally divided between particulate (secondary $PM_{2.5}$) and gaseous forms under most Bay Area conditions. As the temperature decreases, the percentage in particulate form increases, and the opposite happens as the temperature increases. Because of this property of ammonium nitrate, even though the atmospheric oxidation cycle is slow during winter months, production of ammonium nitrate in particulate form can be higher than in the summer.

SO_x and ROG emissions from the applicable commercial and residential space and water heating appliances also contribute to secondary $PM_{2.5}$, as ammonium sulfate and secondary organic aerosols, respectively. Their contribution is included in the model output but is much smaller than the contribution from NO_x emissions, and not provided separately by the model.

3.2 Simulated NO_x Concentrations

In this section, we present Bay Area maps of simulated annual average NO_x concentrations (baseline) and the difference between the control scenario and the baseline scenario, as shown in Figure 3.1. The baseline scenario (left panel) includes emissions from all inventoried sources. The control scenario (not shown) eliminates emissions from applicable commercial and residential space and water heating appliances. The difference between the two scenarios (right panel) shows NO_x contributions attributed to emissions from the targeted building appliances.

For the baseline scenario, the highest annual average NO_x concentrations (over 20 parts per billion, ppb) are evident in downtown San Francisco and downtown Oakland, along the Bay Bridge, and at the San Francisco, Oakland, and San José airports, as shown in Figure 3.1 (left panel). Concentrations between 14 ppb and 20 ppb are found mostly in the areas surrounding those with concentrations above 20 ppb. Concentrations between 8 ppb and 14 ppb cover an area from the Interstate 101 corridor in the west to the Interstate 880 corridor in the east and from the San Mateo–Hayward Bridge in the north to San José in the south. Similar NO_x concentrations are also evident along the Delta and portions of the Interstate 680 corridor.

In the difference plot, annual average NO_x increments over 1.0 ppb from commercial and residential space and water heating emissions are evident in San Francisco, Oakland, Berkeley, El Cerrito, Fremont, and San José, and along the corridor between San Mateo and to San José (Figure 3.1, right panel). Increments between 0.5 ppb and 1.0 ppb are mostly found in areas surrounding those with increments above 1.0 ppb. Increments between 0.3 ppb and 0.5 ppb are seen in the residential areas surrounding major freeways of the Bay Area, as well as over the towns of Napa and Brentwood.

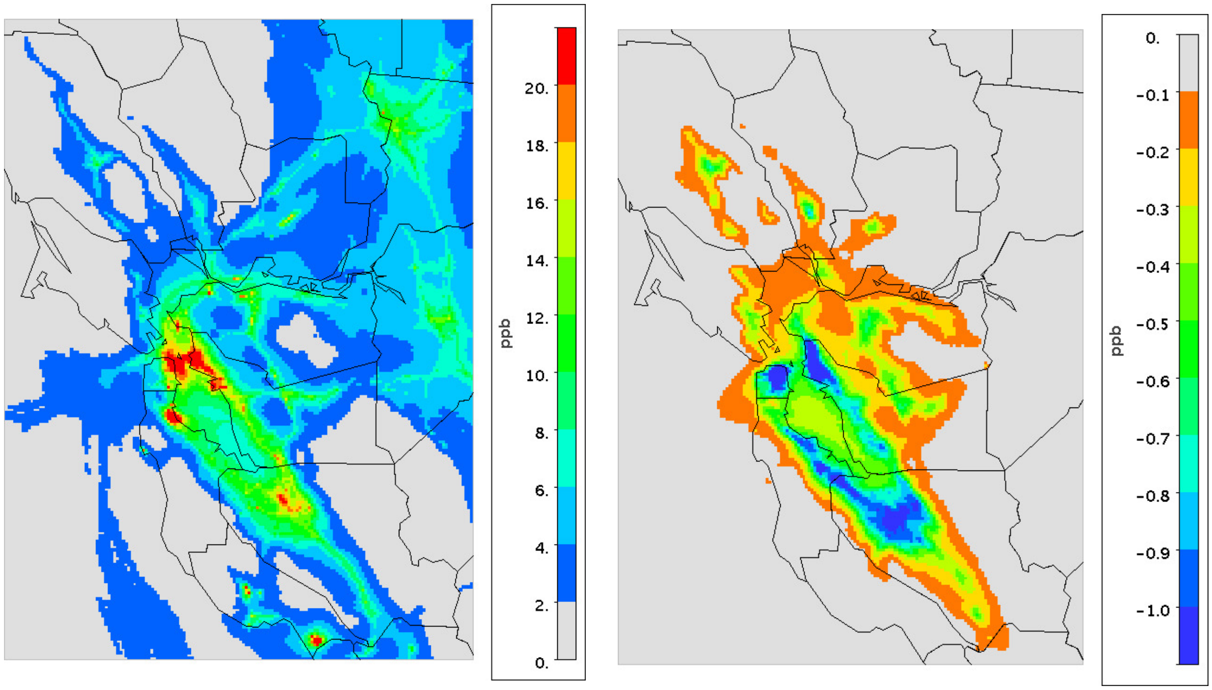

Figure 3.1: Simulated annual average NO_x concentrations for the baseline scenario (left) and the difference between the control and baseline scenarios (right). The difference between the two scenarios (control – base) shows the NO_x contribution from building appliances covered by proposed rule amendments.

3.3 Simulated $PM_{2.5}$ Concentrations

In this section, we present maps of annual average $PM_{2.5}$ concentrations for the baseline scenario (Figure 3.2) and the difference between the control and baseline scenarios (Figure 3.3). The differences shown between the control and baseline scenarios reflect $PM_{2.5}$ contributions attributed to commercial and residential space and water heating emissions covered by proposed amendments to Rules 9-4 and 9-6. Note that the existing form of Rule 9-6 would reduce 2018 NO_x emissions from commercial and residential water heating when fully implemented; however, in the treatment of modeling results, the control case reflects pollutant concentration differences associated with the proposed amendments only, as discussed in Appendix A.1. For $PM_{2.5}$, these differences are presented in two parts: (1) secondary $PM_{2.5}$ contributions from applicable commercial and residential space and water heating emissions, and (2) total $PM_{2.5}$ contributions from these emissions.

Baseline $PM_{2.5}$ Simulation

Figure 3.2 shows annual average $PM_{2.5}$ concentrations for the simulated baseline scenario. In the Bay Area, annual average $PM_{2.5}$ concentrations over 12 µg/m^3 are evident in San José and east of Martinez. The same concentration level is also found in relatively small areas in Oakland, Richmond, Mountain View, and Livermore. Concentrations between 9 µg/m^3 and 12 µg/m^3 are mostly seen in the areas surrounding those with concentrations above 12 µg/m^3 and along major freeways from Oakland to Gilroy and from San José to Mountain View.

Annual average simulated $PM_{2.5}$ concentrations were compared against observations and model performance was evaluated (Koo et al., 2022). Simulated annual average $PM_{2.5}$ concentrations were generally within ten percent of the annual average observations at most Bay Area air monitoring locations. The model tends to slightly overestimate $PM_{2.5}$ in the South Bay (e.g., San José) and underestimate in the North Bay (e.g., Napa).

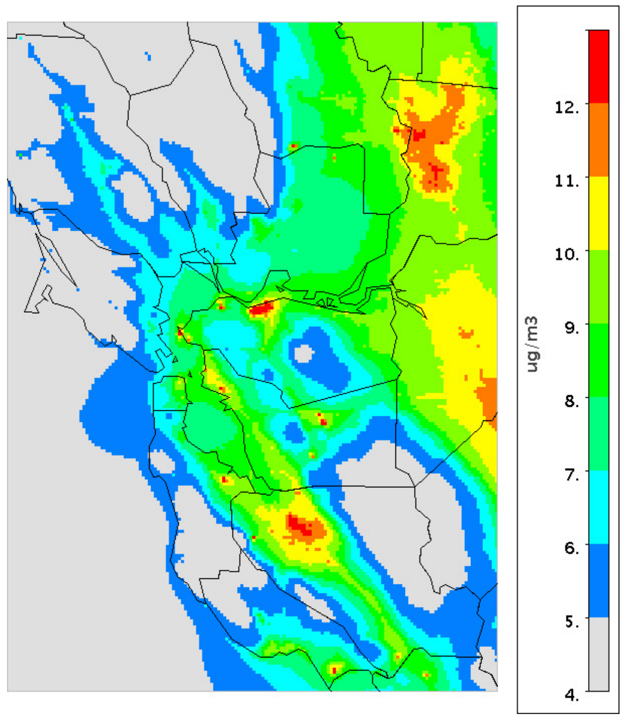

Figure 3.2: Simulated annual average $PM_{2.5}$ concentrations for the baseline scenario.

Difference in $PM_{2.5}$ Between Control and Baseline Scenarios

Figure 3.3 shows secondary and total annual average $PM_{2.5}$ contributions from applicable commercial and residential space and water heating appliances. Secondary $PM_{2.5}$ contributions are the highest (between 0.15 µg/m^3 and 0.18 µg/m^3) over San José, coinciding with areas where the highest NO_x reductions occur in this region (Figure 3.3, left panel). Contributions between 0.12 µg/m^3 and 0.15 µg/m^3 are seen over the entire metropolitan San José region, surrounding the highest reduction areas, and over relatively small areas in downtown San Francisco and downtown Oakland. Contributions between 0.09 µg/m^3 and 0.12 µg/m^3 extend from Oakland to Gilroy and from San Mateo to San José following the Interstate 880 and 101 corridors. Comparable contributions also extend from San Ramon to Livermore following the Interstate 680 and 580 corridors, respectively. Contributions between 0.04 µg/m^3 and 0.09 µg/m^3 extend over much of the residential areas of the Bay Area and beyond. This wide area of contributions is due to diffusion and dispersion of pollutants in the atmosphere while forming secondary $PM_{2.5}$.

Note that while the areal distribution of secondary $PM_{2.5}$ matches well with the areal distribution of ambient NO_x reductions (Figure 3.1, right panel) from commercial and residential space and water heating emissions in San José, it does not match in San Francisco and Oakland. This is because San Francisco and Oakland are relatively windy, especially during summer months, compared to San José and, as a result, experience less secondary $PM_{2.5}$.

Total annual average $PM_{2.5}$ contributions from applicable commercial and residential space and water heating appliances exceed 0.30 μg/m^3 in San Francisco and Oakland (Figure 3.3, right panel). Contributions between 0.21 μg/m^3 and 0.30 μg/m^3 are seen in areas surrounding those with contributions above 0.30 μg/m^3. Contributions between 0.09 μg/m^3 and 0.21 μg/m^3 cover residential areas along the major freeways of the Bay Area from Richmond/San Pablo to Gilroy, from San José to San Francisco, and from Concord to Livermore. The same total $PM_{2.5}$ contribution level is found over Napa, Santa Rosa, and Brentwood. In the rest of the Bay Area, contributions are less than 0.09 μg/m^3.

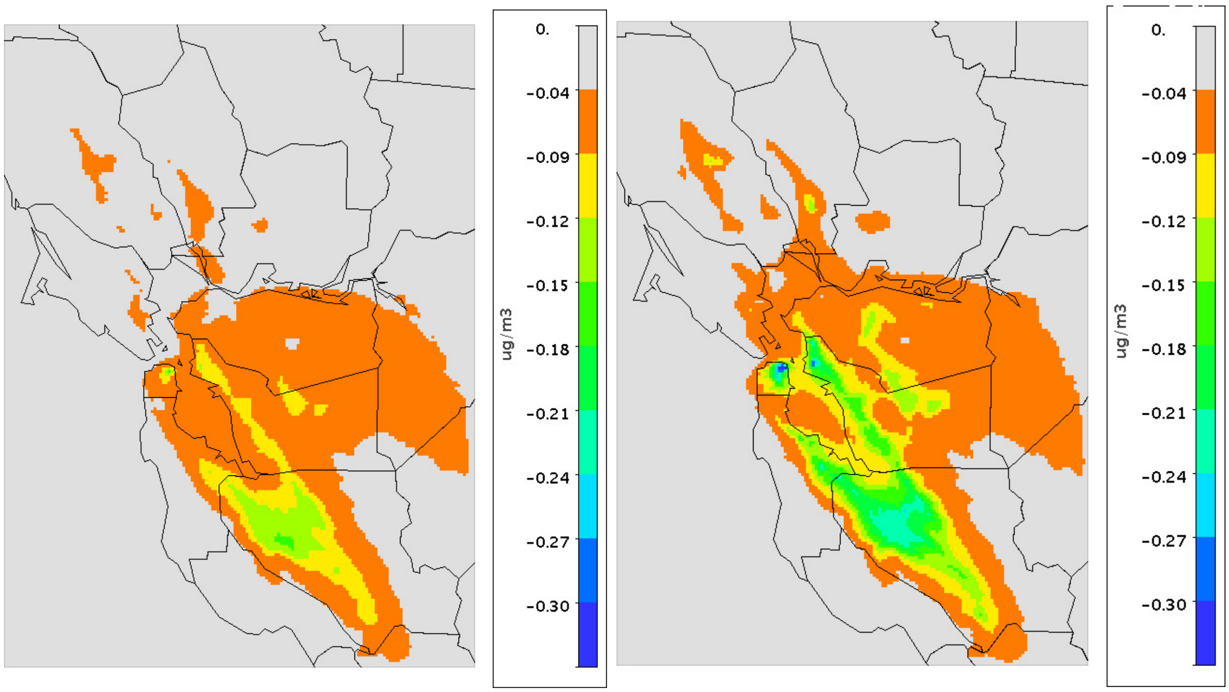

Figure 3.3: Simulated reductions in annual average ambient secondary (left) and total (right) $PM_{2.5}$ concentrations with controlled emissions from building appliances covered by proposed amendments to Rules 9-4 and 9-6. The maximum difference in total $PM_{2.5}$ is -0.42 μg/m^3 near downtown San Francisco.

4. Health Impacts of $PM_{2.5}$

BenMAP-CE version 1.5.8.11 (EPA, 2021) was used to evaluate the health impacts of $PM_{2.5}$ from emissions of targeted building appliances. BenMAP-CE was designed to estimate changes in human health due to changes in ambient air quality for specific populations and to estimate conventional valuations of these impacts (in 2020 U.S. dollars). The valuation process considers the direct and indirect costs of illnesses and the willingness to pay (WTP) to avoid premature death. Direct costs include actual medical costs and lost worker hours, while indirect costs reflect WTP to avoid pain and suffering. Additional information on the BenMAP-CE computer program is provided in Appendix A.2 and A.3.

Changes in air quality evaluated in BenMAP-CE were the differences in secondary and total $PM_{2.5}$ levels with and without emissions contributed by targeted building appliances at 1-km grid resolution over the entire Bay Area (left and right panels of Figure 3.3, respectively). In other words, health impacts were estimated for secondary and total $PM_{2.5}$ contributions due to emissions from these sources.

4.1 Preparation of Population Data

In addition to information about air pollutants contributions, BenMAP-CE requires population data to be grouped in a specific way to apply the available health impact functions. Using modules accompanying BenMAP-CE, we regrouped age and race/ethnicity classifications in the 2010 U.S. Census Bureau's population data for 2010 (the most recent comprehensive U.S. Census data available supported by BenMAP-CE) and estimated the grouped population in each 1-km grid square of the modeling domain. We then used BenMAP-CE to project the 2010 gridded population to 2020. Figure 4.1 shows a map of the gridded residential population for the Bay Area in 2020 used in this assessment. Even though BenMAP-CE estimates $PM_{2.5}$-related health impacts for each group, for the purposes of this evaluation, we focused on health impacts for the general population. Appendix A.2 provides additional information about the population groups used in BenMAP-CE.

Downtown San Francisco is the most densely populated area (over 10,000 people per 1-km grid square) of the Bay Area (Figure 4.1). Areas with populations between 8,000 and 10,000 people per 1-km grid square are located mostly in areas surrounding those with more than 10,000 people per 1-km grid square and at some grid cells in downtown Richmond, El Cerrito, Oakland, and San José. Areas with populations between 4,000 and 8,000 people per 1-km grid square are located in residential areas surrounding Interstates 80, 580, and 880, as well as a portion of Interstate 101. In other residential areas, there are fewer than 4,000 people per 1-km grid square.

Figure 4.2 shows residential population exposure to secondary $PM_{2.5}$ concentrations (left panel) and total $PM_{2.5}$ concentrations (right panel) attributed to emissions from applicable commercial and residential space and water heating appliances. Residential exposures were estimated by multiplying residential population in each grid cell by the simulated annual average $PM_{2.5}$ concentration of that cell. Mapping the estimated exposure brings those areas with relatively smaller population but elevated $PM_{2.5}$ levels to the forefront. Similarly, it also highlights those areas that are densely populated but have relatively lower $PM_{2.5}$ levels.

The effect of population weighting can be seen in Figure 4.2. The grid cell population itself is the highest in downtown San Francisco. However, the exposure to total $PM_{2.5}$ is the highest in San Francisco, Oakland, Berkeley, San José, and several areas surrounding the Interstate 880 and 101 corridors. Outside of San Francisco, these relatively less densely populated areas are also highlighted in the exposure maps.

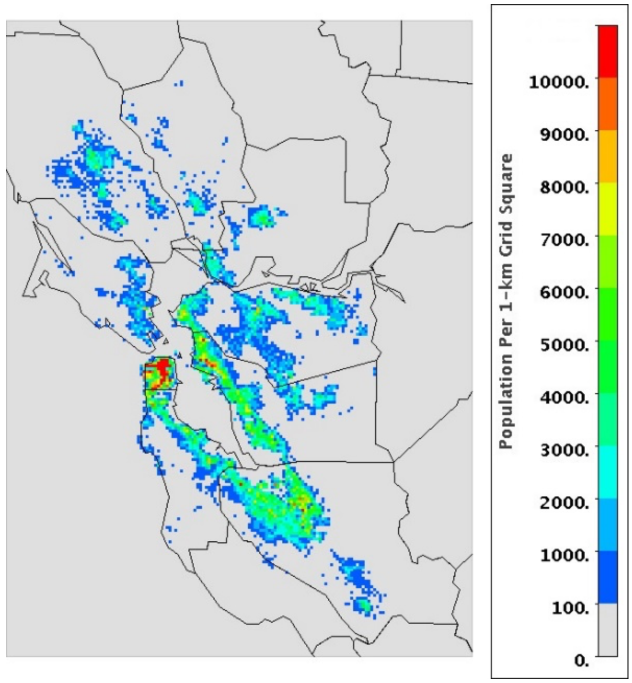

Figure 4.1: The 2020 population of CMAQ 1-km grids as projected by BenMAP-CE.

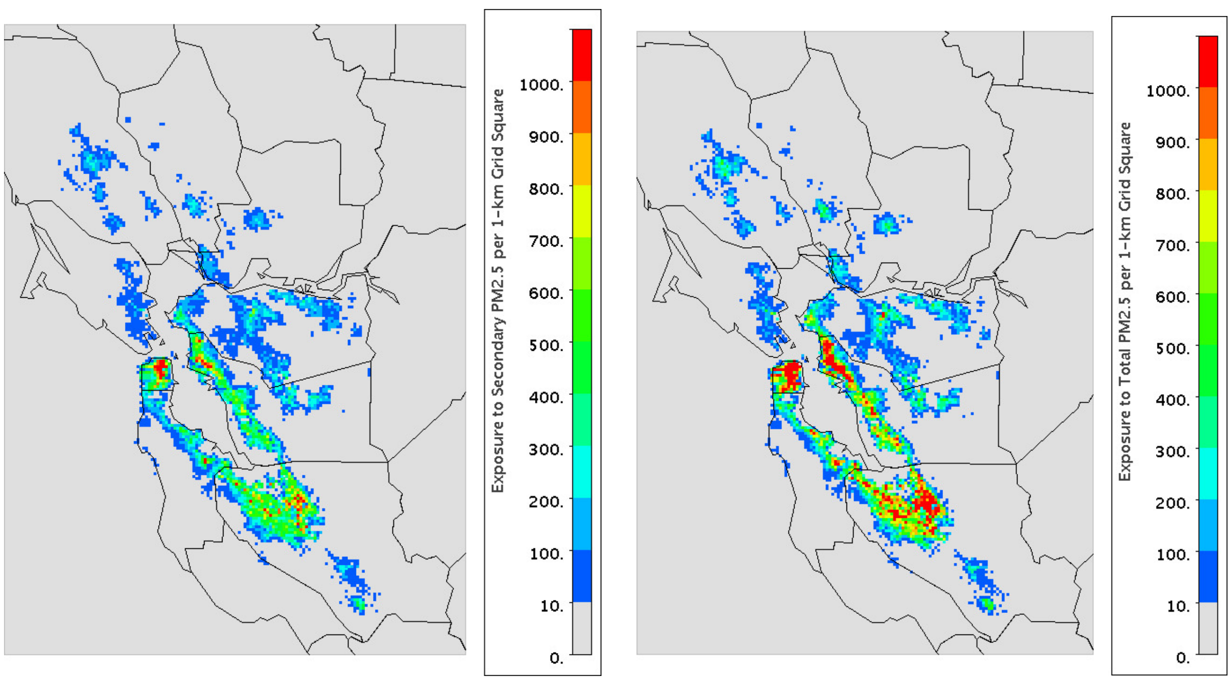

Figure 4.2: Simulated residential exposures to secondary $PM_{2.5}$ (left panel) and total $PM_{2.5}$ (right panel) from natural gas combustion emissions of building appliances covered by proposed amendments to Rules 9-4 and 9-6.

4.2 Application of BenMAP-CE

Staff downloaded the U.S. EPA's latest released version of BenMAP-CE (EPA, 2021) and added three health impact functions to the U.S. EPA-recommended set of health impacts functions available in BenMAP-CE to ensure that the premature mortality endpoint in the Bay Area was evaluated rigorously. Two of the added functions are based on California-wide and nationwide analyses of a 1980–2000 cohort (Jerrett et al., 2013). The third added function is a meta-analysis summarizing 53 single studies, 17 of which have been published since 2015 (Vodonos et al., 2018).

Staff ran BenMAP-CE and aggregated its 1-km grid results to the Air District's jurisdiction. The aggregated results (Tables 4.1 and 4.2) show that reductions in secondary and total $PM_{2.5}$ concentrations would reduce incidence of premature mortality within the Air District's jurisdiction by 23 to 52 cases and by 37 to 85 cases per year, respectively. The ranges reflect different epidemiological studies. The valuations[6] assigned to these are 230 to 530 million U.S. dollars and from 380 to 870 million U.S. dollars, respectively. Among the set of health impacts evaluated, avoided mortality accounts for about 95% of the total valuation of reduced total $PM_{2.5}$ levels.

The other health impacts in the EPA's recommended BenMAP-CE configuration include selected chronic/severe illnesses, hospital admissions/emergency room visits due to respiratory and cardiovascular diseases, selected minor health effects, and asthma-related effects. The health impacts evaluated showed decreased annual incidence as a result of reductions in $PM_{2.5}$ levels with elimination of emissions from applicable commercial and residential space and water heating appliances. For example, for non-fatal acute myocardial infarction (heart attack), 2.6 to 24 non-fatal heart attacks would have been prevented 2020 with the modeled reductions in secondary $PM_{2.5}$ and 4.2 to 39 non-fatal heart attacks would be prevented with the modeled reductions in total $PM_{2.5}$. (Again, the ranges reflect different epidemiological studies.) The associated valuations are estimated to be 0.23 to 2.1 million U.S. dollars and 0.38 to 3.5 million U.S. dollars, respectively. Another example is the benefit of 4,100 and 6,700 fewer lost days of work, valued at 1.1 million U.S. dollars and 1.8 million U.S. dollars, respectively.

[6] Valuations are not identical to cost savings. Some valuations are based on cost savings, but the most highly valued component (mortality) is based on an estimate of willingness to pay (WTP).

Table 4.1: Estimated health impacts avoided with decreased $PM_{2.5}$ from elimination of emissions from applicable commercial and residential space and water heating appliances in the Bay Area.

Health Impact[a]	Avoided Incidence, Per Year	
	Secondary $PM_{2.5}$	Total $PM_{2.5}$
Premature mortality		
All causes[b]	23–52	37–85
Chronic/severe illness		
Non-fatal acute myocardial infarction (heart attack)	2.6–24	4.2–39
Hospital admission, neurological[c]	7.7	13
Incidence, out of hospital cardiac arrest	0.45	0.73
Incidence, stroke	1.5	2.4
Incidence, lung cancer	1.9	3.1
Hospital admissions[d]		
Respiratory[e]	2.4	3.9
Cardiovascular[f]	3.0	4.9
ER visits		
Respiratory[g]	13	20
Cardiovascular[h]	6.2	10
Other effects		
Restricted activity days	24,000	39,000
Work loss days	4,100	6,700
Hay fever/allergic rhinitis	440	710
Asthma-related effects		
Asthma symptoms/albuterol use	9,200	15,000
Onset of asthma	71	110

[a] Each health impact is associated with one or more unique International Classification of Diseases-9-Clinical Modification (ICD-9-CM) code(s) (Medicode, 1996).

[b] Includes all ICD-9 codes.

[c] First hospital admission (cause-specific, to indicate onset of the chronic disease) for dementia, Alzheimer's disease, or Parkinson's disease (ICD-9 codes 290, 331.0, or 332, respectively), and other neurological morbidities.

[d] Hospital admissions due to acute exposure to air pollution are assumed to pass through the emergency room; however, the calculated value of hospital admissions does not account for the cost incurred in the emergency room visit. This strategy avoids double-counting.

[e] Includes all respiratory diseases (ICD-9 codes 460–519).

[f] Includes cardio-, cerebro-, and peripheral vascular diseases (ICD-9 codes 410, omitting 410.x2; 410–414; 426–427; 428; 429; 430–438; 440–448).

[g] Includes respiratory diseases (ICD-9 codes 480–486, 491, 492, 496, 460–465, 466, 477, 493, 786.07).

[h] Includes all cardiac outcomes (ICD-9 codes 390–549).

Table 4.2: Valuations of avoided health impacts with decreased $PM_{2.5}$ from elimination of emissions from applicable commercial and residential space and water heating appliances in the Bay Area.

Health Impact[a]	Total Valuation in 2020 U.S. Dollars, Million Dollars Per Year	
	Secondary $PM_{2.5}$	Total $PM_{2.5}$
Premature mortality		
All causes[b]	230–530	380–870
Chronic/severe illness		
Non-fatal acute myocardial infarction (heart attack)	0.23–2.1	0.38–3.5
Hospital admission, neurological[c]	0.11	0.19
Incidence, out of hospital cardiac arrest	0.019	0.03
Incidence, stroke	0.059	0.096
Incidence, lung cancer	0.056	0.091
Hospital admissions[d]		
Respiratory[e]	0.028	0.045
Cardiovascular[f]	0.055	0.090
ER visits		
Respiratory[g]	0.013	0.021
Cardiovascular[h]	0.0084	0.014
Other effects		
Restricted activity days	1.9	3.2
Work loss days	1.1	1.8
Hay fever/allergic rhinitis	0.31	0.52
Asthma-related effects		
Asthma symptoms/albuterol use	0.0037	0.0059
Onset of asthma	3.6	5.8
Sum		
All health impacts included	240–540	400–890

[a] Each health impact is associated with one or more unique International Classification of Diseases-9-Clinical Modification (ICD-9-CM) code(s) (Medicode, 1996).

[b] Includes all ICD-9 codes.

[c] First hospital admission (cause-specific, to indicate onset of the chronic disease) for dementia, Alzheimer's disease, or Parkinson's disease (ICD-9 codes 290, 331.0, or 332, respectively), and other neurological morbidities.

[d] Hospital admissions due to acute exposure to air pollution are assumed to pass through the emergency room; however, the calculated value of hospital admissions does not account for the cost incurred in the emergency room visit. This strategy avoids double-counting.

[e] Includes all respiratory diseases (ICD-9 codes 460–519).

[f] Includes cardio-, cerebro-, and peripheral vascular diseases (ICD-9 codes 410, omitting 410.x2; 410–414; 426–427; 428; 429; 430–438; 440–448).

[g] Includes respiratory diseases (ICD-9 codes 480–486, 491, 492, 496, 460–465, 466, 477, 493, 786.07).

[h] Includes all cardiac outcomes (ICD-9 codes 390–549).

5. Simulated Changes in 24-hour $PM_{2.5}$ and 8-hour Ozone Levels

In addition to evaluating air quality and health impacts of annual average $PM_{2.5}$, in this assessment staff also examined modeled changes to levels of 24-hour-average $PM_{2.5}$ and 8-hour-average ozone at air quality monitoring stations. These quantities are relevant to determining compliance with state and federal ambient air quality standards.[7] While this assessment did not include a formal modeling attainment demonstration for these pollutants (for example as described by EPA guidance, EPA 2018), it did examine how peak levels are influenced by reduction in emissions from commercial and residential space and water heating emissions, providing insights into how proposed amendments to Rules 9-4 and 9-6 might influence achieving and maintaining state and federal ambient air quality standards should the proposed rules be fully implemented. [8]

To assess the effects that the elimination of NO_x and $PM_{2.5}$ emissions from modeled appliances might have on the likelihoods of short-term $PM_{2.5}$ and/or ozone exceedances, we analyzed modeled differences on high-$PM_{2.5}$ and high-ozone days. Specifically, we extracted modeled predictions from monitored locations on dates when observations indicated a 24-hour average of at least 30 $\mu g/m^3$ for $PM_{2.5}$ or an 8-hour average of at least 65 ppb for ozone at that location on that date (Tables 5.1 and 5.2). For 24-hour $PM_{2.5}$, using this subset of the data, the mean difference between this scenario and the baseline scenario was -0.68 $\mu g/m^3$, and the control scenario was lower than the baseline scenario in all cases (Figure 5.1). The level of 8-hour ozone was sometimes higher in the control scenario, but there was an overall decrease of -0.021 ppb on average (Figure 5.2).

[7] For $PM_{2.5}$, the metric is determined using the 98th percentile of measurements, averaged over 3 years. For ozone, the metric is determined using the annual, fourth-highest daily maximum 8-hour measured concentration, also averaged over 3 years.

[8] For context, the current federal standard for 24-hour $PM_{2.5}$ is 35 μg/m3 and the federal standard for 8-hour ozone is 70 ppb. For $PM_{2.5}$, the metric is determined using the 98th percentile of measurements, averaged over 3 years. For ozone, the metric is determined using the annual, fourth-highest daily maximum 8-hour measured concentration, also averaged over 3 years.

Table 5.1: Pairwise comparison of modeled baseline versus control when and where observed 24-hour $PM_{2.5}$ concentrations were at least 30 μg/m³. The mean difference is -0.68 μg/m³.

			Modeled		
Date	**Site**	**Observed**	**Baseline**	**Control**	**Difference**
2018-01-04	Concord	53.3	38.92	38.55	-0.376
2018-01-03	Concord	52.0	41.10	40.82	-0.280
2018-01-03	Vallejo	48.0	15.66	15.58	-0.081
2018-01-01	SJ Knox	45.0	33.93	32.63	-1.297
2018-01-03	San Rafael	44.3	22.89	22.69	-0.207
2018-01-03	San Francisco	39.5	24.74	23.96	-0.785
2018-01-03	Livermore	39.0	36.67	36.17	-0.497
2018-01-03	Laney College	38.2	33.18	32.53	-0.658
2018-01-01	SJ Jackson	38.0	32.47	31.44	-1.026
2018-01-03	San Pablo	36.6	19.06	18.84	-0.223
2018-01-02	SJ Knox	36.2	59.99	57.23	-2.754
2018-01-03	Oakland West	35.6	30.75	29.97	-0.782
2018-01-04	Vallejo	34.2	18.49	18.35	-0.142
2018-01-02	SJ Jackson	33.2	63.85	61.46	-2.385
2018-01-02	Oakland West	33.0	26.14	25.70	-0.439
2018-01-02	Concord	32.4	27.86	27.62	-0.237
2018-01-04	San Pablo	32.2	21.93	21.41	-0.521
2018-01-02	Laney College	31.9	31.09	30.57	-0.522
2018-01-03	Berkeley AP	31.9	25.04	24.57	-0.474
2018-01-14	San Rafael	31.0	20.32	20.00	-0.319
2018-01-15	San Rafael	31.0	7.92	7.87	-0.056
2018-01-03	Oakland	30.4	20.59	20.15	-0.443
2018-12-09	San Francisco	30.3	34.90	33.57	-1.334
2018-01-03	Napa	30.2	11.54	11.18	-0.362

Table 5.2: Pairwise comparison of modeled baseline versus control when and where observed 8-hour ozone concentrations were at least 65 ppb. The mean difference is -0.021 ppb.

			Modeled		
Date	Site	Observed	Baseline	Control	Difference
2018-08-09	San Martin	80	78.70	78.64	-0.062
2018-08-09	Livermore	78	74.12	74.21	+0.093
2018-08-09	Bethel Island	78	59.94	59.75	-0.197
2018-08-18	Livermore	76	58.94	58.76	-0.180
2018-08-09	San Ramon	76	71.45	71.63	+0.180
2018-08-18	San Ramon	72	53.13	53.12	-0.005
2018-08-03	Livermore	71	63.75	63.53	-0.221
2018-06-22	Livermore	69	67.66	67.37	-0.292
2018-08-08	Livermore	69	57.68	57.57	-0.104
2018-09-21	Bethel Island	68	51.84	51.93	+0.088
2018-10-19	Napa	68	46.90	46.82	-0.082
2018-10-20	Bethel Island	67	62.23	62.26	+0.025
2018-08-09	Los Gatos	67	63.35	64.32	+0.975
2018-08-03	San Martin	67	62.18	62.19	+0.012
2018-09-20	Napa	66	44.62	44.78	+0.162
2018-06-02	San Martin	66	65.77	64.65	-1.113
2018-10-19	San Martin	66	52.03	52.43	+0.402
2018-09-20	Fairfield	66	53.93	53.87	-0.058

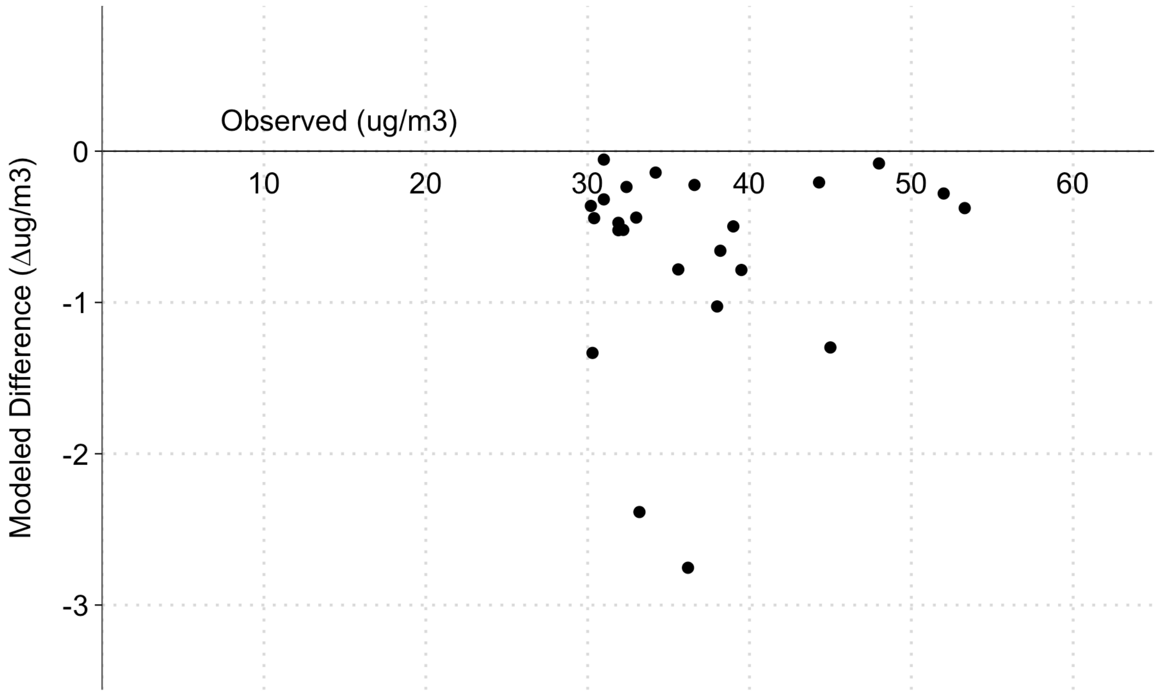

Figure 5.1: Differences between modeled baseline vs. control when and where observed 24-hr $PM_{2.5}$ concentrations were at least 30 μg/m^3. The mean difference is -0.68 μg/m^3.

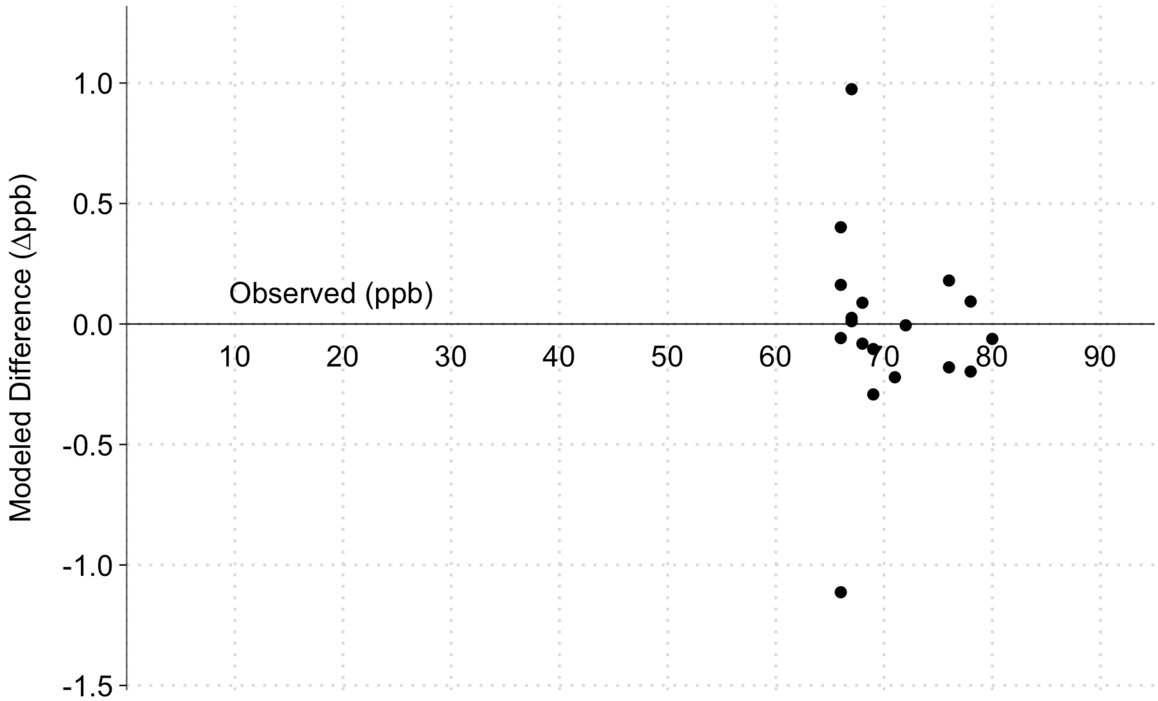

Figure 5.2: Differences between modeled baseline vs. control when and where observed 8-hr ozone concentrations were at least 65 ppb. The mean difference is -0.021 ppb.

When assessing modeled differences for all modeled dates, rather than just "high concentration" dates, the mean difference for $PM_{2.5}$ at monitored locations was -0.30 μg/m^3, with a pairwise bootstrapped 95% confidence interval of (-0.32, -0.29) μg/m^3, based on 16 dates modeled (n = 62) at 17 sites (p = 17).

6. Summary and Key Findings

Staff evaluated ambient air quality and health impacts from commercial and residential space and water heating emissions as supplemental information to support proposed amendments to Air District Rules 9-4 and 9-6, which limit NO_x emissions from natural gas-fired furnaces, water heaters, and boilers.

Using the CMAQ model, staff estimated ambient NO_x levels from the appliances covered by the proposed rule amendments, as well as the levels of particles and ozone caused by NO_x. Using the BenMAP-CE model, staff also estimated the health impacts of simulated fine particulate matter and the associated valuations of those impacts in U.S. dollars.

This modeling-based assessment featured results from CMAQ simulations conducted for the year 2018, which were used to develop a control scenario that estimated the benefits of proposed rule amendments that would reduce emissions from commercial and residential natural gas combustion emissions associated with space heating and water heating.

The methodological approach developed for this project was carefully evaluated. Options were weighed and discussed among the modeling team, and the strategy that was anticipated to provide the best modeling results was adopted. In addition, consideration was given to providing results that would support the needs of anticipated end users.

The key findings of this assessment are listed below:

- NO_x emissions from the targeted building appliances caused production of **secondary $PM_{2.5}$** across most residential areas of the Bay Area with an annual average contribution between 0.04 µg/m^3 and 0.18 µg/m^3, resulting in an estimated **23 to 52 deaths per year** (Table 4.1).
- Emissions from the targeted building appliances produce increments of **total $PM_{2.5}$** across most residential areas of the Bay Area, with an annual average contribution between 0.10 µg/m^3 and 0.42 µg/m^3, resulting in an estimated **37 to 85 premature deaths per year** (Table 4.1).
- The valuations of the health impacts from **secondary $PM_{2.5}$** were estimated to be between **240 to 540 million U.S. dollars annually** (Table 4.2).
- The valuations of the health impacts from **total $PM_{2.5}$** were estimated to be between **400 to 890 million U.S. dollars** annually (Table 4.2).
- For the modeled control scenario at monitored locations on dates when observations indicated 24-hour $PM_{2.5}$ was at least 30 µg/m^3, the mean modeled decrease in **24-hour $PM_{2.5}$ was -0.68 µg/m^3** (Figure 5.1).
- For the modeled control scenario at monitored locations on dates when observations indicated 8-hour ozone was at least 65 ppb, the mean modeled decrease in **8-hour ozone was -0.021 µg/m^3** with overall results indicating no significant change in ozone. (Figure 5.2).

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Appendix A

A.1 Bay Area Natural Gas Emissions

Modeled emissions estimates for natural gas combustion were based on residential and non-residential natural gas consumption data for the Bay Area obtained from the California Energy Commission (CEC, 2019). The consumption data were provided by county in units of therms and converted to units of cubic feet using natural gas heat content values. For residential usage, natural gas consumption data for 2019 were further divided into four emissions inventory categories: space heating, water heating, cooking, and other (e.g., appliances such as pool water heating, spa and hot tub heating, clothes dryers, and barbeque grills). This categorization was based on information from CEC, 2019 and the Pacific Gas and Electric Company (PG&E) by Dickerson, 2003.

For commercial and industrial sources, CEC end-use consumption data by sector was used to apportion non-residential natural gas usage (excluding power generation consumption) for Bay Area counties into commercial and industrial usage. The resulting estimates represent natural gas consumption for permitted (or “point”) sources and non-permitted (or “area”) sources such as small-scale shops and businesses. To avoid double-counting, facilities in the Air District’s point source inventory that use natural gas were assigned to commercial or industrial categories using each facility’s Standard Industrial Classification (SIC) code. In addition, commercial and industrial natural gas throughputs reported by the point sources were subtracted from the total throughput for those sectors to generate area source consumption values. For commercial area sources, natural gas consumption was further split by application (space heating, water heating, and other) using information from PG&E (Dickerson, 2003).

Once natural gas consumption data were categorized and reconciled, emission factors that represent the mass (lb) of a pollutant released per million standard cubic feet (mscf) of natural gas burned were applied to develop county-level emissions estimates. In general, emission factors were taken from EPA’s AP-42 Compilation of Emission Factors.[9] For NO_x, a base emission factor of 93 lb/mscf, or 40 nanograms per joule (ng/joule) was used, which is the pre-2009 NO_x emission limit established by the current version of Rule 9-6 and is also consistent with AP-42.

Beginning in 2009, the current Rule 9-6 requires residential water heaters to meet a 10 ng/joule limit (or 23 lb/mscf), which is achieved over time as the appliance fleet turns over. Assuming a turnover of 7.7% per year resulting from a 13-year water heater lifespan (Elwell, 2022), the effective NO_x emission factor in 2018 was calculated to be 39 lb/mscf, as shown in Table A1. Similarly, the current version of Rule 9-6 requires commercial water heaters to meet a 14 ng/joule (33 lb/mscf) NO_x emission limit starting in 2013. Applying the same turnover rate yields an effective NO_x emission factor of 65 lb/mscf in 2018 (see Table A1). Given the assumed fleet turnover, the current version of Rule 9-6 for water heaters was estimated to reach full implementation in 2021 for residential heaters and in 2025 for commercial heaters. For space heaters, Bay Area appliances were estimated to meet the 40 ng/joule NO_x emission

[9] https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-fifth-edition-volume-i-chapter-1-external-0

requirement of the current Rule 9-4 in 2018. This estimation was based on an assumed 18-year lifespan for space heating equipment (Elwell, 2022).

Table A1: Natural gas combustion emission factors (lb/mscf).

EIC	Description	Emission Factors (lb/mscf)						
		CO	NO_x	SO_x	TOG	ROG	PM_{10}	$PM_{2.5}$
060-030-0110-0000	Commercial – water heating	40	65[a]	0.6	11	4.8	7.6	7.6
610-608-0110-0000	Residential – water heating	40	39[a]	0.6	11	4.8	7.6	7.6
--	All other appliances	40	93	0.6	11	4.8	7.6	7.6

[a] For water heaters, NO_x emission factors reflect the impact of the current version of Rule 9-6 in 2018.

Table A2 shows natural gas emissions in the Bay Area for commercial and residential area sources, as well as permitted sources. As noted above, the permitted source sector includes emissions from commercial and industrial operations that are tracked as individual facilities ("points"). NO_x emissions from commercial and residential natural gas combustion are about 76% of NO_x emissions from total natural gas combustion for these three sectors combined.

Table A3 shows NO_x emissions for appliances targeted by Rules 9-4 and 9-6. As discussed above, Rule 9-6 had not been fully implemented by 2018, so a portion of the 2018 baseline NO_x emissions will be reduced when full implementation takes place. As shown in Table A3, this portion of the baseline NO_x emissions is 576 tons, or 13.5% of the 2018 total of 4,267 tons emitted by the targeted appliances. The remaining 86.5% (3,690 tons) will be addressed by the proposed rule amendments. For the CMAQ modeling analysis, the control case removed the entire 4,267 tons of NO_x associated with the targeted appliances to simulate the full impact of emissions from this source sector. To estimate benefits attributable to proposed amendments only, modeled reductions in concentrations of selected species were multiplied by a scaling factor of 0.865.

Specifically, this scaling factor was applied to modeled reductions in NO_x and secondary $PM_{2.5}$ concentrations (the latter adjustment was necessary because NO_x participates in secondary $PM_{2.5}$ formation). Adjusted secondary $PM_{2.5}$ reductions were then added to total reductions in primary $PM_{2.5}$ concentrations[10] to calculate a total $PM_{2.5}$ benefit from the proposed amendments. All BenMAP, exposure, and NAAQS analyses were based on the estimated pollutant reductions associated with proposed rule amendments only, with any reductions associated with current rule versions being excluded.

[10] Reductions in emissions of primary $PM_{2.5}$ and other pollutants besides NO_x are solely due to proposed rule amendments, so no adjustment was needed.

Table A2: Bay Area 2018[a] natural gas combustion emissions (ton/yr).

EIC	Description	2018 Annual Emissions (ton/yr)						
		CO	NO_x	SO_x	TOG	ROG	PM_{10}	$PM_{2.5}$
060-020-0110-0000	Commercial – space heating	237.8	552.8	3.6	65.4	28.8	45.2	45.2
060-030-0110-0000	Commercial – water heating	291.5	475.7	4.4	80.2	35.3	55.4	55.4
060-995-0110-0000	Commercial – other	237.8	552.8	3.6	65.4	28.8	45.2	45.2
--	*Commercial subtotal*	*767.0*	*1581.3*	*11.5*	*210.9*	*92.8*	*145.7*	*145.7*
610-606-0110-0000	Residential – space heating	1,036.6	2,410.0	15.5	285.1	125.4	196.9	196.9
610-608-0110-0000	Residential – water heating	847.3	828.3	12.7	233.0	102.5	161.0	161.0
610-610-0110-0000	Residential – cooking	92.0	213.9	1.4	25.3	11.1	17.5	17.5
610-995-0110-0000	Residential – other	83.2	193.5	1.2	22.9	10.1	15.8	15.8
--	*Residential subtotal*	*2,059.1*	*3,645.7*	*30.9*	*566.3*	*249.2*	*391.2*	*391.2*
Various	Permitted - all source types	1,055.3	1,662.6	16.5	604.1	265.8	122.1	122.1
--	**Grand Total**	**3,881.4**	**6,889.5**	**58.9**	**1,381.3**	**607.8**	**659.1**	**659.1**

[a] Natural gas combustion emissions represent the Air District's latest estimates for residential (2019), commercial (2018), and permitted (2018) sources. These estimates were considered representative of 2018 conditions for modeling purposes.

Table A3: NO_x emissions from appliances targeted by proposed rule amendments (ton/yr).

Description	NO_x Emissions (ton/yr)		
	2018 Baseline	Reduction from existing Rule 9-6	Reduction from proposed amendments
Commercial – space heating	552.8	--	552.8
Commercial – water heating	475.7	235.2	240.5
Residential – space heating	2,410.0	--	2410.0
Residential – water heating	828.3	341.1	487.2
Total	**4,266.7**	**576.3**	**3,690.5**
Percentage	*100.0%*	*13.5%*	*86.5%*

A.2 BenMAP-CE Computer Program

Applications of BenMAP-CE computer program require the development of two sets of inputs: ambient $PM_{2.5}$ concentrations and population data. The calculations implemented by BenMAP-CE include population exposure, using health impact functions to estimate the incremental change in selected human health outcomes.

Epidemiological data are used to develop concentration-response functions, which BenMAP-CE uses to quantify the links between pollutant exposure and adverse health outcomes. These functions are typically stratified by population subgroups (e.g., age, race, and ethnicity) and account for the effects associated with a specific duration and degree of pollutant exposure (Table A4).

Population data and pollutant concentration data input to BenMAP-CE must be prepared in a manner consistent with these concentration-response functions. Epidemiological data linking $PM_{2.5}$ exposure and mortality are typically stratified by age group (e.g., infants, 18 years of age, and older) and reflect an annual averaging period. The BenMAP-CE program overlays population data onto changes in ambient pollutant concentrations to calculate spatially resolved impacts associated with pollutant exposure.

In this study, BenMAP-CE's companion tool, PopGrid, was used to estimate the 2010 population in each of the 1-km grids over the entire Bay Area where annual average $PM_{2.5}$ concentrations were estimated. We then used BenMAP-CE to project the 2010 1-km grid population to 2020. $PM_{2.5}$ health impacts were estimated for a total of 304 population groups (Table A2). They comprised nineteen age, four race, and two ethnic groups, as well as male and female groups. BenMAP-CE's racial classification schema is identical to that of the Centers for Disease Control and Prevention (CDC), from which BenMAP-CE obtains baseline health data. CDC's schema is aligned with the U.S. Census 2010 schema, except that multiracial ("2 or more races," for example) as well as "other race" responses are reclassified into one of the four "single-race" bins based on auxiliary data. Therefore, multiracial and other classifications have not been dropped; they have been reclassified into one of the four categories.

Table A4: Demographic groups and characteristics available in BenMAP-CE.[a]

Race	Ethnicity	Age
White, African American, Asian, American Indian	Hispanic, Non-Hispanic	<1, 1–4, 5–9, 10–14, 15–19, 20–24, 25–29, 30–34, 35–39, 40–44, 45–49, 50–54, 55–59, 60–64, 65–69, 70–74, 75–79, 80–84, ≥85

[a] Based on Table JI (U.S. EPA 2021); both males and females included.

A.3 Discount Rates

In general, benefits realized from the reduction in air pollution might need to be discounted because of (1) societal preferences for current over future benefits, (2) the need for future-year benefits estimates to be comparable with current-year benefits for cost-benefit analyses, and (3) the ability to compare future benefits with those occurring during the analysis year.

This assessment estimates annual valuations (in 2020 US dollars) of health impacts attributed to emissions targeted by the proposed rule amendments. Valuations are for impacts that occur within a year, but costs can extend to future years. In BenMAP-CE, discount rates[11] can be applied to economic valuations, providing an estimate of future costs in dollar amounts for the analysis year.

[11] Discounting is based on the concept that the value of a dollar decreases with time. For example, in 20 years $1 is worth $0.55 today at an annual discount rate of 3% and $0.26 at an annual discount rate of 7%.

For example, for the case of a cardiac arrest, costs calculated within BenMAP-CE are assumed to extend beyond the year of the event, and annual costs beyond the first year can be discounted using an assumed discount rate. BenMAP-CE provides two sets of pre-calculated unit costs, one associated with a 3% discount rate and one for a 7% discount rate. Economic valuations presented in this report assumed an annual discount rate of 3%.