ZIP Code-Level Estimation of Air Quality and Health Risk Due to Particulate Matter Pollution in New York City

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ABSTRACT: Exposure to PM$_{2.5}$ is associated with hundreds of premature mortalities every year in New York City (NYC). Current air quality and health impact assessment tools provide county-wide estimates but are inadequate for assessing health benefits at neighborhood scales, especially for evaluating policy options related to energy efficiency or climate goals. We developed a new ZIP Code-Level Air Pollution Policy Assessment (ZAPPA) tool for NYC by integrating two reduced form models—Community Air Quality Tools (C-TOOLS) and the Co-Bene Risk Assessment Health Impacts Screening and Mapping Tool (COBRA)—that propagate emissions changes to estimate air pollution exposures and health benefits. ZAPPA leverages custom higher resolution inputs for emissions, health incidences, and population. It, then, enables rapid policy evaluation with localized ZIP code tabulation area (ZCTA)-level analysis of potential health and monetary benefits stemming from air quality management decisions. We evaluated the modeled 2016 PM$_{2.5}$ values against observed values at EPA and NYCCAS monitors, finding good model performance (FAC2, 1; NMSE, 0.05). We, then, applied ZAPPA to assess PM$_{2.5}$ reduction-related health benefits from five illustrative policy scenarios in NYC focused on (1) commercial cooking, (2) residential and commercial building fuel regulations, (3) fleet electrification, (4) congestion pricing in Manhattan, and (5) these four combined as a "citywide sustainable policy implementation" scenario. The citywide scenario estimates an average reduction in PM$_{2.5}$ of 0.9 μg/m$^3$. This change translates to avoiding 210–475 deaths, 340 asthma emergency department visits, and monetized health benefits worth $2B to $5B annually, with significant variation across NYC’s 192 ZCTAs. ZCTA-level assessments can help prioritize interventions in neighborhoods that would see the most health benefits from air pollution reduction. ZAPPA can provide quantitative insights on health and monetary benefits for future sustainability policy development in NYC.

KEYWORDS: particulate matter, emissions, health benefits, New York City, policy research, ZIP code, ZAPPA, COBRA, C-TOOLS

INTRODUCTION

Fine particulate matter (PM$_{2.5}$) (particulate matter of size less than 2.5 μm) has been associated in multiple epidemiological studies with adverse health outcomes, such as cardiovascular and respiratory disease, neurological impacts, lung cancer, and premature mortality. Recent estimates show a global burden of 8.7 million premature mortalities due to ambient PM$_{2.5}$ from fossil fuel combustion. Despite steady improvements in air quality in the United States because of the Clean Air Act Amendments and other state and local emission control measures, air pollution is estimated to account for 5–10% of annual deaths nationally, with approximately 88 400 deaths attributed to PM$_{2.5}$ pollution.

PM$_{2.5}$ is a complex pollutant that includes both primary (directly emitted from combustion sources, such as vehicle and power plants, road dust, and cooking) and secondary (formed by various physical and chemical processes due to the interaction between gaseous precursors (NOx, SOx, NH$_3$, VOC) and aqueous chemistry) components. To reduce PM$_{2.5}$ levels in ambient air to protect public health, continued reductions in both primary PM and precursor gases that form secondary PM are essential. Thus, to estimate total PM$_{2.5}$ that cause adverse health impacts in humans, one must adequately characterize both primary and secondary components to study PM$_{2.5}$ health impacts.

New York City (NYC), the densest city in the United States with an area of 783 km$^2$ and a population of more than 8.41 million (population density of 27 346 people/sq-km), continues to experience major impacts from PM$_{2.5}$. NYC has an ever-increasing energy demand in all its emissions sectors (buildings, on-road, and power generation). Despite
multiple policies addressing fuel switching and technology changes, emissions remain high enough to impact the city’s population. In the past decade, multiple studies focused on PM$_{2.5}$ pollution in NYC, including concentration trends, source apportionment, health burden, and emission control. Despite declines in PM$_{2.5}$ concentrations (New York City Community Air Survey (NYCCAS) 2019 and U.S. EPA monitoring observations from 2011 to 2020), the health burden attributed to current ambient levels of PM$_{2.5}$ is still high enough to be of concern. The NYC Department of Health and Mental Hygiene estimates that annually (2015–2017 average) almost 2000 premature deaths and more than 6500 emergency department (ED) visits and hospitalizations can be attributed to PM$_{2.5}$ emissions in the region from multiple sources. Fine particulate emission sources in NYC include fuel combustion for heating and hot water in commercial and residential buildings, commercial cooking, on-road vehicles, and off-road high or low-construction and freight distribution. Traffic emissions from the New York Metropolitan Statistical Area (NYMSA) were estimated to have caused ~1800 premature deaths due to exposure to PM$_{2.5}$ and O$_{3}$, with 20% due to emissions from medium-duty trucks (MDT) and 17% due to the heavy-duty trucks (HDT) sector. Jin et al. used multiple estimates of PM$_{2.5}$ exposures for New York state from varying techniques (satellite remote sensing, air quality modeling, land use regression modeling, etc.) and assess gains in air pollution-related health benefits for a decadal period and state a 28% uncertainty because of choice of different techniques for estimating air pollution levels. Johnson et al., however, use a comprehensive air quality model to assess the PM$_{2.5}$ related health benefits of various policy scenarios including NYC’s Roadmap to 80 × 50. But this study highlights the inability to perform rapid turn-around of multiple scenarios because of the complex modeling framework and the associated computational burden.

NYC is demographically and geographically diverse with about 192 (fused in some cases to facilitate stable health rate estimates) ZIP Code Tabulation Areas (ZCTAs) established by the U.S. Census Bureau within its five counties. Each ZCTA has varying population demographics and emission sources, and its residents experience unique impacts from pollution exposure. Health and monetary cobenefits from pollution reduction vary among ZCTAs because of these distinct population characteristics and differential impacts of policy at the local scale. The areal extent of the ZCTAs vary from an average of 0.8 sq km in densely populated Manhattan County to an average of 10.8 sq km in Richmond County of NYC (see Table S7). Typically, PM$_{2.5}$ studies are performed at coarse resolution (grids of 36 km × 36 km, 12 km × 12 km or sometimes county level), but NYC county-level assessment inadequately characterizes this known variability in air pollution and its impacts within the city. To address these limitations, new high resolution modeling approaches have been implemented, including utilizing satellite-derived Aerosol Optical Depth, air quality models like the Community Multiscale Air Quality (CMAQ) model, neural network forecast models, and statistical Bayesian models. Chang et al. (2017) developed a hybrid modeling approach that characterized the near-road impacts of traffic-related primary PM$_{2.5}$ at a very high resolution and demonstrated that the hybrid approach estimated 24% more on-road PM$_{2.5}$-related premature mortality than just using CMAQ. But the long lag time of this computationally intensive modeling prohibits iterative policy assessment and rapidly assessing responses to emerging policy goals. Studies, such as Clougherty et al. (land-use regression (LUR)) and Huang et al. (LUR plus temporal predictors), have predicted PM$_{2.5}$
concentration at finer resolution in NYC using nonregulatory observations, such as those from NYCCAS and satellite retrievals. However, these approaches cannot be feasibly integrated in a tool for rapid assessment of changes in specific input drivers for estimating potential benefits of policy outcomes. There is thus a need for a tool that is computationally less resource intensive, that includes highly resolved local emissions, has the ability to characterize and visualize potential changes in air quality levels, and quantify health benefits at a high resolution in a rapid turnaround manner. More importantly, such a tool needs to be enabled for easier use by policy makers without the comprehensive technical expertise that is needed for using detailed chemistry-transport models.

This study describes the development of the new ZIP Code Air Pollution Policy Assessment (ZAPPA) tool, that integrates two reduced-form modeling systems to support the assessment of change at the ZCTA level in adverse health events and associated costs attributable to change in PM$_{2.5}$ emissions. The tool integrates and expands two existing models: the University of North Carolina at Chapel Hill’s C-TOOLS (Community Air Quality Tools) and the Environmental Protection Agency (EPA’s) Co-Benefits Risk Assessment (COBRA) screening model to provide hyper-local health impact assessment (HIA). ZAPPA’s unique capability to associate ZCTA-specific population and health incidences with its PM$_{2.5}$ concentration increases its accuracy in estimating the health burden. It can model both baseline PM$_{2.5}$ concentrations and quantify the health benefits of changes in emissions in individual sectors in a subset of the city or the entire city within a few hours, and empowers the user to perform interpretive analyses easily and generate tables and maps.

We evaluated ZAPPA’s air pollution estimates against air pollution monitoring data in New York city and used ZAPPA to assess health benefits of five illustrative policy scenarios.

### METHODS

**ZAPPA Development.** The web-based ZAPPA tool (https://treehug-app.its.unc.edu/zappa/) integrates C-TOOLS and COBRA. C-TOOLS$^{39,40}$ [Community Air Quality Tools (both C-LINE and C-PORT)] is a suite of local-scale air quality screening tools previously developed and applied in multiple studies.$^{40,41}$ In ZAPPA, C-TOOLS uses

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**Figure 2.** ZCTA-level PM2.5 emissions from (a) area sources, (b) point sources, (c) line sources for on-road, and (d) line sources for ships in transit (SIT).
Table 1. Paired-Wise Comparison of PM$_{2.5}$ (All in μg/m$^3$) at Observation Locations and Model Evaluation Using Statistical Measures$^{49}$

| network | site name | NYC borough | ZCTA ID | observed | modeled | bias (modeled-observed) | % difference |
|---------|-----------|-------------|---------|----------|---------|-------------------------|--------------|
| AQS JHS 126 | Brooklyn | 11222 | 7.87 | 7.99 | 0.12 | 1.5% |
| AQS PS 274 | Brooklyn | 11221 | 6.42 | 6.69 | 0.27 | 4.0% |
| AQS PS 314 | Brooklyn | 11220 | 6.42 | 7.90 | 1.48 | 18.7% |
| AQS CCNY | Manhattan | 10031 | 8.14 | 10.17 | 2.03 | 19.9% |
| AQS Division Street | Manhattan | 10038 | 8.01 | 10.58 | 2.57 | 24.2% |
| AQS Intermediate School 143 | Manhattan | 10033 | 8.50 | 11.26 | 2.76 | 24.5% |
| AQS IS 45 | Manhattan | 10035 | 7.32 | 9.34 | 2.02 | 21.6% |
| AQS PS 19 | Manhattan | 10009 | 8.23 | 11.54 | 3.31 | 28.7% |
| AQS Freshkills West | Staten island | 10314 | 7.33 | 6.37 | −0.96 | −15% |
| AQS Richmond Post Office | Staten island | 10302 | 6.76 | 6.80 | 0.04 | 0.5% |
| AQS IS 52 | Bronx | 10459 | 6.13 | 7.86 | 1.73 | 22.0% |
| AQS IS 74 | Bronx | 10474 | 7.12 | 7.14 | 0.02 | 0.2% |
| AQS Morrisania | Bronx | 10452 | 6.62 | 10.05 | 3.43 | 34.1% |
| AQS Pfizer Lab Site | Bronx | 10467 | 8.19 | 8.67 | 0.48 | 5.5% |
| AQS Maspeth Library | Queens | 11378 | 6.46 | 6.18 | −0.28 | −4.5% |
| AQS Queens College 2 | Queens | 11367 | 6.60 | 5.89 | −0.71 | −12.0% |
| NYCCAS Staten Island | Richmond | 10306 | 6.12 | 6.33 | 0.21 | 3.3% |
| NYCCAS Queens | Queens | 11367 | 6.59 | 5.52 | −1.07 | −19.3% |
| NYCCAS New York | New York | 10026 | 6.77 | 10.89 | 4.12 | 37.8% |

model evaluation using statistical measures

| model evaluation statistics | results | acceptance criteria | satisfies |
|-----------------------------|---------|---------------------|----------|
| FB (fractional bias) | 3.36% | within ±30% | yes |
| MG (geometric mean bias) | 0.88 | closer to ±1 | yes |
| NMSE (normalized mean square error) | 0.05 | closer to 0 | yes |
| VG (geometric variance) | 1.04 | ranges between ±1 | yes |
| FAC2 (fraction of data within a factor of 2 of observations) | 1 | closer to ±1 | yes |
| MFB (mean fractional bias) | 9.10% | within ±30% | yes |

meteorological inputs from LaGuardia Airport and NYC-specific annual emissions from the year 2016 for dispersion.

The Co-Benefits Risk Assessment (COBRA) model estimates total PM$_{2.5}$ concentrations, a range of health impacts due to changes in PM$_{2.5}$ including premature mortality, and monetized health impacts at a county-scale resolution for the entire U.S.$^{43}$ We adapted COBRA to produce similar estimates at ZCTA resolution for NYC, taking advantage of the high-resolution dispersion outputs from C-TOOLS. After total PM$_{2.5}$ is calculated for a given emissions scenario (Figure 1), the change in PM$_{2.5}$ from baseline is computed for any change in PM$_{2.5}$ due to changes in PM$_{2.5}$, including premature mortality, and monetized values of health benefits achieved by the change in total PM$_{2.5}$ compared to baseline concentrations. More details are in the Supporting Information (section A1).

Emissions Processing. Emissions for NYC are derived from the NEI 2016v1 emissions modeling platform,$^{44}$ which is a product of the National Emissions Inventory Collaborative and includes a full suite of base year (2016) emissions. These are augmented for ZAPPA with some adjustments or replacements whenever more accurate or higher resolution data specific to NYC was available, such as emissions from building boilers, commercial cooking, and link-level traffic information.$^{25,45}$ The overall emissions for PM$_{2.5}$, NOx, SO$_2$, VOC, and NH$_3$ from NYC have been divided into three major groups: (1) all area emissions from ground-level, excluding the following two source categories; (2) point emissions from power generation; and (3) line emissions from on-road vehicles and ships in transit, based on the dispersion algorithms that C-TOOLS supports (Figures 2 and S1–S3). Emissions estimates by tier at the source classification code (SCC) level are assigned to each of the ZCTA polygons using the Sparse Matrix Operator Kernel Emissions (SMOKE)$^{46}$ by applying spatial surrogates (for area sources). More information on emission types and years (Tables S1–S6) and web integration processes (sections A1–A6) are detailed in the SI. We estimated secondary organic aerosols (SOA) by first scaling source-specific estimates of VOCs to SOA (see COBRA manual), and then dispersing the SOA-equivalent of VOC emissions in C-TOOLS. The VOC emissions are anthropogenic and do not include biogenic sources.

Meteorological Data. ZAPPA modeling uses annual meteorological inputs from the LaGuardia (LGA) station (NY14732 NYC LGA; 11 km from center of NYC domain) processed through AERMET, AERMOD’s meteorological preprocessor.$^{7}$ We increased roughness length by 0.25 m (against an urban roughness length standard 1.0 m for the rest of the city) in the Manhattan borough (New York county) to...
include the effect of building downwash phenomenon. Emissions sources are modeled using 100 representative hours for the year and applying weights for LGA 2016 (using the Meteorologically Weighted Averaging for Risk and Exposure (METARE) approach) for computing annual average concentrations.

**Receptor Network.** ZCTA-level polygons are the building blocks for the modeling in this study. 237 polygons representing 192 ZCTAs were used to allocate emissions, and a receptor network was created based on the geometry. For ZCTA polygons with an area between 100 000 and 500 000 sq feet (about the area of a Manhattan city block), a single receptor was placed at the centroid of the polygon. For larger ZCTA polygons, we used an approach based on k-means clustering, which first divides the ZCTA into ten smaller Voronoi polygons, while preserving the shape of the original polygons.
Receptors are then placed at the centroid of each of the ten polygons, yielding a total of 1990 receptors that provide a high-resolution spatial representation of the ZCTA polygons. Receptor height is taken as 1.8 m based on the average breathing height and height of monitors.

**Model Evaluation.** We evaluated individual receptor-based total PM$_{2.5}$ estimates using a set of statistical performance measures suggested by the literature\textsuperscript{49} (Table 1) against 16 EPA Air Quality System (AQS) monitoring locations in NYC.

**Health Benefits Assessment.** The change in ambient PM$_{2.5}$ concentration in each scenario is used to estimate health impacts using the COBRA Applications Programming Interface (API). COBRA defaults were updated with NYC-specific ZCTA-level population data, ZCTA-level baseline health incidence, baseline emissions, and NYC-specific concentration–response (C–R) functions for asthma ED visits\textsuperscript{50,51} and cardiovascular hospital admissions.\textsuperscript{23,51} ZAPPA estimates change in air pollution-related health impacts and the economic value of these impacts using an approach that is consistent with EPA regulatory impact analyses.\textsuperscript{73,52} Incidence data for HIA consisted of nine different end points: adult and infant mortality; nonfatal heart attacks; respiratory-related and cardiovascular-related hospitalizations; acute bronchitis; upper and lower respiratory symptoms; asthma-related ED visits; asthma exacerbations; minor restricted activity days (i.e., days on which activity is reduced, but not severely restricted); and workdays lost due to illness (Table S9). Additional details on these functions can be found in the COBRA manual.\textsuperscript{43} We used 3-year annual average rates (2015–2017) at the ZCTA-level for the following outcomes: rate of asthma ED visits, all-cause mortality, and respiratory and cardiovascular hospitalizations. The remaining baseline rates are at the county level (2016) from the COBRA tool (see Table S8). All benefits are annual counts based on current population and incidence with no projected data.

## RESULTS

### 2016 Baseline.** Based on ZAPPA, NYC experiences an annual average of 8.0 ± 3.3 μg/m$^3$ total PM$_{2.5}$ across ZCTAs. Primary (direct) emissions make up the majority (59%) of citywide PM$_{2.5}$, which includes contribution from both local (35% of citywide PM$_{2.5}$) and transported sources (24% of citywide PM$_{2.5}$) (Figure 3). The local sources of primary PM$_{2.5}$ include area sources (90%, mostly building emissions), on-road...
sources (8%), electrical generating units (EGU) emissions (1%), and ships in transit (<1%). The local (in situ) generation of primary PM$_{2.5}$ is highest in the ZCTAs of Bronx and Manhattan (average ZCTA concentration in Bronx, 1.9 ± 0.6 μg/m$^3$, and Manhattan, 5.7 ± 1.8 μg/m$^3$). Secondary PM$_{2.5}$ (Figure 3a and 3b) comprises 41% of the citywide total. Of the secondary PM$_{2.5}$ species, the contribution from ammonium sulfate (45%) is highest, followed by secondary organic aerosols (SOA) (40%) and ammonium nitrate (15%). The ZCTAs of Manhattan and Staten Island are the most influenced by transport, evidenced by the higher concentrations of transported primary PM$_{2.5}$ and transported SOA in these boroughs (Figure 3a and 3b). This is due to the influence of westerly winds and increased turbulence attributed to complex geography aided by water bodies and high-rise buildings. Figure 3 shows that the transported components of PM$_{2.5}$ decrease moving eastward.

The quantitative evaluation (Table 1) of total PM$_{2.5}$ concentrations demonstrates that the modeled baseline is well within desired acceptance criteria of previous studies when compared against monitored concentrations (EPA and NYCCAS), thus showing the robustness of our modeled estimates.

Figure 4. Avoided health incidences (mortality and ER visits due to asthma) because of the PM$_{2.5}$ change (μg/m$^3$) after implementing strategy-based scenarios in NYC using ZAPPA.
**Results from Five Policy-Based Emissions Reduction Scenarios.** Sc1, Commercial Charbroiling. NYC-based studies identified commercial cooking as a major source of PM$_{2.5}$ throughout the city. Commercial cooking (4204 tons per year (tpy)) contributes about 37% of locally emitted PM$_{2.5}$, the single highest contribution from any SCC category in NYC. In 2015, NYC took a step forward in addressing this pollutant source when New York City Council passed Local Law 38 of 2015. The law updated the NYC Air Code to include regulation of commercial cooking emissions, requiring the installation of emission control devices on grills and char broilers in restaurants cooking significant amounts of meat with an expected reduction of 75% PM$_{2.5}$ emissions.

We applied ZAPPA to the scenario of full implementation of this law and found a reduction of 7.6%, (0.6 ± 0.5 μg/m$^3$) in average PM$_{2.5}$ across all 192 ZCTAs (Table 2). The widespread reduction reflects the presence of commercial charbroiling in all five counties (Figure 4a), with the largest reductions in neighborhoods with the most restaurants. Drilling down geographically, specific ZCTAs (Figure S4) in Manhattan (ID 10165, 10170, 10020, and 10110) and Brooklyn (Kings County) (ID 11217, 11201, and 11211) were identified as accruing significantly greater reductions than average (14–37% of base PM$_{2.5}$). This scenario had the greatest potential health benefits, including the greatest number of avoided mortalities per year (144–324 deaths) (Table 2) and an estimated an annual monetary benefit of $3.5B, with $3.4B from avoided mortality (Table S10). ZAPPA results (Figures 4a and S5a) show the variable distribution of these benefits within counties, pointing to the tool’s ability to support future analyses of inequitable air pollution exposures and impacts in NYC, as has been documented in other studies.

**Sc2, Electrification of Passenger Vehicles.** On-road mobile sources account for more than 10–16% of total PM$_{2.5}$ mass concentrations (and about 8% of emissions) in NYC. The NEI 2016 EPA inventory shows that approximately 87% of passenger cars are fueled by gasoline. This scenario assesses the potential effects of 100% electrification of private passenger cars and school buses in NYC. We found that the total PM$_{2.5}$ citywide average would fall by 0.3 ± 0.1 μg/m$^3$ (highest decrease, 1.0 μg/m$^3$ in Table 11247; lowest, 0.01 in 10308) (Figure 4b). The spatial pattern of the reductions generally followed traffic density with the greatest decreases in central Queens (ID 114271.0 μg/m$^3$), Manhattan (ID 10022–0.9 μg/m$^3$), and Brooklyn (ID 11201–0.8 μg/m$^3$), all locations where major roads or bridge approaches intersect. Health benefits follow a similar pattern to the PM$_{2.5}$ reductions with avoided premature deaths well distributed across most of the city. The greatest number of avoided ED visits for asthma were seen in the ZCTAs of northern Manhattan and southern Bronx where baseline rates tend to be highest. We estimated a total monetary benefit of $1.8B, with $1.78 B per year from mortality alone (Table S10 and Figure S5b).

**Sc3, Congestion Pricing in Midtown Manhattan.** The Central Business District Tolling Program (CBDTP), the nation’s first congestion pricing program, will start in NYC in 2022 and will require vehicles to pay to enter midtown and downtown Manhattan, potentially reducing congestion and improving air quality. The scenario we tested reduces the traffic volume AADT (annual average daily traffic) by 15% (based on public estimates) in the 30 ZCTAs in the zone—an analysis comprising only part of a county for air pollution and health benefit estimation. PM$_{2.5}$ reduction across the ZCTAs ranges between 0.00 and 0.18 μg/m$^3$ (Table 2 and Figure 4c). Highest PM$_{2.5}$ reduction (an average of 0.15 μg/m$^3$) was observed in the ZCTAs of lower Manhattan (ID 10111, 10165, and 10170, Figure S4). Overall, this scenario resulted in six fewer mortalities and three fewer asthma ED visits in the midtown Manhattan per year (Table 2 and Figure 4c). This scenario illustrates the contribution that ZAPPA can make to cost-benefit analyses for a policy yielding two kinds of monetized benefits: indirect health benefits attributable to air pollution reductions (Table S10 and Figure SSc3) and direct overall monetized benefits (proposed to be about $15B) due in this case to increased toll pricing. However, this does not account for the anticipated health benefits from the improved public transit system that should result from increased funding.

**Sc4, No. 4 Oil Prohibition in All Commercial and Residential Buildings.** This scenario involves the prohibition of all No. 4 oil (a blend of residual and distillate fuel oils) in NYC buildings for heating and hot water production as required by Local Law 43 of 2010. We calculated the citywide PM$_{2.5}$ emissions coming solely from No. 4 oil for each borough: Manhattan (45.4 tpy), Bronx (32.5 tpy), Queens (11.9 tpy), Brooklyn (7.3 tpy), and Staten Island (1.4 tpy), and reduced them to zero. We found an average reduction in average PM$_{2.5}$ of 0.01–0.10 μg/m$^3$ (Table 2 and Figure 4d) across all 192 ZCTAs with substantial variation within counties. This scenario resulted in spatially nonhomogeneous reduction due to high-rise buildings dominating the ZCTAs of lower Manhattan (highest in ID 10110 and 10036: 0.1 μg/m$^3$) and Bronx (highest in ID 10453 and 10452:0.05 μg/m$^3$). The scenario avoided a total 15 deaths and asthma ED visits per year (Table 2). We estimated a total annual monetary benefit of $156 M (higher estimate), with $153 M only from mortality (Table S11 and Figure S5d).

**Sc5, City-Wide Sustainable Scenario.** The fifth (Sc5) policy-based scenario involved the combined implementation of the four previous scenarios (commercial cooking emissions controls, electrification of passenger vehicles, congestion pricing in midtown and lower Manhattan, and No. 4 oil prohibition in all buildings). This scenario would reduce PM$_{2.5}$ emissions by 1930 tpy citywide and would result in a citywide average decrease in ambient PM$_{2.5}$ of 11%, that is, 0.9 μg/m$^3$ (Table 2). The highest reduction per ZCTA (4.12 μg/m$^3$) was in ZCTA ID 10165 (lower Manhattan) (Figure 4e), while the lowest was in 10307 (0.08 μg/m$^3$) in southern Staten Island. A cluster of ZCTAs in mid and lower Manhattan (10075, 10110, 10111, 10128, 10162, 10165, 10170, 10171, 10199, 10278, and 10280) had an average reduction of 2.3 μg/m$^3$ because of the concentration of targeted emissions sources in a region of high population density. ZCTAs in central Brooklyn (ZCTA ID 11201, 11217, 11205, and surrounding), northeast Queens (ZCTA ID 11103, 11424, and 11104), and southern Bronx (ZCTA ID 10458 and 10451) also had large reductions in health risks like mortality (ZCTA ID 10022, 10016, and ID 10222 in Manhattan avoided about 10 deaths each) and asthma ED visits (ZCTA ID 10457 and 10456 in the Bronx avoid about 11 asthma ED visits). Although the reduction in PM$_{2.5}$ concentrations in some ZCTAs (especially central and southern Brooklyn) was smaller when compared to reductions in lower Manhattan, end points like asthma ED visits and respiratory admissions showed larger reductions because of higher baseline rates of those health outcomes. This
scenario estimates an average reduction in PM$_{2.5}$ of 0.9 µg/m$^3$, which translates to avoiding 210–475 (upper–lower bound) deaths and 340 asthma emergency department visits. The monetized health benefits range from $2B–$5B annually.

### DISCUSSION

We developed ZAPPA, a novel high-resolution modeling framework that combines the two reduced-form models C-TOOLS and COBRA, to facilitate rapid policy assessment at the neighborhood, as opposed to county, level. We used NYC-specific emission inventories, city population demographics and health incidence data to ensure the most specific achievable estimates for small-areas. ZAPPA estimates ZCTA-level total PM$_{2.5}$ in NYC, while accounting for primary and secondary PM$_{2.5}$ from local and transported components into the city. Modeled PM$_{2.5}$ compared well against routine monitoring data, using multiple measures of model performance.

We used ZAPPA to test the impacts of various illustrative emission-reduction strategies based on existing sector-specific policies for buildings, on-road, and commercial cooking sources. We demonstrated how ZAPPA can be used to compare estimated health savings from proposed policies, and support emissions-based sensitivity analyses for the development of new policies. The spatial variability of benefits across ZCTAs is driven by baseline concentrations from all emission sources, design of the emissions reduction policy/program, and variation in baseline rates of health outcomes. When all four scenarios were combined (Sc$_5$), median reduction in ambient PM$_{2.5}$ at the ZCTA level ranged from 0.08 (ID 10307 in Staten Island) to 4.1 µg/m$^3$ (ID 10165 in Manhattan). Health benefits were similarly variable, with many avoided ED visits and hospitalizations occurring in Brooklyn and Bronx ZCTAs where baseline health incidence rates are high. The maximum monetized benefits ranged from $0.01 M (ID 11430 Queens) to $56 M (ID 10002 Manhattan). Regulation of commercial cooking emissions from commercial charbroiling (Sc1) had the largest PM$_{2.5}$ reductions of the sector-specific scenarios, ranging from 0.06 µg/m$^3$ (ID 11307 in Richmond and 11697 in Queens) to 3.52 µg/m$^3$ (ID 10165). It has been reported that restaurants cause long-term average PM$_{2.5}$ increases of 0.1 to 0.3 µg/m$^3$ over distances between 50 and 450 m, and ZAPPA allows users to estimate accrued health benefits to the local neighborhoods of emissions reduction measures.

In on-road scenarios Sc2, 100% electrification of cars and school buses, and Sc3, 15% AADT reduction Central Business District due to congestion pricing, we saw a wide range of reductions (highest 1.09 µg/m$^3$ (ZCTA ID 11427 Queens) and lowest 0.01 µg/m$^3$ (ZCTA ID 10308 Staten Island)) across neighborhoods. The PM$_{2.5}$ reductions from Sc2, a fleet-wide emissions reduction scenario, were widely distributed across ZCTAs, as were the health benefits. In comparison, the PM$_{2.5}$ reductions and associated health benefits from Sc3 were limited to ZCTAs in lower and midtown Manhattan, where traffic volume was reduced by congestion pricing (Figure 4c). Like the scenarios illustrated here, the Transportation Climate Initiative (TCI$^{60}$) has modeled regional policy scenarios at state and county scales, showing reductions in mortality with implementation of cap-and-invest programs. ZAPPA’s ZCTA-level analysis could be used to better estimate the health impact of these policy scenarios at a neighborhood level and for populations with disproportionate exposure to air pollution.

Given evidence of disproportionate health outcomes in low-income communities in NYC,$^{50}$ scenarios Sc2 and Sc3 suggest that policy solutions are most effective when they impact traffic in neighborhoods with the highest baseline rates of air pollution-related health outcomes, such as the electrification of medium-duty and heavy-duty trucks or low and zero emissions zones in heavily residential neighborhoods.

Our fourth scenario to prohibit of No. 4 oil in all buildings (Sc4) illustrates the extension of existing building fuel policies and evaluation of potential benefits. This strategy’s analysis showed widespread health benefits due to the spatial correlation between population and building density in NYC. However, we found significantly greater impacts in the ZCTAs of northern Manhattan and the south Bronx where the majority of buildings burning No. 4 oil are located. The stack height of building boilers is closer to pedestrian level than point-based emission sources (i.e., power plants), making buildings emissions especially relevant to NYC public health. While the overall PM$_{2.5}$ reduction is less significant and nonuniform in this scenario, it is one of the most viable scenarios$^{51}$ for NYC regulation from an economic perspective, since cleaner fuel alternatives are available and competitively priced. While the total ambient PM$_{2.5}$ concentration in NYC is a function of both local/in situ and transported emissions, all emissions reductions scenarios presented here only target local emissions, limited to the reach of NYC policy impacts. Overall, about 11% reduction in total PM$_{2.5}$ (0.9 µg/m$^3$) is estimated when all four scenarios are implemented together. This reduction translates into achieving $2B–$5B monetized health benefits annually.

ZAPPA shows efficient integration and usage of local data sets in studying NYC’s air quality and health burden; however, we acknowledge that there are uncertainties associated with C-R functions, baseline health rates, NEI-based emissions inventory, and in our methodical approach to spatially distribute emissions to ZCTA that ZAPPA does not quantify. While we have shown the impact of illustrative emissions scenarios, they do not take system-wide changes into account. For example, electrification of cars and buses shows direct benefits from this scenario, while there are potential offsets due to increase in emissions in the power sector depending on the fuels used. These limitations can be addressed in future work by coupling with energy systems modeling or other approaches. The innovation of ZAPPA is that it combines two robust reduced-form models and is designed for rapid assessment of a diverse range of emissions reduction scenarios to inform policy development. While ZAPPA makes a significant advance in estimating concentrations of primary pollutants at high resolution from local sources, as in other reduced form models,$^{52}$ it has limitations with estimating secondary aerosols due to various simplifying assumptions about the emissions to air quality relationships. For this study, we have used VOC to SOA emissions conversion and then dispersed the converted SOA emissions to estimate SOA concentrations. This approach is comparable to other reduced form models in the literature.$^{50,63}$ Additionally, while C-TOOLS-based dispersion estimates for local NYC sources are at ZCTA level, the transported components from outside the city are county-level estimates from COBRA, which we believe is a reasonable approximation. Despite these limitations, the significant advantage that ZAPPA has in allowing the user to rapidly evaluate multiple policy options for screening purposes is to be highlighted.
We used ZAPPA to test a suite of scenarios based on existing air quality and sustainability policies to demonstrate its effectiveness as a screening tool. Beyond quantified health benefit estimates, ZAPPA also provides estimates of cost savings from monetized health benefits. ZAPPA has several unique benefits compared to typical chemical transport models, such as resolution (ZCTA-level emissions and population embedded results), efficiency (faster run time), ease of use (web-based scenario development), and integrated assessment (integrating air quality and health benefits modeling in a single framework), making it a powerful tool for comparing policy options and ensuring that benefits are distributed equitably. ZAPPA’s ability to model health benefits at ZCTA-level offers a strong potential for studying environmental justice issues, given previous findings that both the population-weighted average exposure and the exposure differences between minorities and whites increased substantially when switching from the coarsest to the finest resolution grid.

We anticipate that ZAPPA can be expanded to other cities in the U.S. and the world for assessing PM$_{2.5}$-based health impacts, designing emissions reduction scenarios, and to further identify vulnerable populations with disproportionate impacts, designing emissions reduction scenarios, and to further identify vulnerable populations with disproportionate impacts, designing emissions reduction scenarios, and to further identify vulnerable populations with disproportionate impacts, designing emissions reduction scenarios, and to further identify vulnerable populations with disproportionate impacts, designing emissions reduction scenarios, and to further identify vulnerable populations with disproportionate impacts, designing emissions reduction scenarios, and to further identify vulnerable populations with disproportionate impacts, designing emissions reduction scenarios, and to further identify vulnerable populations with disproportionate impacts.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.1c07325.

Additional tables and figures on emissions inputs, health data and health impact studies, and results from illustrative scenarios (PDF)

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Notes

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