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Identification of Effects of Regulatory Actions on Air Quality in Goods Movement Corridors in California

Jason G. Su,*[†] Ying-Ying Meng,[‡] Melissa Pickett,[‡] Edmund Seto,[∥] Beate Ritz,[§] and Michael Jerrett[†,§]

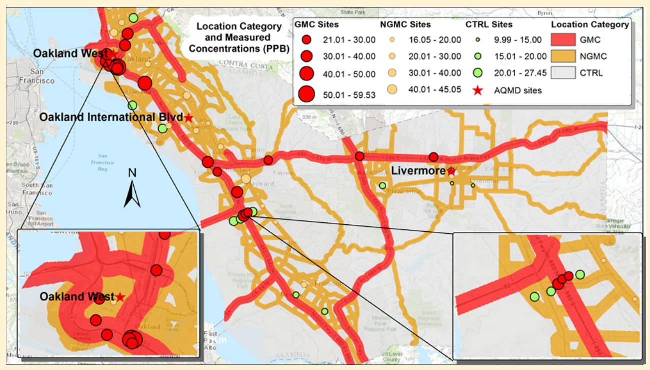
[†]50 University Hall, Environmental Health Sciences, School of Public Health, University of California—Berkeley, Berkeley, California 94720-7360, United States

[‡]Center for Health Policy Research, University of California—Los Angeles, Los Angeles, California 90095-7143, United States

[§]Fielding School of Public Health, University of California—Los Angeles, Los Angeles, California 90095-1772, United States

[∥]Department of Environmental and Occupational Health Sciences, School of Public Health, University of Washington, Seattle, Washington 98195-7234, United States

ABSTRACT: Few studies have assessed the impact of regulatory actions on air quality improvement through a comprehensive monitoring effort. In this study, we designed saturation sampling of nitrogen oxides (NO_X) for the counties of Los Angeles and Alameda (San Francisco Bay) before (2003–2007) and after (2008–2013) implementation of goods movement actions in California. We further separated the research regions into three location categories, including goods movement corridors (GMCs), nongoods movement corridors (NGMCs), and control areas (CTRLs). Linear mixed models were developed to identify whether reductions in NO_X were greater in GMCs than in other areas, after controlling for potential confounding, including weather conditions (e.g., wind speed and temperature) and season of sampling. We also considered factors that might confound the relationship, including traffic and cargo volumes that may have changed due to economic downturn impacts. Compared to the pre-policy period, we found reductions of average pollutant concentrations for nitrogen dioxide (NO_2) and NO_X in GMCs of 6.4 and 21.7 ppb. The reductions were smaller in NGMCs (5.9 and 16.3 ppb, respectively) and in CTRLs (4.6 and 12.1 ppb, respectively). After controlling for potential confounding from weather conditions, season of sampling, and the economic downturn in 2008, the linear mixed models demonstrated that reductions in NO_2 and NO_X were significantly greater in GMCs compared to reductions observed in CTRLs; there were no statistically significant differences between NGMCs and CTRLs. These results indicate that policies regulating goods movement are achieving the desired outcome of improving air quality for the state, particularly in goods movement corridors where most disadvantaged communities live.



1. INTRODUCTION

In accountability studies, air pollution exposures were usually modeled or based on proximity to the nearest monitoring stations, and adverse outcomes were assessed using a cross-sectional design; policy regulation proposals were then developed with the goal to reduce air pollution and to improve public health on the basis of the estimated effect sizes derived from the models.[1−6] Relatively few studies were available on identifying health impacts due to policies that directly aimed to improve air quality.[7−9] Difficulties in conducting an accountability study include a lack of data on air quality and health outcomes, and interventions that are part of complex programs affecting air quality in different ways, especially when evaluating regulations that are implemented over an extended period of time.[9] Among those issues, high-density air-quality-monitoring data were not typically collected, especially during both the pre- and post-policy periods.[7] For example, a study by Morgenstern and colleagues[10] applied a novel data-driven source-receptor model to explore the statistical relationships between source emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_X) and monitored concentrations of fine particulate matter (PM) with an aerodynamic diameter $\leq$2.5 μm ($PM_{2.5}$) in the eastern United States between 1999 and 2005. They found that the Title IV Phase 2 emissions reduction program implemented between 1999 and 2005 reduced $PM_{2.5}$ concentrations by an average of 1.07 $\mu g/m^3$. Gauderman and colleagues[11] tracked lung function growth and convincingly demonstrated that air quality improvements in Southern California were significantly associated with improvements in lung function/growth in a large cohort of children, but they did not tie this to a specific policy action. These studies did not have high-density air-quality-monitoring data for the pre- and post-policy periods to identify improvements in air quality due to small-area variations

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(e.g., 30 m). Routine government monitors are typically designed to measure background pollutant concentrations and the capability to detect spatial variability is limited.[12] In addition, no study to date has identified the differential impacts of an air quality regulation and associated differential improvements in health outcomes.

In 2006, the California Air Resources Board (CARB) and local air quality management districts implemented an "Emissions Reduction Plan for Ports and Goods Movement".[13] The goods movement regulatory actions sought to reduce total statewide emissions and contained numerous strategies to facilitate air pollution reduction, which included: requiring newer, cleaner burning engines for trucks, ships, and locomotives or retrofitting older engines to meet new standards, requiring ships to use shore-based electrical power rather than idling in the port, and enforcing idling limits for trucks and trains.[13] It mandated the reduction of the total statewide international and domestic goods movement related emissions to the 2001 levels or lower by the year 2010, the reduction of the statewide diesel particulate matter (PM) health risk from goods movement by 85% by the year 2020, and the reduction of NO_X emissions from international goods movement in the South Coast Air Basin by 30% from projected 2015 levels and 50% from projected 2020 levels. In 2007, the 1-h average state standard for nitrogen dioxide (NO_2)—a traffic pollution marker—was lowered from 250 to 180 ppb, and an annual average state standard was established for NO_2 at 30 ppb. In sum, the years 2006 and 2007 marked an important milestone in regulating pollution from goods movement with stricter standards. Though the plan aimed for statewide reductions in criteria pollutant concentrations, it is expected that low-income communities and communities of color would benefit most due to having the highest exposures. Goods are moved from California's ports throughout California by way of major state and federal highway systems, and this is a major component of California's economy; however, it also creates disproportionate environmental exposure burden (e.g., air pollution and noise) for the residents living in these corridors. It is well-known that low-income communities and communities of color are more concentrated in these environmental corridors, and that they bear a disproportionate burden of environmental exposures and associated health risks.[14−21] Policy makers, environmental justice groups, and researchers are especially interested in identifying whether this disproportionate burden has been reduced. However, to our knowledge, no such study has been conducted to date.

In this study, we designed high-density air-quality-monitoring networks for Los Angeles in Southern California and for the San Francisco Bay Area in Northern California. Measurements were made on NO_2 and NO_X for both pre- and post-policy periods. We did so to identify whether small-area variations in pollutant concentrations and improvements in air quality over time due to goods movement regulatory policies could be detected. These two areas were chosen mainly because (1) they are the two biggest urban regions in California, (2) we have historical high-density air-pollution-monitoring data for the pre-goods movement policy period, and (3) they contain three major U.S. ports: Los Angeles, Long Beach, and Oakland. We hypothesized that areas near goods movement corridors would experience greater reductions in traffic-related air pollutants (TRAP) than those in areas away from goods movement areas, which were used as control areas.

At the same time as California implemented the CARB policies, the global economy began its decline (in December 2007) and took a particularly sharp downward turn in September 2008, creating the Great Recession.[22] This severe economic recession created widespread impacts on various industrial sectors, including housing, stocks, and the import and export business.[23] Bagliano and Morana[23] argued that the import and export business was the key transmission mechanism of real shocks. These economic dynamics also impacted the amount of goods movement and transportation in the U.S. and in California. To identify the impact of policy regulations on improvements in air quality, we considered a series of factors that might confound the relationship, including traffic and cargo volumes that may have changed due to economic downturn impacts, weather, and season of sampling.

2. MATERIALS AND METHODS

2.1. Study Sites. With a population of 18.2 million, the metropolitan Los Angeles area is the largest conurbation in the State of California and the second-largest in the United States. Los Angeles is also consistently ranked as one of the most polluted metropolitan areas in the United States, partially due to heavy reliance on automobiles for transportation and because more than 40% of all goods transported into the United States move through the Long Beach−Los Angeles port complex (referred as LA−LB Port hereafter), generating thousands of truck trips per day.[24] The San Francisco Bay Area, commonly known as the Bay Area, is the second-largest metropolitan area in California, with 7.44 million people. The Port of Oakland is a major container shipping facility in the San Francisco Bay. It is the fifth-busiest container port in the United States, after Long Beach, Los Angeles, Newark, and Savannah.

2.2. Definition of Location Category and Study Period. We defined locations as being one of three categories: "goods movement corridors" (GMCs), zones within 500 m of truck-permitted freeways (9475 highway segments), ports, or railways;[25] "nongoods movement corridors" (NGMCs), areas within 500 m of truck-prohibited freeways (216 highway segments) or within 300 m of connecting major roadways; or "controls" (CTRLs), areas outside of the above two corridors that were dominated by local roads. Due to time required to implement the air quality regulations and subsequent impacts on health outcomes, we used the end of 2007 as a cutoff point for policy regulation, with 2003−2007 defined as the pre-policy peroid and 2008−2012 as the post-policy period. NO_2 and NO_X concentrations, measured through specially designed monitoring networks, were compared for the pre- and post-policy periods, and their relative improvements in GMCs and NGMCs were analyzed using CTRLs as the reference group.

2.3. NO_X Fixed-Site Saturation Monitoring. The fixed-site saturation monitoring for the pre-policy period in Alameda was originally designed for the East Bay Children's Respiratory Health Study (EBCRHS). The same period saturation sampling in Los Angeles was designed for the Los Angeles Family and Neighborhood Study (LA FANS). The post-policy campaigns in these two regions were specifically designed to identify the effects of regulatory actions on improvements in air quality. All the sites in the post-policy period were selected from the pre-policy period sites for the purpose of comparing changes in air quality. Location−allocation algorithms were used, separately, to select original and subset sample sites in each region. We used two standard 2-week seasonal (dry/wet or spring/fall) fixed-site saturation sampling periods to identify long-term

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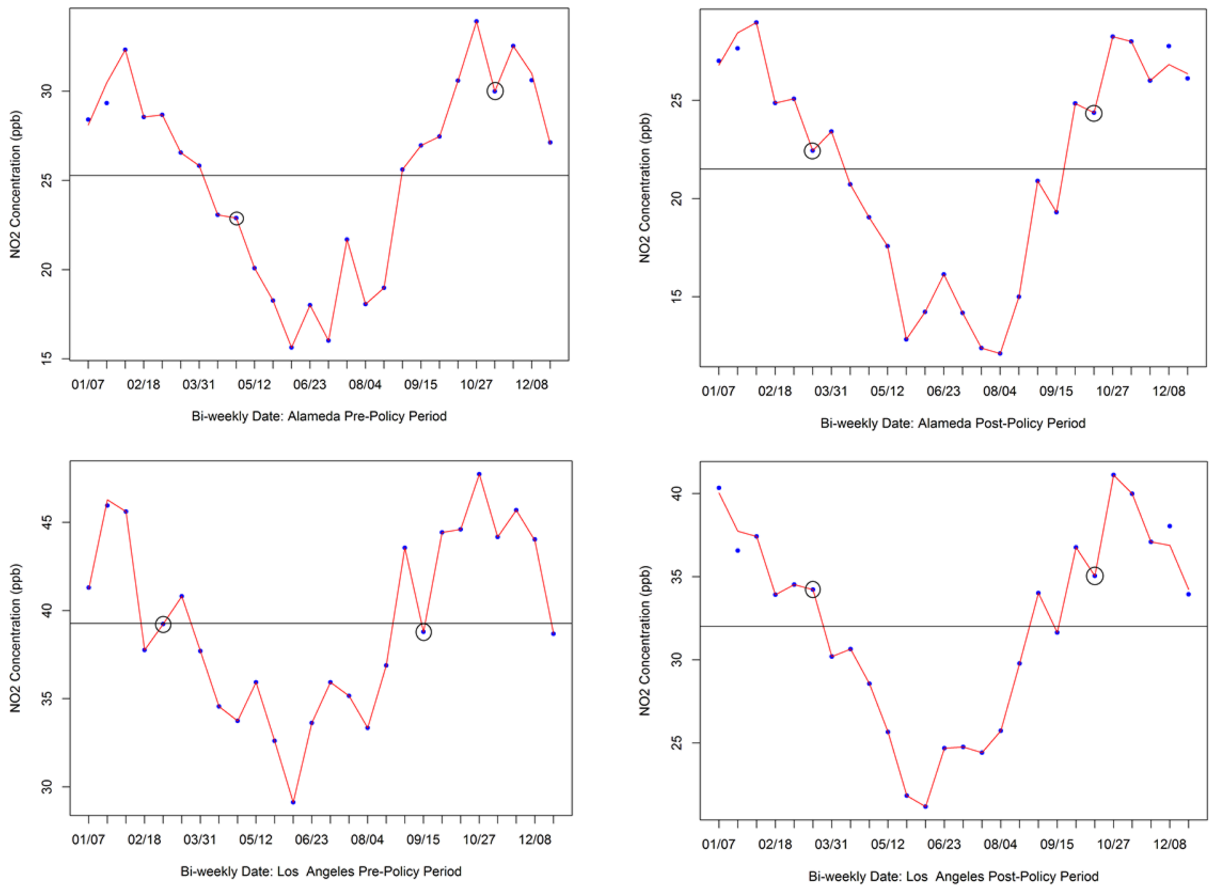

Figure 1. Long-term 2-week average NO_2 concentrations, separately, for Alameda and Los Angeles for the pre- and post-policy periods. The pre-policy period included data from 2003 to 2007 and the post-policy period included data from 2008 to 2012. The multiple year long-term means are marked by horizontal lines and corresponding 2-week time periods of fixed-site saturation monitoring are marked by hollow circles.

annual pollutant concentrations.[26−33] Measurements for each policy period in each region were selected after reviewing historical long-term government monitoring data with the goal that these two 2-week monitorings would allow us to estimate long-term average concentrations most accurately. Figure 1 shows long-term 2-week average NO_2 concentrations, separately, for Alameda and Los Angeles for the pre- and post-policy periods. The pre-policy period included data from 2003 to 2007 and the post-policy period included data from 2008 to 2012. The corresponding 2-week time periods of fixed-site saturation monitoring are marked by hollow circles. Figure 1 indicates that the concentrations measured at the times of fixed-site saturation monitoring were close to the corresponding multiple year long-term means (the horizontal lines). Though weather conditions during fixed-site saturation sampling were not exactly the same as the long-term mean conditions, it is very likely that the sampling campaigns detected small area variations in long-term pollutant concentrations

2.3.1. Fixed-Site Saturation Sampling in the Pre-policy Period. In Los Angeles, we selected neighborhood monitoring locations (n = 201) using a location−allocation algorithm[34] that took into account variability in traffic pollution and the spatial distribution of our childhood respiratory health study population, specifically, participants in the LA FANS. This method optimally locates monitors for the purpose of measuring traffic pollutants with fine-scale spatial variability. We used passive air filter samplers from Ogawa & Co. USA, Inc. (Pompano Beach, FL) to conduct monitoring in two seasons during September 2006 (late summer warm season) and February 2007 (midwinter rainy season). Each air sampler collected NO_2 and NO_X during a two-week period of deployment. In total, we obtained measurements from 183 sites in September 2006 and from 181 sites in February. In addition to these 183 sites, we colocated 15 samplers at Southern California Air Quality Management District (SCAQMD) air-monitoring stations, deployed 50 duplicates, and collected data from 30 field blanks.[31] The mean pollutant concentrations from the fall 2006 and spring 2007 Ogawa measurements were used as pollutant concentrations for the pre-policy period.

In the Bay Area (Alameda County), we selected 95 locations in the bounding region of the EBCRHS area (see Figure 1, Ostro et al.[35]) using the same location−allocation algorithm. Passive Palmes diffusion tubes (Gradko International, P/N: DIF100RTU-R) were used for all 95 sites, and 49 subset sites used Ogawa diffusion badges (Ogawa USA, PN: PS-100) to measure concentrations of NO_2, both for fall 2004 and spring 2005. On the basis of a linear regression of Palmes tube measurements with Ogawa sampler measurements (variance explained R^2 = 0.95), all Palmes tube measurements were converted to corresponding Ogawa equivalents.

We expect that the data collected close to the start of the implementation of the plan will resemble pre-policy pollution levels best. The fixed site saturation monitoring we conducted is expected to cover the small-area variations in TRAP during this time period.

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2.3.2. Fixed-Site Saturation Sampling in the Post-policy Period. In fall 2012 and spring 2013, we successfully designed and deployed two new rounds of NO_X sampling in Los Angeles and Alameda Counties. For the first round of deployment in Los Angeles, Ogawa samplers were deployed at 72 sites (92 monitors) in fall 2012, and collected from 70 sites (90 samplers with two samplers lost due to vandalism). Data were available from 25, 21, and 24 sites in GMCs, NGMC and CTRLs areas, respectively. Of note, all Ogawa samplers colocated with government sites had effective measurements. For our second round of deployment in Los Angeles County in spring 2013, Ogawa samplers were deployed and collected at 72 sites with a total of 92 monitors. The number of sites with effective data collection was 26, 22, and 24, for GMCs, NGMCs, and CTRL areas, respectively, with all government colocated sites having effective measurements.

In the San Francisco Bay Area (mainly in Alameda County), we successfully deployed 60 monitors at 49 sites and retrieved all deployed monitors in fall 2012 and spring 2013, during the same periods when Ogawa monitors were deployed and collected in Los Angeles. The number of sites with effective data collection was 19, 16, and 14, for GMCs, NGMCs, and CTRLs areas, respectively. All Ogawa monitors colocated with government sites had valid measurements.

2.4. Analysis of Potential Confounding Factors. We considered a series of factors that might confound our analyses, e.g., the lower traffic and cargo volumes due to the economic downturn. We decided to use total traffic (98.6% of which being non-commercially registered vehicles) and weighted cargo volumes to control for potential confounding from impacts of the economic downturn. Even though these measures are related to levels of exposure, it is appropriate to adjust for them to observe reductions in exposure due to the policy impact e.g., one can interpret the results from these adjusted models as the impact of the policy that is not due to the reduction in total vehicle miles traveled on roadways or the reduction in overall cargo movement (two factors most closely related to the economic downturn) but due to other changes that influenced pollution levels (such as cleaner trucks, etc.). We also included other factors, such as changes in wind speed and temperature, to control for their effects on air quality in the two regions. We describe these factors in detail in the following:

2.4.1. Distance-Weighted Cargo Volume (TEU/km). We acquired monthly and annual cargo volumes for the Oakland, LA, and LB ports from corresponding port authorities for the 2003−2012 period. The geographic boundary layer of the three ports was acquired from CalTrans (California Department of Transportation) for 2011. We used twenty-foot equivalent units (TEU) statistics for cargo volumes in the three ports. TEUs are a standardized maritime industry measurement used when counting cargo containers of varying lengths. Because of the adjacency of LA and LB ports, we added up monthly and annual cargo volumes, merged corresponding spatial boundaries, and treated them as a single LA−LB port complex. We assumed a linear distance decay to estimate the impact from port cargo. For an air quality sampling site, TEUs were first calculated through TEUs/km separately for the Oakland and LA−LB ports, and then the two separate values were added up to create a single distance-weighted cargo volume. Distance-weighted cargo volumes were used to control impacts from the economic downturn by comparing the pre-policy and post-policy period data.

2.4.2. Traffic Data [Annual Average Daily Traffic (AADT)]. Highway and major roadway AADT for all vehicles were acquired from CalTrans, and they are the total volumes for the year divided by 365 days. The traffic count year starts October 1 and goes through September 30 (e.g., 2004 data are from 10/1/2004 to 9/30/2015). Traffic counting is performed using electronic counting instruments that are moved from location to location throughout the state in a program aiming to collect continuous traffic counts, and sampling locations largely remained the same across the years. The resulting counts are adjusted to create an AADT value and compensates for seasonal influence, weekly variation, and other variables that might influence counts. For each Ogawa saturation monitoring site, we identified its nearest CalTrans counting station and, for the pre-policy period, assigned 2004 AADT values if the Ogawa site was deployed in 2004−2005 (in Alameda) or 2006 AADT values if the Ogawa site was deployed in 2006−2007 (in Los Angeles). For the post-policy period, we assigned 2012 AADT values to corresponding Ogawa sites deployed in 2012−2013 (in Alameda and Los Angeles). Each CalTrans counting station has measurements on "back" AADT (traffic south or west of the station) and "ahead" AADT (traffic north or east of the station) for each year. We used the mean statistics as the AADT for a counting station. These AADT means calculated on highways and major roadways were then used to control for the impact of the economic downturn when comparing pre- and post-policy periods, with the expectation that the economic downturn would reduce traffic volumes.

2.4.3. Weather Data. We acquired daily weather data from the California Irrigation Management Information System (CIMIS) for 2003−2012 for the entire State; this includes 167 active weather stations statewide. Daily temperature and wind speed data were aggregated to monthly and annual means for each individual station. The spatial interpolation algorithm of inverse distance weighting was used to create statewide monthly and annual surfaces for temperature and wind speed. Monthly and annual temperatures and wind speeds at each Ogawa monitor were then estimated.

2.5. Modeling Techniques. First, we estimated the independent effects of location category and policy period on pollutant concentrations while adjusting for possible confounding factors. We treated a monitoring site as a random effect. The model we employed is shown in eq 1:

$$Y_{si} = \beta_0 + \beta_1 C_s + \beta_2 P_i + \beta_3 F_{si} + \gamma_s + \varepsilon_{si} \quad (1)$$

Y_{si} is the pollutant concentration at site s for policy period i. C_s is the location category, i.e., GMCs, NGMCs, or CTRLs, with CTRLs being the reference. P_i indicates the policy period during pollutant sampling, with the pre-policy period being the reference. F_i represents confounding factors that might impact the relationship between measured concentrations and policy regulation, including traffic density, ship cargo volume, weather, and season of sampling. β_0 is the model constant; β_1 is a vector of coefficients for location categories; β_2 is a vector of coefficients for the two policy periods; β_3 is a vector of coefficients for possible confounding factors. γ_s is the random effect at site s and ε_{si} is the error term of site s for policy period i. Because the location category of a site did not change between the two policy periods, C_{si} was simplified in the model to C_s. Similarly, since regulation policies were the same across all sites, P_{si} was simplified to P_i. Separate models as in eq 1 were used to model pollutant concentrations of NO_2 and NO_X. Finally, we created an interaction term between location

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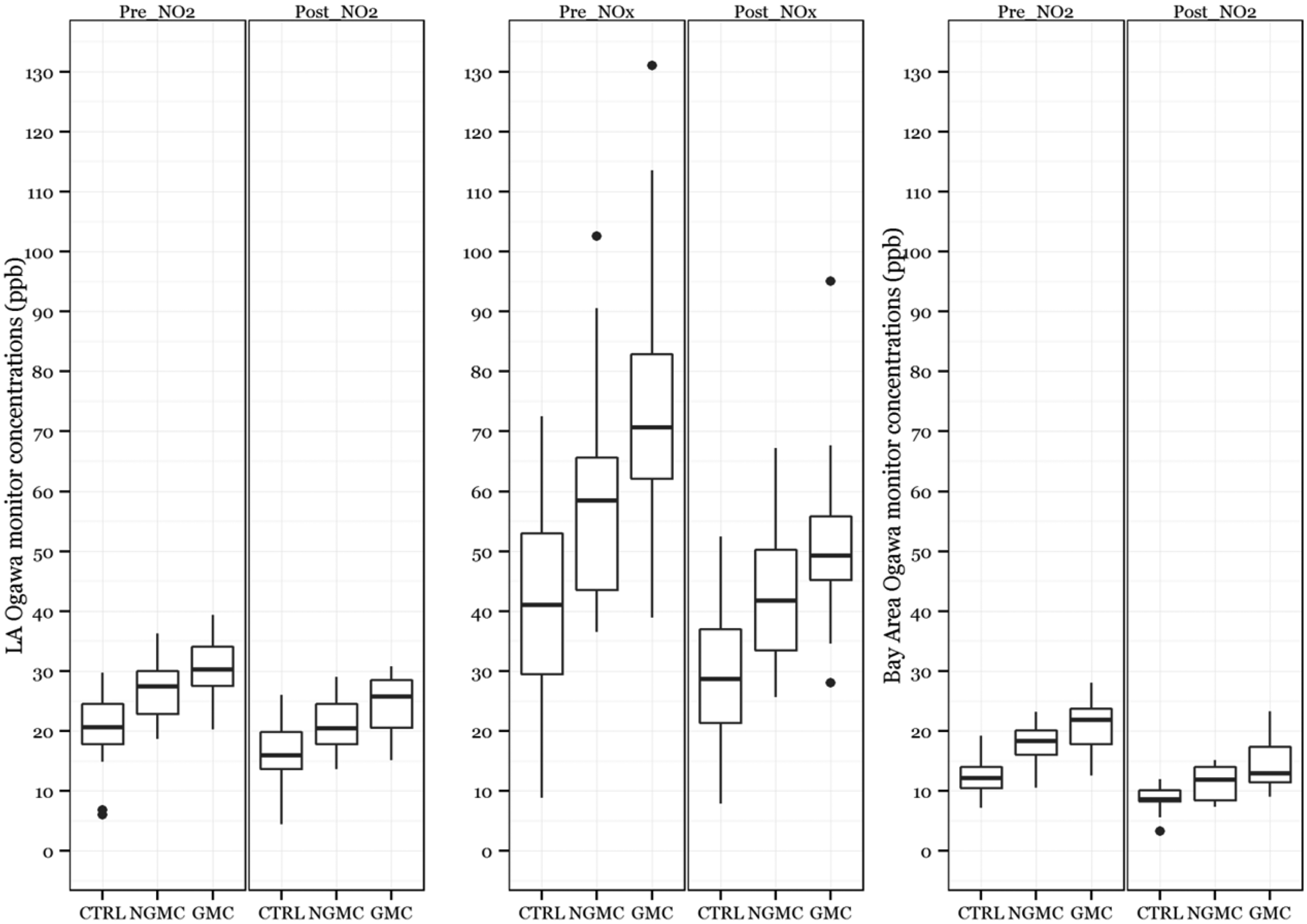

Figure 2. Boxplots of the measured NO_2 and NO_X concentrations for the pre-policy (left side of a panel) and post-policy (right side of a panel) periods for the Los Angeles (first two panels) and Bay Area (the third panel), summarized by location category. NO_X for the pre-policy period was not sampled for the Bay Area and the comparison was thus not listed.

category and policy period to assess whether reductions in pollutant concentrations in GMCs from the pre- to the post-policy period were greater than corresponding reductions in CTRLs. The modeling technique is described below in eq 2

$$Y_{si} = \beta_0 + \beta_1 C_s + \beta_2 P_i + \beta_3 F_{si} + \beta_4 C_s \times P_i + \gamma_{si} + \varepsilon_{si} \quad (2)$$

where $C_s \times P_i$ is the interaction between location category of site s and policy period i. β_4 is a vector of coefficients of interactions between location categories and policy periods. Other variables have the same definition as in eq 1.

3. RESULTS

3.1. Descriptive Statistics. On the basis of the Ogawa measurements (Figure 2), we found that pollutant concentrations for NO_2 and NO_X were generally the highest in GMCs, followed by NGMCs, and the lowest in CTRLs. This is true for the pre-policy and post-policy periods. Compared to the pre-policy period, the reductions of median pollutant concentrations for NO_2 and NO_X in GMCs were 6.4 and 21.7 ppb. The reductions were smaller in NGMCs, with 5.9 and 16.3 ppb, respectively. In CTRLs, reductions were smallest, with corresponding reductions of 4.6 and 12.1 ppb, respectively. The reductions of NO_X concentrations in GMCs were more than 2 times those of corresponding reductions in CTRLs. These relationships were largely similar for the Bay Area, where concentrations for NO_2 and NO_X were lower compared with those of Los Angeles.

The annual cargo volumes for the LA−LB port complex were 1 298 396 and 1 119 293 TEUs, respectively, for the pre-policy and post-policy periods. These annual volumes were 191 617 and 196 200 TEUs, respectively, for the Oakland port. In Los Angeles, the vehicle kilometers traveled (VKT) within 500 m of the saturation monitoring sites were 727 454 and 708 174, respectively, for the pre-policy and post-policy periods. These VKTs respectively were 693 012 and 640 348, for Alameda. During the pre-policy period, the mean temperatures for the dry and wet seasons were, respectively, 69 and 55 °F for Los Angeles, and its average wind speeds for the same seasons were, respectively, 2.9 and 3.4 mph. The mean temperatures for the dry and wet seasons were, respectively, 60 and 52 °F for Alameda, and its average wind speeds for the same seasons were, respectively, 3.5 and 2.3 mph. During the post-policy period, the mean temperatures for the wet and dry seasons were, respectively, 66 and 58 °F for Los Angeles, and its average wind speeds for the same seasons were, respectively, 2.8 and 3.2 mph. The mean temperatures for the wet and dry seasons were, respectively, 61 and 54 °F for Alameda, and its average wind speeds for the same seasons were, respectively, 2.7 and 2.4 mph.

We estimated the agreement of Ogawa monitoring data with colocated government monitoring. Colocated site data existed

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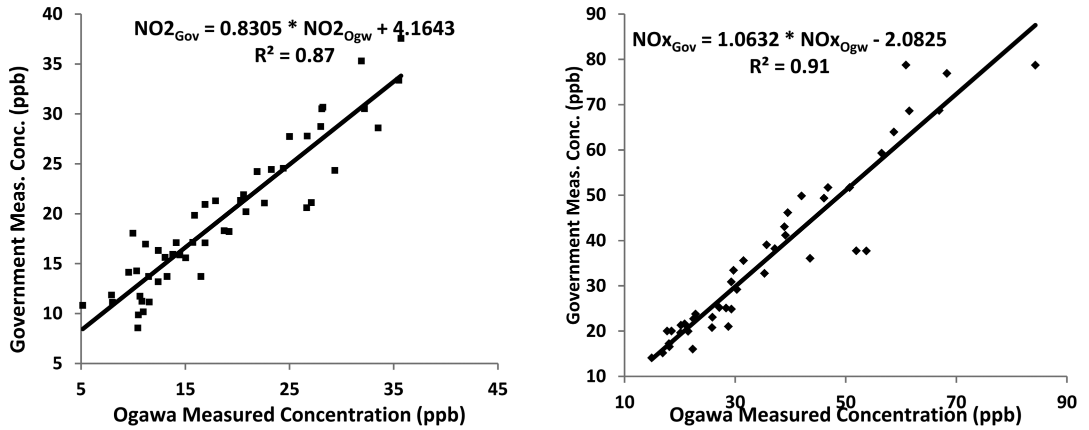

Figure 3. Agreement between the government monitoring and Ogawa monitoring at the colocated sites.

Table 1. Modeling the Effect of Policy Regulations on Pollutant Concentrations for NO_2 While Controlling for Traffic, Cargo Volume, weather Conditions, Season, and Region[a]

		coefficient	SE	*t* value	*p* value
no interaction (R^2 = 0.93)	(intercept)	31.1658	2.134	14.61	<0.001
	condition: GMCs	4.5906	0.598	7.68	<0.001
	condition: NGMC	1.9323	0.612	3.16	0.002
	period: post-policy	−5.5782	0.229	−24.36	<0.001
	precipitation (in.)	−1.5157	0.247	−6.14	<0.001
	temp (°F)	−0.0348	0.031	−1.13	0.259
	wind speed (mph)	−2.0274	0.248	−8.18	<0.001
	weighted cargo (TEU/km)	0.000004	0.000003	1.40	0.162
	AADT	0.00001	0.000003	4.11	<0.001
	season: spring	−0.9453	0.345	−2.74	0.006
	county: Los Angeles	7.2839	0.624	11.68	<0.001
with interaction (R^2 = 0.93)	(intercept)	30.5478	2.143	14.25	<0.001
	condition: GMCs	6.2383	0.897	6.96	<0.001
	condition: NGMCs	3.0293	0.925	3.27	0.001
	period: post-policy	−4.8130	0.391	−12.30	<0.001
	precipitation (in.)	−1.5829	0.246	−6.44	<0.001
	temp (°F)	−0.0402	0.031	−1.31	0.189
	wind speed (mph)	−2.0156	0.247	−8.17	<0.001
	weighted cargo (TEU/km)	0.000004	0.000003	1.43	0.154
	AADT	0.00001	0.000003	4.11	<0.001
	season: spring	−0.9589	0.342	−2.80	0.005
	county: Los Angeles	7.3431	0.628	11.69	<0.001
	condition: GMCs × period: post-policy	−1.2959	0.519	−2.50	0.013
	condition: NGMCs × period: post-policy	−0.8892	0.543	−1.64	0.101

[a]The reference group for goods movement corridor (GMCs) and non-GMCs (NGMCs) is control area (CTRLs); the reference group for post-policy period is pre-policy period. Bay Area is the reference group for county. Fall is the reference group for season.

for Los Angeles and Alameda for 2004−2005 (Alameda), 2006−2007 (Los Angeles), and 2012−2013 (Alameda and Los Angeles). For NO_2, 56 and for NO_X 50 colocated samples were retrieved (in Alameda, Ogawa was only used to measure NO_2 in the 2004−2005 pre-policy period). Figure 3 indicates that Ogawa-measured concentrations correlated well with government measurements (R^2 = 0.87 for NO_2 and 0.91 for NO_X), with NO_2 being slightly underestimated and NO_X being slightly overestimated.

3.2. Linear Mixed Effects Modeling Results. The linear mixed effects modeling results for NO_2 and NO_X are shown in Tables 1 and 2. In the model without interaction terms, after controlling for traffic density, cargo volume, weather, and season of sampling, the adjusted mean pollutant concentrations were 5.6 [±0.2 standard error (SE)] ppb lower for NO_2 and 20.1 (±1.1) ppb lower for NO_X in the post-policy period compared with the pre-policy period. NO_2 and NO_X concentrations were 4.6 and 16.5 (±2.6) ppb higher in GMCs than in CTRLs; in NGMCs, they were 1.9 (±0.6) and 5.6 (±2.7) ppb higher than in CTRLs areas. We also found greater precipitation and higher wind speed to be associated with lower NO_2 and NO_X concentrations, likely due to dampening and dispersion effects. As expected, the total number of vehicles traveled on highways and connecting roadways was positively associated with NO_2 and NO_X concentrations. Interestingly, ship cargo volumes did not significantly impact NO_2 and NO_X concentrations. Lower NO_2 and NO_X concentrations in the spring season (rainy season) and higher concentrations in Los Angeles were observed.

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Table 2. Modeling the Effect of Policy Regulations on Pollutant Concentrations for NO_X while Controlling for Traffic, Cargo Volume, Weather Conditions, Season, and Region

		coefficient	SE	*t* value	*p* value
no interaction (R^2 = 0.91)	(intercept)	119.7145	17.118	6.99	<0.001
	condition: GMCs	16.5153	2.603	6.35	<0.001
	condition: NGMCs	5.6098	2.699	2.08	0.038
	period: post-policy	−20.0842	1.117	−17.99	<0.001
	precipitation (in.)	−2.1494	1.130	−1.90	0.057
	temp (°F)	−0.7159	0.254	−2.82	0.005
	wind speed (mph)	−9.0078	1.051	−8.57	<0.001
	weighted cargo (TEU/km)	0.00002	0.00001	1.79	0.074
	AADT	0.0001	0.00001	4.97	<0.001
	season: spring	2.2594	2.791	0.81	0.418
	county: Los Angeles	19.6691	3.135	6.27	<0.001
with interaction (R^2 = 0.91)	(intercept)	121.7994	16.761	7.27	<0.001
	condition: GMCs	30.5738	4.252	7.19	<0.001
	condition: NGMCs	9.1136	4.448	2.05	0.040
	period: post-policy	−15.5481	1.766	−8.80	<0.001
	precipitation (in.)	−2.7320	1.116	−2.45	0.014
	temp (°F)	−0.8329	0.250	−3.33	0.001
	wind speed (mph)	−9.0094	1.032	−8.73	<0.001
	weighted cargo (TEU/km)	0.00002	0.00001	1.84	0.066
	AADT	0.0001	0.00001	4.99	<0.001
	season: spring	1.2884	2.744	0.47	0.639
	county: Los Angeles	20.1594	3.135	6.43	<0.001
	condition: GMCs × period: post-policy	−10.1561	2.449	−4.15	<0.001
	condition: NGMCs × period: post-policy	−3.1693	2.569	−1.23	0.217

After taking into consideration the interaction between location category and policy period, the above-described associations basically remained the same. The adjusted mean pollutant concentrations were 4.8 (±0.4) and 15.5 (±1.8) ppb lower in the post-policy period compared with the pre-policy period for NO_2 and NO_X. In GMCs and NGMCs, the pollutant concentrations of NO_2 and NO_X were significantly higher than in CTRLs, with respective differences of 6.2 (±0.9) and 3.0 (±0.9) ppb for NO_2 and of 30.6 (±4.3) and 9.1 (±4.4) ppb for NO_X. The interaction terms showed that reductions of both NO_2 (mean = 1.3 ppb and SE = 0.5 ppb) and NO_X (mean = 10.2 ppb and SE = 2.4 ppb) from the pre- to post-policy period were statistically significantly larger in GMCs than reductions in CTRLs while controlling for potential confounding factors, such as traffic, cargo volume, and weather. While we also observed reductions in NGMCs between the pre- and post-policy period, the interaction term between NGMCs and policy period was not statistically significant (p = 0.1 for NO_2 and 0.2 for NO_X).

4. DISCUSSION AND CONCLUSIONS

This paper identifies differential improvements in air quality across three traffic areas due to goods movement regulatory actions. We classified locations of interest for pre- and post-policy interventions according to three categories, specifically, GMCs, NGMCs, and CTRLs. Our results suggest that the goods movement regulations implemented in 2006 and 2007 in California by CARB are achieving the desired results. After controlling for traffic density on highway and connecting roadways, cargo volumes in the ports, weather conditions, and season of sampling, we found that the reduction of pollutant concentrations in goods movement corridors from the pre-policy period to the post-policy period was statistically significantly greater than corresponding reduction in background control areas, and these associations held true for both NO_2 and NO_X. In nongoods movement corridors, reductions were greater than in background control areas; however, they were not statistically different.

We focused on improvement of air pollution due to policies regulating emissions from goods movement measured using the standard traffic markers NO_2 and NO_X. The research findings are consistent with other relevant studies that identified significant reductions in emissions and air pollutant concentrations due to regulatory actions in California and elsewhere.[11,36−41] Contributing factors likely include (1) a general temporal trend due to changes in weather conditions and other unknown factors, (2) the economic downturn of 2008, and (3) implementation of emission reduction strategies. A previous study found that if emissions follow a business-as-usual pattern, the level of pollutant concentrations in California would increase, not decrease.[42] After controlling for confounding from weather conditions, including precipitation, temperature, wind speed and season of sampling, we still found significant reductions in air pollution from the pre-policy to the post-policy period. Though we did not consider the impact of a full set of weather factors, like mixing height and stability of atmosphere, we expect that precipitation, temperature, and wind speed would capture the main weather impact from the pre-policy period to the post-policy period. In addition, we expect that comparing concentrations at the same time across the three traffic areas made confounding from weather conditions unlikely due to the fact that the three traffic areas were broadly affected by the same weather. This finding is strengthened by the relatively larger reduction in the GMCs than in other areas, either busy roads without truck traffic or background residential areas. The temporal trends would be unlikely to show punctuated spatial variation, in agreement with the expectation of relatively larger reduction in GMCs. In our

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modeling process, we also controlled for the impact of the economic downturn in 2008 using total traffic counts from the roadways and cargo volumes from the ports and still identified significant policy period effects that were probably not solely attributable to the effects of the economic recession. We understand that, during the post-policy period, both the heavy duty vehicles and the passenger cars reduced pollutant emissions; however, we did not include the reduction in NO_X emissions in GMCs due to the improvements in the passenger cars' emissions rate in our models. The emissions reduction in GMCs was mainly generated by improvements in emissions rates from heavy duty vehicles due to the fact that we observed much larger reduction in goods movement corridors than other areas, which would have likely had a higher proportion of light duty vehicles for the pre- and post-policy periods. These results thus corroborate the notion that policy interventions and not the economic down turn contributed to the reduction in air pollution. Our analysis distinguished three categories of areas to allow us to conclude that (1) concentration changes in the GMCs are mainly attributable to goods movement policies, given the significantly larger reductions in the GMCs compared to other areas; (2) changes in concentrations that have occurred on nontruck freeways are most likely attributable to more general mobile emission reduction policies; and (3) changes in concentrations that occurred in control areas most likely represent reductions in regional emissions due to more general policies. The latter two effects, however, may also have been influenced to a lesser extent by goods movement policies. The more general mobile emission reduction policies included, for example, the California Global Warming Solutions Act of 2006 (AB 32).[43,44] Though its focus is on curbing greenhouse gas emissions, the implementation of AB 32 is thought to simultaneously reduce emissions of traditional criteria pollutants in California.[45] The EPA rules on emissions from light duty vehicles (https://www3.epa.gov/otaq/ld-hwy.htm#regs) also contributed to the overall reduction of emissions in California, though those rules did not specifically target California. Though we contributed the reductions of TRAP in the goods movement corridors largely to CARB regulatory policies implemented in 2006–2007, the coincidence of the EPA nationwide diesel rules changes in 2007 and the CARB rules made it difficult, and perhaps impossible, to totally decouple them. We also understand that in estimating AADT, the actual traffic count might be overestimated, particularly for background stations when the nearest traffic counting station was used. Despite these caveats, it is very likely that the regulatory policies aimed at removing big on-road polluters did help improve the air quality for California residents, with greater improvements for those living close to goods movement corridors.

For the more than 50 saturation sampling sites that were colocated with government continuous monitoring for 2004–2005, 2006–2007, and 2012–2013, we found that Ogawa-measured concentrations correlated well with government measurements (R^2 = 0.87 for NO_2 and 0.91 for NO_X), with NO_2 being slightly underestimated and NO_X being slightly overestimated. This indicates the usefulness of saturation monitoring for measuring NO_X concentrations for the region. For the more than 70 Ogawa monitors deployed in Los Angeles for 2012, the minimum, maximum, and standard deviation of the measured concentrations for NO_X were 8.1, 74.2, and 15.2 ppb. The Southern California Air Quality Management District maintains 15 continuous government monitoring sites, and they correspondingly measured the following values during the time period of the Ogawa sampling campaign, 14.1, 49.4, and 11.8 ppb, respectively. The lowest Ogawa-measured NO_X concentrations were 6 ppb lower than the corresponding lowest measured concentrations of the continuous government monitoring site. In contrast, the highest Ogawa-measured NO_X concentrations were 25 ppb higher than the corresponding highest measurement from the government site. Similar contrasts were identified for the 2006–2007 and the 2013 data (not shown). These findings demonstrate that the saturation monitoring network we employed is better suited for detecting small-area variations of pollutant concentrations, as we would expect.[31,46,47] In accountability studies estimating small-area variations, special purpose-designed monitoring networks are better suited for this purposes than reliance on government monitoring.

We found that the reductions in NO_X were much greater than the reductions in NO_2 in the GMCs. This was likely due to the diesel particular filter (DPF) retrofit program, which could reduce emission factors by more than 50% for black carbon (BC) and NO_X.[48] However, direct emissions of NO_2 can increase significantly, and on-road fleet tests have shown that the NO_2/NO_X emission ratio increased from 0.03 to 0.18. DPF-equipped trucks have substantially lower BC and higher NO_2 emission factors than trucks without DPFs. Selective catalytic reduction (SCR) systems for NO_X control should be used to significantly reduce emission factors, not only for BC and ultrafine particles (UFP), but also for NO_2.

The current study used a special purpose-designed air monitoring network to assess air quality improvements. These modeling techniques will be enhanced in the next phase of our study by integrating these special purpose-designed monitoring networks with the government continuous air quality monitoring system across the state to model statewide multiple year pollution surfaces for the pre-policy and post-policy periods. These statewide surfaces will then be available to be used to assess improvements in health outcomes among California Medicaid enrollees that might be related to the implementation of these goods movement policies.

In sum, our analysis demonstrated that reductions in the NO_2 and NO_X pollutants were observed in all areas, but they were significantly greater in GMCs compared to reductions observed in control areas. While we cannot rule out completely the influence of the Great Recession or other more general policies aimed at reducing other emissions, the results suggest that policies regulating goods movement are achieving the desired outcomes in improving air quality for the state, particularly in the goods movement corridors where most disadvantaged communities live.

AUTHOR INFORMATION

Corresponding Author

*Phone: (510) 643-0102; fax: (510) 642-5815; e-mail: jasonsu@berkeley.edu.

Notes

The authors declare no competing financial interest.

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