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Impact of Temporary Freeway Closure on Regional Air Quality: A Lesson from Carmageddon in Los Angeles, United States

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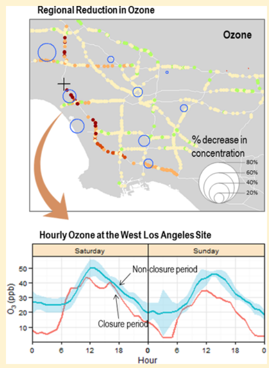
Supporting Information

ABSTRACT: Large cities in the United States face multiple challenges in meeting federal air quality standards. One difficulty arises from the uncertainties in evaluating traffic-related air pollution, especially the formation of secondary pollutants such as ozone and some particulate matter. Current air quality models are not well suited to evaluate the impact of a short-term traffic change on air quality. Using regional traffic and ambient air quality data from Southern California, we examine the impact of a two-day freeway closure on traffic and several criteria air pollutants (CO, NO_2, O_3, PM_{10}, $PM_{2.5}$). The results indicate that regional traffic decreased about 14% on average during the closure. Daily average $PM_{2.5}$ levels decreased by about 32%, and daily 8 h maximum ozone levels decreased by about 16%. However, the daily 1 h maximum NO_2 concentration was higher at some sites during the closure. Despite the mixed results with NO_2, this study provides empirical evidence to support traffic reduction as an effective strategy to address chronic air pollution problems, especially with regard to ozone, in Southern California.



■ INTRODUCTION

In the United States, the National Ambient Air Quality Standards (NAAQS) provide a regulatory framework for managing local and regional air quality. Yet local governments in large metropolitan areas face multiple challenges in meeting the federal standard. One difficulty arises from the uncertainties in assessing air pollution from mobile sources. The current air quality assessment framework yields useful estimates for long-term policy intervention. However, existing air quality models prove less accurate for evaluating short-term impacts due to varying atmospheric conditions, traffic patterns, and other anthropogenic factors. For example, simulation-based studies often suggest that certain land use and transportation planning can significantly improve regional air quality.[1,2] However, researchers using regression-based models find that such strategies may actually worsen localized emissions and exposure in certain neighborhoods.[3,4] In particular, at the local level, simulation models may not accurately estimate local pollutant concentrations because of limited data quality and variability in local traffic and atmospheric conditions.[5]

Instead of using models, researchers have studied natural experiments to assess targeted interventions. In Dublin, Ireland, Clancy et al. investigated the long-term effect of coal sale ban and found a 50% reduction in pollutant concentrations.[6] Hedley et al. also assessed the effects of restriction on sulfur-containing fuel in Hong Kong and found reduced pollutant concentrations up to 70%.[7] Similarly, Friedman et al. examined the traffic management surrounding the 1996 Atlanta Olympic Games and found a significant correlation between morning rush hour traffic and various criteria pollutants.[8] The daily peak ozone concentration decreased by 28% during the 17 days of the Olympic Games. In New York City, Whitlow et al. examined the short-term effect of traffic exclusion and observed little change in particulate matter (PM) mass concentrations but found a 58% reduction in ultrafine particle number

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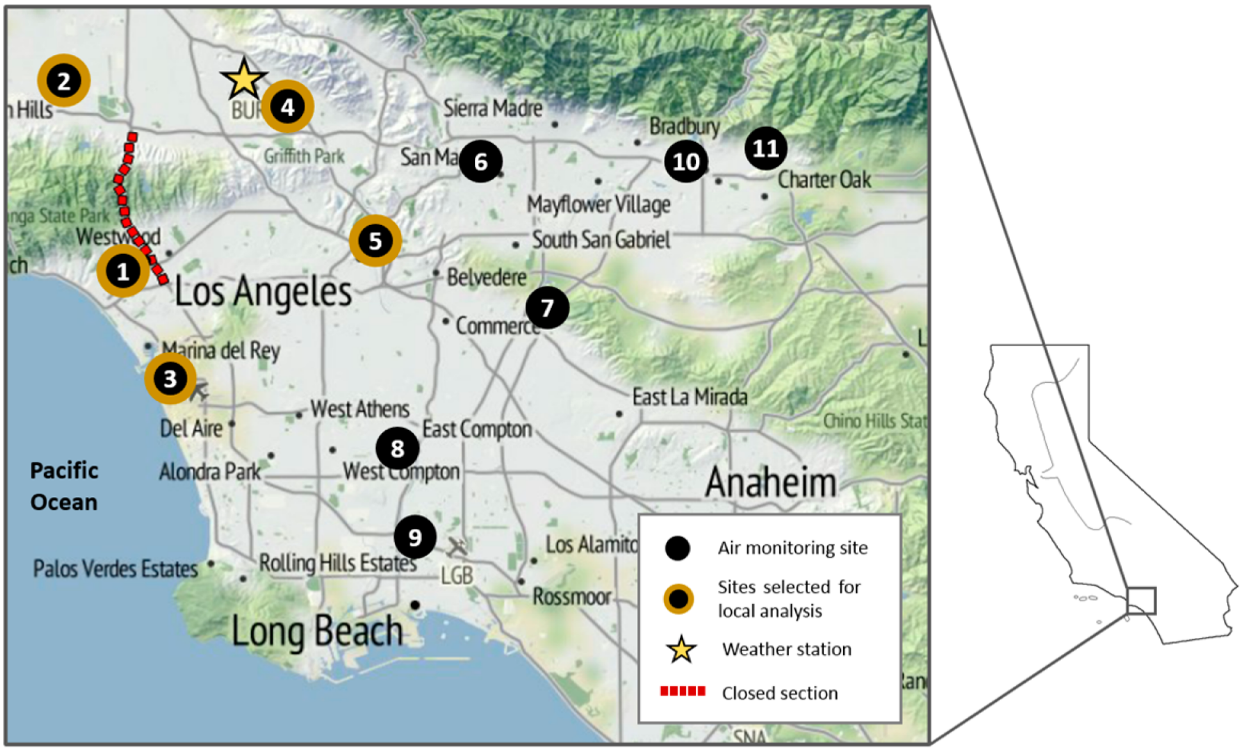

Figure 1. Map of study area. Air monitoring sites: (1) West LA, (2) Reseda, (3) LA Airport, (4) Burbank, (5) Downtown LA, (6) Pasadena, (7) Pico Rivera, (8) Compton, (9) Long Beach, (10) Azusa, (11) Glendora.

concentrations.[9] Compared to model-based studies, natural experiments allow more direct assessment of policy impact. However, they are not without limitations. When a study period is long, they are subject to many confounding factors, such as macroeconomic, technology, cultural, and demographic changes. Even when the study period is short, limited geographic scale, meteorological variability, and other unknown anthropogenic activities make it difficult to isolate the true impact of traffic on air pollution.[10]

In order to address this gap, we investigate a temporary freeway closure on local and regional air quality. From June 16 to 17, 2011 (Saturday and Sunday), a 15 km segment of Highway I-405 was closed for construction. The freeway closure, also known as "Carmageddon", offers a unique opportunity to assess the impact of traffic-related emissions on air quality. It also allows for examining the effect of a short-term closure on air pollution. According to a recent report, freeway traffic decreased across the region.[11] However, changes in local traffic near the closure site were mixed: traffic decreased on some arterials but increased on others.

To our knowledge, only one study has investigated the impact of Carmageddon on air pollution.[12] Using fixed-site and mobile measurements in the area immediately surrounding the construction site, the researchers examined the trends of various pollutants, including ultrafine particles, black carbon, polycyclic aromatic hydrocarbons, $PM_{2.5}$, and carbon dioxide. They found substantial reductions in concentrations of these pollutants 50 m downwind of the closure site: 83% in particle number concentration, 36% in $PM_{2.5}$ mass, and 62% in black carbon. They also found sizable reductions (18−36%) in ambient $PM_{2.5}$ concentrations at eight monitoring stations across the South Coast Air Basin. While their study is useful to understand the short-term traffic impact on near-roadway particle emissions, it provides little information regarding secondary pollutants, such as ozone and nitrogen dioxides, which are critical for regional air quality management.

The purpose of this study is to investigate the impact of a two-day closure of a major freeway on ambient concentrations of important criteria pollutants, including region-wide ozone levels. Despite significant air quality improvement in Los Angeles over the past decades, the U.S. EPA still classifies Los Angeles as an "extreme" nonattainment area for ozone. Controlling ozone in highly urbanized areas like Los Angeles is very challenging because ozone is a secondary pollutant whose concentrations depend on emissions of precursors, such as volatile organic compounds and NO_x. Understanding how ozone responds to traffic reduction during Carmageddon provides useful information for developing effective policies to control ambient ozone levels in the greater Los Angeles region.

■ METHODS AND MATERIALS

Study Area and Time Period. This study compares the difference in regional traffic and air pollution between typical days and the Carmageddon days at 11 air monitoring stations in the South Coast Air Basin (Figure 1). To minimize seasonal effects, the present study focused on three summer months (June−August). The *closure period* was defined as 2 days of the freeway closure (July 16−17, 2011, Saturday and Sunday). The comparable *nonclosure period* was defined as approximately 6 weeks before and 6 weeks after the closure period (June 1−July 15, 2011 and July 18−August 31, 2011). As the closure took place on a weekend and previous work has shown that emissions differ between weekdays and weekends, the analysis considered only weekends and not weekdays during the 3 month study period.[13] R statistical software was used for all statistical analyses and ArcGIS 10.1 for mapping.[14,15] Also, MySQL database software was used to process a large volume of traffic data covering the entire South Coast Air Basin.[16]

Table 1. Weekends with Similar Meteorological Conditions to Those during the Closure Period[a]

		temp. (°C)		wind speed (kph)		wind direction (deg)	
status	selected weekends	mean	s.d.	mean	s.d.	mean	s.d.
nonclosure	6/25/2011–6/26/2011	20.9	1.4	9.3	1.0	128	19
	7/09/2011–7/10/2011	22.2	1.8	11.1	0.5	148	5
closure	7/16/2011–7/17/2011	20.5	1.7	8.1	0.1	116	17
nonclosure	7/23/2011–7/24/2011	21.6	1.1	8.7	1.0	113	4
	7/30/2011–7/31/2011	22.0	1.6	8.2	0.8	130	21
	8/06/2011–8/07/2011	20.2	0.0	9.6	0.6	123	9
	8/13/2011–8/14/2011	20.8	1.1	9.4	0.4	117	23
	8/20/2011–8/21/2011	19.7	0.1	8.8	2.2	133	56

[a]Note: There was no precipitation during the study period. Data source: daily meteorological data from CARB's AQMIS.

Meteorological Data. To ensure similar meteorological conditions between the closure and the nonclosure periods, we developed and applied criteria for days considered to be comparable based on temperature, precipitation, wind speed, and wind direction. Daily meteorological data were obtained from the Air Quality and Meteorological Information System (AQMIS) maintained by the California Air Resources Board. The weather station at Burbank Airport, located approximately 16 km northeast of the closure center, was selected for this study. A comparison with results from other six weather stations in the South Coast Basin showed little or no differences compared to the results based on the Burbank weather station (Table S1, Supporting Information). Because meteorological data from other weather stations were sparse and inconsistent, the Burbank weather station, which had more comprehensive data, was chosen as the most representative proxy for regional meteorological conditions. Using the daily meteorological data from the Burbank station, we averaged the data over entire weekends to compare Saturday and Sunday together rather than separately. The following criteria were used to identify nonclosure weekends with similar weather conditions as the closure weekend.

(1) Mean temperature within ±3 °C.
(2) Mean wind speed within ±3 km/h (kph).
(3) Mean wind direction within ±45° (degrees).
(4) Mean precipitation within ±0.25 mm.

Table 1 shows the meteorological conditions during the closure and nonclosure periods that met the criteria. This screening method yielded seven weekends with similar meteorological conditions to those on the closure weekend. The average temperature on these weekends varied from 19.7 to 22.2 °C. Average wind speed ranged from 8.1 to 11.1 kph and the wind direction from 113° to 148°. No precipitation occurred during the study period, as is typical for Southern California this time of year.

Traffic Data. Traffic data come from the Performance Management System (PeMS) of the California Transportation Department (CalTrans). PeMS maintains approximately 11000 traffic detectors covering 5400 miles of freeway across the 12 districts in California. District 7, which serves Los Angeles and Ventura Counties, has over 4000 detectors sensing traffic every 30 s.[17] The data are aggregated to produce hourly and daily traffic flow per segment, a section of freeway between the midpoints of three contiguous loop detectors. It is assumed that the center loop detector represents the common traffic flow which was assumed to be constant for each segment.[17] Caltrans uses an algorithm to impute missing or bad data from the raw sensor data and records "percent observed" parameter to indicate the proportion of observed points to be determined as "good" data.[18] Thus, we only included traffic count data with a "percent observed" value greater than 50%.

To assess the regional traffic impact of the closure, we selected all traffic data covering the entire western part of South Coast Air Quality Management District. For a full traffic analysis, it is necessary to investigate local traffic and transit ridership. However, transit data were not available at the time of the investigation because a substantial portion of data was missing on the closure weekends. Also, data on surface-level traffic were sparse and unreliable for use in our study. Given these limitations, we assessed regional traffic impact by comparing the average traffic flow between the closure and nonclosure periods. In addition, a site-specific analysis measured hourly changes in traffic and pollutant concentrations for five air quality monitoring stations near the closed segment of the freeway (Figure 1). Trends in local traffic around air monitoring stations were estimated by averaging hourly traffic volume data from all detectors within a 5 km radius of each monitoring station.

The outcome measure for traffic was a percentage change in average regional traffic volume (across traffic nodes) relative to nonclosure weekends. Because the distribution was right-skewed and non-normal, we chose a nonparametric Wilcoxon rank-sum test (also called Mann–Whitney *U* test) to evaluate differences between nonclosure and closure periods.

Air Pollution Data. Ambient concentrations of five air pollutants (CO, NO_2, O_3, PM_{10}, $PM_{2.5}$) came from the U.S. Environmental Protection Agency's Data Mart for 11 air quality monitoring stations across the South Coast Air Basin (Figure 1). Most air monitoring sites do not measure all five air pollutants, but the 11 stations measure both NO_2 and ozone almost all throughout the study period. NO_2, a component of nitrogen oxides (NO_x), is associated with local on-road vehicle emissions, whereas ozone gradually forms in the atmosphere, reflecting a larger, regional-scale influence. Because of this difference in the geographical influence of the two pollutants, studying their response illustrates the impacts at the local and regional scales. For the regional analysis, we chose to use temporal averaging periods corresponding to the NAAQS: daily maximum 8 h concentration for CO and ozone, daily maximum 1 h concentration for NO_2, and daily mean concentration for PM_{10} and $PM_{2.5}$. The average concentrations of each air pollutant for each of the 11 stations were collected and aggregated into two groups (nonclosure period vs closure period). We also performed a site-specific analysis for five monitoring stations near the closure (Figure 1). The site-specific analysis used average hourly pollutant concentrations from the Air Quality and Meteorological Information System

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Table 2. Percentage Change in Regional Traffic and Air Pollution[a]

variable	measurement	unit	nonclosure (m_1)	closure (m_2)	P	% Δ $(m_2 - m_1)/m_1$
traffic	daily mean	vehicle/segment/day	43 062	37,090	<0.001***	−14%
CO	daily max 8 h	ppm	0.34	0.32	0.141	−6%
NO_2	daily max 1 h	ppb	18.90	19.15	0.926	1%
PM_{10}	daily mean	mg/m^3	30.55	25.70	0.268	−16%
PM_{25}	daily mean	mg/m^3	15.88	10.73	0.009***	−33%
O_3	daily max 8 h	ppb	57.95	48.89	0.090*	−16%

[a]Statistical significance (Wilcoxon rank-sum test): *$p < 0.10$; **$p < 0.05$; ***$p < 0.01$. Data sources: daily traffic counts from Caltrans' PeMS; daily NAAQS measurements from U.S. EPA's Data Mart.

(AQMIS) for each of the five monitoring stations. These five sites were the ones most likely to be impacted by the closure because of their proximity to it. Ozone at farther downwind sites, Azusa (site 10) and Glendora (site 11), was not significantly different on the closure weekend (Figure S1, Supporting Information).

The outcome measure of the air pollution data was a percentage change in average pollutant concentrations on a closure weekend relative to nonclosure weekends. We used the same nonparametric tests used for traffic analysis to compare mean differences between closure and nonclosure periods. For the regional analysis, the differences between closure and nonclosure weekends were first computed for each of the 11 monitoring sites, and these differences were averaged for the whole region. For the site-specific analysis, the mean percentage differences were compared for each of the selected sites.

■ RESULTS AND DISCUSSION

Regional Analysis. Table 2 summarizes regional traffic and air quality during the nonclosure and closure periods. In general, a noticeable reduction in both traffic and pollutant levels occurred during the closure period. Average traffic flow, defined as the number of vehicles per segment per day, dropped from 43062 to 37090, a 14% reduction (significant at the 0.1% level). Concentrations of four of the pollutants were lower during the closure. $PM_{2.5}$ had the largest reduction (33%), followed by ozone (−16%), PM_{10} (−16%), CO (−6%), and NO_2 (1%). The traffic and $PM_{2.5}$ levels were significantly different at the 1% level between the closure and the nonclosure weekends. Ozone levels were also lower during the closure, but the difference was just marginally significant. The decreases in CO and PM_{10} were not statistically significant. Interestingly, NO_2 showed an increase of 1%, but this difference was not statistically significant.

Figure 2 shows maps with the percentage change in traffic and air pollution between nonclosure and closure days. The maps in the first row show an overall reduction in traffic throughout the entire region (Figure 2a). The north and south ends of the closed segment along I-405 showed the greatest reduction in traffic. However, there was a small increase in traffic near the intersection of I-405 and I-101. This increase in traffic is largely offset by a decline in traffic along the westbound lanes of I-101. During the nonclosure period, the westbound lanes of I-101 usually had severe congestion reaching over 120000 vehicles a day (data set from the current study). However, there was much less traffic along these corridors during the closure. Traffic around the southbound lanes of I-405 also decreased substantially by over 80%. However, traffic volume increased near the intersection of I-10 and I-405, indicating some spillover effects of detoured traffic from the closed freeway. In general, traffic continued to decrease toward the south of the I-405 corridor.

Figure 2b−f shows the percentage change in the concentrations of five pollutants quantified by hourly measurements from the California Air Resources Board. Throughout the region, there were consistent reductions in all pollutant concentrations even at sites distant from the closure. Ozone and CO showed the most noticeable decline across the monitoring stations (Figure 2b and 2f). Near the closed segment, ozone was 30% lower (Figure 2f) and CO was 12% lower (Figure 2b). While no PM_{10} and $PM_{2.5}$ measurements were available near the closed segment, there was a consistent reduction across the region, where data are available (Figure 2d and 2e). Increases in NO_2 in excess of 30% near the closure were unexpected (Figure 2c). However, further investigation of NO_2 revealed that there may be a trend of increasing and then gradually decreasing NO_2 going from west to east. We found a statistically significant decrease in NO_2 concentrations during the closure weekend when only the eastern half of the domain was considered in the analysis (Figure S2, Supporting Information). The increase in NO_2 near the closure site was not statistically significant.

Site-Specific Analysis. *Daily Change in Traffic and Air Pollution.* Table 3 summarizes the difference in traffic and air pollutant concentrations between the closure and the nonclosure weekends for each of the five monitoring sites near the closure center. The first row in the table represents percentage changes in mean hourly traffic flow within a 5 km radius buffer of each monitoring station. In order of increasing distance, the West Los Angeles site is 5 km away from the center, followed by Reseda (13 km), LA Airport (16 km), Burbank (18 km), and Downtown LA (23 km). The magnitude of change in traffic generally followed this order. For example, the reduction in traffic was 46% at the LA Airport site, compared to the 8% at the Downtown LA site. On the basis of the measured decrease in traffic and knowledge about the emission inventory, we can estimate the expected decrease in primary pollutant concentrations. This estimate assumes that emissions from on-road mobile sources are directly proportional to traffic volume, that the basin-wide inventory is spatially homogeneous, and that emissions from different sources mix similarly in the atmosphere. According to the California Air Resources Board, on-road mobile sources accounted for 53% of CO emissions and 59% of NOx emissions in the South Coast Air Basin in 2012, the closest year for which the emission inventory is available.[19] Thus, a 46% reduction in traffic would produce a 24% and 27% reduction in ambient CO and NOx concentrations, respectively. However, this is a simplified analysis that does not take into account the many variables that could affect actual concentrations.

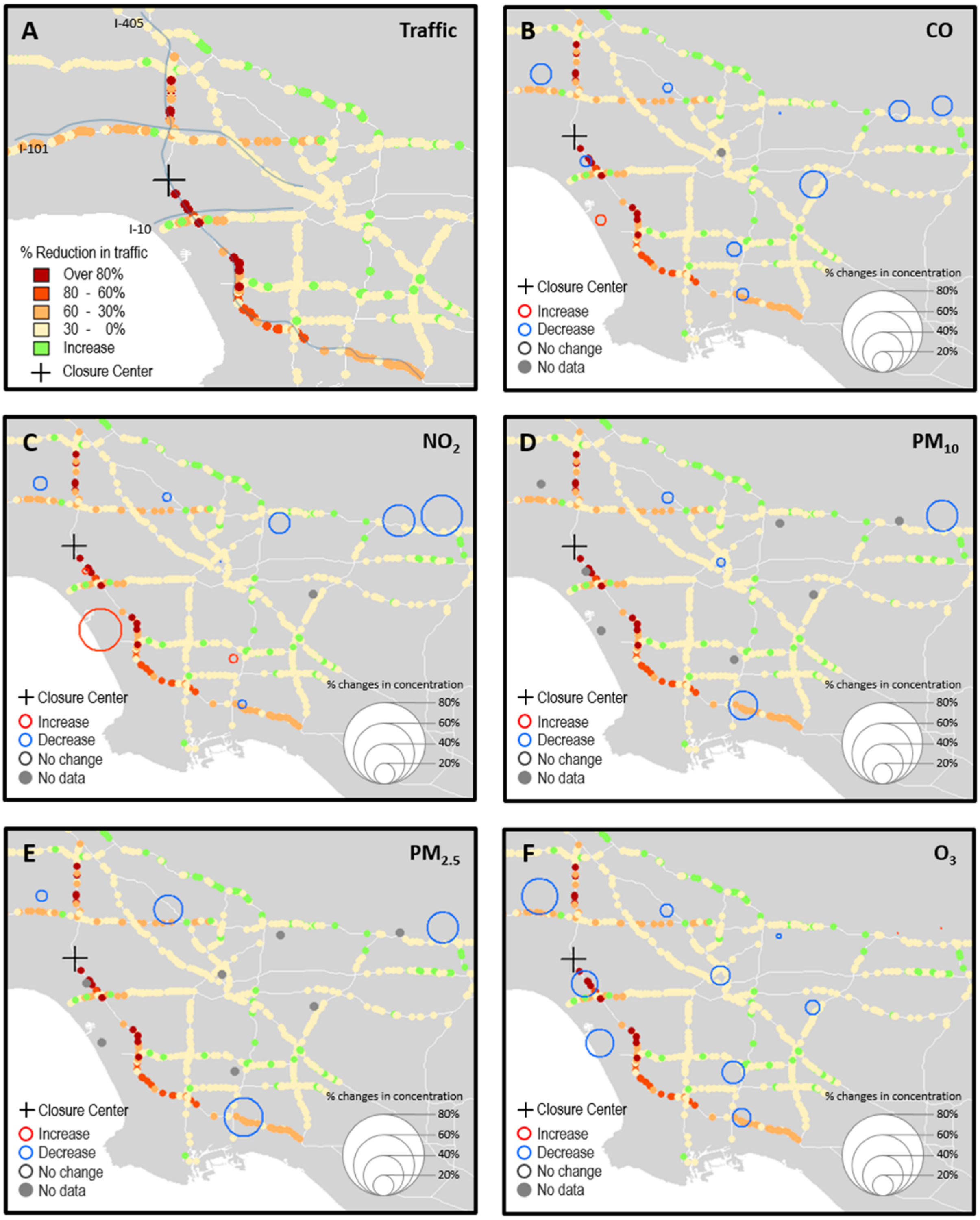

Figure 2. Percentage change in traffic and pollutant concentrations between nonclosure and closure periods: (A) %Δ in traffic during the closure, (B) %Δ in CO during the closure, (C) %Δ in NO_2 during the closure, (D) %Δ in PM_{10} during the closure, (E) %Δ in $PM_{2.5}$ during the closure, and (F) %Δ in ozone during the closure. Data sources: hourly traffic data from Caltrans' PeMS; hourly measurements from CARB's AQMIS.

At the five monitoring sites, concentrations of most pollutants based on hourly measurements were relatively lower during the closure weekend. CO levels were 8−15% lower, except for the LA Airport, where a 39% increase occurred. However, this increase was not statistically significant and may be an artifact of a step change in CO concentrations at this site in the end of June, when the baseline jumped from ∼0.15 to ∼0.00 ppm for reasons that are unknown. Where available, PM_{10} and $PM_{2.5}$ levels declined across the sites, and the differences were statistically significant. Across all the monitoring sites, ozone concentrations were significantly lower by 17−55%. Downtown LA had a substantial reduction in ozone (−22%) despite its marginal decrease in traffic (−8%). NO_2 concentrations were higher on the closure weekend at two

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Table 3. Difference in Traffic and Pollutants Within 5 km Buffer of Air Pollution Monitoring Site on Closure vs Nonclosure Weekends[a]

	West LA		Reseda		LA Airport		Burbank		Downtown LA	
variables	% Δ	*p*	% Δ	*p*	% Δ	*p*	% Δ	*p*	% Δ	*p*
traffic	−46%	<0.001***	−43%	<0.001***	−47%	<0.001***	−16%	0.009***	−8%	0.019**
CO	−12%	0.003***	−15%	0.001***	39%	0.103	−8%	0.100		
NO_2	19%	0.485	−8%	0.054*	45%	0.221	−4%	0.218	0%	1.000
PM_{10}							−10%	0.016**	−13%	0.105
PM_{25}			−13%	0.012**			−29%	<0.001***		
O_3	−30%	<0.001***	−55%	0.002***	−31%	<0.001***	−17%	0.056*	−22%	0.012**

[a]Distance from the closure center: West LA (5 km), Reseda (13 km), LA Airport (16 km), Burbank (18 km), Downtown LA (23 km). Statistical significance (Wilcoxon rank-sum test): *$p < 0.10$; **$p < 0.05$; ***$p < 0.01$. Data sources: hourly traffic data from Caltrans' PeMS; hourly measurements from CARB's AQMIS.

of the sites, West LA and LA Airport; however, these differences were not statistically significant. On the basis of the hourly data, NO_2 concentrations peaked at the very end of the closure period, near 11 p.m. on Sunday night, and there was a concomitant peak in CO at these sites. The following section describes hourly patterns in more detail.

Hourly Change in Traffic and Air Pollution. Analysis of hourly data allows examination of temporal trends underlying the results of the previous analyses. Figure 3 illustrates hourly traffic changes on Saturdays and Sundays between nonclosure and closure weekends at Burbank and West LA monitoring sites. Burbank and West LA were chosen for further analysis because they had the most complete measurements across all air pollutants and shared similar geographic and traffic environments with being close to the intersection of two major freeways. The figures depict hourly ozone, NO_2, and CO profiles. PM_{10} and $PM_{2.5}$ were not measured at both sites and hence are not presented here.

Both sites displayed a sizable reduction in traffic during the closure, especially between 10 a.m. and 8 p.m (Figure 3a). West LA experienced larger traffic reduction than Burbank, with a maximum hourly reduction of ~1500 vehicles/segment/hour. Usually congestion takes place during rush hour (typically 6−10 a.m., 4−7 p.m.), so the magnitude of traffic reduction during those hours is substantial. Despite the substantial drop in freeway traffic, changes in pollutant levels were mixed. Compared to the noticeable reduction in ozone over most hours at both sites (Figure 3d), CO and NO_2 levels were elevated during the first and last 6 h of closure (Figure 3b and 3c), even though freeway traffic was not.

In attempting to explain this anomaly, we offer two possibilities. First, the increase in NO_2 during the first and last 6 h of the closure may have resulted from drivers responding quickly to the construction schedule. Closure of onramps to I-405 began on Friday at 7 p.m., so traffic patterns must have shifted beginning at this time, and effects on air quality would have carried over into the early hours of Saturday. LA Metro, the agency in charge of the whole operation, announced that the construction will end earlier than originally scheduled.[20] In fact, the construction ended around Sunday at noon, and the entire section of the freeway was in full operation after much of the Sunday afternoon. The sudden rise in NO_2 levels on Sunday night may not be explained by the early reopening of the freeway because no radical changes in traffic occurred during that time. However, drivers may have responded preemptively to early closure and reopening of the freeway, especially around the neighborhoods near the closure site.

Second, increased NO_2 can be explained by the combination of wind effects and traffic emissions from nearby arterial streets during the closure. A close examination of wind parameters at the West LA site revealed that NO_2 decreased when it was upwind (approximately 9:00−18:00 on Saturday and Sunday) and increased when it was downwind (approximately 19:00−24:00 on Saturday and Sunday) (Figures S3 and S4, Supporting Information). Therefore, when it is downwind, NO_2 concentrations could have been affected by prevailing wind coming from nearby arterial streets running parallel to I-405. Previous studies have argued that traffic spillover onto surface streets did not occur, at least not enough to compensate for the traffic reduction on freeways.[11,12] However, another study has found statistically significant increases during the closure on three nearby arterials: Sepulveda Boulevard, Van Nuys Boulevard, and Overland Avenue.[11] Interestingly, all these arterials are located east of the closure site and running parallel to I-405. Freeway traffic diverted to these nearby arterials may explain the high levels of NO_2 at the West LA site in the first and last 6 h when the mean wind direction changed from southwesterly to northeasterly. Furthermore, the hourly CO level also follows the similar pattern as the changes in NO_2 concentrations (Figure 3d). Because CO is sensitive to local traffic activities, increasing CO levels during the first and last 6 h also suggest that traffic may have diverted to the surface streets running parallel to I-405 and contributed to the increase in NO_2 concentrations.

Limitations. The findings of this study are consistent with previous studies that traffic management has considerable impacts on local and regional air quality.[8,9,12,21] However, mixed results with NO_2 call for more investigation regarding how traffic influences localization of secondary air pollutants. Our use of ambient monitoring data is a limitation in this respect. Ambient concentration data allowed for examining the effects of the freeway closure on regional air quality. Yet, the ambient data provide little information about air quality at the fine-grained level. Another limitation with our study is that the ambient regulatory data are sparse and missing at some monitoring sites, which could potentially introduce errors in calculating the percentage change for specific sites. We made a trade-off between comprehensiveness and precision with our data, and our focus was to understand the regional response of criteria pollutants with respect to the short-term freeway closure. To achieve both precision and comprehensiveness, further studies could use a combination of a mobile monitoring platform and a regulatory monitoring data to better understand the complex behavior of secondary air pollutants, such as NO_2 and ozone.

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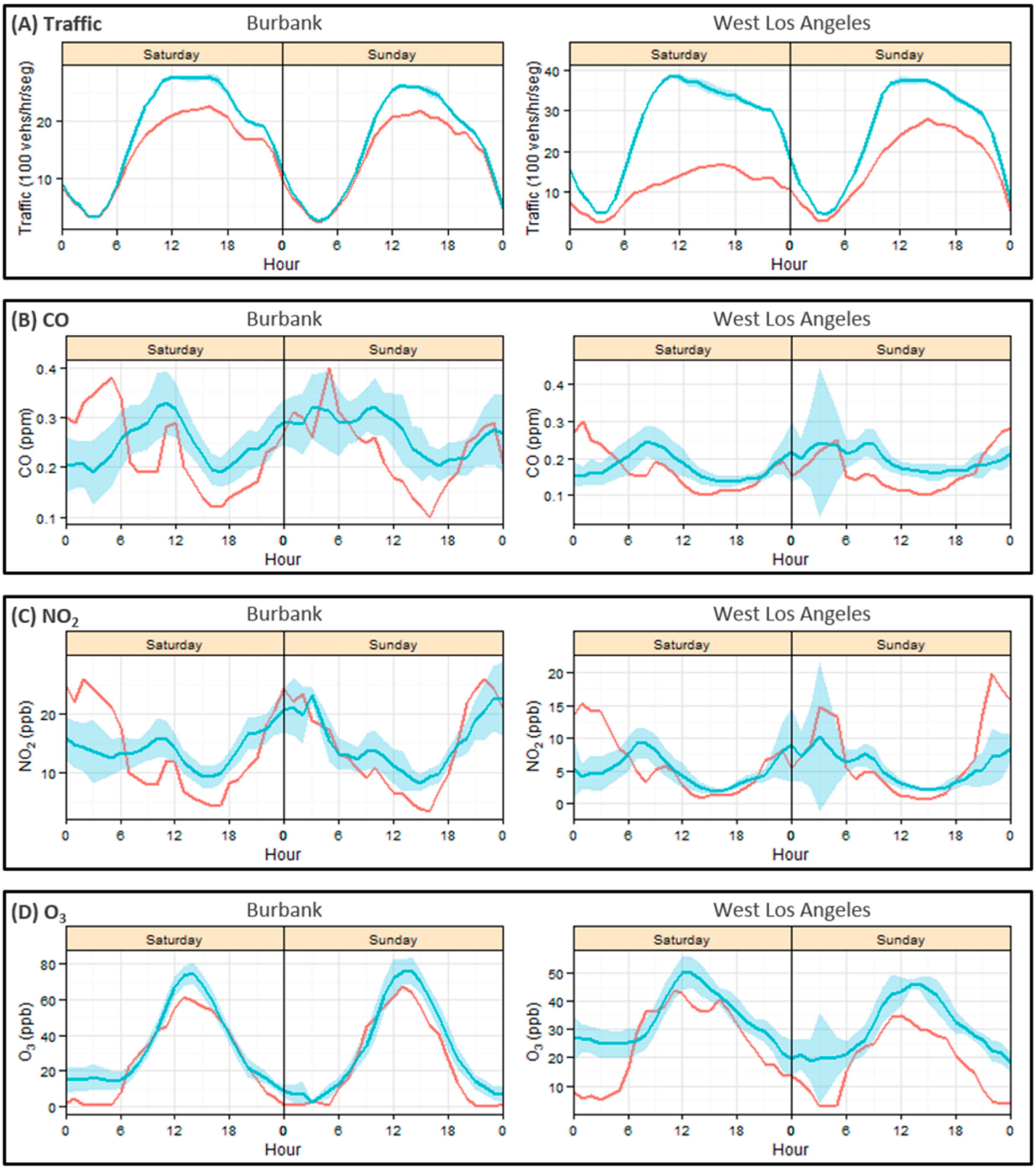

Figure 3. Hourly traffic, CO, NO_2, and ozone in Burbank and West Los Angeles on closure vs nonclosure weekends. (A) Hourly traffic change on weekends in Burbank and West Los Angeles. (B) Hourly CO change on weekends in Burbank and West LA. (C) Hourly NO_2 change on weekends in Burbank and West LA. (D) Hourly ozone change on weekends in Burbank and West LA. The red line represents the closure weekend, and the blue line represents nonclosure weekends. The blue shaded band represents the 95% confidence interval. Data sources: hourly traffic data from Caltrans' PeMS; hourly measurements from CARB's AQMIS.

Policy Implications. From an air quality management perspective, it is worth highlighting that the region-wide ozone levels substantially decreased during the closure period. If anything else, this is the most important finding from this study. The magnitude of decrease in ozone during the closure period is comparable to the typical increase in ozone on weekends compared to weekdays in the Los Angeles area.[22,23] Even though emissions of precursors are lower on weekends, reduced titration of ozone and increased formation of odd oxygen result in higher ozone on weekends in this region.[24] Results from Carmageddon suggest that, on average, the decrease in emissions associated with the closure period might have been large enough to eliminate the weekend ozone effect. The typical decrease in emissions from weekdays to weekends results in an increase in ozone concentration, but a larger Carmageddon-sized decrease in emissions may eliminate the increase in ozone. The air quality impacts of Carmageddon illustrate that reductions in emissions can bring down ambient

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ozone concentrations but that these reductions must be even larger than what was seen during the event to achieve lower ozone on weekdays. Despite decades of effort to meet the federal air quality standards, Los Angeles continues to rank as one of the most polluted regions in terms of ozone and traffic-related air pollution. Carmageddon provides a unique opportunity to assess the effectiveness of a simple intervention and thus be used as a basis for developing a region-wide emission reduction program. Unlike air quality models that pose many challenges for a posteriori evaluation, this study provides empirical evidence to show that even a short-term traffic exclusion can lead to a substantial air quality improvement across a large metropolitan area.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Comparison of results using meteorological data from other weather stations; impact of Carmageddon on ozone concentrations at the downwind sites; comparison of NO_2 between western and eastern halves of the domain; effects of wind on NO_2 concentrations. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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