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Separating the Air Quality Impact of a Major Highway and Nearby Sources by Nonparametric Trajectory Analysis

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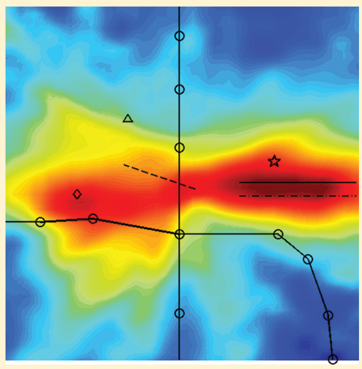
Supporting Information

ABSTRACT: Nonparametric Trajectory Analysis (NTA), a receptor-oriented model, was used to assess the impact of local sources of air pollution at monitoring sites located adjacent to highway I-15 in Las Vegas, NV. Measurements of black carbon, carbon monoxide, nitrogen oxides, and sulfur dioxide concentrations were collected from December 2008 to December 2009. The purpose of the study was to determine the impact of the highway at three downwind monitoring stations using an upwind station to measure background concentrations. NTA was used to precisely determine the contribution of the highway to the average concentrations measured at the monitoring stations accounting for the spatially heterogeneous contributions of other local urban sources. NTA uses short time average concentrations, 5 min in this case, and constructed local back-trajectories from similarly short time average wind speed and direction to locate and quantify contributions from local source regions. Averaged over an entire year, the decrease of concentrations with distance from the highway was found to be consistent with previous studies. For this study, the NTA model is shown to be a reliable approach to quantify the impact of the highway on local air quality in an urban area with other local sources.



INTRODUCTION

The main objective of this paper is to estimate the near roadway impact of a major urban highway and other nearby sources on air quality by applying a new receptor based modeling technique, Nonparametric Trajectory Analysis (NTA), to observations of black carbon (BC), carbon monoxide (CO), nitrogen oxides (NOx), and sulfur dioxide (SO_2). Source-oriented dispersion models and methods can also be used to estimate the concentrations of air pollutants near a roadway, but these models require *a priori* information about the location and magnitude of emissions from all sources in the study domain. NTA and other receptor-oriented approaches use ambient data collected at monitoring sites to identify and quantify the impact of sources.

Numerous studies have reported the effects of major highways on local air quality for a wide range of pollutants.[1] To isolate the impact of the highway, it is necessary to account for the impact of other air pollution sources that could possibly cloud the interpretation of data collected in the vicinity of the highway. One methodology for accounting for other sources is the background subtraction method, the concentrations at a monitoring station upwind of the highway are subtracted from (or compared to) concentrations at one or more receptor monitoring stations downwind. An alternative approach is to measure pollutant concentrations at several distances downwind of the highway and observe the rate of decrease with distance; this is the gradient method.[2−4] Of course, a major difficulty with both these

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methods is determining when the highway is upwind and when it is downwind of a monitor station, especially under light wind conditions. Wind speed and direction can vary on a time scale of minutes; periods of relatively constant winds that make the terms "upwind" and "downwind" meaningful must be carefully selected based on the variability of the wind direction. This often leads to the exclusion of most of the data, while NTA makes use of much more of the data. When properly applied, the background subtraction and gradient methods can be very useful. However, they cannot identify or quantify nonhighway sources as NTA does. These nonhighway sources may obscure the interpretation of data intended to determine the impact of a highway on local air quality.

Unlike the gradient and related methods, instead of working with a relatively small number of selected periods with winds in the right direction relative to a specific, single source, NTA constructs back-trajectories and concentrations covering all available data to estimate the localized influence of all air pollution sources in the area. In this case, "local" refers to within ∼5 km of the sampling stations. Obviously, this degree of spatial resolution requires measurements with time resolution finer than the standard 1-h averages. In this case, concentrations of species of interest and wind data were made on a 5-min average basis. Working with the totality of this data, NTA is able to determine the local geographical regions that are the source of high concentrations of pollutants observed at the monitor stations (i.e., receptors).

In the past, 1-h was the shortest time resolution commonly available for meteorology and air quality data. So that analysis using 1 or 5-min averages was out of the question. 1-min and 5 min average meteorological data are becoming more common. The automated weather stations at major airports and other locations report 2-min running averages every minute. Routine air quality data is often logged every 1 or 2 min but only reported as 1-h averages. But special studies such as the subject of this paper are increasingly taking short-time averaged data.

The NTA model and its application to measure the impact of a major highway on air quality in Las Vegas, NV are described below. Measurement data were collected at four sites transecting both sides of I-15, a major interstate in Las Vegas. The NTA estimates of the highway contribution are compared with the more conventional gradient method and are in reasonable agreement though the NTA model identified the presence of other sources of air pollution in addition to the interstate highway.

NTA METHODOLOGY

Nonparametric Trajectory Analysis (NTA) is a receptor-oriented model that uses ambient measurement data to quantify the effects of nearby sources on local air quality. The NTA model uses relatively short-time resolution data (1 to 5 min average) on pollutant concentrations and wind speed and direction to construct back-trajectories.[5] Making use of nonparametric regression, NTA calculates point estimates of the conditional expected value of a pollutant at a receptor provided the air parcel has passed through a specific point prior to reaching the receptor site.

Assume there are n back-trajectories with m points equally spaced in time along each trajectory arriving at a receptor. Let the points on the back-trajectories be given by (x_{ij}, y_{ij}) where $i = 1,...,m$ and $j = 1,...,n$, further let C_j be the concentration at the receptor at the start of the jth back-trajectory, then the NTA value at point

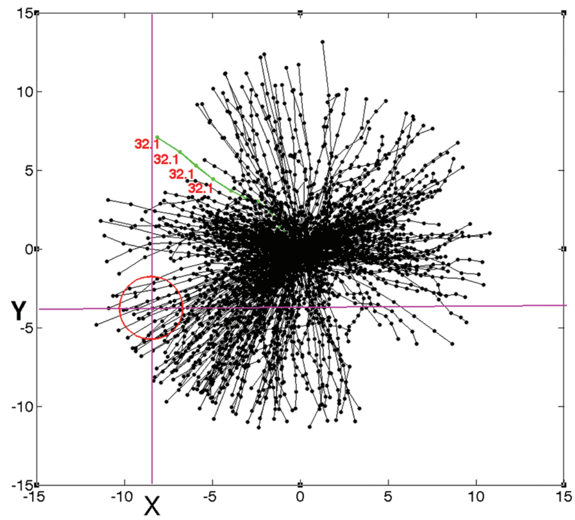

Figure 1. Back-trajectories (black lines) of air parcels arriving at a receptor site located at the origin (0, 0). Each point along a trajectory represents the location of the air parcel at 5-min intervals and is associated with the concentration observed when the trajectory arrives at the receptor site. The green line illustrates the two-dimensional trajectory of an air parcel arriving at the receptor site and the corresponding air pollutant concentration (32.1 ppb in this case). The NTA value for point (X,Y) is the weighted sum of the values associated with the trajectory points inside the red circle whose radius is the smoothing parameter (h).

(X,Y) is the expected value of concentration C given that air passes over point (X,Y) before reaching the monitoring station and is given by

$$\frac{\sum_{i=1}^{m}\sum_{j=1}^{n} C_j W_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{n} W_{ij}} \qquad (1)$$

where

$$W_{ij} = K\left(\frac{X - x_{ij}}{h}\right)K\left(\frac{Y - y_{ij}}{h}\right) \qquad (2)$$

and

$$\begin{aligned} K(u) &= 0.75(1 - u^2) \quad &&\text{for}|u| \leq 1 \\ K(u) &= 0 &&\text{otherwise} \end{aligned} \qquad (3)$$

Note that the weights W_{ij} are all non-negative and have a maximum value of $0.75^2 = 0.5625$. The smoothing parameter h is the radius of a circle centered at (X,Y) within which the expected value of concentration C is determined based on empirical data observed at a receptor (see Figure 1). The NTA value for point (X,Y) is the weighted sum of the values associated with the trajectory points within a radius of h (red circle in Figure 1). The weights for each trajectory point are based on the distance of the point from (X,Y).

In this work, the smoothing parameter, h, is 0.5 km. This means that a back trajectory must pass within a radius of 0.5 km of the analysis point (X, Y) to be included in the NTA calculation. NTA results are generally not very sensitive to the value of the smoothing parameter. The value of 0.5 km was arrived at

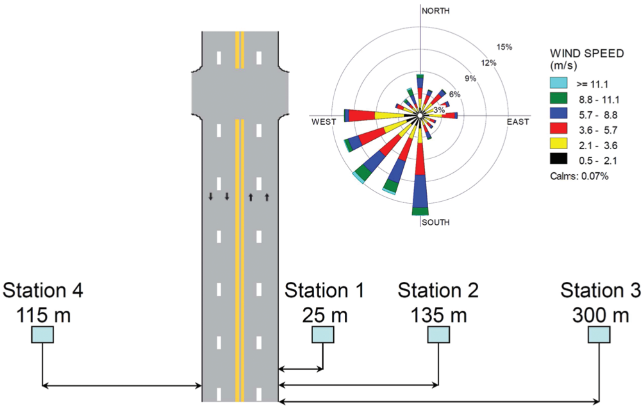

Figure 2. Schematic diagram showing the location and distances of monitoring stations from I-15. The annual wind rose shows the prevalence of winds from the south and west in the study area.

empirically as it gives results that are not too smooth or too rough. The smoothing parameter can be estimated by computationally intensive methods; however, these methods are time-consuming and give smoothing parameters that are in agreement with the much faster empirical methods. The NTA analysis points (X, Y) are defined on a 50×50 grid with the origin at the receptor and X and Y limits of -5 km and $+5$ km, thus the underlying grid resolution is 10 km $\div$ 50 = 0.2 km or 200 m. The effective resolution is twice this, or 400 m. Given the 500 m smoothing parameter, the effective minimum resolution of the NTA results in this study is about 500 m.

In addition to the smoothing parameter, the NTA model has the following major inputs. A matrix of x coordinates and a matrix of corresponding y coordinates of the points on the back-trajectories. These matrices are configured so that each column represents a trajectory. Associated with each of these columns is the concentration of the pollutant at the receptor at the time the trajectory reaches the receptor.

The NTA model is unique in using constructed back-trajectories on the scale of a few kilometers and meteorological data on the time scale of minutes to identify local source-receptor relationships. These back-trajectories are constructed using wind speed and direction observations that have both measurement error and natural variability. The effect of this uncertainty in wind speed and direction is increased uncertainty in the back-trajectories and an associated increase in the uncertainty of the NTA results. The errors in the NTA results in this paper include the effects of errors in the trajectories. The effect of the errors in the trajectories is to increase the overall error of NTA results by about 25 to 35%. These results and the exact methods for calculating the back−trajectories and associated errors are the subject of a paper now in preparation.

APPLICATION OF NTA TO LAS VEGAS DATA

The NTA results given below use 5-min averaged observations from a study to determine concentrations and variations in concentrations of mobile source related air pollutants as a function of distance adjacent to I-15, a heavily traveled freeway in Las Vegas, NV.[6] The annual average daily traffic (AADT) count is in excess of 150,000 vehicles. Data were collected at various distances on both sides of the freeway (Figure 2) to assess its impact on near-road air pollutant concentrations. Monitoring station 4 is located on the predominantly upwind side of the freeway and used to compare concurrently measured concentrations at three sites located on the predominantly downwind side of the freeway. The study was performed from December 2008−December 2009.

Table 1. Air Pollutants and Covariates Measured at Each Location Adjacent to I-15

pollutant or covariate	method
CO	NDIR
NO, NO_2, NOx	chemiluminescence
SO_2	fluorescence
black carbon	light absorption at 880 nm
wind speed/direction	sonic anemometer

Sample Collection and Analysis. Table 1 shows the measurement methods of the relevant data used in this paper.

Description of the Las Vegas Site. The study site is located in south Las Vegas along the I-15 freeway, just north of the intersection of I-215 and south of the Russell Road intersection. The site was selected after carefully considering numerous sites in the Las Vegas area.[7] The site is located in an area of mostly commercial properties. I-15 is mostly at grade in this area; however, the site is located adjacent to a cut section (i.e., below grade) with gentle slopes on each side of the freeway up to at-grade level where the monitors are located. The cut section allows a freight railroad spur line to pass over I-15. The railroad is located close to the site but is used infrequently (once per day). The McCarran International Airport is located about 1 km east and predominately downwind of the site.

NONHIGHWAY SOURCES IDENTIFIED BY NTA

In addition to the highway, the NTA results given below show that the monitoring stations are significantly impacted by nearby nonhighway sources. These are identified as a Local Industrial Area (LIA) west of the highway within 3 km of the monitoring stations and McCarran International airport with the main runway 1−5 km east of the highway and monitoring stations. The term "airport" is used here to represent all the sources east of the highway, but these are dominated by the emissions of aircraft, ground support vehicles, and general traffic associated with the airport. Like the "airport", the LIA is also a complex source. It includes many small manufacturing and construction related businesses. Many of these are located within 1 or 2 km of the I-215 interstate highway that runs east−west through the area. Thus, the LIA emissions include some I-215 emissions. Also, the LIA emissions will have some contribution from local vehicle traffic, especially diesel trucks. Thus, in the sections below, "nonhighway" sources means sources other than the I-15 highway, not exclusively nonvehicular sources. The following section describes how NTA identifies the impact of these nonhighway sources and the method used to estimate the impact of the highway independent of these local sources.

The NTA maps for BC at stations 2 and 4 are shown in Figure 3 and Figure 4 respectively. These two sites are chosen because each is approximately 100 m from the highway and each had a full complement of air quality measurements, including sulfur dioxide. Even though the two stations are separated by only about 200 m, the NTA maps are very different with one showing high concentrations to the west of the highway

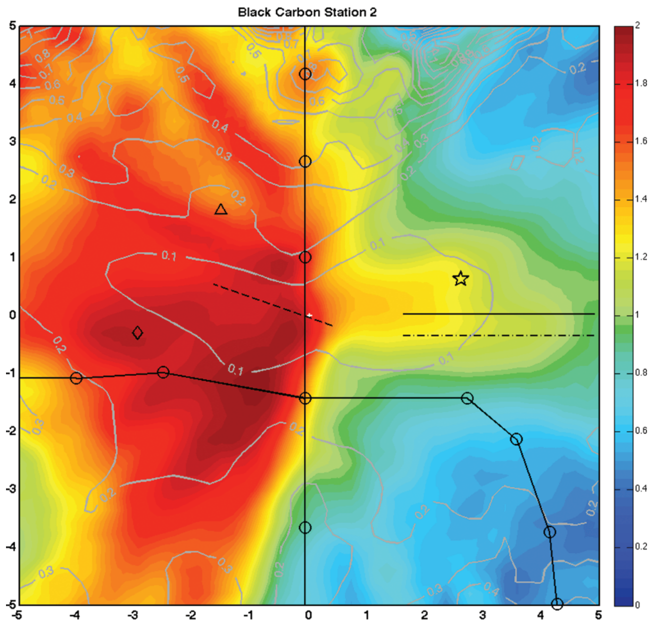

Figure 3. NTA map for black carbon at Station 2 (135 m east of the highway). The units of black carbon are μg m^{-3}. The gray contour lines are the 5-sigma errors in the NTA estimates. On this map, north is at the top, the units are km. The north–south solid line is I-15 with intersections shown as circles. The east–west solid line is I-215. The monitoring stations are located along the rail spur shown as a dashed line crossing I-15. The airport terminal is the star shown north of the primary and secondary runways. The small triangle in the upper left quadrant is the location of a cement plant; the diamond is the location of a large truck and taxi depot. The Local Industrial Area (LIA) is the area west of I-15 bounded by the cement plant to the north and the taxi depot to the west.

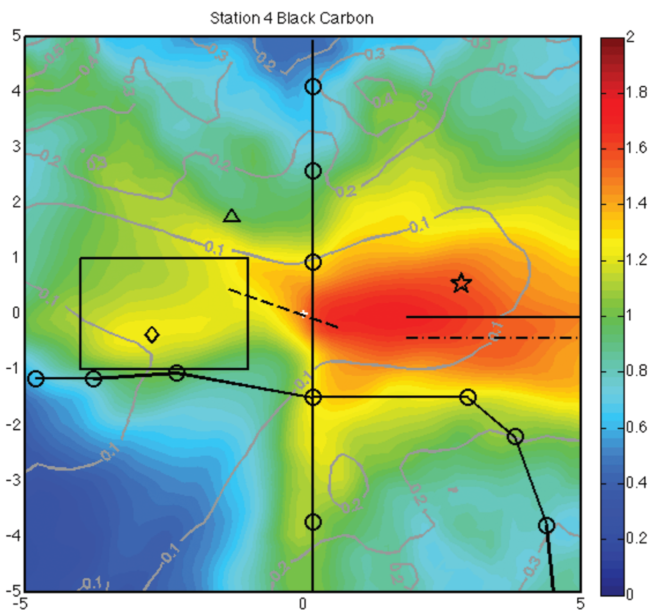

Figure 4. NTA map for black carbon at station 4, 115 m west of the highway. The large rectangular box is the area used to determine the NTA results in Table 2.

(Figure 3) and the other to the east (Figure 4). Figure 3 shows that high concentrations of BC (about 2 μg m^{-3}) are associated with back-trajectories spread widely over the area west of the highway. On the other hand, Figure 4 shows that the area of highest concentrations for station 4 (about 1.8 μg m^{-3}) is toward the east and centered near the main runway of the airport. The reason for the difference in these two maps is I-15 a major highway that runs north–south between the two stations. Before arriving at station 2, back-trajectories from the west must pass over the highway; likewise, for station 4, the back-trajectories from the east must pass over the highway. Thus, air coming from the west over the LIA must pass over the highway before arriving at station 2. Air coming from the east over the airport must pass over the highway before arriving at station 4. Consequently, the highest average concentrations at station 2 are those associated with back-trajectories from the west (Figure 3) as these pass over two sources, the LIA and the highway. Similarly, the highest average concentrations at station 4 are associated with back-trajectories from the east that have passed over the highway and the airport (Figure 4).

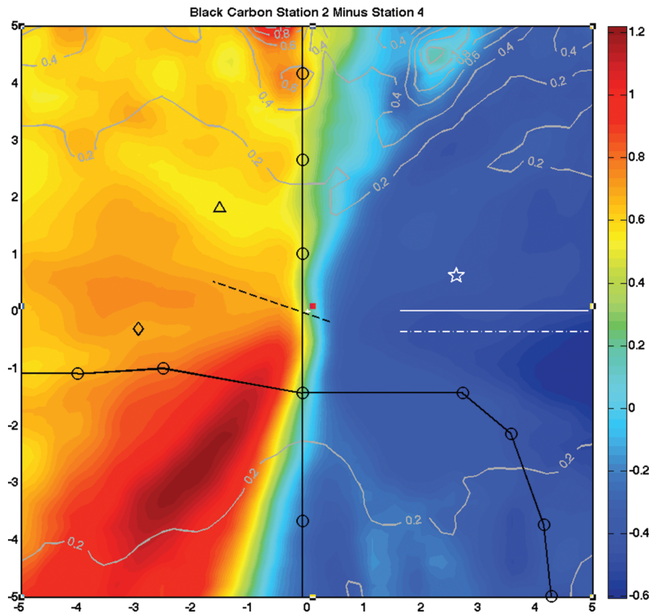

Figure 5. Contribution of I-15 to black carbon concentrations observed approximately 125 m downwind of I-15.

During periods of low wind speeds, air could meander back and forth over the highway. Low wind speeds were quite common in these data: the distribution of wind speeds at station 2 was highly skewed with a peak (mode) at 1.3 ms^{-1} and a maximum of about 12 ms^{-1}. Even if the wind speeds are greater, variable wind directions along the back-trajectories may obscure simple upwind–downwind relationships. However, when averaged over tens of thousands of back-trajectories, these complications caused a minor increase in the NTA results.

In Figures 3 and 4, the areas to the east of station 2 and to the west of station 4, respectively, are regions where air has not yet passed over the highway before reaching the receptor and represent the impact of the airport (Figure 3) and the LIA alone (Figure 4). On average, air passing over the airport has a black carbon concentration of about 1.3 to 1.4 μg m^{-3} when it reaches station 2. Similarly, NTA shows that the LIA impact on station 4 varies from about 1.1 to 1.3 μg m^{-3}. These values may be taken as upwind or background values and used to estimate the impact of the highway separate from these local sources. Figure 3 shows that for station 2 the downwind concentration of BC is at most about 1.8 to 2 $\mu g\ m^{-3}$, subtracting 1.1 to 1.3 $\mu g\ m^{-3}$ background, gives an approximate average highway impact of 0.5−0.9 $\mu g\ m^{-3}$ black carbon at station 2 with transport from the west. The following section provides a discussion of the spatially variable impact of the highway in the presence of other local sources including the airport and the LIA.

HIGHWAY IMPACT IDENTIFIED BY NTA

The NTA estimates of the highway contribution of BC concentrations observed at station 2 were calculated as the difference between the NTA results for station 2 (Figure 3) and station 4 (Figure 4). The results are shown in Figure 5. When station 2 is downwind of I-15, the impact of the highway is positive for back-trajectories coming from the west. The back-trajectories coming from the east of I-15 almost always had higher BC concentrations at station 4 than station 2 as it is downwind of the highway for these back-trajectories. Thus, the east side of the Figure 5 has mostly negative values; these are shown as shades of blue in the figure.

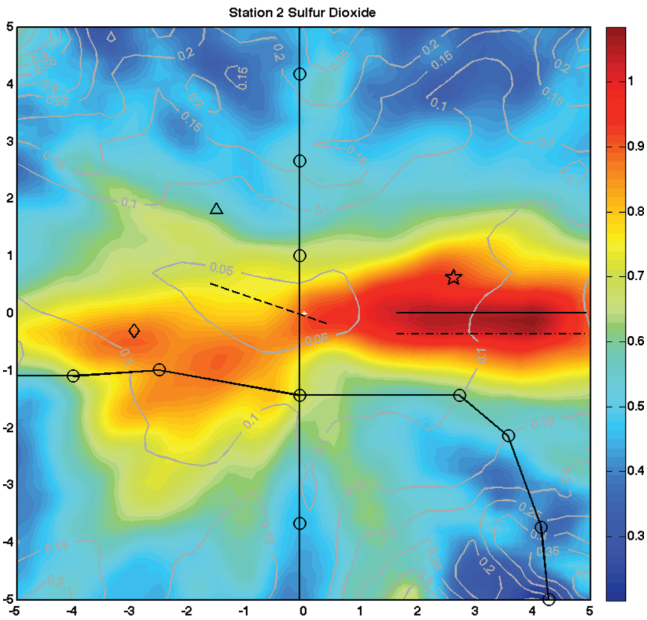

Figure 6. NTA map of sulfur dioxide in ppb at station 2.

The impact of the highway on station 4 seen in Figure 5 is determined by taking the absolute value of the negative values to the east of the highway and is about half of the impact of the highway on station 2. Note that the highway impact on station 4 is quite uniform, except for an area of anomalous positive values in the northeast. The 5-sigma error contours in the figure are about 1 $\mu g\ m^{-3}$, while the values are about 0.15 $\mu g\ m^{-3}$. Looking closely at the data, the cause is found to be few periods where BC at station 2 is much higher than all the other stations. These high BC numbers at station 2 seem to be real and not instrumental errors. Nonetheless, the NTA error analysis has correctly identified the effect on NTA. In fact, a similar area of large errors is seen in the same place in Figure 3. The ability to use the errors in the NTA to identify areas affected by outliers or questionable data is one of the major strengths of the method.

The NTA map of BC from the highway is unusual in that the greatest impact of the highway is not associated with locations perpendicular to the highway near stations 2 and 4 as expected but with back-trajectories coming from southwest to south southwest (195−245 degrees azimuth). Winds from this direction were especially common in the summer. The high concentrations may be associated with a vortex formed when the air from this direction meets the sunken highway and railway overpass described above in the site description section.

The NTA maps were calculated for all the stations for BC, CO, and NOx. The results for NOx and CO are generally similar to those for BC. Only stations 2 and 4 had measurements for SO_2. The NTA results for SO_2 at station 2 are given in Figure 6. The highest concentrations of SO_2 at station 2 occur with transport from the airport and are centered on the main and secondary runways. Since station 2 is east of the highway, the high

Table 2. Highway Impact from NTA Maps

	average	std. dev.	highway	std. dev.	average/background	std. dev.	average/background composite of other studies[b]
				BC ($\mu g\ m^{-3}$)			
station 1	2.20	0.0715	1.08	0.0977	1.97	0.13	1.8
station 2	1.84	0.0669	0.719	0.0943	1.64	0.11	1.6
station 3	1.41	0.0747	0.288	0.1000	1.25	0.10	1.2
background[a]	1.12	0.0665					
				CO (ppm)			
station 1	0.536	0.011	0.184	0.0157	1.52	0.06	21
station 2	0.455	0.0093	0.102	0.0145	1.29	0.05	3.8
station 3	0.439	0.0129	0.0864	0.0170	1.24	0.05	1.4
background[a]	0.352	0.0111					
				NOx (ppb)			
station 1	83.80	2.81	39.55	3.64	1.89	0.12	1.8
station 2	64.54	3.23	20.29	3.98	1.45	0.11	1.6
station 3	59.80	3.39	15.55	4.11	1.35	0.10	1.3
background[a]	44.25	2.32					

[a] Station 4. [b] Values from Figure 2 in Karner et al.[1]

concentrations from the airport have no highway contribution. The NTA values west of the highway represent the impact of the LIA and the highway. Unlike BC, CO, and NOx, the airport is the dominant source of SO_2 in the area. This is reasonable because the allowable sulfur content in jet fuel at the time of this study was still high (~500 ppm) compared to the ultralow sulfur fuel used by cars and trucks (~15 ppm).

Upwind−Downwind Analysis. A version of an upwind−downwind analysis can be done with the NTA maps in Figures 3 and 4. The NTA analysis area is the 2 × 3 km box shown in black in Figure 4. The first column of Table 2 gives the average values of BC, CO, and NOx observed at each station when the air parcel has passed over the box before reaching that station. As explained above, this is a sum of the impact of the LIA and the highway. The value for station 4 is taken to be the impact of the LIA alone and is assumed to be the background. The second column is the standard deviation of the NTA values in the box, which is much greater than the standard deviation due to errors in the NTA. The highway column is the estimated impact of the highway, which is given by the average in the first column minus the background. The standard deviation of this number is given next. The ratio of the average to the background is given next along with its standard deviation. For comparison, the background-normalized values from a compilation of studies for the same distance are shown. For BC and NOx, the concentrations normalized to the background are very similar to those reported in the literature.[1] CO, on the other hand, does not behave at all like CO in previously reported studies near highways. In this study the background CO was almost twice the amount of CO contributed by the highway at Station 1. It is not clear why the CO background was much higher in this study than the other highway related pollutants but likely the result of relatively high CO emissions from the LIA and other roadways

Finally, the NTA results for BC were compared to the gradient method. The Supporting Information contains a brief description of the analysis and a graph comparing the gradient method, NTA, and literature values for BC. The NTA results are seen to be in good agreement with the literature values and the gradient method. The results for CO and NOx are similar to BC.

ASSOCIATED CONTENT

S Supporting Information. Text and Figure S1. This material is available free of charge via the Internet at http://pubs.acs.org.

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