*Environ. Sci. Technol.* **2010,** *44,* 5334–5344

# Near-Roadway Air Quality: Synthesizing the Findings from Real-World Data

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*Received January 3, 2010. Revised manuscript received April 26, 2010. Accepted May 20, 2010.*

Despite increasing regulatory attention and literature linking roadside air pollution to health outcomes, studies on near roadway air quality have not yet been well synthesized. We employ data collected from 1978 as reported in 41 roadside monitoring studies, encompassing more than 700 air pollutant concentration measurements, published as of June 2008. Two types of normalization, background and edge-of-road, were applied to the observed concentrations. Local regression models were specified to the concentration-distance relationship and analysis of variance was used to determine the statistical significance of trends. Using an edge-of-road normalization, almost all pollutants decay to background by 115−570 m from the edge of road; using the more standard background normalization, almost all pollutants decay to background by 160−570 m from the edge of road. Differences between the normalization methods arose due to the likely bias inherent in background normalization, since some reported background values tend to underpredict (be lower than) actual background. Changes in pollutant concentrations with increasing distance from the road fell into one of three groups: at least a 50% decrease in peak/edge-of-road concentration by 150 m, followed by consistent but gradual decay toward background (e.g., carbon monoxide, some ultrafine particulate matter number concentrations); consistent decay or change over the entire distance range (e.g., benzene, nitrogen dioxide); or no trend with distance (e.g., particulate matter mass concentrations).

## Introduction

Since the early 2000s, there has been increased regulatory interest in understanding and mitigating near-road air pollution in the United States. The U.S. Environmental Protection Agency's 2001 Mobile Source Air Toxics (MSAT) Rule identified locations near heavily trafficked roads as important microenvironments for MSAT exposure (*1*). In 2003, California Senate Bill 352 classified freeways and other busy traffic corridors as facilities with the potential to emit hazardous air pollutants (*2*). The bill required environmental review of proposed school sites located within a quarter mile (∼400 m) of urban or rural roads with average daily traffic exceeding 100,000 and 50,000 vehicles, respectively. In 2004, the Sierra Club litigated to prevent expansion of highway US 95 in Las Vegas, Nevada, citing concerns regarding near-road air pollutants. The lawsuit settlement agreement committed state and federal agencies to monitoring at several roadside locations and to pilot mitigation strategies at nearby schools (*3*). A 2005 California Air Resources Board (CARB) land use guide recommended siting "sensitive land uses" further than 500 feet (∼150 m) from a freeway or high-traffic road (*4*).

Concern over near-road pollution is motivated by a growing body of literature examining associations among pollutant concentrations, health impacts, and road proximity. To date, empirical findings on health effects related to near-road pollutant exposures have been mixed (*5*−*17*), and there have been few attempts to synthesize what is known about real-world near-road pollutant concentrations. This study begins to fill this gap by synthesizing and evaluating approximately three decades of published real-world monitoring data and characterizing the relationships that exist between pollutant concentrations and road proximity.

Two meta-analyses of near-road air quality have been undertaken in recent years. In the first, Brugge et al. (*13*) reviewed cardiopulmonary health risks associated with near-road exposures and concluded, from a review of eight studies, that ultrafine particle number, black carbon, carbon monoxide (CO), and oxides of nitrogen ($NO_X$, including nitric oxide [NO], and nitrogen dioxide [$NO_2$]) are elevated near roadways and the most important exposure zone extends to those individuals residing 30 m from freeways. In the second study, Zhou and Levy (*18*) performed a meta-analysis to determine important parameters affecting the "spatial extent" of impacts resulting from mobile source air pollution. They reviewed 33 studies; 18 were monitoring studies; the remainder involved dispersion modeling, land use regression, biomonitoring, and epidemiology. Spatial extent was defined as the distance at which roadway effects were no longer observable; it focused on measures of pollution concentration or health impacts. Their findings varied as a function of the spatial extent definition (concentration vs. health impacts), pollutant type, and local meteorology. Overall, they observed that the concentration-based spatial extent of mobile source impacts ranged from 100−500 m from roads. One limitation to this study, as noted by Zhou and Levy, was that results for particulate pollutants were not disaggregated by particulate size and mass fraction, a limitation that has been addressed in this study.

This paper advances understanding of the dispersion of near-road air pollutant concentrations by synthesizing findings from 41 monitoring studies undertaken beginning 1978 and published by June 2008. The findings document, by individual pollutant type, the distances over which near-road concentrations decay to background. Concentration measurements are normalized using two techniques: normalizing to a background and an edge-of-road concentration.

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10.1021/es100008x

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Published on Web 06/18/2010

The findings also complement other work describing the physical and atmospheric processes governing the shape and rate of decay curves for individual pollutants (*18*); such prior work has dealt mostly with chemical reactivity and dispersion impacts on the atmospheric transport and fate of given pollutants such as $NO_2$ and ultrafine particles (*19*). Finally, our results will help validate modeling tools or assess under which conditions model estimates are most robust. Pollutant exposure is determined by many factors such as time of day and location of activities (*20*); to the extent that exposure occurs in the near-road environment, this study provides a stronger scientific context for designing buffer zones to avoid exposure to higher pollution concentration levels.

## Methods

**Data Assembly and Preparation.** To populate our database, we included reported distance/concentration pairs from all monitoring studies we identified that included information or findings on near-road concentration gradients. If upwind or background data were unavailable, downwind data were still included in the database. A comprehensive literature search was completed to identify and include data available as of June 2008; however, it is possible that studies not previously cited or widely distributed were missed. No judgment was made regarding the quality of the fieldwork or the instrumentation used. Rather, we assumed that study authors performed the necessary quality assurance and quality control to validate their data.

Although a diversity of measurement approaches and technologies have been used to assess near-road concentrations, the most frequently applied method was to arrange pollutant monitoring equipment along a vector approximately perpendicular to the road. Distances and pollutants varied among studies, as did motivation. Some studies collected data solely to observe near-road conditions; others were designed to improve model verification or calibration. Collected measurements typically involved measurement campaigns conducted over periods ranging from several hours to several weeks or longer. Meteorology also varied widely.

Our analysis unit was one distance/concentration pair (e.g., a single CO measurement at 30 m from the edge of road). We identified 780 such pairs from 41 papers (*8, 21−60*); the literature represents wide geographic, meteorological, and traffic operational variation. (The Supporting Information includes an annotated bibliography of all studies.)

Our final database includes distance/concentration pairs that spanned 263 unique measurement sets. A measurement set is defined here as a group of distance/concentration pairs originating from the same study and representing one pollutant under one set of measurement conditions. Many studies reported results from different observation days, seasons, or traffic conditions. If these data were available from the study results, we recorded them as separate measurement sets for analysis.

To partially control for the important influence of wind direction on observed concentration (*31*), data were only entered into the database for concentrations measured when wind was approximately from the road or was aggregated over meteorological conditions including winds from the road. Studies typically used prevailing wind patterns to orient monitors to measure downwind impacts, but four studies (13 measurement sets total) reported observations under parallel wind conditions (*31, 44, 58, 59*). These measurements were not included.

Field measurements were grouped by pollutant type or surrogate (EC includes black carbon, black smoke, and the reflectance of PM filters). Ultrafines were also grouped but as a separate category. The term "ultrafine" typically refers to particles less than 100 nm in diameter (*61*), and particle number concentrations (as opposed to mass concentrations) are typically used to quantify ultrafine roadside concentrations. We categorized particle number concentration into three groups: UF1 particle number denotes data collection beginning at 3 nm, UF2 particle number signifies data collection beginning at 15 nm, and fine particle number begins at 300 nm (0.3 $\mu$m, just above the ultrafine classification). We also grouped volatile organic compounds (VOC) into two categories. The first was VOC1 including eight VOCs whose concentrations generally varied with distance from road; examples include 1,3-butadiene and methyl tert-butyl ether. VOC2 included four VOCs whose concentrations generally did not vary with distance from road; examples include propane and *n*-butane. (The Supporting Information contains further details on data reduction and complete information on pollutant grouping.)

**Normalization.** Monitored concentration data are typically normalized to wind speed or traffic volume (*58*), to a reference near-road distance (*43, 44*), or by subtracting out background concentration (*41, 53*). There are problems in normalizing to traffic volume or meteorological conditions when aggregating data across numerous studies. First, many studies do not provide sufficient information (e.g., temporal resolution) to derive similar measures of traffic or meteorological conditions elsewhere. Second, even when data can be gathered, studies frequently aggregate or resolve data to the units most useful for that particular study interest. For example, daily traffic might be used for cumulative effects, whereas peak hour traffic might be applied for a study interested in acute effects.

We have chosen two types of normalization procedures that can easily be replicated in future studies and rely on factors that are usually readily available from or described in published work. The first, normalizing to background, yields the relative concentration of pollutants measured in the near-road zone compared to nearby concentrations unaffected by (typically upwind of) the road. This normalization can directly identify whether and where measured concentrations fall to background levels. The normalization divides observed near-road concentrations by the reported background value; as values approach one, near-road concentrations approach background.

The second approach, normalizing to edge-of-road, yields the relative concentration of pollutants in the near-road zone compared to concentrations measured at the point of expected maximum roadway influence: the roadway edge. This type of normalization indirectly allows assessment of whether and where measured concentrations fall to background levels. This approach has two benefits relative to background normalization. First, it enables use of data from (many) studies for which no background measurements were published or recorded. Second, it avoids data comparison problems—since there is no standard protocol in use to measure near-road background concentrations, background concentrations reported in monitoring may result from a variety of measurement approaches and locations relative to the road being studied.

Edge-of-road normalization involves dividing all concentrations in a measurement set by the edge-of-road concentration. If the edge concentration was unavailable, in most cases an exponential fit of the individual measurement set was used. Previous work has shown that an exponential decay describes the atmospheric fate of pollutants which vary by distance (*43, 55, 56, 59*). We also used linear regression to estimate an edge concentration for pollutants that showed little variation with distance according to the supporting annotated bibliography. This did not affect the shape of the decay curve in the event that the concentration actually varied exponentially with distance. The estimated value was used simply to normalize the rest of the measurement set. If the

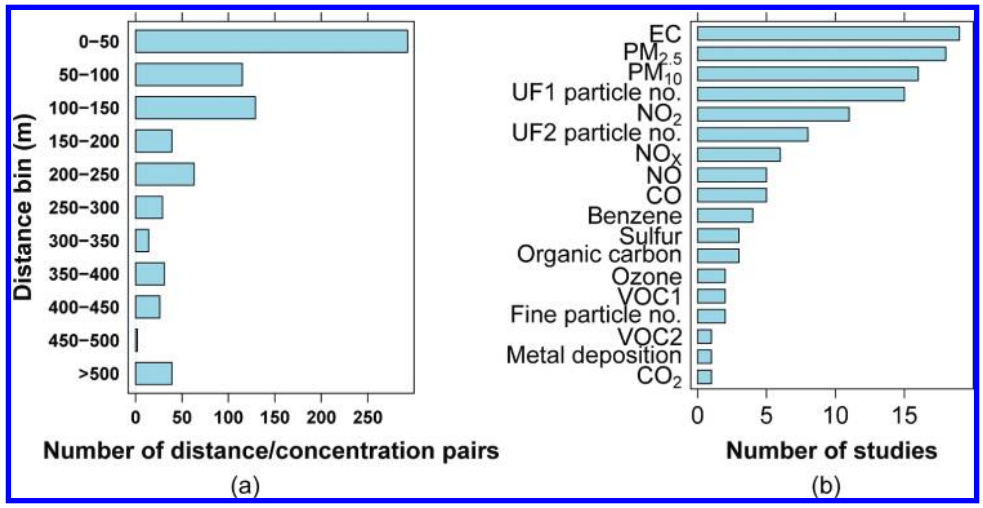


**FIGURE 1. Database summary: (a) observations grouped by 50 m distance bin and (b) studies grouped by pollutant. EC in (b) refers to direct and surrogate measures; measures of particle number (UF1, UF2, Fine) and VOCs (VOC1, VOC2) are discussed in the text and the Supporting Information. The sum of bars in (b) exceeds the 41 studies in our database—some studied several pollutants.**

edge concentration was underpredicted by linear regression, then normalized downwind values were artificially increased relative to the edge-of-road concentration; however, the point at which background was reached should not have been affected. We also used ANOVA assessments (discussed below) to quality check the assignment of edge concentrations. The ANOVA coefficients for near-road values confirmed that the assigned edge concentrations were reasonable.

The edge-normalized values indicate whether and at what distance from the road concentrations reach a stable value. In concept, stability is indicative of near-road concentrations approaching or reaching background, although it is numerically possible (though physically less likely) that stability could also represent a steady concentration above background. (See the Supporting Information for further edge normalization details.)

While many factors affect the magnitude of observed near-road concentrations (*22, 35, 40, 59, 62*), if the *shape* of the concentration decay curve is expected to be roughly similar across multiple studies for a given pollutant, dividing by the roadway edge concentration should preserve the shape while removing the absolute magnitude of the observations. This intuition has been confirmed by recent work on the influence of roadway configuration and sound/vegetation barriers on observed concentrations (*62*) and in other normalized comparisons undertaken by Zhu et al. (*58*) for three facilities normalized to unit wind speed and traffic volume. Others have taken a similar approach with more limited data; for example, Pleijel et al. (*43*) compared Swedish and Canadian monitoring data for $NO_2$ by dividing all observations by the $NO_2$ concentration at 10 m from the road.

**Local Regression.** Locally weighted regression (loess) was used to regress concentration on distance for both sets of normalized data. Loess is a robust smoother that does not impose a functional form on the relationship between the dependent and independent variables (*63*). The smoother uses a specified data window that moves along the *x* axis of a scatterplot. At each data point a fitted value is calculated using the subset of the data contained within the moving window. The size of the subset is defined as a percentage of total data and is referred to as the smoothing parameter; larger smoothing parameter values produce smoother concentration vs distance curves. Local regression has previously been applied to near roadway data by Gramotnev and Ristovski (*59*). However, the authors did not specify the value of the smoothing parameter used. We set the smoothing parameter by visual inspection. Parameter values of 0.75 and 0.70 (background normalization and edge normalization, respectively) produced smoothed curves sufficient for the purpose of our research.

**Analysis of Variance.** Discussion of statistical significance is rare in the near-road literature. In studies that do conduct statistical analysis, paired *t*-tests comparing observed concentrations to a reference group typically located closest to the roadway are used (*46, 50*). Sabin et al. (*47*) used paired *t*-tests and an analysis of variance (ANOVA) to test differences in the dry deposition rates of metals between downwind locations. However, there is some question as to whether near-road pollution concentrations (in addition to other meteorological and traffic measurements) meet the normality criteria for a *t*-test, and in at least one study the nonparametric Mann–Whitney test has been used (*22*). The distribution of observed near-road concentrations may be skewed since there are generally a large number of low-concentration observations. If deviation from normality is very large, then ANOVA results may not be robust. To overcome this possibility, we performed an ANOVA to identify the magnitude and significance of changes in concentration by distance from road and augmented the ANOVA results with the nonparametric Kruskal–Wallis test [ref *64*, pp 103–104]. R was used for all statistical analyses (*65*) and figure preparation (*66*).

## Results and Discussion

The literature confirms intuition: meteorology—wind speed and direction—strongly affects near-road pollutant concentrations. When wind flows from the road to receptors, concentration gradients are more pronounced and extend to a greater distance than when wind is parallel to or away from receptors (*31*). Traffic volume and fleet composition (*22, 59*) and other factors such as the presence of a noise barrier (*62*) can also contribute to differences in observed concentrations of traffic-related air pollution. In general, concentrations decay to background within a few hundred meters downwind of a road, although studies measuring pollutants solely in the evening hours indicate that higher concentrations persist beyond 500 m (*57*). Most of the observations collected from the studies were obtained within 150 m of the roadway (Figure 1a). Studies focused on particulate matter (PM) mass, particle number concentrations, elemental carbon and surrogates (EC), and all oxides of nitrogen (Figure 1b). Approximately 68% of included studies involved some measurements near freeways or highways; the remainder involved measurements only near arterial and/or local roads.

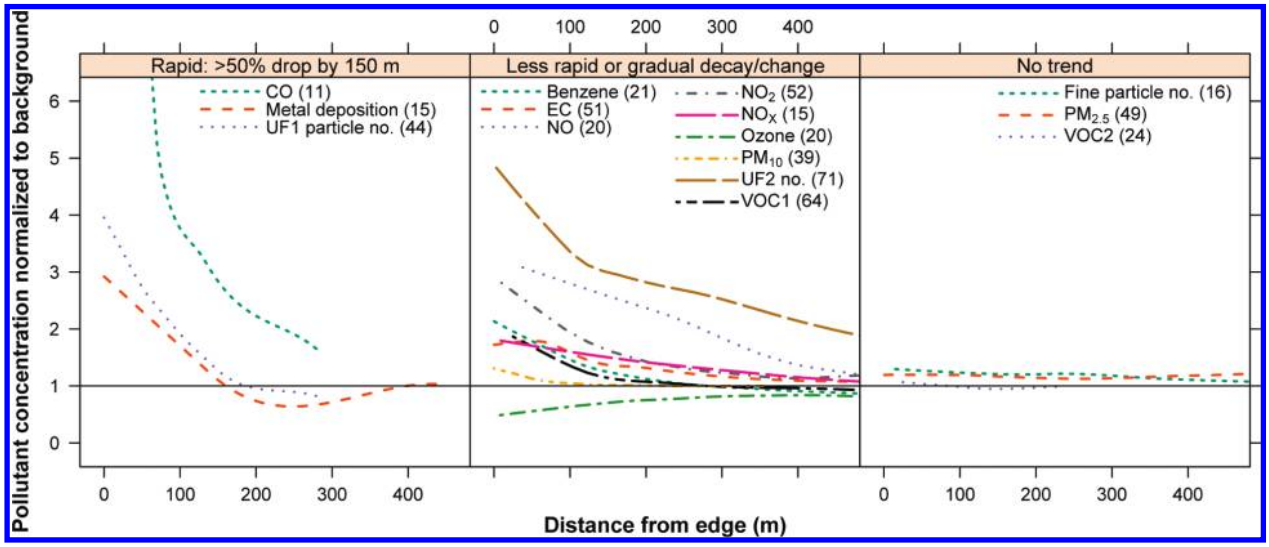


**FIGURE 2. Local regression of background normalized concentrations on distance. The horizontal line indicates background concentration. A loess smoother (alpha =0.75, degree =1) is fitted to each pollutant which is placed into one of three groups. The regression sample size, n, is given in parentheses after each pollutant.**

**TABLE 1. Summary of Background Normalized Data**

| group | pollutant | approximate multiplier above background concentration at edge-of-road | approximate distance required to reach background concentration (m)[a] |
|---|---|---|---|
| rapid: >50% drop by 150 m | CO | 21[b] | —[c] |
| | metal deposition | 2.9 | 161 |
| | UF1 particle no. | 4.0 | 189 |
| less rapid or gradual decay/change | benzene | 2.1 | 280 |
| | EC | 1.7 | 420[d] |
| | NO | 3.3 | 565[e] |
| | $NO_2$ | 2.9 | 380[f] |
| | $NO_X$ | 1.8 | 570[e] |
| | $PM_{10}$ | 1.3 | 176 |
| | UF2 particle no. | 4.8 | 910[e] |
| | VOC1 | 2.0 | 270 |

[a] The approximate distances were derived from an expanded version of Figure 2; the distance point at which the smoothed line reached a value of one on the *y*-axis is cited here as background. [b] Near-road CO concentrations extended outside of the range plotted in Figure 2. [c] CO concentrations did not reach background within the 285 m for which data were measured. [d] Background normalized concentrations attained an approximate minimum value of 1.1 at this distance from the road. [e] Reached background concentrations outside of the range plotted in Figure 2. [f] Background normalized concentrations attained an approximate minimum value of 1.08 at this distance from the road.

**Background Normalization.** The background-normalized concentrations are shown in Figure 2, and near-road concentrations and distance-to-background values are summarized in Table 1. (The Supporting Information contains supplemental figures illustrating the data used to produce Figures 2 and 3.)

In Figure 2, the range on the *y*-axis has been constrained to six times above background concentration. The only pollutant exceeding this is CO, which was observed to reach 20 times above background at the roadway edge. The range on the *x*-axis in Figure 2 has been constrained to 0−450 m from the edge of road where most of the data fall (Figure 1a). We also excluded data from two studies because the sampling and vehicle fleet characteristics were very unique relative to the rest of the studies. One study measured concentrations only at night; another study measured near-road conditions in 1978, when vehicle emissions and near-road concentrations were substantially higher than the values reported in other studies (*45, 57*). Organic carbon and sulfur are not shown in Figure 2 due to limited data. (See the Supporting Information for further discussion of omitted data.)

Changes in pollutant concentrations over distance generally fell into three groups. The first showed rapid initial concentration decay—defined here as at least a 50% decrease in peak/edge-of-road concentration by 150 m—followed by consistent but more gradual decay toward background; the second consistently decayed or changed over the entire distance range, while the third showed no trend with distance.

One pollutant, ozone, which is shown in the second panel, displayed a unique increasing trend, beginning below background near the road and gradually approaching background by 400 m from the edge. However, ozone values were consistent with expected near-road titration due to interaction with direct vehicle emissions of NO to form $NO_2$ (*67*).

All pollutants except for CO, UF2 particle number, NO, and $NO_X$, reached background by approximately 400 m. UF2 particle number concentrations should generally be lower than UF1 particle number concentrations (*38, 48, 68*). Reasons for anomalously high UF2 particle numbers are discussed below along with other study limitations. Generally, the high concentrations shown in the first 100 m drop off by 400 m, even considering the between-study differences in methods

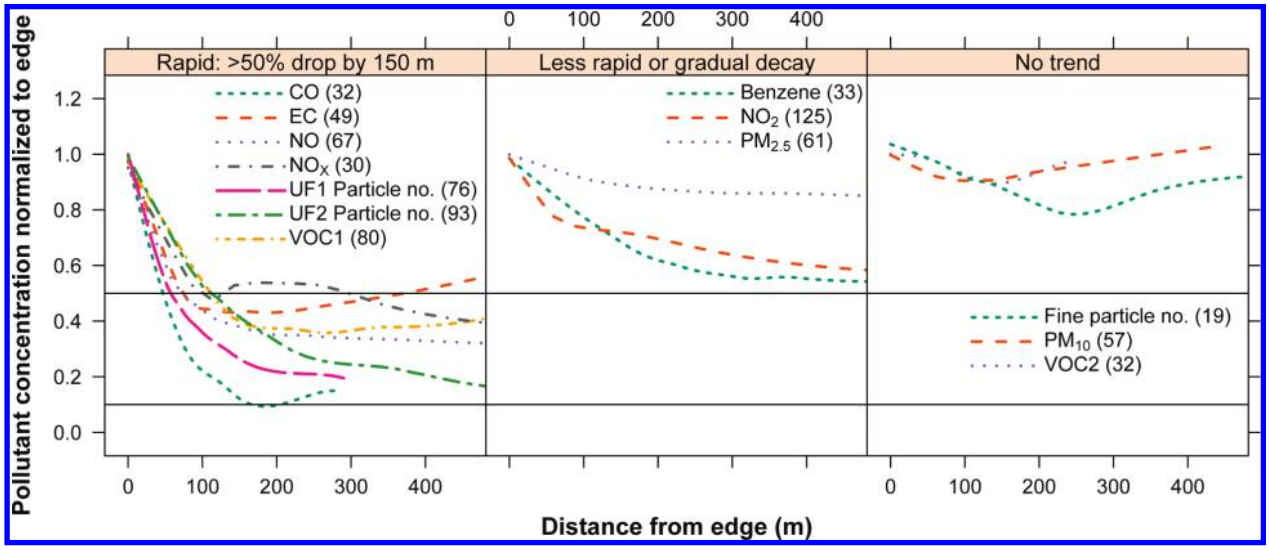


**FIGURE 3. Local regression of edge normalized concentrations on distance. The horizontal black lines show a reduction from the edge-of-road concentration of 90% (at 0.1) and 50% (at 0.5). A loess smoother (alpha = 0.70, degree = 1) was fitted to pollutant data which was placed in one of three groups. The regression sample size, n, is given in parentheses after each pollutant. The n includes an estimated (not in the literature) edge-of-road value to facilitate normalization.**

**TABLE 2. Summary of Edge Normalized Data[a]**

| group | pollutant | percentage decrease[b] | distance (m) | reached background |
|---|---|---|---|---|
| rapid: >50% drop by 150 m | CO | 90 | 170 | yes |
| | EC | 56 | 130 | yes |
| | NO | 65 | 200 | yes |
| | $NO_X$ | 52 | 115 | yes |
| | UF1 particle no. | 79 | 210 | yes |
| | UF2 particle no. | 86 | 570[c] | yes |
| | VOC1 | 62 | 180 | yes |
| less rapid or gradual decay | benzene | 45 | 320 | yes |
| | $NO_2$ | 42 | 550[c] | yes |
| | $PM_{2.5}$ | 22 | 986[d] | no |

[a] Distances and percentage decreases were derived from an expanded version of Figure 3. [b] For pollutant concentrations that reached background: defined as percent decrease in edge-of-road concentration at the stabilization distance. For pollutants that did not reach background: defined as percent decrease in edge-of-road concentration at the furthest distance for which measurement data were available. [c] Reached background outside of the range plotted in Figure 3. [d] Data for $PM_{2.5}$ extended to 986 m from the edge of road.

and traffic characteristics; this is notable considering the wide variation in data and the inherent limitations of this normalization method (i.e., the lack of common protocols used to define background). The curves indicate (ignoring ozone) that concentrations of certain pollutants are elevated near roadways and decrease as the distance increases, while other pollutants show no roadway influence. These background normalized results suggest that a range of approximately 160−400 m is sufficient to reach background concentrations for the majority of pollutants.

**Edge Normalization.** The results for the normalization to roadway edge are shown in Figure 3 and summarized in Table 2. We were able to include more data in the edge normalization than background normalization since background measurements or estimates were not required for normalizing in this method. Of the 138 total measurement sets comprising Figure 3, 114 did not include an edge-of-road concentration. Exponential fits (total number of measurement sets for each pollutant in parentheses) were used to determine edge concentrations for benzene (6), CO (3), EC (6), NO (5), $NO_2$ (14), $NO_X$ (4), UF1 particle number (6), UF2 particle number (14), and VOC1 (16). Linear regression was used to estimate an edge concentration for $PM_{10}$ (9), $PM_{2.5}$ (11), fine particle number (3), and VOC2 (8). The remaining nine measurement sets contained only two distance/concentration pairs. Edge-of-road concentrations for these pollutants were also estimated using linear regression including EC (1), $NO_2$ (2), $NO_X$ (1), UF1 particle number (3), and UF2 particle number (2). We omitted organic carbon, sulfur, and metal deposition from Figure 3; the data for these pollutants were too sparse to smooth without significantly increasing the smoothing parameter. We also omitted ozone because its increasing concentration with increased distance from the road would plot outside the range of Figure 3. Data from the nighttime-only Zhu et al. (*57*) study were also excluded. (See the Supporting Information for details on omitted data and edge normalization.)

Edge normalization provides the percentage decrease in pollution concentration as measured from the roadway edge to the distance of interest (Figure 3). For concentrations that varied by distance, the percentage of the near road high concentration at which leveling occurred represents a proxy of that pollutant's background concentration; this assumes that the roadway influence has dropped to approximately zero when no further changes occur in the smoothed curve.

Figure 3 shows CO, benzene, EC, NO, $NO_X$, $NO_2$, $PM_{2.5}$, and UF1 particle number, UF2 particle number, and VOC1 all decreased as distance from road increased. $PM_{10}$, fine particle number, and VOC2 showed ambiguous or little to no trend with distance.

**TABLE 3. ANOVA and Kruskal-Wallis Results: Background Normalization[a]**

| | ANOVA | | | 0–80 m | | 80–120 m | | >120 m | |
|---|---|---|---|---|---|---|---|---|---|
| | Df | *F* | Kruskal–Wallis *p*-value[e] | coeff.[f] | n | coeff.[f] | n | coeff.[f] | n |
| benzene | (2,18) | 17.13[d] | 0.0027 | 1.967 | 6 | | 1 | −0.968[d] | 14 |
| CO | (1,9) | 6.14[b] | 0.0140 | 12.41 | 7 | | | −9.97[b] | 4 |
| EC | (1,49) | 9.62[c] | <0.001 | 2.41 | 36 | | | −1.119[c] | 15 |
| metal deposition | (1,13) | 30.8[d] | 0.0022 | 3.06 | 5 | | | −1.947[d] | 10 |
| NO | (2,17) | 4.48[b] | 0.0320 | 5.13 | 4 | | 1 | −3.22[b] | 15 |
| $NO_X$ | (1,13) | 4.80[b] | 0.0022 | 5.55 | 5 | | | −4.26[b] | 10 |
| $NO_2$ | (2,49) | 13.49[d] | <0.001 | 2.63 | 21 | | 10 | −1.378[d] | 21 |
| UF1 p.m. no. | (2,41) | 6.06[c] | <0.001 | 4.72 | 29 | | 4 | −3.46[c] | 11 |
| UF2 p.m. no. | (2,68) | 8.90[d] | <0.001 | 6.84 | 27 | −3.46[b] | 10 | −4.34[d] | 34 |
| VOC1 | (2,61) | 37.6[d] | <0.001 | 2.09 | 18 | −0.826[b] | 2 | −1.037[d] | 44 |
| VOC2 | (1,22) | 4.31[b] | 0.0431 | 1.053 | 8 | | | −0.0817[b] | 16 |
| fine PM no. | (2,13) | 3.48 | 0.1426 | | 4 | | 2 | | 10 |
| ozone | (2,17) | 1.64 | 0.547 | | 5 | | 1 | | 14 |
| $PM_{10}$ | (2,36) | 3.00 | <0.001 | 1.424 | 27 | | 3 | −0.412[b] | 9 |
| $PM_{2.5}$ | (2,46) | 0.383 | 0.791 | | 24 | | 3 | | 22 |
| sulfur | (2,3) | 0.987 | 0.1717 | | 2 | | 1 | | 3 |

[a] The last five rows contain those pollutants with insignificant *F* statistics. [b] Statistical significance is indicated as follows: $p < 0.05$. [c] Statistical significance is indicated as follows: $p < 0.01$ [d] Statistical significance is indicated as follows: $p < 0.001$. [e] The Kruskal–Wallis *p*-value is taken from the nonparametric Kruskal–Wallis test whose null hypothesis is that there is no difference in the mean ranks of the groups. [f] Refers to the regression coefficients extracted from a linear regression of normalized concentrations on distance bin. The coefficient in the 0–80 m bin was the model intercept which represents the mean normalized value in that range, while the coefficients in the other two distance bins represent mean changes relative to the first bin. Missing values in the table indicate insignificant results as judged by the omnibus *F* and the Kruskal–Wallis *p*-value, or no data, evidenced by a blank n for the cell.

We again categorized rapidly decaying pollutants as those which decreased at least 50% from their peak value by 150 m. Several pollutants exhibited sharp declines within the first 100–150 m before leveling off. CO and UF1 particle number showed the greatest declines. Benzene, $NO_2$, and $PM_{2.5}$ showed gradually decreasing trends. $NO_2$ declined continuously to 450 m indicating that background concentrations were not reached over the plotted distance range but flattened beginning at approximately 550 m from the roadway edge. UF2 particle number showed substantial declines over the entire plotted distance range but did not appear to level until approximately 570 m from the road. The majority of the edge-normalized pollutant concentrations appear to reach background by 115 to 300 m from the edge of road.

**Analysis of Variance.** Some of the most frequently cited studies using real-world observations (*55, 56*) show substantial pollutant reductions by 80 m from the road, only slightly shorter than the 100 m zone of highest exposure for some pollutants found in a recent meta-analysis (*18*).

Near-road concentrations have traditionally been modeled as a Gaussian plume [e.g. ref *11*] with as much as 96% of the concentration dissipating by 150 m (*69*). Our work, however, suggests that decay regimes may be more complex and possibly organized into those pollutants that, under certain conditions, decay rapidly, those that decay gradually, and those that do not decay. To test this hypothesis, we divided our data into three different groups organized by findings in the literature. Specifically, the first bin (0–80 m) represents the window of anticipated peak concentration, as evidenced by our synthesis and widely referenced work (*55, 56*), the second bin (80–120 m) captures the window which some of the literature has flagged as the end of the spatial extent of mobile source impacts (*18*), and finally, the third bin (120 m and beyond) represents a reference for the distance range where the literature (modeled and monitored) suggests a substantial decline in observed roadway influence. Some pollutants have no data in the second bin, but this simply reduces the test to a comparison between the first and third groups. The null hypothesis in this case is that there is no difference in mean observed concentrations between observations near the road (i.e., the first distance bin) and observations further downwind of the road (distance bins two and three).

The mean values (coefficients) for the pollutant within distance category are reported in Tables 3 and 4 for background and edge normalized data, respectively. The coefficients in the second and third distance bins (i.e., 80–120 m and >120 m) are mean changes relative to the first category. It should be noted that the means are not directly comparable to the loess plots, since the loess algorithm uses a weighting function to calculate its fitted values at each data point.

All coefficients in the second and third bin for both normalization methods are negative, since concentrations generally decrease when moving from the first to the second and third distance categories. Results from the Kruskal–Wallis test and ANOVA are generally in agreement, indicating that any deviations from normality are generally not severe enough to affect the ANOVA results.

**Background Normalized Concentrations.** Mean values of multipliers above background in the first 80 m from the road range from a factor of 1.05 for VOC2 to 12.4 for CO. For $PM_{10}$, the ANOVA *F*-statistic differs from the Kruskal–Wallis *p*-value. $PM_{10}$ is on average 1.42 times above background concentrations (0–80 m) and declines by an average of approximately 0.4 from the near road value beyond 120 m (28% decrease). Benzene also shows a small but significant increment above background at 1.97, declining to 1.0 past 120 m (49% decrease). Each of the remaining pollutants that vary by distance both begin at a higher above-background increment than $PM_{10}$ and decrease more sharply. Thus, the relationship of $PM_{10}$ with distance appears to be weak, if it exists. $PM_{2.5}$, fine particle number, and sulfur do not vary by distance, and VOC2 shows a small but statistically significant relationship with distance bin, decreasing by 8% over the distance range greater than 120 m from the road.

**Edge Normalized Concentrations.** Results show that 10 pollutants out of 11 had mean concentration values less than or equal to one in the 0–80 m range. Mean concentration values for $PM_{10}$, $PM_{2.5}$, and VOC2 for the same distance range

**TABLE 4. ANOVA and Kruskal-Wallis Results: Edge Normalization[a]**

| | ANOVA | | | 0–80 m | | 80–120 m | | >120 m | |
|---|---|---|---|---|---|---|---|---|---|
| | Df | *F* | Kruskal–Wallis *p*-value[e] | coeff.[f] | n | coeff.[f] | n | coeff.[f] | n |
| benzene | (2,24) | 4.40[b] | 0.0282 | 0.876 | 7 | | 3 | −0.255[c] | 17 |
| CO | (2,24) | 15.42[c] | <0.001 | 0.652 | 16 | −0.564[c] | 2 | −0.477[d] | 9 |
| EC | (2,37) | 6.16[c] | 0.0057 | 0.740 | 20 | | 1 | −0.264[c] | 19 |
| fine PM no. | (2,13) | 3.86[b] | 0.0184 | 1.018 | 4 | | 2 | −0.202[b] | 10 |
| metal deposition | (1,13) | 144.7[d] | 0.00182 | 1.000 | 5 | | | −0.615[d] | 10 |
| NO | (2,52) | 16.02[d] | <0.001 | 0.751 | 25 | −0.574[d] | 3 | −0.385[d] | 27 |
| $NO_X$ | (2,22) | 3.95[b] | 0.0369 | 0.737 | 8 | −0.609[b] | 2 | | 15 |
| $NO_2$ | (2,97) | 34.8[d] | <0.001 | 0.883 | 41 | −0.248[d] | 17 | −0.1777[d] | 42 |
| UF1 p.m. no. | (2,61) | 15.04[d] | <0.001 | 0.611 | 41 | −0.277[c] | 7 | −0.353[d] | 16 |
| UF2 p.m. no. | (2,74) | 40.5[d] | <0.001 | 0.763 | 29 | −0.239[d] | 12 | −0.445[d] | 36 |
| VOC1 | (2,61) | 6.83[c] | 0.0042 | 0.730 | 18 | −0.448[b] | 2 | −0.241[c] | 44 |
| ozone | (2,17) | 0.807 | 0.319 | | 5 | | 1 | | 14 |
| $PM_{10}$ | (2,41) | 1.507 | 0.214 | | 22 | | 7 | | 15 |
| $PM_{2.5}$ | (2,46) | 0.877 | 0.0334 | | 16 | | 5 | | 28 |
| sulfur | (1,2) | 0.061 | 0.655 | | | | 1 | | 3 |
| VOC2 | (1,22) | 3.71 | 0.066 | | 8 | | | | 16 |

[a] The last five rows contain those pollutants with insignificant *F* statistics. [b] Statistical significance is indicated as follows: $p < 0.05$. [c] Statistical significance is indicated as follows: $p < 0.01$. [d] Statistical significance is indicated as follows: $p < 0.001$. [e] The Kruskal–Wallis *p*-value is taken from the nonparametric Kruskal–Wallis test whose null hypothesis is that there is no difference in the mean ranks of the groups. [f] Refers to the regression coefficients extracted from a linear regression of normalized concentrations on distance bin. The coefficient in the 0–80 m bin was the model intercept which represents the mean normalized value in that range, while the coefficients in the other two distance bins represent mean changes relative to the first bin. Missing values in the table indicate insignificant results as judged by the omnibus *F* and the Kruskal–Wallis *p*-value, or no data, evidenced by a blank n for the cell.

not shown in Table 4 averaged 0.98, providing evidence that edge concentrations were not consistently underestimated.

Concentrations were significantly different for CO, NO, $NO_2$, VOC1, UF1, and UF2 particle number when comparing the second (80–120 m) and third distance bins (>120 m) to the first (0–80 m). $NO_X$ concentrations were significantly different when comparing the second distance bin to the first. Benzene, EC, metal deposition, and fine particle number showed significant decreases in concentration when comparing the third distance bin to the first. Ozone, $PM_{10}$, $PM_{2.5}$, sulfur, and VOC2, all show insignificant *F* statistics.

The Kruskal–Wallis *p*-value indicates significant differences among means by distance group across all pollutants ($p < 0.05$) except for ozone, sulfur, $PM_{10}$, and VOC2. $PM_{2.5}$ is the only pollutant which shows disagreement between tests. This is likely due to the distribution of $PM_{2.5}$ measurements. When distributions are non-normal, Kruskal–Wallis is more likely to reject a false null hypothesis than ANOVA. A significant decrease in concentration with increasing distance for $PM_{2.5}$ is consistent with graphical evidence from Figure 3. A similar explanation likely holds for background-normalized $PM_{10}$.

**Limitations and Differences between Normalization Methods.** We have introduced the first comprehensive use of the edge normalization technique to the literature, partially to offset limitations of using the standard background normalization. We find that normalizing on the basis of the edge-of-road concentration offers advantages to normalizing by the background concentration because the definition of background concentrations differs across studies in the absence of a standard protocol. If, in a particular study, background is mischaracterized as either too high or too low, that study's results can obscure or overstate trends when pooled with other findings. Different studies variously defined background as concentrations measured at the edge of the upwind lanes, some distance from the upwind lanes, the nearest stationary monitoring site, or other locations. These inconsistencies also raise the possibility that our database may include "background" concentrations which reflect roadway influence. This situation could have occurred if investigators measured background during very low wind speed (meandering wind), when roadway pollutants could drift toward the background monitor. If such situations occurred, they would have artificially increased background values and reduced the observed near-road (downwind) impacts. In general, high background concentrations will tend to generate flatter gradients, and low background concentrations will generate steeper gradients.

For example, background measurements of $PM_{10}$ for a study in Macao, China were taken on a separate island at sites located 2–4 km away from the roadways under study (*54*). The resultant low background measurements tended to inflate the background-normalized Macao concentrations relative to other studies in our database that typically measured background just upwind of the roadway under study.

As another illustration, different background measurement protocols resulted in anomalous UF2 particle number findings. Particle number concentrations increase with measurement of smaller-diameter particles (*38, 48, 68*). However, in Figure 2, normalized UF2 particle number (>15 nm diameter) concentrations exceeded UF1 particle number (>3 nm diameter) concentrations. Part of the explanation involves a study by Hitchins et al. (*31*) which measured UF2 particle numbers. The authors did not take background measurements but did report concentrations when the wind direction was from the receptors to the road—a background estimation approach that has been used in some other studies [e.g. ref *27*]. Additionally, Hitchins et al. (*31*) reported concentration values under several different wind speed scenarios. The highest values of UF2 particle number were reported at the lowest wind speed, but the background value was given for conditions with a higher wind speed. In this case, normalizing by the reported background concentration resulted in exaggerated concentration values. If another study contemporaneously reported background and near road values, it would likely show lower normalized concentrations. This highlights the difficulties associated with pooling data from studies that frequently employ different measurement and reporting protocols. Depending upon the sample size

**TABLE 5. Summary of Pollutant Profiles under Both Normalization Methods[a,e]**

| | distance from road at which leveling begins or background reached (m) | | percentage of near-road high concentration at which leveling begins or background is reached | | edge-of-road multiplier above background concentration (multiples of background) | |
|---|---|---|---|---|---|---|
| | EN | BN | EN | BN[b] | EN[c] | BN |
| $NO_X$ | **115** | 570 | 48 | 56 | 2.1 | 1.8 |
| EC | **130** | 420 | 44 | 59 | 2.3 | 1.7 |
| CO | **170** | —[d] | 10 | 5 | 10 | 21 |
| VOC1 | **180** | 270 | 38 | 50 | 2.6 | 2.0 |
| UF1 particle no. | **210** | 189 | 21 | 25 | 4.8 | 4.0 |
| NO | **200** | 565 | 35 | 30 | 2.9 | 3.3 |
| benzene | **320** | 280 | 55 | 48 | 1.8 | 2.1 |
| $NO_2$ | **550** | 380 | 58 | 34 | 1.7 | 2.9 |
| UF2 particle no. | **570** | 910 | 14 | 21 | 7.1 | 4.8 |
| metal deposition | — | 161 | — | 34 | — | 2.9 |

[a] Table entries are sorted based on the edge normalized distance at which background concentrations are reached (**bold**). Pollutants that showed significant results in both ANOVA models are included. [b] Calculated as the inverse of the edge-of-road multiplier above background concentrations. [c] Calculated as the inverse of the percentage of near road high at which leveling occurs. [d] Missing values indicate no smoothed data for estimation (e.g., metal deposition) or similar limitations. [e] Abbreviations: EN is edge normalization; BN is background normalization.

across studies, a single study can substantially alter the position of a pollutant's background normalized curve by reporting a background concentration much higher or lower than the background values found in other studies.

In general, it is likely that the bias across studies is for some reported background values to underpredict (be lower than) actual background, due to lengthy averaging periods for background vs near-road measurements, or use of monitoring locations at relatively unpolluted sites distant from areas immediately upwind of the roads studied. This bias would tend to increase the background normalized values estimated here and lengthen the estimated distance required to reach background (affecting results shown in Figure 2). Biasing the distance required to reach background could result in a pollutant being placed into a different decay category depending on the normalization method used.

When normalizing by edge concentrations, the data yield their own background value by virtue of leveling off. The general assumption with edge normalization is that, when pooling data from numerous studies, if the regression approaches a horizontal line, this approximately signifies that roadway influence has diminished to background.

A limitation of the information derived from edge normalization is the possibility that concentrations level off at values which are site-specific—for example, due to abnormally high background concentrations or due to conditions that inhibit dispersion and result in stabilized concentrations above background. If site-specific situations caused the distance at which background was reached to vary across studies, or caused the stabilized value to be an unusually large fraction of the edge-of-road concentration, the regression results (Figure 3) may be biased (e.g., stabilized values higher than background, or the point of stabilization at a shorter distance than would be expected without unusually high background). Finally, while predicting an edge-of-road concentration does not affect the shape of an individual measurement set, it may affect the shape and position of the smoother. If the edge concentration were consistently underpredicted, Figure 3 would show an initial increase in concentrations moving away from the edge of road. Similarly, if the edge concentration was consistently overpredicted, the observed decrease in concentrations would be exaggerated.

Table 5 summarizes the concentration gradients of each pollutant that showed a significant variation with distance in both ANOVA models (see Tables 3 and 4 for significance). Overall, compared to background normalization, edge normalization showed a more rapid decline to background concentrations for EC, $NO_X$, NO, UF2 particle number concentrations, and VOC1, and a less rapid decline for $NO_2$. Benzene and UF1 particle number concentrations declined to background at similar distances from the road under both normalization methods. Background normalization has more pollutants in the "gradual decay" category than edge normalization (nine and three, respectively). These results are consistent with the hypothesis that background normalization results in increased distance-to-background values and partially explains why pollutants can change decay categories depending on the normalization method. These differences would likely be smaller if studies better matched background concentrations to the location of near-road measurements.

The findings show that, for almost all pollutants, the influence of the roadway on air pollution concentrations decays to background between 115−570 m according to edge normalization and between 160−570 m based on background normalization. These ranges cover all background normalized pollutants except for CO, which declines continuously to 285 m (end point of available CO data), and UF2 particle number, which achieved background after 910 m; and all edge-normalized pollutants except for metal deposition which was too sparse to smooth and $PM_{2.5}$, which achieved background by 990 m. Edge-of-road concentrations were elevated from 1.7−20 times above background.

The trends indicated by both normalization methods are broadly consistent, not considering the specific distance at which background is reached. As Table 5 indicates, there is general agreement in terms of the increment at the roadway edge relative to background concentrations (at least to an order of magnitude, in the case of CO, and much closer for benzene, EC, $NO_X$, and UF1 particle number).

**Relevance for Future Research.** Key considerations for future near-road work include the following: standardizing the location and method of obtaining background measurements and reporting more completely on site conditions. Some studies at specific sites have assessed how changes in traffic volumes or meteorological characteristics affected near-road concentrations (*40, 70, 71*). Greater and more consistent specification of site conditions in future work will broaden understanding of the key factors that contribute to near-road concentrations. This study is based on published, mostly daytime, data available as of June 2008. These data were aggregated from studies with nonuniform sampling procedures and nonuniform locations (i.e., different roadway,

geographic, and meteorological conditions). The majority of field studies were conducted at-grade with no obstructions to air flow between the road and the pollution monitors. Such obstructions have been shown to affect observed concentrations (*62*). Data were only entered when wind direction was approximately from the road to the receptors. Additionally, the sampling periods employed by each investigator typically varied from several hours to several weeks or longer. Concentrations averaged over longer periods will likely vary less than those measured during shorter intervals. Background concentrations were not always averaged over the same period as the associated near-road measurements, nor were they taken in similar locations relative to the road. The choice of background measurement technique can over- or understate roadway increments for a single study; as evidenced by Table 5, the variability in reporting background concentrations may result in an overall bias to overestimate the distance at which pollutant concentrations decay to background.

Some omitted data (*57*) (described in the Supporting Information), combined with more recent findings (*72*), indicate that nighttime or presunrise conditions can lengthen, to perhaps two or three thousand meters, the distance at which near-road pollutant concentrations decay to background. Additionally, nighttime near-road ultrafine particle number concentrations can occasionally exceed daytime conditions, despite reduced traffic volumes (*72*). Further work is needed to integrate daytime and nighttime findings and to assess their relative importance given daytime and nighttime differences in travel activity, near-road pollutant concentrations, and factors affecting human exposure.

In addition to integrating nighttime and daytime near-road findings, future work should update the findings presented here to reflect ongoing research. Additional near-road measurement results were published following assembly and analysis of the data presented in this paper [e.g. refs *73*−*75*]. Findings from recent studies are consistent with results presented here—they show that daytime near-road concentrations are generally indistinguishable from background within several hundred meters from the road.

## Acknowledgments

Support for this research was partially provided by the UC Davis-Caltrans Air Quality Project (http://AQP.engr.ucdavis.edu/) and the Caltrans Division of Research and Innovation. Dr. Song Bai provided valuable statistical assistance.

## Supporting Information Available

Annotated bibliography of all studies included in the synthesis, further discussion on data reduction, omitted data, and edge normalization as well as supplementary figures. This material is available free of charge via the Internet at http://pubs.acs.org.

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