Ambient Near-Road Mobile Source Air Toxics Concentrations in the United States

Analysis of near-road MSAT monitor concentrations and the potential contribution from roadways.

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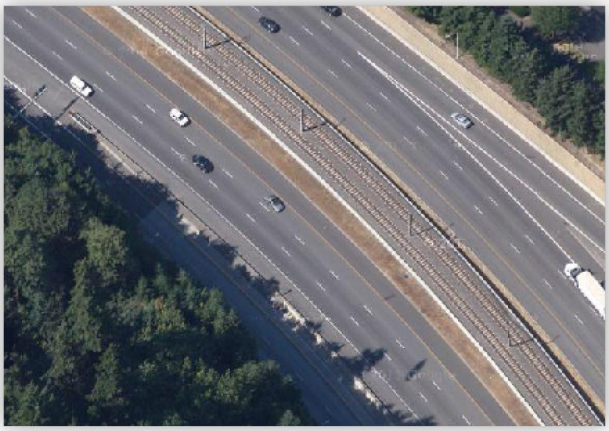

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Glossary

- **AADT (Annual Average Daily Traffic)**
- **AMCV (Air Monitoring Comparison Values), and ESL (Effects Screening Level)** – developed by TCEQ and used to describe chemical-specific air concentrations set to protect human health and welfare for acute and chronic exposures for ambient and permitting applications. Texas ESLs are set to a hazard quotient of 0.3 (i.e., cancer risk threshold is 30-in-a-million rather than 100-in-a-million for ESLs).
- **AQS (U.S. EPA's Air Quality System)**
- **ASIL (Acceptable Source Impact Level)** – developed by the State of Washington, established to show that a health risk from a source is insignificant over acute (24-hr) and chronic exposures.
- **EPA (U.S. Environmental Protection Agency)**
- **EPA OAQPS (U.S. EPA Office of Air Quality Planning and Standards)**
- **EPA SAT (U.S. EPA School Air Toxics)** – method for comparison of 1- to 14-day exposures, developed by the U.S. EPA and based on a methodology similar to the MRL designation method. Used a hierarchical set of criteria to choose between MRLs, 10*RfC, and 100-in-a-million risk for acute exposures. This study also used 100-in-a-million cancer risk benchmarks from EPA OAQPS values for 2009.
- **FE-AADT (Fleet-Equivalent Annual Average Daily Traffic)** – see https://www3.epa.gov/ttn/amtic/nearroad.html.
- **FHWA (Federal Highway Administration)**
- **HPMS (Highway Performance Monitoring System)**
- **Mann-Whitney U Test** – a nonparametric test of the null hypothesis that it is equally likely that a randomly selected value from one population will be less than or greater than a randomly selected value from a second population.
- **MDL (Method Detection Limit)** – the minimum sample concentration detectable for the monitor and method, reported in EPA's Air Quality System repository.
- **MRL (Minimum Risk Levels)** – minimum risk levels for no adverse effects for 1- to 14-day exposures, developed by the U.S. Agency for Toxics Substances Disease Registry.
- **MSATs (Mobile Source Air Toxics)** – a group of air toxics emitted by cars and trucks, including benzene, 1,3-butadiene, formaldehyde, acrolein, naphthalene, and polycyclic organic matter.
- **NATA (National Air Toxics Assessment)**

- **NESHAP (National Emissions Standards for Hazardous Air Pollutants)** – rule set forth by the U.S. EPA in 1989 that set a 100-in-a-million cancer risk threshold for benzene concentrations.
- **NEPA (National Environmental Policy Act)**
- **NO_x (Oxides of Nitrogen)**
- **POM (Polycyclic Organic Matter)** – a broad class of compounds that generally includes all organic structures having two or more fused aromatic rings.
- **r^2 (Pairwise Correlation of Determination)**
- **REL (Reference Exposure Level)** – reference exposure level for no adverse effects, for acute (1-hr, 8-hr) and chronic response times, developed by the California Environmental Protection Agency.
- **RFC (EPA Reference Concentration)** – a chronic benchmark dose-response level for no appreciable risk of deleterious effects during a lifetime.
- **SAAC (Significant Ambient Air Concentrations)** – concentrations of a toxic pollutant in the ambient air that, if exceeded, may have an adverse effect on human health' developed by Virginia Department of Environmental Quality.
- **TCEQ (Texas Commission on Environmental Quality)**
- **Urban Air Toxics** – thirty hazardous air pollutants identified in the Clean Air Act (see https://www.epa.gov/urban-air-toxics/about-urban-air-toxics).
- **VOCs (Volatile Organic Compounds)**

Summary

Mobile source air toxics (MSATs) include 1,3-butadiene, acetaldehyde, acrolein, benzene, ethylbenzene, formaldehyde, naphthalene, and polycyclic organic matter (POM). During 2016-2018, one or more of these species were measured at 17 monitoring sites in the United States that are adjacent (within 50 m) to major roadways, as part of the broader network of near-road monitoring sites that also measure criteria pollutants. We assessed the relationship of MSAT concentrations across near-road monitoring sites to traffic levels and distance from roadway, compared near-road concentrations to concentrations at nearby urban sites (for 13 of the near-road sites), and compared near-road concentrations to health benchmarks. Near-road MSAT annual average concentrations were consistently below acute 24-hr average health benchmarks, chronic non-cancer annual average health benchmarks, and chronic 100-in-a-million cancer risk benchmarks.

Distributions of MSAT multi-year concentrations for formaldehyde, acetaldehyde, and benzene were statistically significantly higher at near-road sites than nearby ambient sites, using non-parameteric Mann-Whitney paired U tests. These results indicate that some MSAT concentrations in urban areas are higher next to major freeways, although the increments are small in both absolute and percentage terms. Correlations of MSAT concentrations and increments with traffic volume and distance to roadway were not statistically significant.

1. Introduction

The U.S. Clean Air Act Amendments of 1990 regulate 187 air toxics that are associated with adverse health effects, including cancer, neurologic effects, reproductive effects, and developmental effects (U.S. Environmental Protection Agency, 2000). The list of air toxics includes a wide variety of chemicals and mixtures, including volatile organic compounds (VOCs) and components of particulate matter such as metals and polycyclic organic matter. The term polycyclic organic matter (POM) defines a broad class of compounds that includes the polycyclic aromatic hydrocarbon compounds (PAHs), of which benzo[a]pyrene is a member.[1] POM compounds are formed primarily from combustion and are present in the atmosphere in gaseous and particulate form. Air toxics emitted by motor vehicles and other mobile sources are sometimes called mobile source air toxics (MSATs). High priority MSATs at national, regional, and urban scales include 1,3-butadiene, acetaldehyde, acrolein, benzene, ethylbenzene, formaldehyde, naphthalene, and POM (U.S. Environmental Protection Agency, 2018a; Health Effects Institute Air Toxics Review Panel, 2007). Seven of these eight air toxics are also on the U.S. Environmental Protection Agency's (EPA) list of 30 urban air toxics that pose the greatest potential health threat in urban areas (https://www.epa.gov/urban-air-toxics/urban-air-toxic-pollutants).

Cancer and non-cancer health impacts associated with environmental exposures to air toxics are assessed with a variety of methods (National Research Council, 1983). One important health risk assessment methodology is dose-response assessment. Dose-response assessment characterizes the relationship between exposure to specific concentrations of a pollutant and resultant health effects. For hazardous air pollutants, dose-response relationships are typically extrapolated to ambient exposure levels based on epidemiological and toxicological data that are based on high concentration exposures; in other words, the concentrations in the environment are much lower than those observed in the worker-exposure and animal studies used to quantify toxicity (U.S. Environmental Protection Agency, 2017).

Multiple federal, state, and international organizations compile dose-response benchmarks for use in health risk assessments. These benchmarks can be used to assess whether ambient or modeled concentrations exceed or are below levels of concern. These types of benchmarks span a range of exposure durations. Acute exposure benchmarks are commonly reported as 1-hr, 8-hr, and 24-hr durations (California Office of Environmental Health Hazard Assessment, 2016; U.S. Environmental Protection Agency, 2018b). Chronic exposure benchmarks are typically compared with annual mean concentrations, but are extrapolated to 30- or 70-year exposure durations. Chronic exposures are further broken down into two separate sets of dose-response values for cancer and non-cancer effects. The chronic exposure assessments typically apply conservative assumptions that illustrate risk for individuals that are exposed to outdoor concentrations of a pollutant for 70 years, though such an exposure scenario is highly unlikely. As noted by Federal Highway Administration (FHWA): "It is

[1] Direct quote from: https://www.epa.gov/sites/production/files/2016-09/documents/polycyclic-organic-matter.pdf

particularly difficult to reliably forecast 70-year lifetime MSAT concentrations and exposure near roadways; to determine the portion of time that people are actually exposed at a specific location; and to establish the extent attributable to a proposed action, especially given that some of the information needed is unavailable." (Federal Highway Administration, 2012)

Multiple risk assessments of air toxics in the United States have been performed on a national level (Woodruff et al., 1998; Caldwell et al., 1998; U.S. Environmental Protection Agency, 2018a; McCarthy et al., 2015; 2009; U.S. Environmental Protection Agency, 2011, 2009). In addition, there have been some monitoring studies examining MSAT concentrations at the metropolitan scale (South Coast Air Quality Management District, 2008, 2015a) and in the near-road environment (Kimbrough et al., 2014; Roberts et al., 2008; Karner et al., 2010; McCarthy et al., 2016). Similar to other pollutants like NO_2, black carbon, and ultrafine particles, benzene was shown to be slightly elevated in the near-road environment compared to the urban background concentrations, although the gradients for benzene are smaller than for many of the other pollutants (Karner et al., 2010). Mobile source air toxics and their modeled cancer risks were also shown to be elevated in the near-road environment through air quality modeling performed in the Los Angeles Basin in California (South Coast Air Quality Management District, 2015b).

MSATs had not been routinely monitored next to roadways in the United States until implementation of the EPA-mandated near-road monitoring network, which began operating in 2014. Prior studies were typically special studies of short duration, rather than long-term routine measurements. Some of the longer-term near-road measurements done in the past decade were by the EPA and by the FHWA, who conducted measurements of MSATs for a year in Las Vegas next to I-95 and intermittently during 12 months in Detroit next to I-96, which had AADT of 165,300 (Kimbrough et al., 2013b; 2014). In Las Vegas, MSAT concentrations had different spatiotemporal trends than other measured pollutants such as $PM_{2.5}$ and NO_x, in that spatial gradients were not as pronounced for the MSAT species, with benzene having surprisingly higher concentrations 100 m from the roadway compared to 20 m from the roadway. They attributed the variation in the MSAT concentrations to nearby sources, which included rail lines, an airport, and busy arterial roads. In Las Vegas, ambient concentrations were within a factor of two of National Air Toxics Assessment (NATA)-modeled concentrations (Kimbrough et al., 2013a). In Detroit, from 2010 to 2011, concentrations of formaldehyde, acetaldehyde, benzene, and 1,3-butadiene were 20%-40% higher 2 m from the roadway than 100 m from the roadway, with mixed results for acrolein (Kimbrough et al., 2013b).

Olson et al. reported on 1,3-butadiene, benzene, and ethylbenzene, among other VOCs, measured in Raleigh, North Carolina, next to I-440, which had an AADT of 125,000 vehicles/day (Olson and McDow, 2009). They found that concentrations of these three species were higher at 13 m from the roadway than at 92 m from the roadway (1,3-butadiene was 2.2 times higher, benzene 1.5 times higher, and ethylbenzene 1.1 times higher), indicating a modest gradient. They found that day-to-day variations in traffic correlated with changes in ambient concentrations of VOCs, but the number of samples was insufficient to determine a robust statistical relationship. These results are consistent

with findings from multiple studies synthesized in Karner et al., which found small, “consistent decay” in VOC concentrations with increasing distance from a roadway (Karner et al., 2010).

In this work, we update and expand on existing literature by reporting on MSAT measurements made with the EPA near-road monitoring network. We present ambient concentrations of MSATs from multiple near-road locations over three years (2016-2018), a comparison of those concentrations to acute and chronic health benchmarks, and a comparison of those concentrations to concentrations at nearby urban locations. The results offer a view of MSATs across multiple types of urban areas, freeways, fleet mixes, and atmospheric settings from across the United States.

2. Methods

We examined the daily, annual, and three-year averaged MSAT concentrations at U.S. near-road monitors between 2016 and 2018. We considered the concentrations of MSAT species (benzo-a-pyrene, 1,3-butadiene, formaldehyde, acetaldehyde, acrolein (unverified), benzene, ethylbenzene, and naphthalene) at near-road sites as well as the near-road increments determined by comparing near-road concentrations with nearby ambient site concentrations. During 2016-2018, 17 near-road monitors in the U.S. measured at least one of the above-listed MSAT species. Three-year annual mean concentrations were compared to traffic volumes and distance of the monitor to the nearest mainline roadway using pairwise correlation of determination (r^2).

2.1 Data Acquisition and Processing

MSAT concentrations, measurement methods, and method detection limit (MDL) values were downloaded directly from the EPA's Air Quality System (AQS).[2] Collocated meteorological data was downloaded directly from AQS pre-generated data files.[3] If collocated data was not available, data from MesoWest was used to determine the percentage of time that winds reaching the near-road monitor were from the direction of the roadway (i.e., the monitor was downwind of the roadway).[4] Annual average traffic volume at the near-road site, and distance to the mainline roadway, were obtained from the EPA's near-road monitoring website.

2.2 Meteorology Data and Downwind Calculation

A representative meteorology record of hourly wind speed and wind direction was determined for each of the 17 near-road sites. A completeness threshold of over 75% of hours (6570 hours) of wind speed and wind direction data for each year was required for a record to be included. Collocated near-road meteorology data meeting these thresholds was available through AQS for five near-road sites. Nearby AQS stations that were within 40 km of the near-road stations and met these thresholds were available for nine near-road sites. MesoWest station data were used for the remaining three near-road sites (Oakland-0012, Berkeley-0013 and Columbus-0038). Distances between a near-road site and the meteorology site are shown in Table 1, which are zero for collocated meteorology stations.

Hourly wind direction was used to determine the percentage of time the near-road monitor was downwind, parallel, or upwind of the target roadway. These three categories were each assigned an

[2] https://www.epa.gov/aqs.
[3] https://aqs.epa.gov/aqsweb/airdata/download_files.html.
[4] https://mesowest.utah.edu.

equal 120 degree wind direction bin. Annual percent of time downwind, parallel, or upwind was calculated from these hourly categories.

2.3 Air Quality Data and Near-Road Site Characteristics

The list of near-road monitoring sites is publicly available through the EPA (https://www3.epa.gov/ttnamti1/nearroad.html). Sites are identified by their AQS site ID codes. Some sites have collocated measurements of MSAT species identified by their parameter occurrence code (POC). If multiple POC codes existed at a site, we used the POC code that best matched the nearby ambient site (described below) by method code and overlapping measurement dates. EPA also provides the geographic coordinates of the monitor and the distance of the near-road monitor from the road, defined as the distance to the edge of the roadway. Although the EPA near-road site metadata does not include a detailed breakdown of vehicle classifications, the metadata does contain AADT and fleet-equivalent AADT (FE-AADT) information for the target road from the year of site installation. EPA developed the FE-AADT calculation to represent an emissions-weighted traffic volume, taking into account both AADT and fleet mix (U.S. Environmental Protection Agency, 2012). FE-AADT is calculated as:

$$(AADT - HD_c) + (HD_m \times HD_c),$$

where HD_c is the volume of heavy-duty vehicles on the target roadway, and HD_m is a scaling factor that represents the ratio of heavy-duty to light-duty emissions of oxides of nitrogen (NO_x), which is a value of approximately 10 in most U.S. locations.

2.4 Initial Data Processing

The downloaded MSAT concentration data was reported by the submitting agency with an associated minimum detection limit (MDL) for each data point. This "alternate MDL" is intended to supersede the method-specific Federal instrument MDL provided by EPA. For data calculations requiring the MDL, if an alternate MDL was not provided, the Federal instrument MDL was used. MSAT concentration values ≤0 were substituted with MDL/2. MSAT concentrations and MDL values that were reported in units other than $\mu g/m^3$ were converted into those units. **Table 1** shows the full list of near-road sites and the MSAT species measured at each site between 2016 and 2018.

Table 1. A list by name and AQS ID code of all nationwide sites measuring MSAT species between 2016-2018, showing which species were measured at each site.

Site Name	State	AQS ID	Distance to road	1,3-Butadiene	Acetaldehyde	Acrolein (unverified)	Benzo[a]pyrene	Benzene	Ethylbenzene	Formaldehyde	Naphthalene	Distance to meteorological station (km)
Providence-0030	RI	44-007-0030	5.0	✓				✓	✓		✓	2.4
Rochester-0015	NY	36-055-0015	11.0		✓					✓		0.8
Seattle-0030	WA	53-033-0030	11.0	✓	✓		✓	✓	✓	✓		0.0
Pleasanton-0015	CA	06-001-0015	15.0	✓				✓	✓			39.2
Laurel-0006	MD	24-027-0006	17.0	✓		✓		✓	✓			0.0
Berkeley-0013	CA	06-001-0013	19.0	✓				✓	✓			17.9
Cheektowaga-0023	NY	36-029-0023	20.0		✓					✓		6.1
Oklahoma City-0097	OK	40-109-0097	20.0	✓	✓			✓	✓	✓		0.0
Fort Lee-0010	NJ	34-003-0010	22.0					✓	✓			7.6
Oakland-0012	CA	06-001-0012	24.0	✓				✓	✓			9.1
Indianapolis-0087	IN	18-097-0087	25.0	✓				✓	✓			0.0
Philadelphia-0076	PA	42-101-0076	25.0				✓					10.8
Queens-0125	NY	36-081-0125	29.0		✓					✓		0.5
Columbus-0038	OH	39-049-0038	32.0	✓		✓		✓	✓		✓	4.1
San Jose-0006	CA	06-085-0006	33.0	✓				✓	✓			4.1
Atlanta-0003	GA	13-089-0003	35.0	✓		✓		✓	✓			2.0
Minneapolis-0962	MN	27-053-0962	35.0	✓	✓			✓	✓	✓		0.0
		Total		**12**	**6**	**3**	**2**	**13**	**13**	**5**	**2**	

2.5 Data Aggregation

Daily, average annual, and three-year-mean near-road concentrations were calculated using all available daily data from the 17 near-road sites. Table 1 lists all near-road sites used in the analysis. Daily and average annual concentrations were compared to health benchmarks (see below).

2.6 Increment Calculations

Daily measurements at a given near-road site were paired with coincident measurements at a nearby, ambient monitoring site; the difference between the two site values was then used as an estimate of the near-road "increment" for each day. The increment is calculated as the difference in concentration between the near-road site and coincident measurements at a nearby, ambient monitoring site for each day:

$$\text{Increment}_i = ([\text{NR}]_i - [\text{AM}]_i)$$

Where [NR] is the concentration of the pollutant at the near-road site, [AM] is the concentration of the pollutant at the nearby ambient site, and i is the ith day. Daily increment values were averaged to obtain longer-term values. Increments were calculated only where comparable methods were used in the near-road and nearby ambient measurements. Note that the nearby sites were not chosen for evaluation of gradients or increments from the same roadway as the near-road site. Rather, the increments were calculated opportunistically using nearby sites that represent urban-scale concentration levels, and are not situated for an ideal increment calculation.

Only near-road and nearby ambient measurement sets with over 75% completeness in at least three out of four quarters (Jan-Mar, Apr-Jun, Jul-Sep, Oct-Dec) were used in the increment calculation. Nearby ambient sites were considered as possible options for comparison to the near-road site if they were within the same urban area and measured the same MSAT species as the near-road site. The final nearby ambient site was chosen for each near-road site after consideration of comparable measurement methods for each parameter, distance to the near-road monitor, confounding factors (such as proximity to oil refineries and other industrial facilities) in the vicinity of the ambient monitor, and the number of days both the near-road and nearby ambient monitors were measuring the same species.

The original list of 17 near-road monitors (**Table 2**) was reduced to 13 during the annual aggregation stage of data reduction. Sites that did not meet the 75% annual completeness threshold include Fort Lee-0010 (benzene and ethylbenzene), Columbus-0038 (1,3-butadiene, acrolein (unverified), benzene, ethylbenzene, and naphthalene), and Providence-0030 (1,3-butadiene, benzene, ethylbenzene, and naphthalene). Philadelphia-0076 met the annual completeness threshold but did not have a nearby ambient site with overlapping dates for comparison. Consequently, these four sites are not used in the increment calculations. Columbus-0038 and Providence-0030 were the only two near-road sites reporting naphthalene concentrations. Thus, we report near-road concentrations for naphthalene but no naphthalene increments for these two sites. A similar situation exists for benzo-a-pyrene, which was measured at Philadelphia-0076 and Seattle-0030. While near-road concentrations are calculated and reported for both sites, a daily average increment is only calculated for Seattle-0030, since Philadelphia-0076 did not meet annual completeness thresholds.

Table 2 lists the 13 near-road sites used in the increment calculations and the nearby ambient monitors chosen after restricting for annual completeness, comparable measurement dates, and

similar instrument methods. The ambient monitor that had MSAT measurements and was closest to the near-road site was used in all but two cases. For Minneapolis, the ambient site 1.8 km away that measured all MSATs was used (AQS ID 27-053-0966), rather than a site 1.3 km away that did not have 1,3-butadiene measurements. At Seattle, the closest ambient monitor did not have benzo-a-pyrene or ethylbenzene, so a monitor site 3.3 km away (AQS ID 53-033-0080) was used.

From the finalized list of paired near-road and nearby ambient monitors, increments were calculated for each pollutant on a daily basis for data between 2016 and 2018 and then averaged to calculate an average daily increment. This resulted in a total of 45 daily average incremental values for benzo[a]pyrene, 1,3-butadiene, formaldehyde, acetaldehyde, acrolein (unverified),[5] benzene, and ethylbenzene across the 13 near-road sites. A discussion of how many increments were calculated for each MSAT species, as well as an assessment of increment significance, follows in Section 3.

[5] Acrolein (unverified) is the terminology used by EPA to report acrolein values. It refers to challenges that exist in verifying acrolein concentrations given available measurement methods.

Table 2. The name and AQS ID of all U.S. near-road sites measuring MSAT species between 2016 and 2018.

Near-Road Site		Nearby Ambient Site	Distance Between Monitors (km)
Site Name	AQS ID	AQS ID	
Atlanta-0003	13-089-0003	13-089-0002	2
Berkeley-0013	06-001-0013	06-001-0011	5.8
Cheektowaga-0023	36-029-0023	36-029-1014	13.8
Indianapolis-0087	18-097-0087	18-097-0078	2.9
Laurel-0006	24-027-0006	24-033-0030	10.1
Minneapolis-0962	27-053-0962	27-053-0966	1.8
Oakland-0012	06-001-0012	06-001-0011	2.9
Oklahoma City-0097	40-109-0097	40-109-1037	15.5
Pleasanton-0015	06-001-0015	06-001-0007	10.6
Queens-0125	36-081-0125	36-081-0124	0.5
Rochester-0015	36-055-0015	36-055-1007	0.8
San Jose-0006	06-085-0006	06-085-0005	4.2
Seattle-0030	53-033-0030	53-033-0080	3.3
Fort Lee-0010	34-003-0010	NA	NA
Columbus-0038	39-049-0038	NA	NA
Providence-0030	44-007-0030	NA	NA
Philadelphia-0076	42-101-0076	NA	NA

2.7 Increment Uncertainty Statistics and Significance

Increment Uncertainty

The calculation of uncertainty for increment values was based on propagation of the estimated daily point uncertainty. This daily point error for both the near-road and nearby ambient sites was estimated by:

$$U_p = (0.5 \times MDL) + (0.1 \times Conc_{daily})$$

where U_p is the daily point uncertainty, *MDL* is the method detection limit provided with the EPA AQS data downloaded (termed the alternate method detection limit), or the federal method detection limit for the instrument if no alternate method detection limit was provided, and $Conc_{daily}$ is the daily concentration of the MSAT species.

The daily increment uncertainty is calculated as:

$$U_{daily\ inc} = \sqrt{{U_{p(NR)}}^2 + {U_{p(NbA)}}^2}$$

where $U_{p(NR)}$ and $U_{p(NbA)}$ are the daily point uncertainties associated with the near-road measurements and nearby ambient measurements, respectively. The daily average uncertainty is then calculated as:

$$U_{\ daily\ 3-year\ inc} = \frac{mean(U_{daily\ inc})}{\sqrt{N}}$$

where *N* represents the days of data where both the near-road and nearby monitors measured a given MSAT species.

Increment Significance

Daily average increment significance was assessed in three ways: (1) increment value, (2) statistical comparison of the near-road and nearby ambient populations, and (3) analytical uncertainty assessment.

Increment value. An increment was not assessed as statistically significant unless it was positive. Negative increments arise when the nearby ambient site used for comparison has a higher concentration of an MSAT than the near-road site. Since a negative increment does not provide information on the roadway contribution of MSATs, we simply constrain these site-pollutant combinations to indicate a result consistent with the null hypothesis (i.e., no measureable contribution from the roadway).

Population comparison. The non-parametric rank-order paired Mann-Whitney U test was used to assess whether the concentration distributions of a near-road and nearby site were statistically different. Because of the non-normal distribution of the MSAT data, a statistical comparison of the near-road and ambient MSAT data populations using a standard t-test would be inappropriate, since the underlying assumption of a standard t-test is that the data are normally distributed. Near-road and nearby data sets were considered to be statistically significant when the Mann-Whitney U test p-value was less than 0.05; this shows that the concentration distributions were not likely to be from the same population at a 95% level of confidence.

Analytical uncertainty assessment. If more than 50% of the daily points at either the near-road or the nearby ambient monitor were below MDL, the calculated increment was assessed as less reliable and, for the purposes of this work, was not considered statistically significant.

All three of the criteria needed to be met for an increment to be deemed statistically significant. For example, if an increment was positive and had a p-value of less than 0.05, but the daily concentrations for the near-road monitor were above MDL only 20% of the time, the increment was not assessed as statistically significant. The term "statistically significant" is defined here as a positive increment that is statistically distinguishable and larger than the instrument analytical uncertainty.

2.8 Health Benchmarks

Dose-response values were aggregated from multiple federal and state agencies. Data was acquired in August 2019. Table 3 shows the sources used for non-cancer benchmarks. Three EPA dose-response value data sets were used as representative federal benchmarks: the Integrated Risk Information System is the EPA's clearinghouse for dose-response information, the Office of Air Quality Planning Standards aggregates benchmarks for health risk assessments, and the School Air Toxics study was a high-profile example where EPA applied benchmarks in a real-world case. We also included benchmarks for agencies from four states: California, Texas, Virginia, and Washington. Note that there may be multiple benchmarks that are appropriate for any given monitoring site due to overlapping state and federal agency jurisdictions.

Table 3. Agency sources and names/abbreviations of various dose-response non-cancer benchmarks acquired for use in this work.

Agency	Abbreviation	Non-cancer Metric	Non-cancer Abbreviation
U.S. Environmental Protection Agency - Office of Air Quality Planning Standards	EPA OAQPS	Reference concentration	RfC
U.S. Environmental Protection Agency - Integrated Risk Information System	EPA IRIS	Reference concentration	RfC
U.S. Environmental Protection Agency - School Air Toxics	EPA SAT	School air toxics method	SAT
California Office of Environmental Health Hazard Assessment	CA OEHHA	Reference exposure level	REL
Texas Commission on Environmental Quality	TCEQ	Air Monitoring Comparison Value	AMCV
Virginia Department of Environmental Quality	VDEQ	Significant Ambient Air Concentration	SAAC
Washington Department of Ecology	WA	Acceptable Source Impact Level	ASIL

Several different terms are used for acute and chronic dose-response benchmarks across different agencies, defined as follows:

- **RfC** (EPA Reference Concentration). A chronic benchmark dose-response level for no appreciable risk of deleterious effects during a lifetime.
- **MRL** (Agency for Toxics Substances Disease Registry). Minimum risk levels for no adverse effects for 1- to 14-day exposures.
- **REL** (California EPA). Reference Exposure Level for no adverse effects, for acute (1-hr, 8-hr) and chronic response times.
- **AMCV or ESL** (TCEQ). Air Monitoring Comparison Values (AMCV), and Effects Screening Level (ESL) are used to describe chemical-specific air concentrations set to protect human health and welfare for acute and chronic exposures for ambient and permitting applications. Texas ESLs are set to a hazard quotient of 0.3 (i.e., cancer risk threshold is 30-in-a-million rather than 100-in-a-million for ESLs). We selected the lower threshold when selecting the ESL or AMCV value in Table 5.

- SAAC (VDEQ). Significant Ambient Air Concentrations of a toxic pollutant in the ambient air that, if exceeded, may have an adverse effect on human health.
- ASIL (WA). Acceptable Source Impact Level, established to show that a health risk from a source is insignificant over acute (24-hr) and chronic exposures.
- School Air Toxics (EPA). Method for comparison of 1- to 14-day exposures based on a methodology similar to the MRL designation method. Used a hierarchical set of criteria to choose between MRLs, 10*RfC, and 100-in-a-million risk for acute exposures. This study also used 100-in-a-million cancer risk benchmarks from EPA Office of Air Quality Planning and Standards (OAQPS) values for 2009.

There are methodological differences in each of these benchmarks that go beyond the scope of this paper. These differences may make some comparisons of these benchmarks at given durations inappropriate. We use these differences to demonstrate the range of dose-response values that may be appropriate to compare at a given site when screening for potential health risks associated with a given pollutant. This is different than a true health risk assessment, where there is a two-step process for highway projects with relevant state or federal agency staff. The first step requires EPA to determine an "acceptable" level of risk due to emissions from a source, which is generally no greater than approximately 100 in a million. The second step considers additional factors, with the goal to maximize the number of people with risks less than 1 in a million due to emissions from a source. The results of this statutory two-step process do not guarantee that cancer risks from exposure to air toxics are less than 1 in a million; in some cases, the residual risk determination could result in maximum individual cancer risks that are as high as approximately 100 in a million. In a June 2008 decision, the U.S. Court of Appeals for the District of Columbia Circuit upheld EPA's approach to addressing risk using this two step decision framework.

The acute dose-response benchmarks ($\mu g/m^3$) used in this study are shown in Table 4, and the chronic dose-response benchmarks used in this study are shown in Table 5. The U.S. Federal Highways Administration recommends a three-tier approach when considering MSATs in National Environmental Policy Act (NEPA) documentation; each of the three tiered approaches use emissions based approaches to screen for meaningful MSAT effects but do not include health risk thresholds. (Federal Highway Administration, 2012).

Table 4. Concentrations (µg/m^3) of acute dose-response thresholds used to screen 24-hr concentration measurements.

Parameter	Effect	MRL	School.Air.Toxic	TX.AMCV	WA.ASIL
1,3-Butadiene	Non-cancer		20	950	
Acetaldehyde	Non-cancer		90		
Acrolein	Non-cancer	6.9	3.5	11	0.06
Benzene	Non-cancer	29	300	320	
Benzo[a]pyrene	Non-cancer		0.02		
Ethylbenzene	Non-cancer	22,000	10,000		
Formaldehyde	Non-cancer	49	98	50	
Naphthalene	Non-cancer		30		

Table 5. Concentrations (µg/m^3) of chronic dose-response thresholds used to screen annual concentrations measurements. The "Effect" column indicates whether the adverse health effect dose-response threshold is for a cancer or non-cancer endpoint.

Parameter	Effect	CA.OEHHA	EPA.IRIS	EPA.OAQPS	TX.AMCV	VA.SAAC	WA.ASIL
1,3-Butadiene	Cancer	0.588	3.33	3.33	20	NA	0.588
Acetaldehyde	Cancer	37.0	45.4	45.4	NA	NA	37
Benzene	Cancer	3.45	12.8	12.8	4.5	NA	3.45
Benzo[a]pyrene	Cancer	0.0909	0.167	0.167	NA	NA	0.0909
Ethylbenzene	Cancer	40	NA	40	NA	NA	40
Formaldehyde	Cancer	16.7	7.69	7.69	5.5	NA	16.7
1,3-Butadiene	Non-cancer	2	NA	2	9.9	NA	NA
Acetaldehyde	Non-cancer	140	NA	9	45	360	NA
Acrolein	Non-cancer	0.35	NA	0.35	2.7	0.46	NA
Benzene	Non-cancer	60	NA	30	84	NA	NA
Benzo[a]pyrene	Non-cancer	NA	NA	0.002	0.003	NA	NA
Ethylbenzene	Non-cancer	2,000	NA	1,000	1,900	868	NA
Formaldehyde	Non-cancer	55	NA	9.8	11	2.4	NA

3. Results

3.1 Near-Road MSAT Concentrations

Table 6 shows the three-year-mean values for MSATs measured at all 17 near-road sites where data was available (for annual mean values, see Table A-1 in the Appendix). These concentrations include ambient background levels. Values labelled "N" indicate the number of data points used in the calculation. As noted in the Section 2, the data used in this table was all available daily data and was not filtered for annual completeness. The distance between the monitoring site and mainline road, and the 2016 Highway Performance Monitoring System (HPMS) AADT and 2016 estimated FE-AADT for the main road, are also listed. Additional information concerning the near-road site traffic data including the target road and estimated percentage of trucks, are presented in Table A-2. Table A-3 lists the percentage of time the measured value was above the MDL for each species at each site throughout the study. Figure 1 shows a graphical representation of the data to assess trends with distance to road and traffic volume using pairwise correlation of determination (r^2) and slope of the linear regression. The r^2 value is a measure of the correlation of the relationship between two variables; the closer the r^2 value is to one, the tighter the relationship. Here, for example, an r^2 value of zero would indicate that traffic data explains none of the variability observed in the concentration data, while a value of one suggests all variability is explained by traffic data. Data is plotted for species where more than three concentration data points were available. The daily average concentrations trends with the distance to the mainline road are shown in Panels A-E of Figure 1, and trends with daily traffic volume are shown in Panels F-J of Figure 1.

The highest concentrations of 1,3-butadiene (0.25 ± 0.16 µg/m^3), acrolein-unverified (0.82 ± 0.79 µg/m^3), and Naphthalene (0.54 ± 0.34 µg/m^3) were recorded at the Columbus-0038 site. This site was also tied for the highest reported concentration of benzene (1.1 µg/m^3) along with San Jose-0006 and Providence-0030. The Columbus monitoring station is located 32 m from a mainline roadway with an AADT of 135,746 (FE-AADT of 272,758). Additionally, satellite imaging of the Columbus-0038 monitoring location reveals that the site is less than 50 feet from Columbus Fire Station 27. Emergency vehicles such as fire trucks are fueled by diesel, and therefore it is possible increased concentrations of MSATS may result from the transit or idling of emergency vehicles at the fire station or from other site-specific factors such as evaporative loss of fuel stored at the fire station (we did not have the resources to examine this issue).

Overall, 1,3-butadiene mean concentrations ranged from 0.016 µg/m^3 in Pleasanton-0015 up to 0.25 µg/m^3 in Columbus-0038 (Table 6). Despite having the highest HPMS AADT values, the sites in California (Pleasanton-0015, Berkeley-0013, Oakland-0012, San Jose-0006) were an order of magnitude lower in 1,3-butadiene concentration than near-road sites in other states. Additionally, the nearby ambient site concentrations of 1,3-butadiene in California were on the same order of magnitude as the ambient sites in other states. The reason for this difference is not immediately

clear from the data set, but may be due to different fuel formulations or other regulations in California. This can be seen in Figure 1, Panel I. The plot also illustrates that the 1,3-butadiene levels were not only lowest for California (highest HPMS AADT sites), but actually exhibited a decreasing trend with increasing AADT across all sites (r^2=0.72), since the concentrations in California were lower while the HPMS AADT was higher.

Species not plotted in Figure 1 because of the low number of data points are acrolein, which ranges from 0.30 µg/m^3 at Atlanta-0003 to 0.82 µg/m^3 at Columbus-0038; benzo-a-pyrene, which was 7.2×10^{-5} µg/m^3 at Seattle-0030 and 9.1×10^{-5} µg/m^3 at Philadelphia-0076; and naphthalene, which was 0.12 µg/m^3 at Providence-0030 and 0.54 µg/m^3 at Columbus-0038. Trends for these species are difficult to discern because of small sample size; however, their values are included here for completeness.

Acetaldehyde mean concentrations ranged from 1.10 µg/m^3 at Cheektowaga-0023 to 2.07 µg/m^3 at Oklahoma City-0097. This species showed no discernable trend with distance to the road (r^2=0.04) or AADT (r^2=0.04). The lowest benzene concentration was reported at Pleasanton-0015 (0.58 µg/m^3), while the highest was 1.1 µg/m^3 at San Jose-0006, Columbus-0038, and Providence-0030. The San Jose-0006 and Providence-0030 sites are located 33 m and 5 m, respectively, from a roadway with no other obvious point sources in the vicinity. Panels B and G of Figure 1 show that benzene did not exhibit a strong trend with either distance to the mainline road (r^2 = 0.005) or HPMS AADT (r^2=0.15). Ethylbenzene was lowest in Atlanta-0003 (0.12 µg/m^3) and highest in San Jose-0006 (0.74 µg/m^3). Like benzene, ethylbenzene showed no emerging trend with either distance to road (r^2=0.04) or HPMS AADT (r^2 = 0.003). Formaldehyde was lowest at Seattle-0030 (1.8 µg/m^3) and highest at Oklahoma City-0097 (3.5 µg/m^3). Plots of formaldehyde (Figure 1, Panels E and J) showed a positive correlation between formaldehyde and increasing distance from the mainline road (r^2 = 0.47), suggesting that formaldehyde concentrations increased with greater distance from the roadway. Additionally, formaldehyde concentration showed a weaker correlation with increasing HPMS AADT (r^2 =0.19), suggesting that as traffic volume increases, so may formaldehyde. These appear to be somewhat contradictory trends, but the correlation suggested by r^2 is stronger with distance to the mainline roadway, and this correlation is likely more reliable.

Table 6. List of all near-road sites in the U.S. by name, AQS ID, and the three-year mean concentration (µg/m^3) and standard deviation of each MSAT measured at that site. "N" is the number of daily data points available for the site in 2016-2018. The distance between the monitor and the mainline roadway, 2016 HPMS AADT, 2016 estimated FE-AADT, and the calculated % of time that the near-site monitor was downwind of the mainline roadway are also listed. Fort Lee-0010 measurements are hourly while the other sites are daily measurements.

Site Name	1,3-Butadiene mean ±stdev	Acetaldehyde mean ±stdev	Acrolein (unverified) mean ±stdev	Benzo[a] pyrene mean ±stdev	Benzene mean ±stdev	Ethylbenzene mean ±stdev	Formaldehyde mean ±stdev	Naphthalene mean ±stdev	Distance to Main-line (m)	2016 HPMS AADT	2016 Estimated FE-AADT	Time Down-wind
Providence-0030	0.20 ± 0.070 N=57				1.1 ± 0.40 N=57	0.46 ± 0.18 N=57		0.12 ± 0.053 N=57	5.0	159500	356833	43%
Rochester-0015		1.18 ± 0.52 N=182					2.2 ± 1.2 N=181		11.0	98306	128179	61%
Seattle-0030	0.14 ± 0.082 N=62	1.23 ± 0.74 N=62		$7.2\times10^{-5} \pm 6.7\times10^{-5}$ N=162	0.94 ± 0.45 N=62	0.53 ± 0.27 N=62	1.8 ± 1.0 N=62		11.0	167093	332515	35%
Pleasanton-0015	0.016 ± 0.016 N=22				0.58 ± 0.60 N=22	0.27 ± 0.19 N=22			15.0	233000	NA	29%
Laurel-0006	0.12 ± 0.12		0.36 ± 0.42 N=168		0.60 ± 0.26 N=168	0.17 ± 0.12 N=168			17.0	199131	482296	25%
Berkeley-0013	0.032 ± 0.063 N=72				0.68 ± 0.54 N=72	0.48 ± 0.41 N=72			19.0	267000	382108	64%
Cheektowaga-0023		1.10 ± 0.52 N=180					2.2 ± 1.2 N=180		20.0	126107	212275	45%
Oklahoma City-0097	0.15 ± 0.070 N=156	2.07 ± 0.79 N=156			0.95 ± 0.32 N=156	0.69 ± 1.8 N=156	3.5 ± 1.5 N=156		20.0	165000	207768	28%
Fort Lee-0010					0.66 ± 0.50 N=4911	0.23 ± 0.41 N=4729			22.0	282912	556501	4%
Oakland-0012	0.047 ± 0.068 N=92				0.77 ± 0.51 N=92	0.49 ± 0.42 N=92			24.0	225000	441675	54%
Indianapolis-0087	0.19 ± 0.23 N=173				0.80 ± 0.47 N=173	0.28 ± 0.28 N=173			25.0	165672	316144	30%
Philadelphia-0076				$9.1\times10^{-5} \pm 1.0\times10^{-4}$ N=144					25.0	210456	344929	36%
Queens-0125		1.57 ± 0.88 N=97					3.4 ± 1.9 N=96		29.0	170874	330810	44%
Columbus-0038	0.25 ± 0.16 N=15		0.82 ± 0.79 N=15		1.1 ± 0.67 N=15	0.31 ± 0.29 N=15		0.54 ± 0.34 N=15	32.0	135746	272758	35%
San Jose-0006	0.059 ± 0.11 N=88				1.1 ± 0.82 N=88	0.74 ± 0.66 N=88			33.0	251000	386540	31%
Atlanta-0003	0.12 ± 0.30 N=85		0.30 ± 0.19 N=69		0.59 ± 0.33 N=84	0.12 ± 0.10 N=81			35.0	147000	320710	28%
Minneapolis-0962	0.10 ± 0.083 N=134	1.31 ± 0.55 N=145			0.72 ± 0.38 N=137	0.22 ± 0.16 N=137	3.0 ± 1.2 N=145		35.0	250000	349504	30%

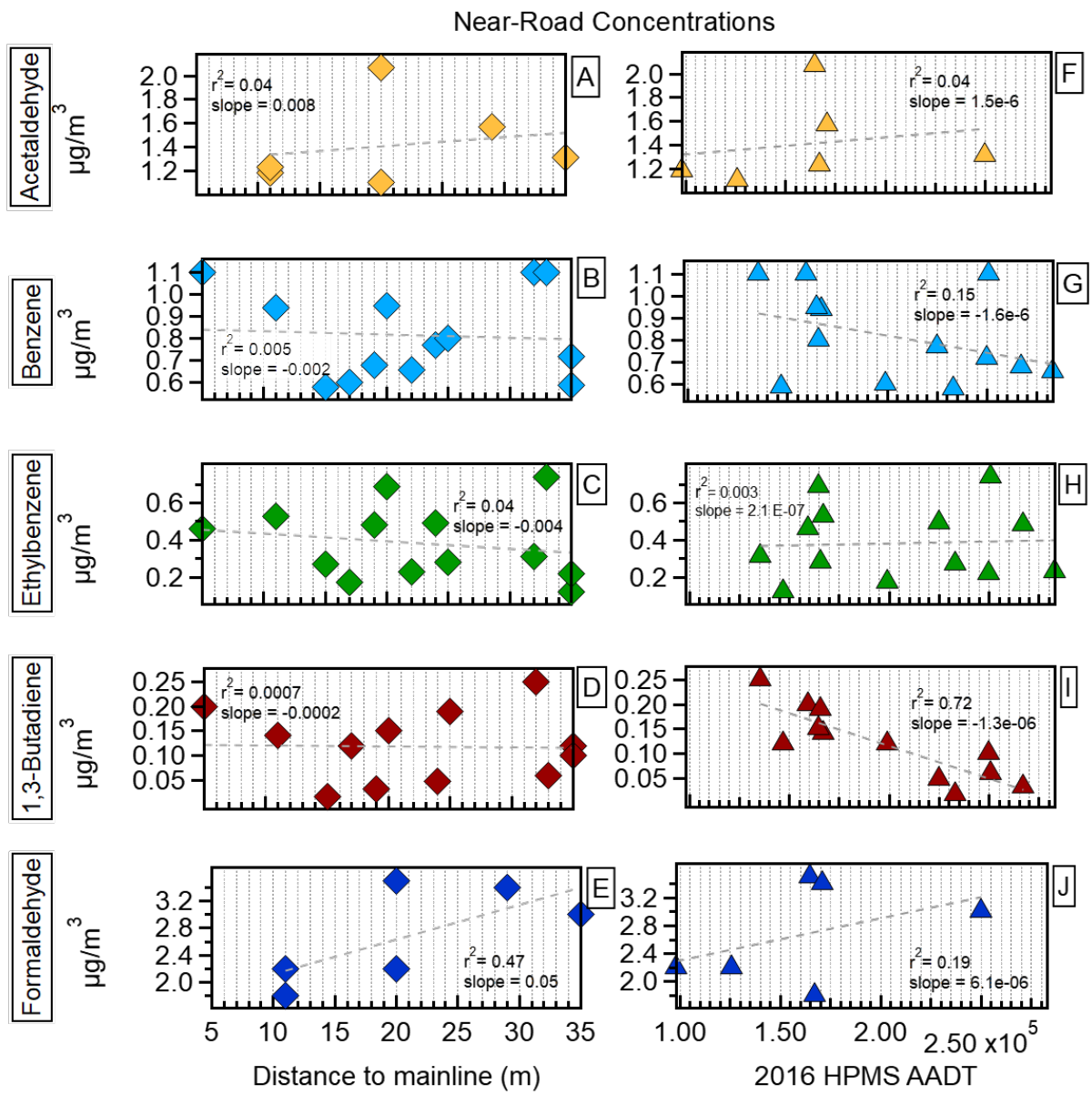

Figure 1. Near-road three-year concentration means for acetaldehyde (yellow), benzene (light blue), ethylbenzene (green), 1,3-butadiene (red), and formaldehyde (dark blue) as a function of distance between the near-road monitor and the mainline roadway (A-E), and 2016 HPMS AADT (F-J). Gray dashed lines indicate a linear regression fit to the data points, and the r^2 and slope of the fit are indicated in each panel.

3.2 Comparison of Near-Road MSAT Concentrations with Health Benchmarks

Daily average concentrations at all near-road monitoring sites with data at any point in the 2016-2018 time period are compared to daily dose-response benchmarks in Figure 2. The entire range of daily average concentrations is shown for each near-road monitoring site, with outliers (1.5 × interquartile range) shown as individual points. All observed near-road daily average concentrations of 1,3-butadiene, acetaldehyde, benzene, benzo[a]pyrene, ethylbenzene, formaldehyde, and naphthalene were well below the acute dose-response thresholds. One pollutant, acrolein, had a range of daily average concentrations that exceeded the State of Washington ASIL ambient screening impact level threshold, but were below the other thresholds (MRL, School Air Toxics, and TCEQ Air Monitoring Comparison Values). Measurements of acrolein are classified in the EPA AQS database as "unverified," indicating that the methodology used to collect and quantify the concentrations is considered suspect by EPA and requires additional validation procedures. We note this only to indicate that the "acrolein – unverified" measurements have not been shown to meet EPA's higher validation requirements for this specific compound.

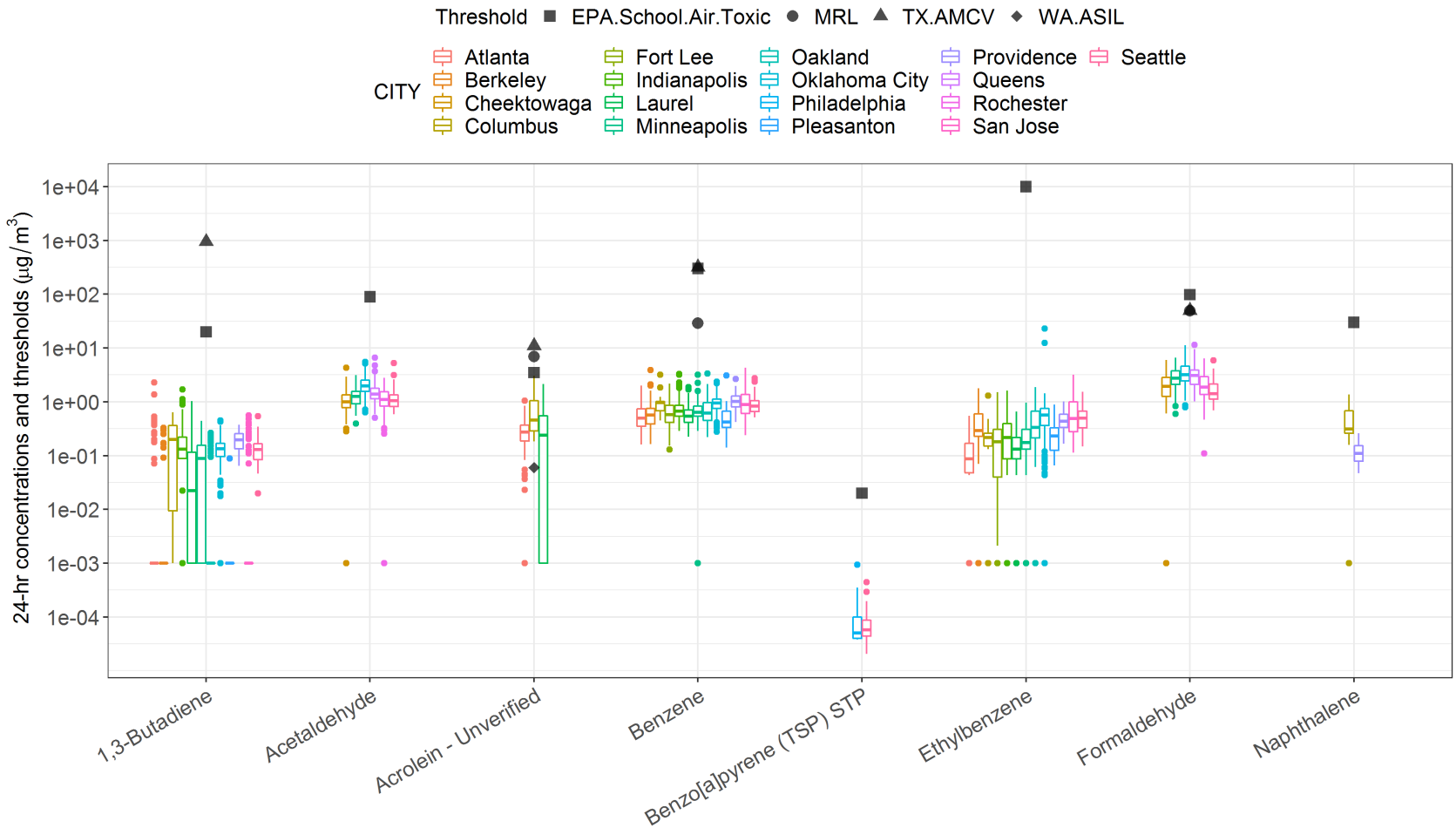

Figure 2. Box plots of 24-hr concentrations (µg/m^3) sampled in 2016-2018 at near-road monitoring sites, compared to four 24-hr acute dose-response benchmarks (Minimum Risk Level, EPA School Air Toxics, Texas Air Monitoring Comparison value and the Washington Acceptable Source Impact Level).

Figure 3 compares annual mean concentrations, aggregated from daily-average concentrations at all near-road monitoring sites with 75% complete observations for any individual year in the 2016-2018 time period, to chronic non-cancer dose-response benchmarks. The annual mean concentrations are individually shown by site and year, with color indicating the site and point size indicating the year. All aggregated annual mean concentrations of 1,3-butadiene, acetaldehyde, benzene, benzo[a]pyrene, and ethylbenzene were well below the chronic dose-response thresholds. One pollutant, acrolein, had a range of annual mean concentrations at or above multiple dose-response thresholds for EPA, California, and Virginia benchmarks. Additionally, all annual mean concentrations of formaldehyde were below three benchmark screening levels (California REL, Tx.AMCV.ESL, and EPA OAQPS) but near, at, or above the Virginia non-cancer SAAC benchmark of 2.4 $\mu g/m^3$.

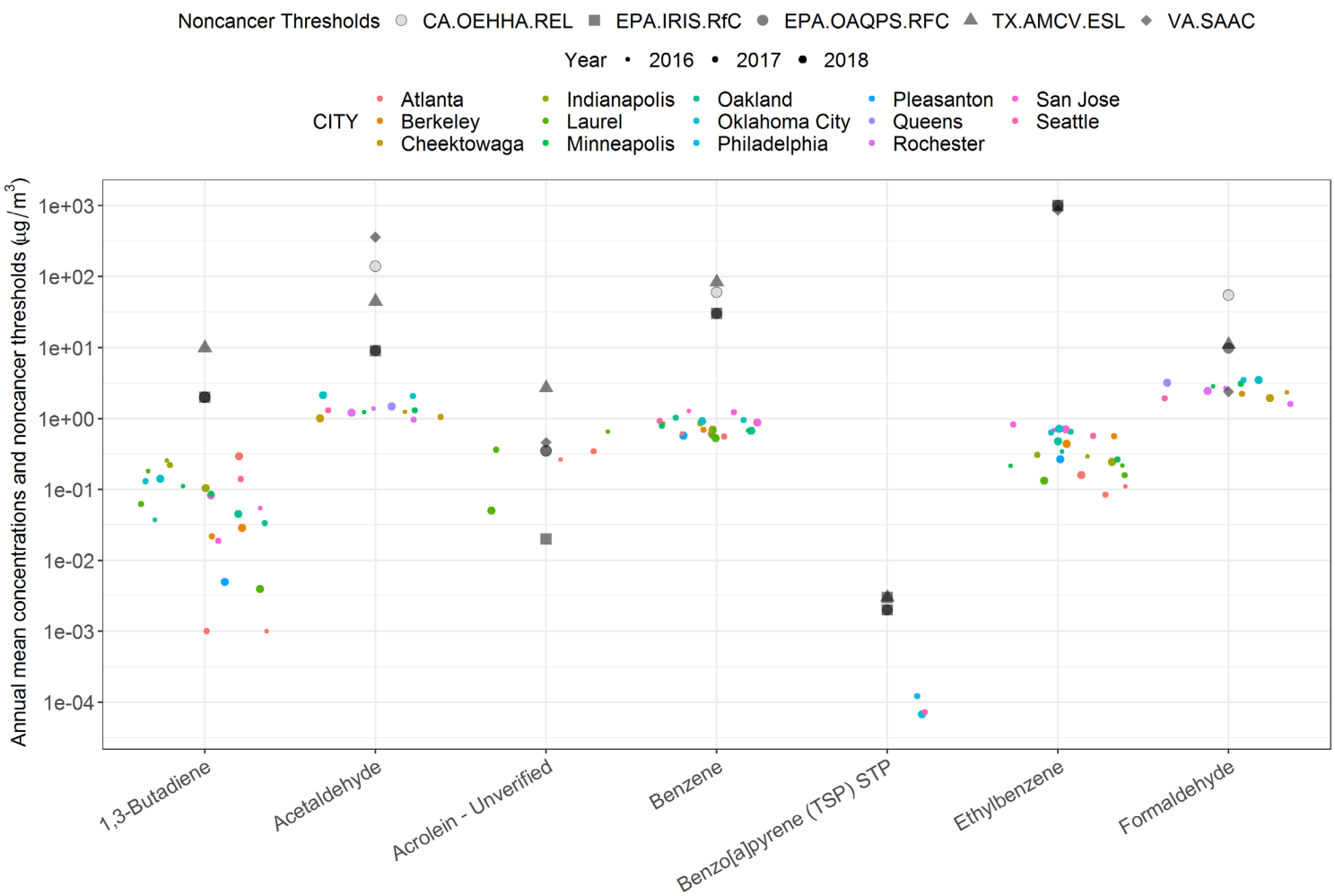

Figure 3. Annual concentrations (µg/m^3) sampled from 2016-18 at near-road monitoring sites compared to chronic non-cancer dose-response benchmarks (EPA OAQPS, EPA Integrated Risk Information System, California Office of Environmental Health Hazard Assessment, Texas Air Monitoring Comparison Value, and the Virginia Significant Ambient Air Concentrations)..

Figure 4 shows annual mean concentrations, aggregated from daily-average concentrations at all near-road monitoring sites with 75% complete observations for any individual year in the 2016-2018 time period, compared to chronic cancer dose-response benchmarks of 100-in-a-million cancer risk. The annual mean concentrations are individually shown by site and year, with color indicating the site and point size indicating the year. All aggregated annual mean concentrations of 1,3-butadiene, acetaldehyde, benzene, benzo[a]pyrene, ethylbenzene, and formaldehyde were well below the chronic dose-response thresholds. Cumulatively, the six pollutants were below the summed 100-in-a-million risk thresholds

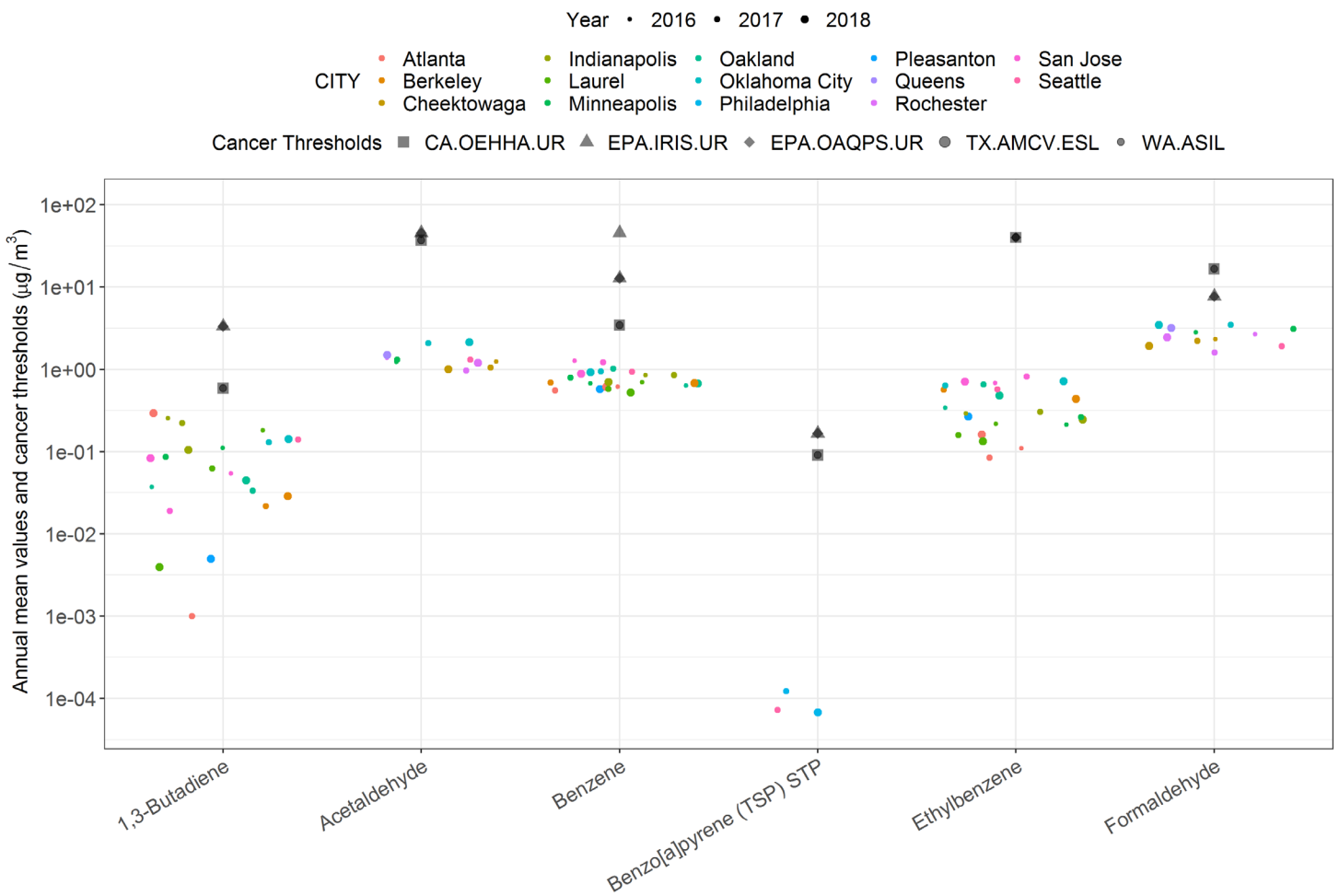

Figure 4. Annual concentrations (µg/m³) sampled in 2016-2018 at near-road monitoring sites, compared to chronic cancer 100-in-a-million risk dose-response benchmarks (EPA Integrated Risk Information System, EPA Office of Air Quality Planning and Standards, California Office of Environmental Health Hazard Assessment, Texas Air Monitoring Comparison Value and Washington Acceptable Source Impact Level).

3.3 Comparison of Near-Road and Nearby MSAT Concentrations

To understand the concentration of MSATs originating from roadways, monitoring sites near the near-road monitoring sites were used to approximate the ambient background levels of MSATs. Daily MSAT increments representing the contribution from traffic were calculated as the difference between the near-road value and the background value. Increments were calculated on a daily basis and then averaged to calculate the daily average MSAT increment for a given site. Uncertainty analysis was performed to assess the validity of calculated increments, as described in Section 2.

A summary of the results from the increment calculations and uncertainty analysis is shown in **Table 7**. The table shows the number of near-road sites where an average increment value was calculated for a given MSAT species between 2016 and 2018 (Column 3). This results in one average increment value per MSAT measured per site. Some calculations resulted in negative increment values, which were then removed, leaving only sites with a positive increment value (Column 4). Of the sites with positive increments, the daily data was assessed, and only the average increments composed of data that were above MDL more than 50% of the time for both the near-road and ambient site were kept (Column 5). Of the sites with positive increments, a Mann Whitney U test was performed on the daily near-road and nearby ambient data, resulting in a p-value. A p-value of <0.05 suggests a statistically significant difference between the near-road and nearby ambient populations (Column 6). Column 7 is the final list of sites with significant increments, determined by taking into account the results from the analytical uncertainty (Columns 5) and population uncertainty (Column 6).

Initially, 45 increments for the seven MSAT species could be calculated from the 13 near-road and nearby ambient site pairs. 1,3-butadiene, benzene, and ethylbenzene were the most commonly measured MSAT species at the near-road sites, initially producing up to 10 potential increments each. Upon assessing the three sources of uncertainty in the increments, no reliable increment values remained for benzo-a-pyrene or acrolein (unverified). At a value of 6, benzene had the largest number of significant increments.

Table 7. MSAT species measured and the number of sites measuring the species in 2016-2018. The number of sites is the number of near-road/ambient site pairs. IQR is the interquartile range (25th to 75th percentile).

MSAT Species	Number of Site-pairs	Number of Sites with Positive Increment Values	Number of Positive Sites with Data Above MDL > 50% of Time	Number of Positive Sites with p-Value < 0.05	Number of Sites with Significant Increments	Median and (IQR) Increment Across All Sites(µg/m^3)	Median and (IQR) Percent Increment Across All Sites (%)
Benzo[a]pyrene	1	1	0	0	0	4.0×10^{-5} (2.2×10^{-5} : 5.4×10^{-5})	283 (146 : 538)
1,3-Butadiene	10	6	3	6	3	0 (0 : 0.08)	0 (0 : 151)
Formaldehyde	6	5	5	5	5	0.30 (-0.27 : 0.68)	14 (-10 : 40)
Acetaldehyde	6	5	5	5	5	0.13 (-0.031 : 0.30)	12 (-3 : 29)
Acrolein (Unverified)	2	1	1	0	0	-0.069 (-0.42 : 0.048)	-25 (-69 : 13)
Benzene	10	7	7	6	6	0.10 (0.03 : 0.26)	17 (-7 : 51)
Ethylbenzene	10	5	5	4	4	0.02 (-0.4 : 0.11)	7 (-22 : 50)

Table 8 shows the comprehensive list of all near-road and ambient sites for which an increment was calculated, the daily average concentration and standard deviation for both sites, the percentage of points that were above MDL for each site, increment values, and increment error, as well as how far the MDL is above the ambient concentration, expressed as a percentage. All data is included in this table regardless of whether the increment was determined to be significant or insignificant. It is evident that the uncertainty in the daily average values is large in comparison to the average value.

In addition to Table 8, a series of box plots showing the daily increment values at each near-road site across the 3-year study period was constructed for each MSAT species of interest. These can be found in the Appendix (Figures A-1 through A-7). Of the 15 instances where the increment was negative, four resulted from monitors reporting data above MDL less than 50% of the time, and all four were for measurements of 1,3-butadiene. The remaining 11 negative increment values may have resulted for a number of reasons. One such reason is a difference in the background levels of a given MSAT species between the near-road site and nearby ambient site. At Berkeley-0013, the freeway is less than 350 m from the San Francisco Bay. Because air masses originate over the water before reaching the freeway and near-road monitor, the background concentrations are lower than they would be for the nearby ambient monitor, which is further inland. The same is true for Oakland-0012, where the monitor is 24 m from the road, which is in turn located less than 400 m from the San Francisco Bay. The air reaching the nearby ambient monitor traverses a larger urban area (2.9 km), which could result in higher concentrations at this ambient monitor. Oakland and Berkeley both produced negative increments (when data was measured above MDL more than 50% of the time) for benzene and ethylbenzene.

Of the four increments calculated for MSATs at the Laurel-0006 site, acrolein[unverified], benzene, and ethylbenzene resulted in negative increment values. Specifically, when expressed as a percentage, they were 38%, 21%, and 17% below the nearby ambient monitor level, respectively. The nearby ambient monitor chosen for Laurel was the closest monitor to the near-road site (10.1 km), located at the Howard University Beltsville Lab. This monitor is surrounded by parkland and on the edge of the U.S. Fish and Wildlife Service's Patuxent National Wildlife Refuge. The Laurel background site did not have any easily identifiable nearby sources that may have caused concentration levels to be elevated above the true ambient background.

Table 8. Three-year mean (µg/m³) values for MSATs at near-road and nearby ambient sites used to calculate increment values (µg/m³). The percentage of data points included in the mean above the MDL is also listed, as is the distance between the near-road and nearby ambient monitors, the calculated increment value, increment error, and how far the increment is above the mean ambient concentration (expressed as percentage).

MSAT Species	Near-Road Site			Nearby Site				Distance Between Monitors (km)	Increment Value	Increment Error	Increment % of ambient
	Site Name	Three-Yr Mean	% of Points Above MDL	Site AQS ID	Three- Yr Mean		% of Points Above MDL				
Benzo[a]pyrene	Seattle-0030	7.4E-05	98	53-033-0080	3.2E-05		36	3.3	4.2E-05	3.4E-06	131
1,3-Butadiene	Oakland-0012	0.047	24	06-001-0011	0.060		24	2.9	-0.013	0.003	-22
	Berkeley-0013	0.04	13	06-001-0011	0.069		25	5.8	-0.032	0.003	-47
	Pleasanton-0015	0.02	5	06-001-0007	0.032		14	10.6	-0.016	0.004	-51
	San Jose-0006	0.06	19	06-085-0005	0.072		32	4.2	-0.014	0.003	-19
	Atlanta-0003	0.12	20	13-089-0002	0.076		23	2	0.045	0.005	60
	Indianapolis-0087	0.19	82	18-097-0078	0.14		67	2.9	0.050	0.005	36
	Laurel-0006	0.11	25	24-033-0030	0.073		8	10.1	0.041	0.008	57
	Minneapolis-0962	0.11	75	27-053-0966	0.091		76	1.8	0.017	0.003	19
	Oklahoma City-0097	0.15	97	40-109-1037	0.042		32	15.5	0.11	0.004	257
	Seattle-0030	0.14	100	53-033-0080	0.054		54	3.3	0.085	0.007	157
Formaldehyde	Minneapolis-0962	2.9	100	27-053-0966	2.8		100	1.8	0.19	0.039	7.0
	Cheektowaga-0023	2.2	97	36-029-1014	2.1		96	13.8	0.14	0.036	6.7
	Rochester-0015	2.2	99	36-055-1007	2.15		99	0.8	0.090	0.029	4.2
	Queens-0125	3.2	100	36-081-0124	3.21		100	0.5	-0.022	0.061	-0.7
	Oklahoma City-0097	3.5	100	40-109-1037	3.1		100	15.5	0.35	0.048	11
	Seattle-0030	1.9	100	53-033-0080	1.5		100	3.3	0.47	0.043	32

MSAT Species	Near-Road Site			Nearby Site				Distance Between Monitors (km)	Increment Value	Increment Error	Increment % of ambient
	Site Name	Three-Yr Mean	% of Points Above MDL	Site AQS ID	Three- Yr Mean		% of Points Above MDL				
Acetaldehyde	Minneapolis-0962	1.26	100	27-053-0966	1.2		100	1.8	0.083	0.018	7.0
	Cheektowaga-0023	1.2	95	36-029-1014	0.94		92	13.8	0.22	0.021	24
	Rochester-0015	1.2	94	36-055-1007	1.0		93	0.8	0.16	0.018	15
	Queens-0125	1.5	100	36-081-0124	1.7		100	0.5	-0.22	0.031	-12.6
	Oklahoma City-0097	2.1	100	40-109-1037	1.9		100	15.5	0.26	0.029	14
	Seattle-0030	1.3	100	53-033-0080	1.08		100	3.3	0.23	0.030	21
Acrolein (Unverified)	Atlanta-0003	0.30	93	13-089-0002	0.29		87	2	0.0063	0.013	2.2
	Laurel-0006	0.38	59	24-033-0030	0.62		80	10.1	-0.23	0.010	-38
Benzene	Oakland-0012	0.78	100	06-001-0011	0.81		100	2.9	-0.033	0.014	-4.1
	Berkeley-0013	0.69	100	06-001-0011	0.85		100	5.8	-0.17	0.018	-20
	Pleasanton-0015	0.58	100	06-001-0007	0.55		100	10.6	0.032	0.012	5.9
	San Jose-0006	1.1	100	06-085-0005	0.84		100	4.2	0.30	0.008	35
	Atlanta-0003	0.60	100	13-089-0002	0.57		100	2	0.031	0.015	5.3
	Indianapolis-0087	0.79	100	18-097-0078	0.69		100	2.9	0.096	0.011	14
	Laurel-0006	0.60	100	24-033-0030	0.76		100	10.1	-0.16	0.010	-21
	Minneapolis-0962	0.74	98	27-053-0966	0.66		98	1.8	0.079	0.011	12
	Oklahoma City-0097	0.93	100	40-109-1037	0.55		100	15.5	0.38	0.015	70
	Seattle-0030	0.93	100	53-033-0080	0.51		100	3.3	0.42	0.024	82

MSAT Species	Near-Road Site			Nearby Site				Distance Between Monitors (km)	Increment Value	Increment Error	Increment % of ambient
	Site Name	Three-Yr Mean	% of Points Above MDL	Site AQS ID	Three- Yr Mean		% of Points Above MDL				
Ethylbenzene	Oakland-0012	0.49	98	06-001-0011	0.73		99	2.9	-0.24	0.012	-32
	Berkeley-0013	0.50	96	06-001-0011	0.84		98	5.8	-0.34	0.016	-40
	Pleasanton-0015	0.27	100	06-001-0007	0.29		100	10.6	-0.022	0.015	-7.6
	San Jose-0006	0.74	100	06-085-0005	0.72		99	4.2	0.018	0.009	2.5
	Atlanta-0003	0.11	72	13-089-0002	0.12		72	2	-0.010	0.008	-8.7
	Indianapolis-0087	0.28	94	18-097-0078	0.21		76	2.9	0.065	0.004	31
	Laurel-0006	0.17	92	24-033-0030	0.21		99	10.1	-0.035	0.005	-17
	Minneapolis-0962	0.24	92	27-053-0966	0.22		96	1.8	0.017	0.005	7.7
	Oklahoma City-0097	0.72	94	40-109-1037	0.30		82	15.5	0.42	0.016	141
	Seattle-0030	0.57	100	53-033-0080	0.41		89	3.3	0.16	0.024	38

To identify trends and correlate increment values with roadway variables, the MSAT increments were compared against distance to the mainline road, 2016 HPMS AADT, and 2016 Estimated FE-AADT. Figure 5 shows the increments for each MSAT species as a function of distance to road (Panels A-E) and the 2016 HPMS AADT (Panels F-J). Increments assessed as statistically significant are shown in darker shades, while statistically insignificant increments are shown for completeness but in a lighter shade. The statistically significant increment values were linearly fit (dashed gray lines), and each r^2 value is reported as a measure of the strength of correlation between the two values. As a guide, an increment of zero is marked with a black dashed line. If vehicles were the main source of an MSAT species measured at a near-road site, we would expect concentrations to decrease with increasing distance to the mainline road (negative slope). While the slopes of the linear fit to the data in Figure 5 panels A-E are negative, they are very low in magnitude, ranging from -0.003 for 1,3-butadiene to -0.009 for ethylbenzene. The same is true for panels E-J, which suggests that the concentrations of acetaldehyde, benzene, ethylbenzene, 1,3-butadiene, and formaldehyde originating from the roadway are potentially very small or largely invariable with respect to distance from the mainline road and AADT. Possible reasons for this result may include high local background levels of these compounds. 1,3-butadiene shows a very strong trend with distance to the mainline road (Panel D, $r^2 = 0.99$), which is counter to what was seen in the near-road concentration vs. distance to mainline plot (Figure 1 Panel D), and with AADT (Panel I, $r^2 = 0.72$). This indicates that there are background sources influencing the near-road levels. However, only three significant increment values were available for 1,3-butadiene, so it is possible that with more data points these correlations may change.

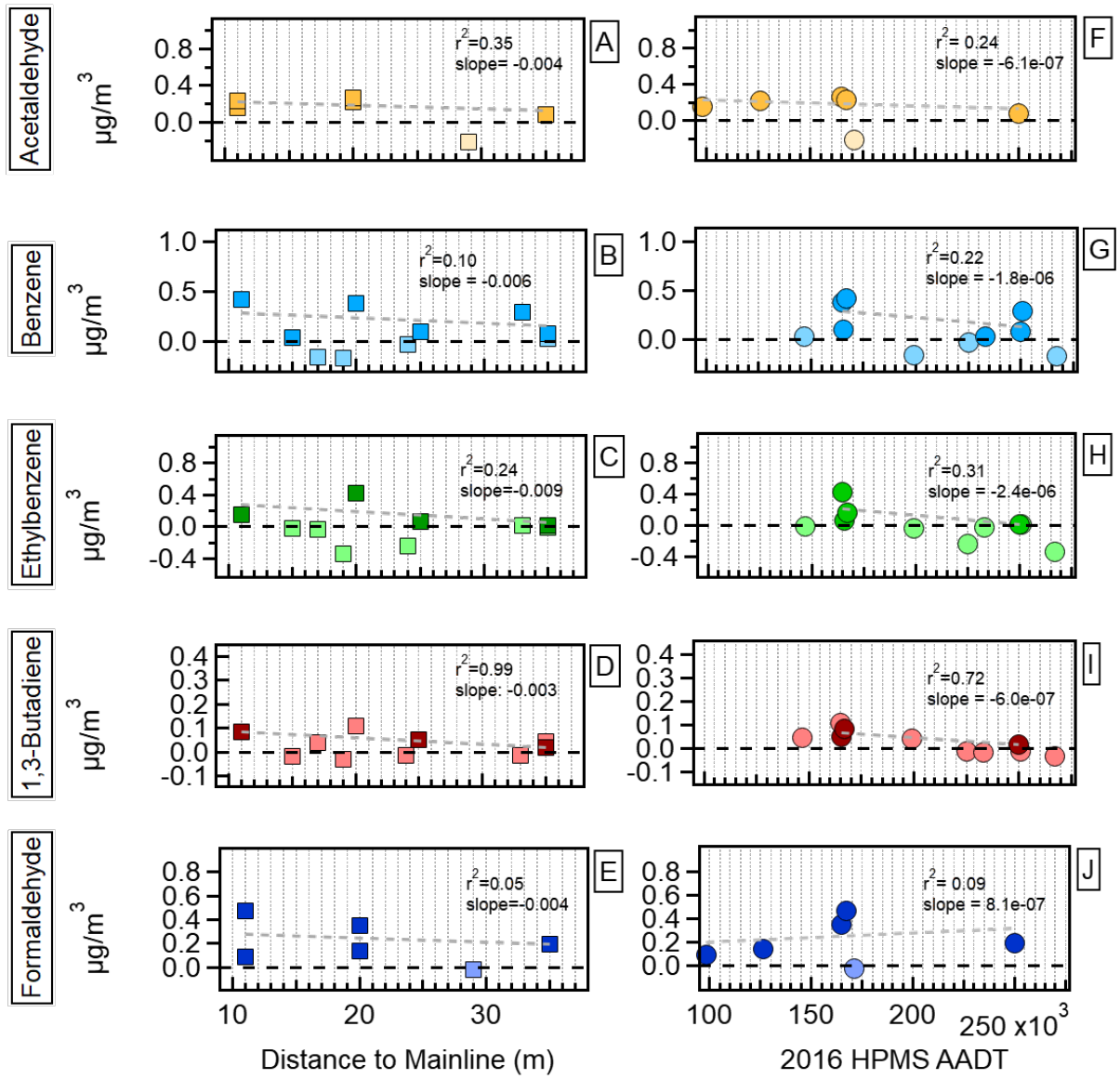

Figure 5. Increment values for acetaldehyde (yellow), benzene (light blue), ethylbenzene (green), 1,3-butadiene (red), and formaldehyde (dark blue) as a function of distance between the near-road monitor and the mainline roadway (A-E), and 2016 HPMS AADT (F-J). Dark colored data points are significant increments, while light colored data points are insignificant increments. Gray dashed lines indicate a linear regression fit to the significant increment data points, and the r^2 and slope of the fit are indicated in each panel. The black dashed line is a guide indicating an increment of 0 µg/m^3.

To quantify the incremental distributions the daily percentage MSAT increment at all cities with at least one complete year of incremental estimates is shown in **Figure 6.** Percentage increments are calculated as:

$$\%\ \text{Increment}_i = 100 \times \frac{([\text{NR}]_i - [\text{AM}]_i)}{[\text{AM}]_i}$$

Where [NR] is the concentration of the pollutant at the near-road site, [AM] is the concentration of the pollutant at the nearby ambient site, and i is the ith day. Increments are shown in Figure 6 as notch box-whisker plots to indicate the confidence interval around the median incremental value. This visualization illustrates the results from Tables 7 and 8. In Figure 6, the median increment is over 10% for formaldehyde, acetaldehyde, benzene, and ethylbenzene. For these pollutants, the confidence intervals (notch) and the interquartile range (lowest part of the box) are usually above 0%, indicating that the distribution is usually positive; that is, near-road site concentrations are higher than concentrations at ambient sites when paired in time.

Pollutants with statistically significantly higher near-road concentrations are acetaldehyde (5 out of 6 sites) and formaldehyde (5 out of 6 sites). Benzene concentrations are significantly higher at near-road sites in 6 out of 10 sites; ethylbenzene near-road concentrations are only higher at 4 out of 10 sites. Butadiene concentrations are only higher at 2 sites out of 10. Across all sites, formaldehyde, acetaldehyde, and benzene concentrations have median increments of over 10% that are statistically significant. Benzene increments are the highest of the MSATs with a median increment of 17% across all sites. 1,3-Butadiene and ethylbenzene increments are indistinguishable from a value of zero; for 1,3-butadiene this is at least partially due to the large fraction of data below detection limits. Acrolein concentrations are lower at the near-road sites than at the nearby ambient sites for the two cities with sufficient data at a near-road and nearby site.

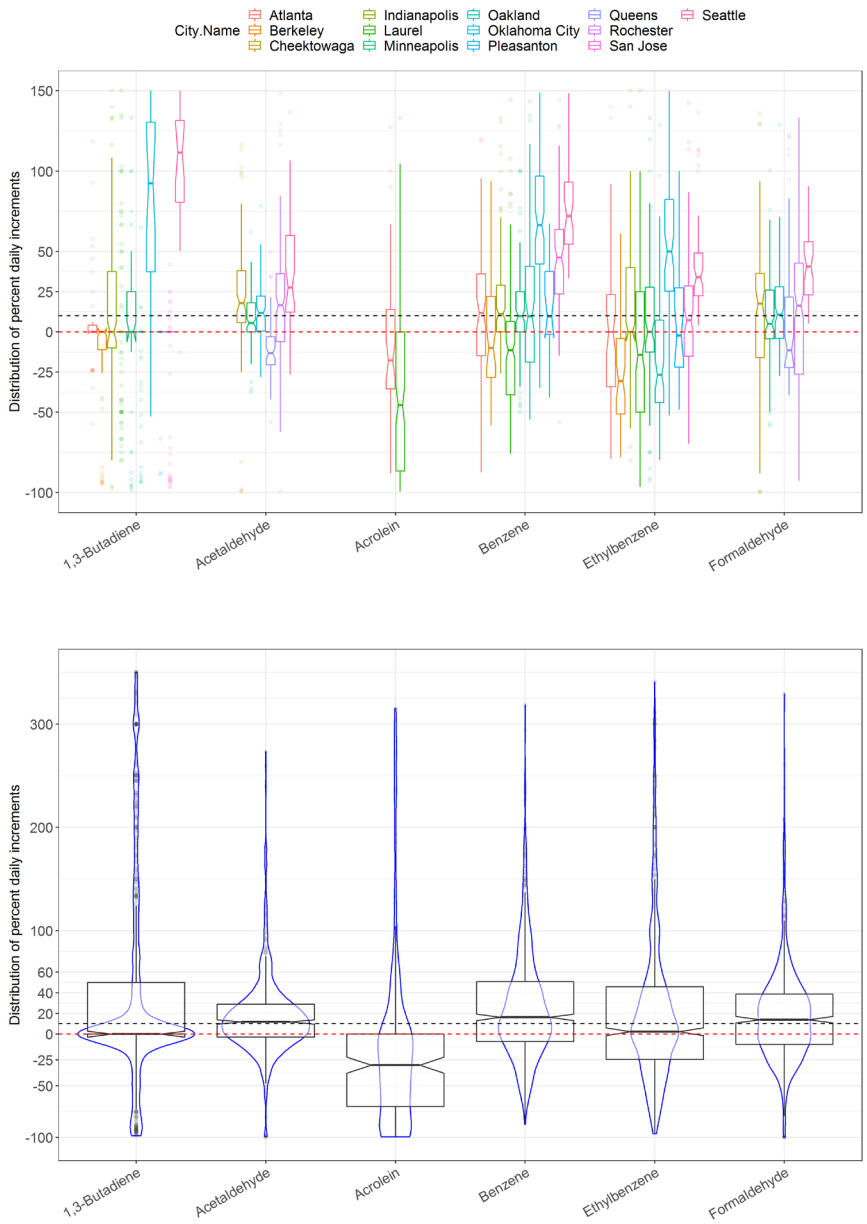

Figure 6. Distribution of percentage daily increments (%) between near-road and ambient sites at all cities individually (top), and the same distribution of percentage daily increments (%) combined across all cities to show the distribution nationally using notched box-whisker and violin plot overlay (bottom). Both plots show a red dashed line to indicate the zero percent difference; black dashed line indicates the 10% increment level.

4. Discussion

4.1 MSAT Near-Road Increments

Near-road three-year-mean concentrations and increments were calculated and compared to distance to mainline road and traffic volume data. Formaldehyde, ethylbenzene, benzene, and acetaldehyde showed no consistent or strong r^2 relationship with either roadway metric. 1,3-butadiene near-road concentrations and increments decreased with increasing AADT, where the highest AADT sites are located in the state of California. The 1,3-butadiene increment also showed a decreasing trend with distance to the mainline road.

In typical studies of near-road air pollution, spatial gradients near roadways are determined by measuring pollutant concentrations at different distances along a transect of the roadway (Karner et al., 2010; Baldwin et al., 2015; Beckerman et al., 2008). In this study, monitoring sites were located at varying distances from different roadways across the United States, not solely along a single transect of a single roadway. Additionally, these different roadways were subject to different meteorological conditions, fleet compositions, and traffic volumes. Given the varied increment levels by site, it is possible that MSAT concentrations are being driven by variations among fleet composition and volume, meteorological patterns, and possibly even local point sources.

4.2 Implications of Concentrations Compared to Health Benchmarks

Comparisons of near-road concentrations and dose-response threshold benchmarks were performed as a screening level analysis to identify which compounds may be of highest importance. Health risk screening assessments often employ a methodology of comparing concentrations to benchmarks in order to prioritize further analyses. In this work, we compared the near-road MSAT daily and annual concentrations to acute and chronic benchmarks. We note that these comparisons with the near-road concentrations not only include contributions from mobile source emissions on the local roadway, but also include contributions from urban, regional, and global background. Therefore, the concentration comparisons are meant to simply prioritize among pollutants requiring additional investigation and are not meant to indicate the roadway contribution to these specific pollutants.

In the analysis of the acute concentrations as compared to daily 24-hr concentrations, Figure 2 showed that the total 24-hr concentrations measured at all of the available sites over a three-year period were below the dose-response benchmarks for 1,3-butadiene, acetaldehyde, benzene, benzo[a]pyrene, ethylbenzene, and formaldehyde. Only acrolein had 24-hr concentrations exceeding an acute benchmark threshold, but concentration increments were negative and the measurement

methodology is considered unverified by EPA. As we noted in Section 3, acrolein is designated by EPA in its AQS database as "acrolein – unverified." EPA data quality evaluation guidelines for ambient air acrolein measurements, published in 2010 (U.S. Environmental Protection Agency, 2010), states:

> *In 2010, OAQPS completed a study that determined acrolein monitoring results could be affected by factors that include how canisters are cleaned in preparation for sample collection and the gas standards used to calibrate analytical equipment. Due to the resulting data quality concerns, EPA worked with the NACAA Monitoring Steering Committee to develop an AQS reporting framework for acrolein measurements that bins data as either "acrolein - unverified" or "acrolein - verified". This document is intended to support state, local, and tribal air pollution control agencies who must decide whether to leave their data in the re-named "unverified" parameter code or move the data to a new "verified" parameter code, both of which are described below…The study showed that acrolein can be elevated even in canisters that are considered clean, resulting in ambient measurements that were biased high. Additionally, the study demonstrated that the accuracy of acrolein gas standards used to calibrate analytical systems was quite variable between laboratories, resulting in significant biases that worsened the uncertainties arising from the growth issue.*

As a result of the qualifications specified by EPA, it is possible that the reported acrolein concentrations are biased high, or biased in unknown directions and magnitudes, because of poor quality calibration standards for acrolein. As a result, the acrolein results from this screening comparison should not be considered quantitative and should be considered a qualitative indication that more research is needed to assess the particular roadway contributions of acrolein on a daily and annual basis.

In the chronic non-cancer comparison, annual formaldehyde concentrations at some sites were as high or higher than the Virginia SAAC standards. This standard was the most stringent of the four examined dose-response thresholds for non-cancer effects for formaldehyde. Thus, for chronic formaldehyde comparisons, the next screening step is to examine the incremental contribution for the roadway concentrations in comparison to the standard to better understand the importance of the near-roadway increment.

We also performed comparisons for the cancer dose-response thresholds, selected as the "bright-line" 100-in-a-million cancer risk thresholds as set forth by EPA in the National Emissions Standards for Hazardous Air Pollutants (NESHAP) 1989 benzene rule. The NESHAP rule is a two-part standard, sometimes described by EPA as a "fuzzy bright line". It is described in the National Air Toxics Assessment (U.S. Environmental Protection Agency, 2019) as follows:

> *First, the [NESHAP] rule sets an upper limit of acceptable risk at about a 1-in-10 thousand (i.e., 100-in-a-million) lifetime cancer risk for the most exposed person. As the rule explains, "The EPA will generally presume that if the risk to that individual [the Maximum Individual Risk] is no higher than approximately 1 in 10 thousand, that risk*

> *level is considered acceptable and EPA then considers the other health and risk factors to complete an overall judgment on acceptability."*
>
> *Second, the benzene rule set a target of protecting the most people possible to an individual lifetime risk level no higher than about 1-in-a-million. These determinations called for considering other health and risk factors, including risk assessment uncertainty, in making an overall judgment on risk acceptability.*

All annual concentrations for each of the six MSATs were individually well below the 100-in-a-million cancer risk threshold. However, since there are multiple pollutants emitted by the same source, we need-assessed the total cumulative risk by summing across all the pollutants based on an assumption of additive linear risk. Cumulative risk involves multiple agents or stressors, which means that assessments involving a single chemical or stressor are not "cumulative risk assessments" under this definition. There is no limitation that the "agents or stressors" be only chemicals; they may be, but they may also be biological or physical agents, or an activity that directly or indirectly alters or causes the loss of a necessity such as habitat. This definition requires that the risks from multiple agents or stressors be combined. This does not necessarily mean that the risks should be "added," but rather that some analysis should be conducted to determine how the risks from the various agents or stressors interact; see U.S. Environmental Protection Agency (2003) for full details.

Cumulatively, the annual concentrations across the six MSATs were also below the 100-in-a-million cancer risk threshold. We note that this is based on the full suite of all six MSATs shown in Figure 4, even though no individual near-road monitoring site has all six measured. Some of the individual pollutants were above 1-in-a-million cancer risk levels. As noted for the non-cancer assessments, these concentrations include contributions from urban, regional, and global background, and therefore more research is recommended to examine the importance of the incremental contribution of the roadway for these pollutants.

5. Conclusions

We examined the MSAT concentrations of 1,3-butadiene, acrolein, acetaldehyde, benzene, benzo[a]pyrene, ethylbenzene, and formaldehyde at 17 near-road monitoring sites in the United States from 2016 through 2018. Near-road MSAT annual average concentrations for 1,3-butadiene, acetaldehyde, benzene, benzo[a]pyrene, and ethylbenzene were consistently below acute 24-hr average health benchmarks, chronic non-cancer annual average health benchmarks, and chronic 100-in-a-million cancer risk benchmarks. Some pollutants were above 1-in-a-million cancer risk benchmarks when considering total (not incremental) near-road concentrations. Acrolein concentrations were above acute and chronic benchmarks at near-road sites, but near-road increments were negative and acrolein concentrations are considered unverified by EPA. Distributions of MSAT multi-year concentrations for formaldehyde, acetaldehyde, and benzene were statistically significantly higher at near-road sites than nearby ambient sites using non-parameter Mann-Whitney paired U tests and visual inspection. These results indicate that these MSAT concentrations in urban areas are higher next to major freeways, although the increments are small in both absolute and percentage terms. Correlations of MSAT concentrations and increments with AADT, FE-AADT, and distance to roadway were not statistically significant.

6. References and Data Sources

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Data Sources

Data sources for dose-response thresholds, accessed in August 2019, are as follows.

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- https://www.epa.gov/sites/production/files/2018-06/acutefinaloutput_6_18_2018_7-49-37_am_2.xlsx
- https://www17.tceq.texas.gov/tamis/index.cfm?fuseaction=report.download&filename=38942019082211055560 1.txt
- https://www17.tceq.texas.gov/tamis/index.cfm?fuseaction=report.download&filename=38942019100813543881 6.txt
- https://oehha.ca.gov/media/downloads/crnr/appendix20bfinalwithnickel.pdf
- https://oehha.ca.gov/media/downloads/crnr/appendixa.pdf
- https://cfpub.epa.gov/ncea/iris/search/index.cfm
- https://www.deq.virginia.gov/Portals/0/DEQ/Air/Permitting/Toxics_Spreadsheet.xlsx
- https://app.leg.wa.gov/WAC/default.aspx?cite=173-460-150

Appendix

MSAT increments at the near-road sites in 2016-2018 are shown in Figures A-1 through A-7.

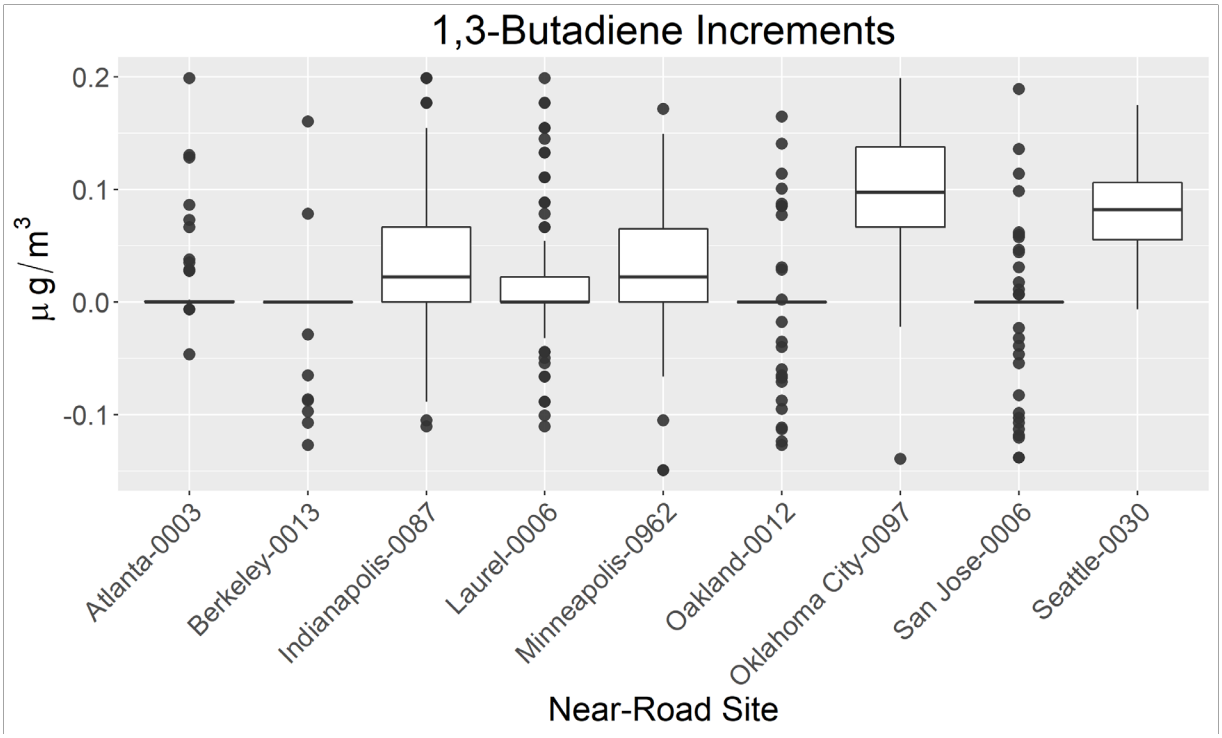

Figure A-1. Daily near-road increments (µg/m^3) for 1,3-butadiene at near-road sites between 2016-2018

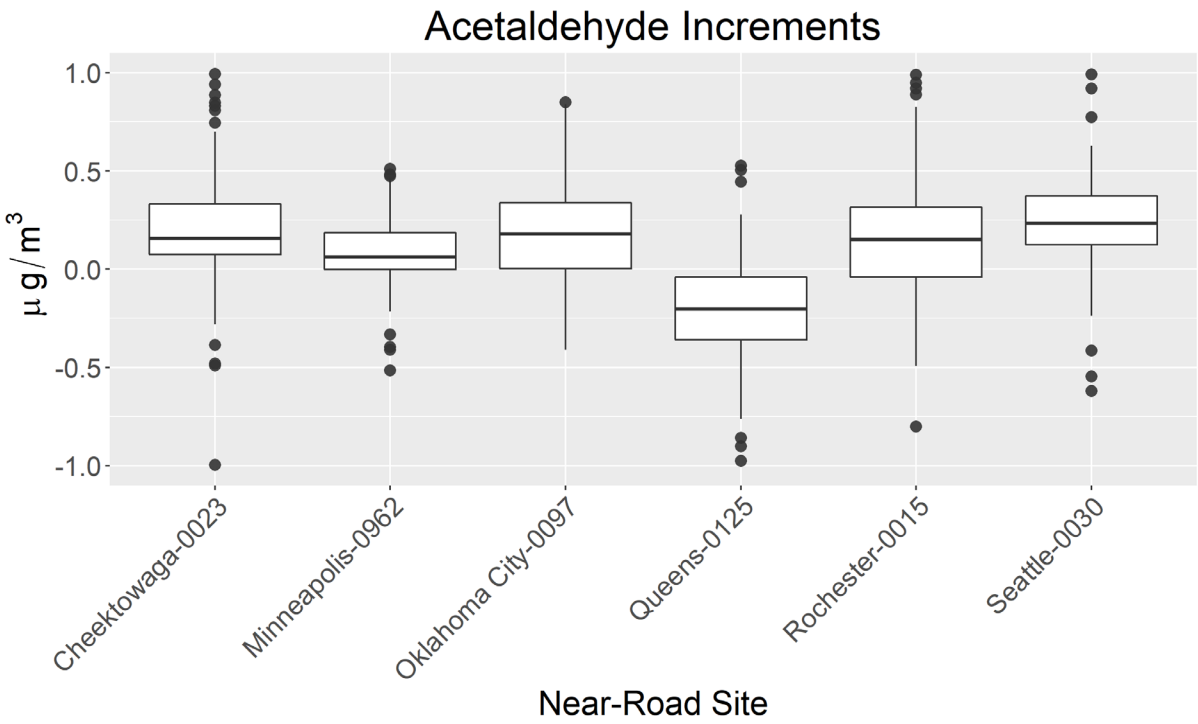

Figure A-2. Daily near-road increments (µg/m^3) for acetaldehyde at near-road sites between 2016-2018

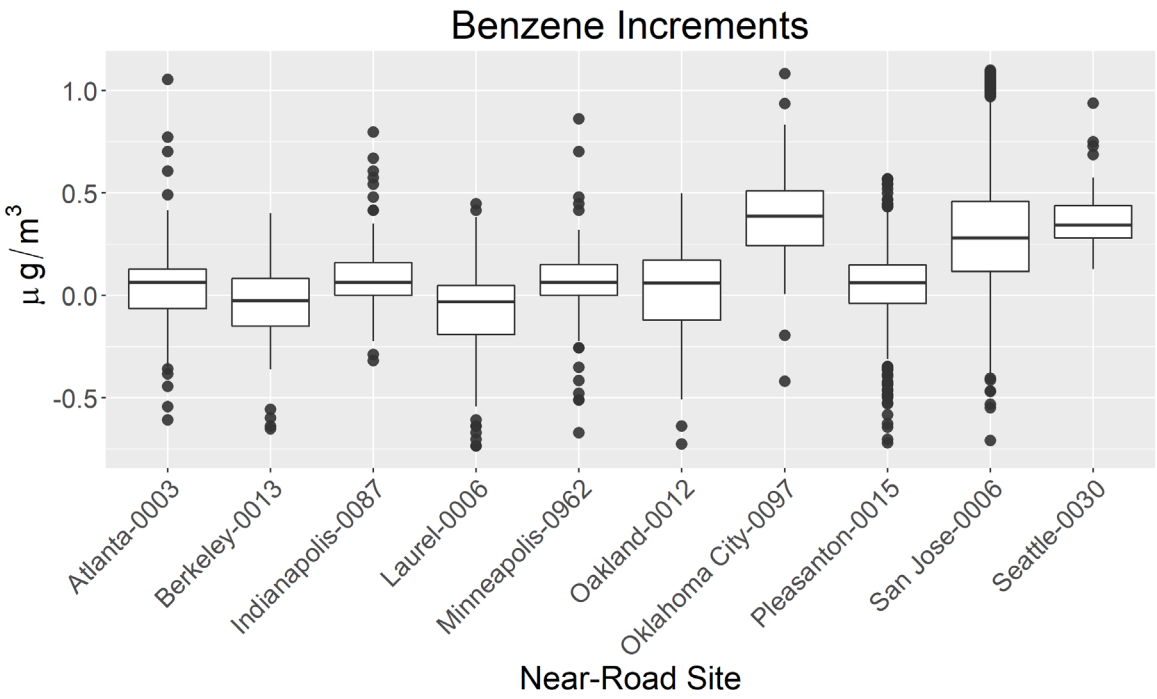

Figure A-3. Daily near-road increments (µg/m^3) for benzene at near-road sites between 2016-2018

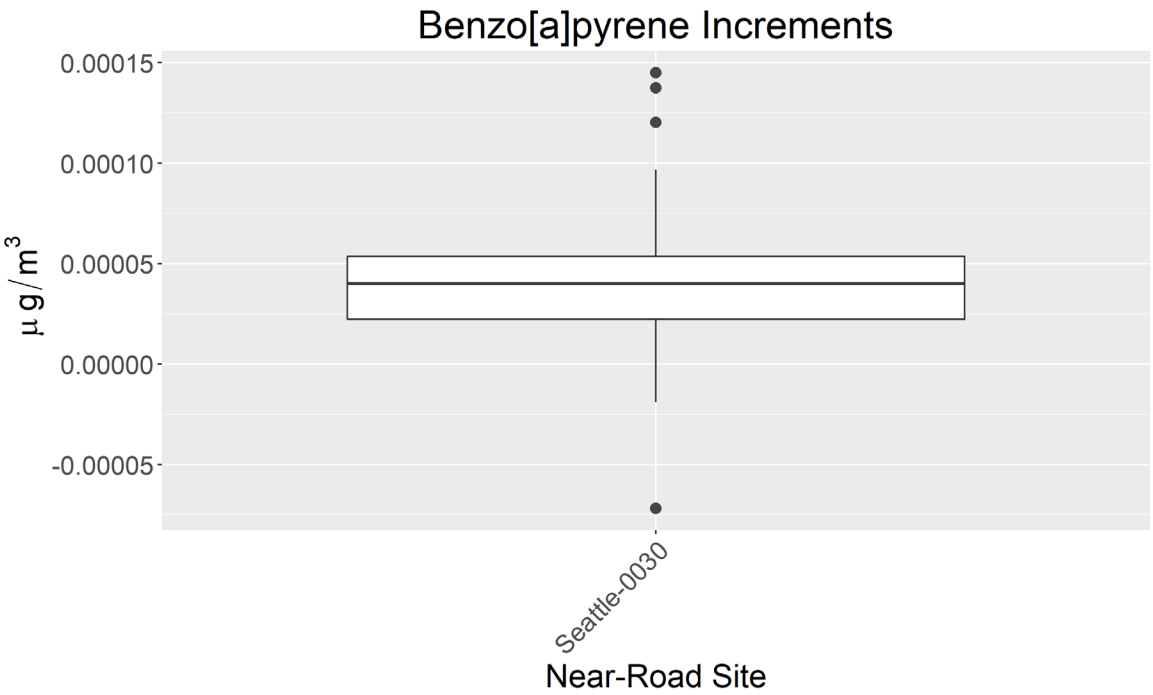

Figure A-4. Daily near-road increments (µg/m^3) for benzo[a]pyrene at near-road sites between 2016-2018

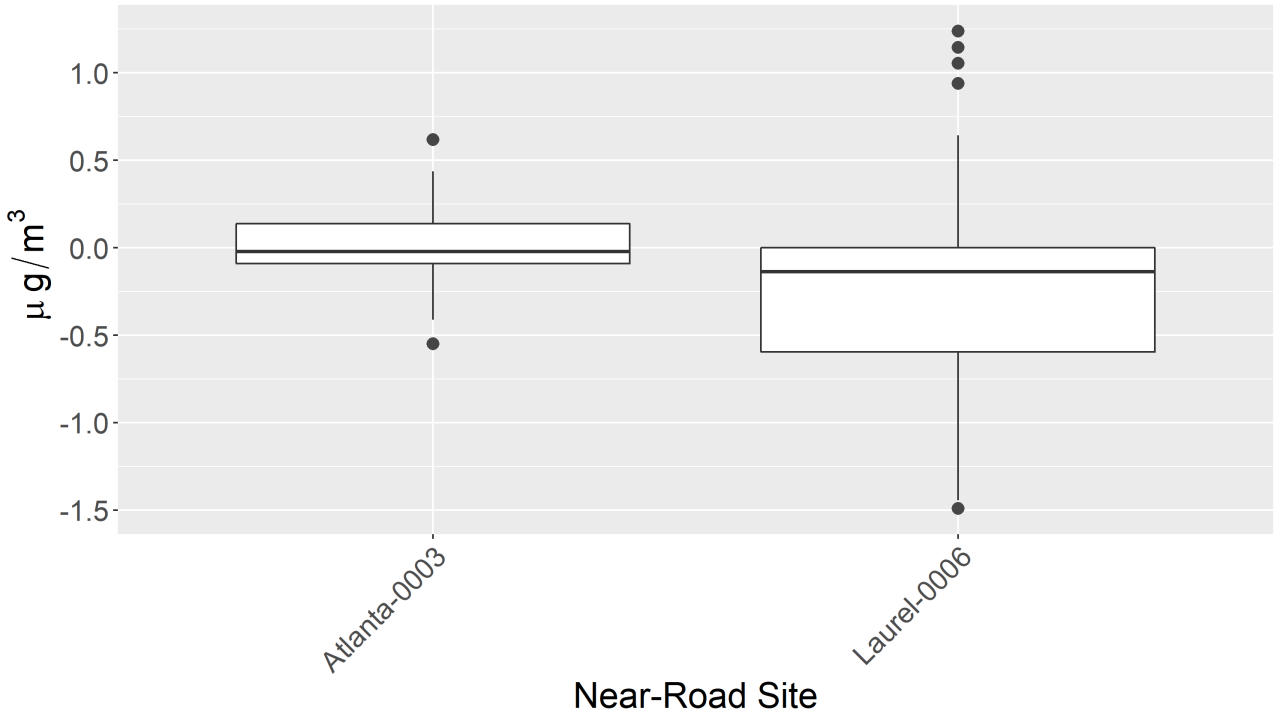

Figure A-5. Daily near-road increments (µg/m^3) for acrolein (unverified) at near-road sites between 2016-2018

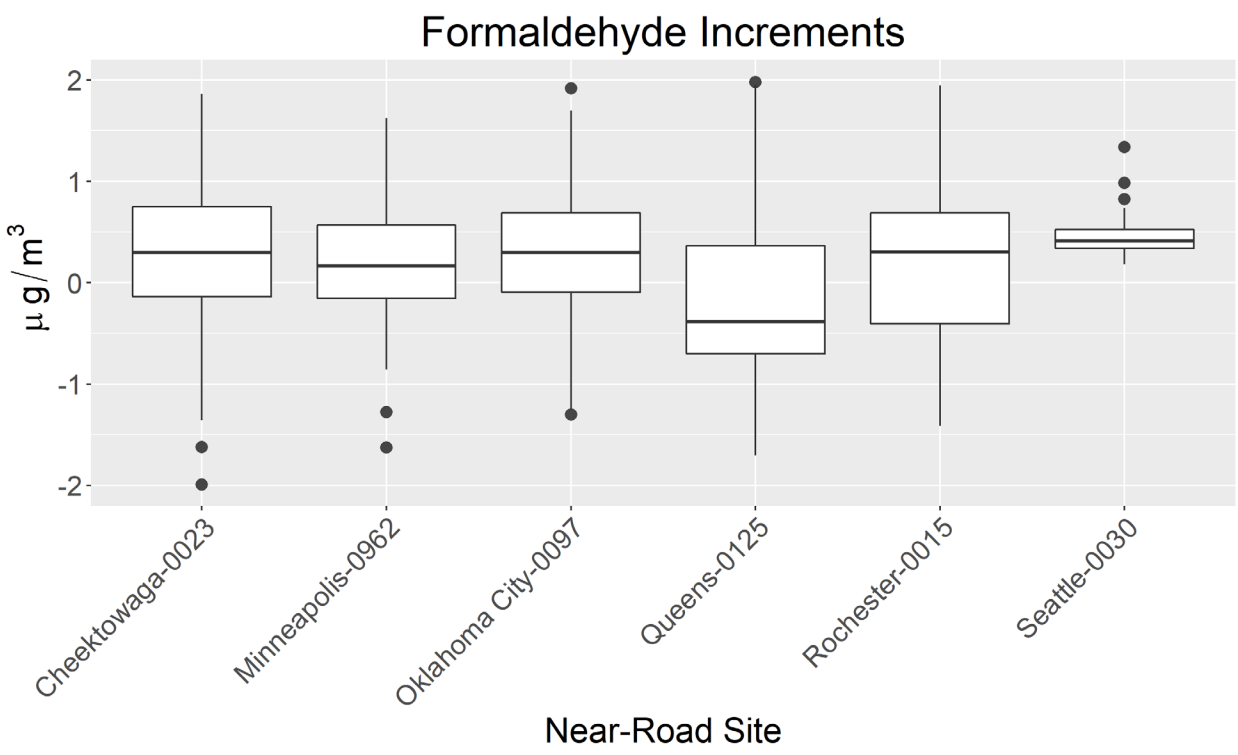

Figure A-6. Daily near-road increments (µg/m^3) for formaldehyde at near-road sites between 2016-2018

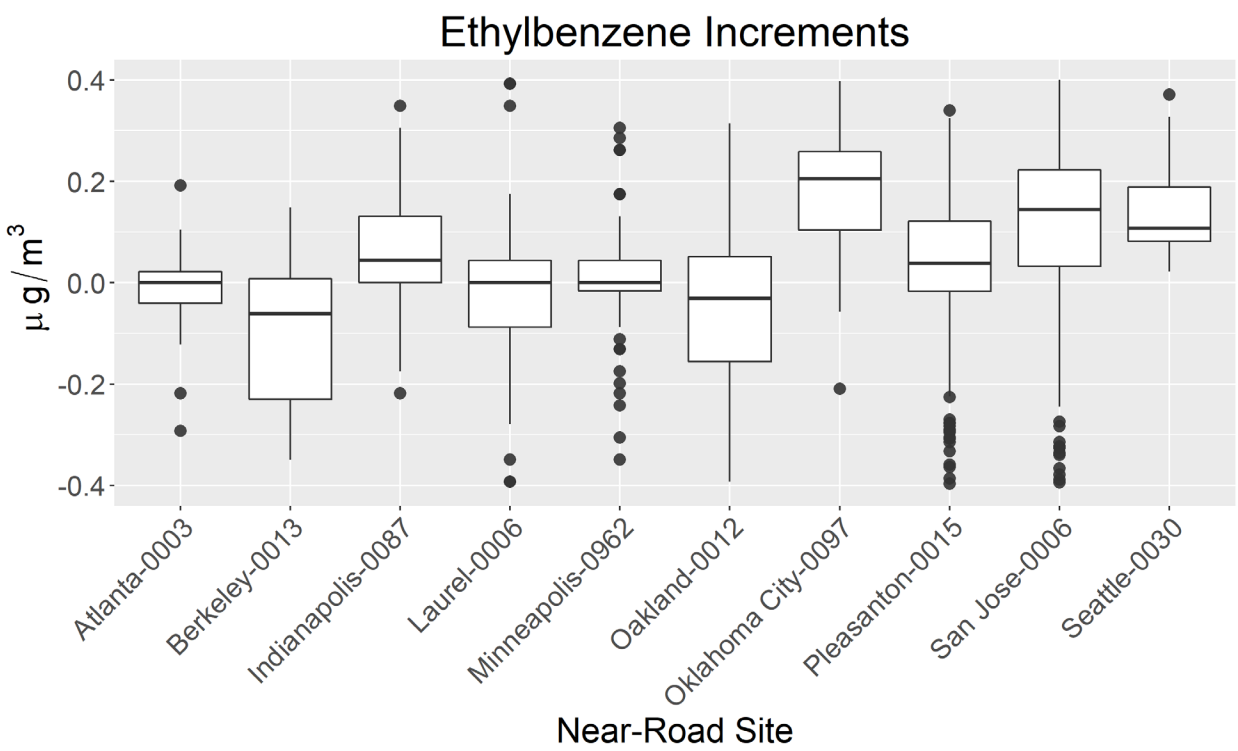

Figure A-7. Daily near-road increments (μg/m^3) for ethylbenzene at near-road sites between 2016-2018.

Table A-1. List of U.S. near-road sites with MSAT measurements by name, the annual mean concentration (µg/m^3), and standard deviation of each MSAT measured at that site. "N" is the number of daily data points available for the site.

Site Name	Year	N	1,3-Butadiene mean ± stdev	Acetaldehyde mean ± stdev	Acrolein (unverified) mean ± stdev	Benzo[a]pyrene mean ± stdev	Benzene mean ± stdev	Ethylbenzene mean ± stdev	Formaldehyde mean ± stdev	Naphthalene mean ± stdev
Providence-0030	2016									
	2017	42	0.21 ± 0.07				1.03 ± 0.40	0.49 ± 0.18		0.13 ± 0.06
	2018	15	0.19 ± 0.07				1.11 ± 0.39	0.38 ± 0.16		0.11 ± 0.04
Rochester-0015	2016	varies		1.38 ± 0.57 (N=61)					2.67 ± 1.34 (N=60)	
	2017	61		0.96 ± 0.38					1.60 ± 0.83	
	2018	60		1.21 ± 0.51					2.45 ± 1.25	
Seattle-0030	2016	varies	0.14 ± 0.08 (N=16)	1.03 ± 0.42 (N=16)		7.13E-5 ± 4.20E-5 (N=15)	0.98 ± 0.45 (N=16)	0.41 ± 0.29 (N=16)	1.31 ± 0.45 (N=16)	
	2017	varies	0.14 ± 0.08 (N=46)	1.30 ± 0.81 (N=46)		7.24E-5 ± 7.38E-5 (N=47)	0.93 ± 0.45 (N=46)	0.57 ± 0.26 (N=46)	1.92 ± 1.06 (N=46)	
	2018									
Pleasanton-0015	2016									
	2017									
	2018	22	0.02 ± 0.02				0.58+0.61	0.27+0.19		
Laurel-0006	2016	56	0.18 ± 0.17		0.65 ± 0.40		0.69 ± 0.34	0.22 ± 0.14		
	2017	54	0.10 ± 0.08		0.36 ± 0.46		0.58 ± 0.21	0.16 ± 0.08		
	2018	58	0.06 ± 0.02		0.09 ± 0.12		0.53 ± 0.19	0.14 ± 0.10		
Berkeley-0013	2016	13	0.01 ± 0				0.67 ± 0.24	0.36 ± 0.24		
	2017	29	0.03 ±+ 0.06				0.69 ± 0.48	0.56 ± 0.44		
	2018	30	0.04 ± 0.08				0.68 ± 0.68	0.44 ± 0.43		
Cheektowaga-0023	2016	61		1.25 ± 0.69					2.34 ± 1.39	
	2017	59		1.05 ± 0.37					2.21 ± 0.96	
	2018	60		1.01 ± 0.40					1.94 ± 1.08	

Site Name	Year	N	1,3-Butadiene mean ± stdev	Acetaldehyde mean ± stdev	Acrolein (unverified) mean ± stdev	Benzo[a]pyrene mean ± stdev	Benzene mean ± stdev	Ethylbenzene mean ± stdev	Formaldehyde mean ± stdev	Naphthalene mean ± stdev
Oklahoma City-0097	2016	38	0.17 ± 0.07	1.99 ± 0.59			1.02 ± 0.33	0.63 ± 0.32	3.66 ± 1.46	
	2017	60	0.15 ± 0.08	2.07 ± 0.75			0.94 ± 0.31	0.61 ± 0.26	3.47 ± 1.41	
	2018	57	0.16 ± 0.07	2.15 ± 0.94			0.94 ± 0.32	0.83 ± 2.97	3.48 ± 1.73	
Fort Lee-0010	2016	varies					0.62 ± 0.50 (N=2973)	0.26 ± 0.34 (N=2929)		
	2017	varies					0.73 ± 0.51 (N=1938)	0.17 ± 0.50 (N=1800)		
	2018									
Oakland-0012	2016	31	0.05 ± 0.06				0.64 + 0.29	0.34 + 0.29		
	2017	30	0.04 ± 0.07				1.02 + 0.49	0.65+0.45		
	2018	31	0.05 ± 0.08				0.67 + 0.63	0.48+0.44		
Indianapolis-0087	2016	54	0.25 ± 0.27				0.85 ± 0.55	0.29 ± 0.32		
	2017	59	0.22 ± 0.27				0.85 ± 0.52	0.30 ± 0.31		
	2018	60	0.11 ± 0.08				0.70 ± 0.30	0.25 ± 0.20		
Philadelphia-0076	2016	29				7.38E-5 ± 5.95E-5				
	2017	58				1.22E-4 ± 1.36E-4				
	2018	57				6.82E-5 ± 5.64E-5				
Queens-0125	2016									
	2017	varies		1.69 ± 1.14 (N=38)					3.64 ± 1.88 (N=37)	
	2018	59		1.50 ± 0.67					3.19 ± 1.86	
Columbus-0038	2016	15	0.25 ± 0.17		0.82 ± 0.79		1.05 ± 0.67	0.31 ± 0.29		0.54 ± 0.34
	2017									
	2018									

Site Name	Year	N	1,3-Butadiene mean ± stdev	Acetaldehyde mean ± stdev	Acrolein (unverified) mean ± stdev	Benzo[a]pyrene mean ± stdev	Benzene mean ± stdev	Ethylbenzene mean ± stdev	Formaldehyde mean ± stdev	Naphthalene mean ± stdev
San Jose-0006	2016	31	0.06 ± 0.11				1.27 ± 0.79	0.68 ± 0.58		
	2017	31	0.03 ± 0.10				1.22 ± 0.90	0.82 ± 0.74		
	2018	26	0.09 ± 0.13				0.88 ± 0.73	0.71 ± 0.67		
Atlanta-0003	2016	29	0.03 ± 0		0.27 ± 0.13		0.61 ± 0.40	0.12 ± 0.08		
	2017	28	0.03 ± 3.37E-3		0.35 ± 0.23		0.55 ± 0.27	0.09 ± 0.05		
	2018	varies	0.30 ± 0.48 (N=28)		0.25 ± 0.20 (N=12)		0.61 ± 0.33 (N=27)	0.16 ± 0.14 (N=24)		
Minneapolis-0962	2016	varies	0.11 ± 0.08 (N=54)	1.23 ± 0.47 (N=59)			0.68 ± 0.34 (N=55)	0.21 ± 0.16 (N=55)	2.82 ± 1.20 (N=59)	
	2017	varies	0.09 ± 0.10 (N=56)	1.30 ± 0.59 (N=58)			0.79 ± 0.47 (N=57)	0.27 ± 0.18 (N=57)	3.08 ± 1.19 (N=58)	
	2018	varies	0.09 ± 0.06 (N=24)	1.50 ± 0.60 (N=28)			0.67 ± 0.20 (N=25)	0.16 ± 0.09 (N=25)	3.2 ± 1.253 (N=28)	

Table A-2. Near-road monitors and relevant roadway information pertaining to each site. The calculated percentage of trucks travelling on the roadway in 2016 is also included.

Site Name	AQS ID	State	Distance to Mainline (m)	Target Road	2016 HPMS AADT	2016 Estimated FE-AADT	2016 % Trucks
Providence-0030	44-007-0030	RI	5	I-95	159500	356833	13.8
Rochester-0015	36-055-0015	NY	11	I-490	98306	128179	3.4
Seattle-0030	53-033-0030	WA	11	I-5	167093	332515	11.0
Pleasanton-0015	06-001-0015	CA	15	I-580	233000		NA
Laurel-0006	24-027-0006	MD	17	I-95	199131	482296	15.8
Berkeley-0013	06-001-0013	CA	19	I-80	267000	382108	4.8
Cheektowaga-0023	36-029-0023	NY	20	I-90	126107	212275	7.6
Oklahoma City-0097	40-109-0097	OK	20	I-44	165000	207768	2.9
Fort Lee-0010	34-003-0010	NJ	22	I-95/US 1	282912	556501	10.8
Oakland-0012	06-001-0012	CA	24	I-880	225000	441675	10.7
Indianapolis-0087	18-097-0087	IN	25	I-70	165672	316144	10.1
Philadelphia-0076	42-101-0076	PA	25	I-76	210456	344929	7.1
Queens-0125	36-081-0125	NY	29	I-495 (L.I.E.)	170874	330810	10.4
Columbus-0038	39-049-0038	OH	32	I-270	135746	272758	11.2
San Jose-0006	06-085-0006	CA	33	US 101	251000	386540	6.0
Atlanta-0003	13-089-0003	GA	35	I-285	147000	320710	13.1
Minneapolis-0962	27-053-0962	MN	35	I-94/I-35W	250000	349504	4.4

Percentage trucks calculation:

EPA developed the FE-AADT calculation to represent an emissions-weighted traffic volume, taking into account both AADT and fleet mix (U.S. Environmental Protection Agency, 2012). FE-AADT is calculated as:

$$(\mathrm{AADT} - \mathrm{HDc}) + (\mathrm{HDm} \times \mathrm{HDc}),$$

where HDc is the volume of heavy-duty vehicles on the target roadway, and HDm is a scaling factor that represents the ratio of heavy-duty to light-duty emissions of oxides of nitrogen (NOx). The number of HDDVs was estimated from FE-AADT and AADT, using the EPA recommended national default scaling value of HDm = 10.

Table A-3. MSAT species at each near-road site between 2016-2018 and the percentage of time they were measured above the method detection limit. MSAT concentration data used for health benchmark comparison, near-road concentration, and increment calculations were considered, which resulted in a range of percentage values in some instances.

MSAT species	Site Name	% of time above MDL
Benzo[a]pyrene	Philadelphia-0076	10
	Seattle-0030	90-98
1,3-Butadiene	Oakland-0012	24
	Berkeley-0013	10-13
	Pleasanton-0015	5
	San Jose-0006	19
	Atlanta-0003	20
	Indianapolis-0087	82-83
	Laurel-0006	25
	Minneapolis-0962	69-75
	Columbus-0038	47
	Oklahoma City-0097	97
	Providence-0030	100
	Seattle-0030	97-100
Formaldehyde	Minneapolis-0962	100
	Cheektowaga-0023	97-98
	Rochester-0015	99
	Queens-0125	100
	Oklahoma City-0097	100
	Seattle-0030	100
Acetaldehyde	Minneapolis-0962	100
	Cheektowaga-0023	95-97
	Rochester-0015	94
	Queens-0125	100
	Oklahoma City-0097	100
	Seattle-0030	100
Acrolein (unverified)	Atlanta-0003	90-93
	Laurel-0006	58-59
	Columbus-0038	27

MSAT species	Site Name	% of time above MDL
Benzene	Oakland-0012	100
	Berkeley-0013	100
	Pleasanton-0015	100
	San Jose-0006	100
	Atlanta-0003	100
	Indianapolis-0087	100
	Laurel-0006	100
	Minneapolis-0962	97-98
	Fort Lee-0010	99
	Columbus-0038	100
	Oklahoma City-0097	100
	Providence-0030	100
	Seattle-0030	100
Ethylbenzene	Oakland-0012	98
	Berkeley-0013	96-97
	Pleasanton-0015	100
	San Jose-0006	100
	Atlanta-0003	72-77
	Indianapolis-0087	94
	Laurel-0006	92
	Minneapolis-0962	92-93
	Fort Lee-0010	58
	Columbus-0038	13
	Oklahoma City-0097	94-95
	Providence-0030	100
	Seattle-0030	100