Community-Scale Air Toxics Monitoring Grant

Evaluation of the Impact of On-Road Mobile Source Air Toxics on Air Quality at Sensitive Receptors Adjacent to Interstate Route 95 in the Providence Metropolitan Area

Final Report

Rhode Island Department of Environmental Management
Office of Air Resources

February 2019

I. Introduction

In 2015, the United States Environmental Protection Agency (USEPA) awarded a Community-Scale Air Toxics Monitoring grant to the Rhode Island Department of Environmental Management (RIDEM) to conduct a project entitled "Evaluation of the Impact of On-Road Mobile Source Air Toxics on Air Quality at Sensitive Receptors Adjacent to Interstate Route 95 in the Providence Metropolitan Area.".

Interstate Route 95 (I-95) passes through Providence neighborhoods with among the highest poverty and childhood asthma rates in the State. Levels of air pollutants measured at the State's Near Road (NR) site, which is adjacent to I-95 in Providence, are consistently considerably higher than those at all other sites in the State, including nearby urban sites. Levels of air pollutants measured at the Vernon Street, Pawtucket (VE) monitoring site, which is adjacent to I-95 north of Providence, also tend to be higher than at other nearby sites.

However, the air pollutant levels measured at the NR and VE sites may not be representative of exposures at sensitive receptors near I-95 in the Providence area. The impact of vehicle emissions on air quality at nearby receptors is affected by a number of factors, including traffic volume and congestion, the height of the receptors relative to the roadway, distance from the roadway, meteorology, topography, land use and the presence of obstructions.

Highway air quality impacts at sensitive receptors near I-95 in Providence are likely to be lower than the impacts at the NR site. The NR site is designed to measure worst-case highway impacts and, as such, is located within a few feet of the section of I-95 with the highest traffic volume in the State. Measurements at the VE site provide valuable information about air quality in the neighborhood adjacent to the site; however, since I-95 traffic in that area is lower than in Providence, the VE measurements may underestimate exposures at some sensitive receptors in Providence. The Rhode Island Community-Scale study was designed to more definitively characterize air pollutant levels at sensitive receptors near I-95 in the Providence area, as well as the factors that influence those levels.

The USEPA requires recipients of Community-Scale grants to submit interim and final reports to document study progress and findings. This document will serve as the Rhode Island project's Final Report. The Final Report must document how the study's Mid-Term Outcomes have been addressed, as well as progress towards addressing Long-Term Outcomes.

The Mid-Term outcomes include:

- Using study data to understand the impacts of highway emissions at sensitive receptors located near I-95 in the Providence metropolitan area and the factors that affect those impacts;
- Disseminating that information to the public so that affected parties and community organizations have accurate information on which to base actions;
- Developing recommendations concerning mitigation procedures for existing sensitive

receptors, where applicable and for siting of future sensitive receptors;

- Developing recommendations for future and long-term monitoring; and
- Providing data to the Rhode Island Department of Health (RIDOH), health researchers, other states, and other interested parties.

The Long-Term Outcomes, as identified in the study design, are:

- Reducing exposures of members of the public to pollutants from highway vehicles, and
- Reducing ambient levels of air pollutants in the near-road environment.

This Final Report will document the findings of the study and will address the Mid-Term and Long-Term Outcomes listed above. The report is structured as follows:

Section I – Introduction

Section II – Study Design and Implementation

Section III - Meteorology

Section IV – Volatile Organic Compound (VOC) Results

Section V – Black Carbon (BC) and Particle Count (PC) Results – Fixed Monitors

Section VI – Spatial Variability Measurements

Section VII – Mid-Term and Long-Term Outcomes

Section VIII – Conclusions and Recommendations

II. Study Design and Implementation

Fixed-site monitors were operated at five sites adjacent to I-95 for a one-year period beginning on April 1, 2017. In addition, to better characterize the spatial variability of pollutant concentrations, monitoring was conducted using portable equipment one day each month throughout the study period in areas around the five fixed sites and at two additional locations.

Fixed Site locations

The five fixed sites included the NR site, which is a worst-case highway impact site, and the VE site, which is adjacent to the highway and residences in Pawtucket, north of Providence. Both of those sites are part of the State's permanent ambient air quality network. For the study, monitoring at those locations was expanded to include all of the study parameters discussed below.

The remaining sites were selected considering the following factors:

- Proximity to sensitive receptors (e.g., residences, schools, day cares, health care facilities and recreational facilities);
- Distance from I-95;
- Altitude relative to of I-95 and receptors;
- Prevailing wind directions;
- Presence of trees and other obstructions;
- Vehicle volume, truck volume and congestion;
- Demographics such as poverty levels in neighborhoods near the receptor;
- Mobile source impact concentrations predicted by USEPA modeling;
- RIDOH asthma data; and
- Community concerns/recommendations.

As is frequently the case, site selection was limited by practical considerations, such as accessibility and safety. In particular, RIDEM was interested in measuring pollutant levels at a school soccer field that is immediately adjacent to I-95 in Providence but was not able to obtain permission to monitor at that location. Data from the selected sites will provide some insight into likely pollutant levels at that location, as discussed below.

The three new fixed sites selected are:

- **The Providence Health Center site (PHC)** is next to the Chaffee Providence Health Center at 1 Warren Way in Providence. The PHC site is approximately 100 feet east of I-95, at the merge of the Thurbers Avenue entrance ramp onto I-95 Northbound (NB), and is directly across the highway from the school soccer field discussed above.

The PHC site is downwind of I-95 when the wind has a westerly component, which is the prevailing wind direction in the area. The site, which is level with the health center building, is approximately 30 feet below the level of the highway and approximately 25 feet east of the steep treed embankment on the side of the highway.

The PHC site was chosen to characterize air pollutant levels at the health center, a sensitive receptor in an otherwise largely industrial area that is frequently downwind of the highway. Selection of this site also provided an opportunity to evaluate traffic impacts in an area that is lower than the level of the adjacent highway. The PHC site is adjacent to the Providence port area and air quality at the site may be impacted by truck traffic on Allens Avenue, which is approximately 430 feet east of the site, and by traffic on the Thurbers Avenue on-ramp, which is southwest and west of the site. Tank farms and industrial operations at the port may also impact air quality at the PHC site.

- **The Bay Street site (Bay)** is 40 feet west of and 7 feet higher than I-95 at the end of the merge of traffic from Route 195 onto I-95 South Bound (SB). The buildings immediately around the Bay site are primarily commercial/industrial, but a day care center is located approximately 400 feet west of the site on Eddy Street, a busy city street.

One of the considerations in the selection of the Bay site was its proximity to the school soccer field discussed above. The soccer field is about 0.25 miles south of the Bay site and, since there are no highway entrances or exits between the Bay site and the soccer field, traffic counts are the same at the two locations. However, the soccer field is immediately north of the Thurbers Avenue exit from I-95 SB and may be impacted by emissions from vehicles slowing down and exiting on that ramp, including trucks headed to the port area. Therefore, pollutant levels at the Bay site may be lower than those that would be measured at the edge of the soccer field closest to the highway.

- **The Niagara site (NI)** is also west of I-95. It is south of the Bay and PHC sites and is approximately 40 feet from and level with I-95 SB. The highway at that location runs in a SE-NW direction. The NI site is within 40 feet of residences. Recreational and day care facilities are also located in the vicinity of the site.

Portable Monitoring locations

Monitoring with portable equipment to characterize the spatial variability of pollutant levels was conducted at all five of the fixed sites, as well as at the following two additional sites:

- **Roger Williams Park (RWP),** a highly used park which includes a zoo, boat rentals, playing fields and other family-oriented facilities. The RWP monitoring locations were east of I-95, south of the PHC site, and directly across the highway from the Niagara site, and
- **Doric Park (Doric),** a municipal park west of I-95 in Cranston, just south of Providence. The park includes basketball and tennis courts, a soccer field, a track, and a tot lot.

The locations of fixed and portable monitoring sites are shown on Figure 1.

Parameters and Schedule

Particle count (PC), a measure of ultrafine particles, and black carbon (BC), an indicator of diesel particulate matter, were measured continuously at the five fixed sites for a one-year period beginning on April 1, 2017. The fixed-site PC monitoring was conducted with TSI Model 3783 Particle Counters and the BC monitoring with Teledyne API Model 633 aethalometers.

Volatile organic compound (VOC) samples were collected for 24-hour periods every sixth day at the fixed sites throughout the study period on the same days that VOC samples were collected at sites in the RI ambient air monitoring network. VOC samples were collected in canisters and were analyzed according to USEPA Method TO-14A/TO-15. The study design also included collection of 3-hour VOC samples one day each month during the morning rush hour period at each of the fixed sites. However, due to an oversight, collection of 3-hour samples did not begin until December 2017. Three-hour rush morning hour samples were collected on five days between December 2017 and March 2018.

Wind speed and wind direction data were collected continuously at the fixed monitoring sites. Since the meteorological sensors at the sites were located on the roofs of the monitoring shelters, approximately 8 feet above the ground, those measurements represent surface wind conditions in the immediate vicinity of the sites. In addition, wind speed and wind direction data are collected by elevated sensors on a meteorological tower on the roof of the Urban League (UL) building in Providence, which is RI's National Air Toxics Trends Site. Ambient temperature is also measured at the UL site. The wind speed and wind direction measurements collected at the UL site are not influenced by local terrain and land use. The wind speed and direction measurements at both the study sites and the UL site, as well as the UL temperature measurements, were used in the analysis of the effects of highway emissions and other local sources on pollutant concentrations at the study sites.

All of the pollutants measured at the study sites were also measured at the UL site, which is in an urban neighborhood approximately 0.5 miles WSW of the Bay site and approximately 0.5 miles from I-95. In addition, BC and VOCs are measured are measured at the State's NCore site in East Providence (EP), a suburban site that is generally downwind of the Providence metropolitan area, and VOCs are measured at the Alton Jones (AJ) site in West Greenwich, a rural site. The data collected at those comparison sites will be used to provide a context for the study measurements.

To study spatial variability in pollutant concentrations, BC and PC were also measured with portable monitors at three to four locations in the vicinity of each of the five fixed sites and the two additional sites discussed above on one day each month. MicroAeth portable aethalometers were used to measure BC. PC portable measurements were initially conducted with a TSI 3781 Condensation Particle Counter but a hand-held TSI 3007 was obtained for that purpose in July 2017. The portable data were used to evaluate the spatial extent of the impact of highway emissions on adjacent areas, as well the effect of other sources, including traffic on city streets on levels of those pollutants.

Traffic parameters were not measured as part of the study. However, hourly total vehicle and truck counts and vehicle speeds measured at several locations along I-95 in the Providence area were supplied to RIDEM by the RI Department of Administration, Division of Statewide Planning.

III. Meteorology

As previously discussed, RIDEM, in conjunction with the RIDOH Air Pollution Laboratory, measures temperature, wind speed and wind direction at the UL site as part of the RI Air Quality Network. The wind sensors at that location are located on a 20-meter tower, so those measurements are not influenced by local terrain and land use.

The UL wind measurements, which reflect overall wind conditions in the area, are important for evaluating impacts of emission sources, like highway traffic. However, localized wind conditions around a receptor may also play a role in pollutant concentrations in the area around receptors. The wind speed/wind direction sensor located on the roofs of the monitoring shelters represent surface conditions at the sites. Since the relative importance of area versus local wind directions on pollutant measurements is not clear, both measurements will be used in the evaluation of the factors that influence pollutant concentrations.

The frequencies of wind directions recorded by the UL elevated sensor and the surface wind sensors at the sites are shown in Figure 2. The wind direction distributions measured at all of the study sites were highly influenced by the local terrain, including the highway and nearby buildings and city streets. Terrain effects are especially notable at the PHC site, which is below the level of the I-95 and east of a steep bank on the side of the highway. At that site, winds were from either the NNW-NNE or SSE-SE, which is the direction of the nearby highway,76% of the time. In comparison, the UL elevated monitored recorded those wind directions 31% of the hours.

The wind direction (WD) frequencies at the Bay site are consistent with funneling of winds down Bay Street, between nearby buildings. 41% of the WD measurements at that site were between W and SW, as compared to 20% of winds from those directions at UL. At NI, the surface sensor favored NNW-NW winds, which is the direction of nearby Niagara Street.

At the VE site, only 4% of hourly wind direction were between NE and SE, as compared to 22% at UL, probably due to a hill located east of the monitoring site. 49% of the wind directions at that site were either S-SSE or N-NNW, the direction of the nearby highway, as compared to 27% of winds from those directions at UL. Similarly, the NR site WD appears to be highly affected by the site's very close proximity to I-95 Northbound (NB). 59% of the NR measurements were from directions between SE and SSW, while only 26% of UL winds were from those directions.

Figure 3 shows the seasonal differences in the UL wind direction frequencies. Winds from the S to SW predominant in the warmer months (May – October), while WNW to NW winds predominate in the cooler months (November – April).

Surface wind speeds measured at the sites were also affected by local terrain. Figure 4 shows the cumulative frequency of wind speeds at the five study sites and UL. Low wind speeds were measured much more frequently by the surface monitors at the study sites than at the elevated UL site. Wind speeds below 2 mph were recorded in 6% of the UL measurements, but made up 37% of the Bay measurements., 43% of those at VE, 44% at NR, 57% at NI, and 88% at the

PHC site. Wind speeds at the UL elevated site corelated better with the surface measurements at the VE, Bay and NI sites (r^2 values 0.74, 0.64 and 0.61, respectively) than with the measurements at the PHC and NR sites (r^2 of 0.35 and 0.14, respectively).

The diurnal patterns of average temperature and wind speeds during warmer and cooler measured at the UL site are shown in Figure 5. In both seasons, average temperatures began to increase at about 7:00 AM and peaked between 1:00 and 3:00 PM. Wind speeds also began to increase at about 7:00 AM but peaked earlier (12:00 – 2:00 PM) in the cooler months than in the warmer months (3:00 – 4:00 PM). Although the diurnal patterns of average wind speeds and temperatures at the UL site are similar, those parameters correlate poorly with each other (r^2 = 0.02).

Figure 6 shows diurnal wind speeds at the UL and study sites in warmer and cooler months. Although wind speeds at all of the study sites were considerably lower than at those recorded by the elevated UL sensors, the shapes of the wind speed patterns at all of the study sites except for NR were similar to UL. Wind speeds at the NR site did not rise to a midday peak, instead remaining relatively constant throughout the day.

IV. Volatile Organic Compound (VOC) Results

As discussed above, VOC samples were collected for 24-hour periods at each study site, as well as at the UL, EP and AJ comparison sites, every sixth day throughout the study period (April 2017 through March 2018). This report focuses on VOCs that are associated with mobile sources, including the BTEX compounds; benzene, toluene, ethylbenzene and xylenes; which are components of both gasoline vapor and mobile and stationary source combustion exhaust. Two other combustions products, 1,3-butadiene and acrolein, are also included. Note that data for a full range of the VOCs measured, including chlorinated solvents, are available on request.

The distributions of the 24-hour concentrations of the BTEX compounds measured at the study and comparison sites is shown in Figure 7. Concentrations of the BTEX compounds at the NR site were considerably higher than at the other sites. The average concentration at the NR site was 71% higher than at the next highest site for benzene, 47% higher for toluene, 38% for ethylbenzene and 36% for the xylenes.

Concentrations of benzene at the Bay, PHC and VE sites were somewhat higher than those at the NI and UL sites. Concentrations of toluene, ethylbenzene and the xylenes at the sites ranked, from highest to the lowest, as follows: NR > PHC > Bay > VE > NI and UL. Concentrations of all BTEX pollutants were lower at the EP (suburban) site than at the study and UL sites and were lowest at the AJ (rural) site.

Concentrations of 1,3-butadiene and acrolein, are shown in Figure 8. Those compounds, which are components of mobile and stationary combustion source exhaust, were also higher at the NR site than the other sites. In particular, the mean NR 1,3-butadiene concentration was 2.4 times higher than at VE, the next highest site.

Note that the concentrations of 1,3-butadiene and benzene measured at the Bay site on January 26, 2018 were much higher than those measured at that site on the other sampling days (see Figure 9). The Bay site acrolein level was also high on that day but was within the range of the concentrations of that substance in the November 21, 2017 Bay site sampled in in the December 23, 2017 samples from the NI and PHC sites.

The elevated VOC levels at the Bay site on January 26, 2018 were likely associated with a nearby temporary source. Since VOC samples are collected over a 24-hour period, the emissions causing the elevated VOC levels could have occurred any time during that day. However, since the VOCs in question are combustion products, the source of the VOCs would likely also emit BC and PC, which are measured continuously. As shown in Figure 10, BC levels recorded that day at the Bay site were unusually elevated between 8:00 and 10:00 AM. PC levels peaked between 11:00 AM and 1:00 PM that day but were not abnormally elevated relative to levels of that pollutant recorded at that site and other sites.

Winds at the UL and Bay sites in the morning of January 26, 2018 were generally from the NW. Wind speeds were typical (7-8 mph as measured at UL and 1-3 mph at the Bay site). The truck loading bays of a nearby company are approximately 50 feet NW of the Bay monitoring site, and

activity in that area may have impacted the VOC and BC levels measured on that day. However, the activity must have been unusual, since the levels of benzene and 1,3-butadiene at the Bay site were much higher on that day than on any of the other sampling days. No records of fires or other unusual activity near the monitor on that day were identified. Therefore, the source of the high VOC levels measured at the Bay site on that day could not be definitively identified.

Note that, if the January 26th benzene and 1,3-butadiene levels measured at the Bay site are excluded as outlier values, the average benzene and 1,3-butadiene concentrations at that site are similar to those measured at the NI site, which is also east of the highway, and lower than the average concentrations at the sites on the other side of I-95, which are more often downwind of the highway.

Health Implications of VOC Exposures

Table 1 displays the average concentrations of the mobile source VOCs measured at each site, along with chronic cancer and non-cancer health benchmarks for those substances derived by the USEPA, the US Agency for Toxic Substances and Disease Registry (ATSDR) and the California Air Resource Board's Office of Environmental Health Hazard Assessment (CARB). The cancer health benchmarks listed are the concentrations that correspond to a one in one million (10^{-6}) lifetime risk, based on the USEPA-derived cancer potencies. Note that the USEPA cancer potency for benzene is a range, rather than a single value. The chronic non-cancer benchmarks listed are: the USEPA Reference Concentration for Inhalation Exposure (RfC), the ATSDR chronic Minimal Risk Level (MRL) and the CARB chronic Reference Exposure Level (REL).

Table 1. Average Mobile Source VOC Levels and Chronic Health Benchmarks

	Average Concentration Average(ppb)								EPA	EPA	ATSDR	CARB
	Bay	NI	PHC	VE	NR	UL	EP	AJ	10-6 Risk	RfC	MRL-Ch	REL-Ch
benzene	0.19	0.16	0.19	0.18	0.33	0.15	0.12	0.08	0.04-0.14	9	3	0.9
toluene	0.34	0.27	0.41	0.32	0.59	0.27	0.18	0.06		1300	1000	80
ethylbenzene	0.06	0.05	0.08	0.06	0.11	0.04	0.03	0.01		230	60	460
xylenes	0.27	0.18	0.33	0.22	0.45	0.19	0.12	0.03		23	80	160
1 3 butadiene	0.04	0.03	0.03	0.04	0.09	0.03	0.02	0.01	0.02	0.90		0.90
acrolein	0.14	0.11	0.12	0.12	0.15	0.11	0.10	0.09		0.009		0.15

Benzene and 1,3-butadiene are known human carcinogens. The average concentrations of both of those substances at all of the study sites are higher than the cancer benchmark level, which corresponds to a 10^{-6} lifetime risk. Lifetime exposure to the concentrations of benzene and 1,3-butadiene measured at the NR site, the site with the highest levels, would be associated with cancer risks of 2.4- 8.2 and 4.5 additional cancers in one-million people exposed, respectively.

Note, however, that, since the public is restricted from the area around the NR site, long-term exposures are not possible at that location. Lifetime exposure to the highest benzene level at the other study sites, which was measured at the PHC and Bay sites, corresponds to a cancer risk of 1.4 - 4.8 in one million. For 1,3-butdiene, the highest risk at sites other than NR site was two cases in one million, measured at the Bay and VE sites. The cancer risks associated with lifetime exposure to the levels of benzene and 1,3-butadiene at the UL comparison site, which is not adjacent to the highway, were 1.1 – 3.8 and 1.5 per million, respectively.

As discussed above, the extremely elevated levels of 1,3-butdiene and benzene in the January 26, 2108 VOC sample taken at the Bay site significantly increased the mean concentrations of those pollutants at that site. If those outlier values are excluded, the average concentrations of those pollutants at the Bay site are similar to those measured at the NI site.

Concentrations of acrolein at all sites, including the AJ rural comparison site, substantially exceeded the USEPA RfC for that substance, which was developed to protect for the most sensitive health effect for that pollutant, development of nasal lesions. This is also true for acrolein levels seen across the United States. Note that the chronic CARB REL for acrolein is considerably less stringent than the USEPA RfC. The average acrolein concentration at the NR site was equal to the CARB REL for that substance, while the concentrations measured at the other sites were lower than the CARB benchmark.

Table 2 compares the maximum concentrations of the VOCs measured at each site with health benchmarks for acute and intermediate exposures. Those benchmarks are the ATSDR acute and intermediate MRLs and the CARB RELs for 8-hour exposures.

Table 2. Maximum Mobile Source VOC Levels and Short-Term Health Benchmarks

	Maximum Concentration (ppb)								ATSDR	ATSDR	CARB
	Bay	NI	PHC	VE	NR	UL	EP	AJ	MRL Ac	MRL Int	8-hr REL
benzene	1.86	0.40	0.47	0.50	0.84	0.50	0.37	0.19	9	6	0.9
toluene	1.06	0.81	1.14	0.86	1.36	1.50	0.77	0.14	2000		
ethylbenzene	0.18	0.13	0.20	0.17	0.23	0.21	0.10	0.02	5000	200	
xylenes	0.87	0.55	0.88	0.87	1.08	0.94	0.39	0.07	2000	600	
1 3 butadiene	0.35	0.10	0.11	0.11	0.17	0.12	0.08	0.03			4
acrolein	0.53	0.43	0.65	0.36	0.28	0.28	0.21	0.26	3		0.30

No VOC concentrations measured exceeded an ATSDR acute or intermediate MRL. However, the CARB 8-hour RELs for benzene and acrolein are ten times more stringent than the acute MRLs for those substances. The abnormally high benzene concentration recorded on January 26, 2018 at the Bay site was approximately twice the CARB 8-hour REL for that substance, which is based on hematologic effects. Note that the second highest level recorded at the Bay site was 0.41 ppb, which is less than half of the CARB REL benchmark. Benzene concentrations in all

samples collected at the other sites, included the NR site, were lower than the short-term health benchmarks for that substance.

The CARB 8-hour REL for acrolein, which is based on respiratory effects, was exceeded on one sampling day, November 27, 2017, at the NI, PHC and VE sites and on two days at the Bay site - January 26, 2018, the day that levels of benzene and 1,3-butadiene were very elevated, and November 21, 2017. It is not clear why the acrolein levels on NI, PHC and VE were elevated on the November 27, 2017. The wind on that day was from the SW in the morning and WNW-NW later in the day, so PHC and VE were downwind of the highway much of the day and NI was also downwind in the morning hours. However, the acrolein levels measured at the NR site, which was also downwind of I-95 that day and which is located between VE and the other sites, was not elevated. BC and PC levels were normal that day at all sites.

On November 21, 2017, the acrolein level at the Bay site was higher than normal and higher than the Cal.8-hour REL health benchmark but was lower than the acrolein level at the Bay site on January 26, 2018 and the acrolein levels observed at the PHC and VE sites on November 27, 2017 discussed above (see Figure 9). Levels of other VOCs, including 1,3-butadiene and benzene, which are also combustion products, were not elevated in the Bay site for November 21, 2017. However, as shown in Figure 11, both BC and PC levels were elevated between 7:00 AM and 1:00 PM on that day. BC levels were particularly high during that period.

As with January 26, 2018, it was not possible to identify the source of the elevated acrolein level at the Bay site on November 21, 2017. Winds were from the predominant direction for that location, SW-SSW, and were relatively strong; the UL wind speed peaked at 12 mph and the Bay wind speed at 5 mph during the period that BC and PC levels were elevated on that day (7:00 AM – 1:00 PM). Since the pattern of pollutant levels and meteorological conditions on November 21, 2017 and January 26, 2018 are not the same, it is unlikely that the elevated acrolein recorded at the Bay site on those days were caused by the same source.

Factors Affecting VOC Concentrations

An analysis of the association between VOC levels and meteorological conditions and traffic parameters was performed to try to identify factors that impact the VOC concentrations at the sites. Note that this analysis is complicated by the fact that VOC samples are taken over a 24-hour period and meteorological conditions and other parameters can vary considerably during the sampling period.

As shown in Figure 12, average concentrations of all of the BTEX compounds, as well as 1,3-butadiene, were higher on days which had lower average wind speeds. This effect, which was also observed at all of the comparison sites, is likely due to the increase in vertical mixing associated with higher wind speeds. The relationship between wind speed and acrolein levels is less clear.

Ambient temperatures were also associated with observed VOC levels but, unlike with wind speed, the relationship between temperature and VOC concentrations was not the same for all of

the mobile source pollutants studied. Since the VOC samples were collected over a 24-hour period, the concentrations of each of the mobile source VOCs at each site were regressed against several temperature metrics, including average, minimum and maximum daily temperatures and temperatures during the morning rush hour.

Benzene and 1,3-butadiene concentrations correlated best with the minimum temperatures during the morning rush hour. A comparison of the average concentrations of those two pollutants on days when minimum morning rush hour temperatures were in the highest and lowest third of sampling-day temperatures is shown in Figure 13. At all sites, the average concentrations of benzene were higher during days with cooler morning temperatures. The same was true for 1,3-butadiene for all sites except for the NR site.

The temperature-concentration relationship for the other BTEX compounds (toluene, ethylbenzene and xylenes) was different from that observed for benzene. As shown in Figure 14, concentrations of those substances tended to be higher with higher temperatures. Benzene levels at the NR site did not correlate well with any of the temperature metrics; however, the correlation between toluene, ethylbenzene and xylenes concentrations and maximum daily temperature (r^2 = 0.32, 0.23 and 0.24), were higher at the NR site than at any of the other sites. Correlations between temperature and concentrations of those pollutants were higher at the PHC, VE and UL sites than at the NI or Bay sites.

Note that 1,3-butadiene is a combustion product present in motor vehicle exhaust but is not a gasoline component. Therefore, it is not present in evaporative emissions. Benzene is a component of gasoline, but the levels of that substance are tightly controlled due to its carcinogenic effects. This is not the case for the other BTEX compounds. Therefore, the ratio of combustion-related emissions to evaporative emissions may be higher for benzene than for the other BTEX compounds. Evaporative emissions and combustion emissions may be affected differently by temperature, which may be one reason that benzene has a different relationship with temperature from the other BTEX compounds.

The graphs in Figure 15 compare average VOC concentrations at each study site on days when the site was downwind of the highway for most of the day and days when the site was upwind of the highway. Average levels of all of the studied VOCs at the VE and NR sites were higher when those sites were downwind of the highway than on days that they were upwind. The same was true at the Bay and NI sites for all of the VOCs except for acrolein.

The PHC site showed a different pattern – ethylbenzene and xylenes were considerably higher on days when the wind had an easterly component than on days with a westerly wind. Since the site is upwind of I-95 when the wind is from the east, it appears that another source or sources significantly impact the ethylbenzene and xylene levels at that site. Cars in the health center's parking lot, which is east of the monitor, may contribute to those levels. PHC ethylbenzene and xylene levels may also be influenced by emissions from port activities and storage tanks, which are also east of the site.

To further investigate the impacts of highway VOC emissions, average levels of each VOC at each site for the 18 weekend sampling days were compared to those on the 48 weekdays that

samples were collected. As shown in Figure 16, average weekday concentrations at all of the study sites tended to be higher than weekend levels for all of the VOCs except for benzene. The weekday-weekend relationship for benzene was variable from site to site. Note that, as shown in Figure 17, the opposite was the case at the three comparison sites – weekend levels tended to be slightly higher than weekday levels, lending further support to the significance of the higher weekday levels at the study sites.

A multivariate regression analysis was performed to better understand the association between meteorological parameters and the concentrations of the studied VOCs. As a first step in this analysis, the concentrations of each of the VOCs were at each site were regressed individually against the following metrics:

- Wind Speed (WS) metrics
    - Average Daily WS at UL,
    - Average Daily WS measured at the site
    - Average 6-9:00 AM (morning rush hour) WS at UL
    - Average WS at site 6-9:00 AM
- Temperature (T) metrics
    - Average Daily T
    - Maximum Daily T
    - Minimum Daily T
    - Average T 6-9:00 AM
- Wind Direction (WD) metrics
    - Number of Hours/Day that the site was downwind of I-95
    - Number of 6-9:00 downwind hours

For each pollutant and site, the metric in each of the above categories with the highest coefficient of determination (r^2 value) was used in a multivariate regression analysis. Note that the r^2 value is the percentage of the variability of the concentrations that can be explained with the factors that are analyzed.

As has already been discussed, temperatures and wind speeds are known to have an association with the concentrations of most or all of the VOCs. In the multivariate analysis, a r^2 value was calculated first for temperature and wind direction together and then was recalculated including those factors plus the wind direction parameter. A substantial increase in the coefficient of determination with the addition of wind direction is consistent with a significant impact on VOC concentrations associated with highway emissions.

The results of this analysis are shown in Tables 3- 7.

Table 3. Regression Analysis of Association of Meteorological Parameters and Bay Site VOCs

	Wind Speed (WS)		Temperature (T)		Wind Direction		Multivariate r^2	
	factor	r^2	factor	r^2	factor	r^2	WS + T	WS + T + WD
benzene	ULWS	0.13	Min T	0.22	E WD	0.01	0.49	0.50
1,3-butadiene	ULWS	0.19	6-9 T	0.08	E WD	0.06	0.36	0.40
acrolein	Bay WS	0.03	Min T	0.09	E WD	0.06	0.15	0.19
toluene	ULWS	0.38	Max T	0.04	E 6-9	0.11	0.38	0.47
ethylbenzene	ULWS	0.33	Max T	0.01	E WD	0.16	0.34	0.49
xylenes	ULWS	0.29	Max T	0.01	E WD	0.20	0.30	0.48

Table 4 Regression Analysis of Association of Meteorological Parameters and NI Site VOCs

	Wind Speed		Temperature		Wind Direction		Multiple r^2	
	factor	r^2	factor	r^2	factor	r^2	WS +T	WS+T +WD
benzene	ULWS	0.11	Min T	0.30	E6-9, S6-9	0.07	0.53	0.59
1,3-butadiene	NI WS	0.30	T 6-9	0.09	E, S6-9	0.03	0.52	0.54
acrolein	ULWS	0.04	Min T	0.01	E, S	0.03	0.06	0.12
toluene	NI WS	0.33	Max T	0.004	E6-9, S6-9	0.14	0.34	0.38
ethylbenzene	NI WS	0.26	T6-9	0.01	E6-9, S6-9	0.19	0.33	0.39
xylenes	NI WS	0.26	T6-9	0.01	E6-9, S6-9	0.20	0.32	0.37

Table 5 Regression Analysis of Association of Meteorological Parameters and PHC Site VOCs

	Wind Speed		Temperature		Wind Direction		Multiple r^2	
	factor	r^2	factor	r^2	factor	r^2	WS +T	WS+T +WD
benzene	ULWS	0.21	Min T	0.10	W, S	0.11	0.41	0.45
1,3-butadiene	ULWS	0.23	Min T	0.04	W, S	0.22	0.33	0.47
acrolein	UL6-9	0.02	Min T	0.01	W, S6-9	0.08	0.03	0.10
toluene	UL6-9	0.34	Max T	0.18	W, S	0.04	0.36	0.39
ethylbenzene	ULWS	0.16	Max T	0.09	W6-9, S6-9	0.08	0.18	0.36
xylenes	ULWS	0.14	Max T	0.07	W6-9, S6-9	0.10	0.16	0.36

Table 6 Regression Analysis of Association of Meteorological Parameters and VE Site VOCs

	Wind Speed		Temperature		Wind Direction		Multiple r^2	
	factor	r^2	factor	r^2	factor	r^2	WS +T	WS+T +WD
benzene	ULWS	0.18	Min T	0.18	W, S6-9	0.12	0.46	0.51
1,3-butadiene	ULWS	0.20	T 6-9	0.08	W, S	0.10	0.33	0.45
acrolein	UL6-9	0.04	Max T	0.04	W, S6-9	0.12	0.05	0.21
toluene	ULWS	0.37	Max T	0.12	W, S	0.04	0.39	0.42
ethylbenzene	ULWS	0.33	Max T	0.06	W, S6-9	0.02	0.34	0.38
xylenes	ULWS	0.27	Max T	0.05	W, S6-9	0.01	0.27	0.30

Table 7 Regression Analysis of Association of Meteorological Parameters and NR Site VOCs

	Wind Speed		Temperature		Wind Direction		Multiple r^2	
	factor	r^2	factor	r^2	factor	r^2	WS +T	WS+T +WD
benzene	ULWS	0.29	Min T	0.03	W, S	0.23	0.39	0.53
1,3-butadiene	ULWS	0.33	Max T	0.10	W, S	0.31	0.34	0.54
acrolein	UL 6-9	0.16	Max T	0.02	W, S	0.15	0.17	0.24
toluene	UL6-9	0.42	Max T	0.32	W, S	0.24	0.49	0.57
ethylbenzene	ULWS	0.38	Max T	0.25	W, S	0.23	0.46	0.54
xylenes	ULWS	0.37	Max T	0.24	W, S	0.22	0.45	0.51

Both temperature and wind speed correlated significantly with benzene levels at tall sites except for the NR site. Temperature correlated poorly with NR benzene levels. The r^2 calculated when both temperature and wind speed were considered together was, for each of the sites, higher than the sum of the r^2 values for each of those factors individually. Taken together, wind speed and temperature explained 39% of the variability in benzene levels at the NR site, 41% at the PHC site, 46% at VE, 49% at Bay and 53% at NI. Note that the January 26, 2018 outlier values for benzene and 1.3-butadiene at the Bay site were excluded from this analysis.

Adding wind direction (number of downwind hours/day) to the benzene regression analysis caused the greatest increase in the r^2 value at the NR site. Wind direction explained an additional 1% of the benzene variability at Bay, 4% at PHC, 5% at VE, 5% at NI and 14% at the NR site. This is consistent with the conclusion that benzene levels at the NR site are more highly impacted by highway emissions than at the other sites.

At all sites, 1,3-butadiene levels correlated considerably more strongly with wind speed than with temperature. Taken together, wind speed and temperature explained 33% of the variability in 1,3-butadiene levels at the PHC and VE sites, 34% at NR, 36% at Bay, and 52% at the NI site. As with benzene, the addition of wind direction (number of downwind hours/day) to the 1,3-butadiene regression analysis increased the r^2 value most for the NR site. Substantially associations with wind direction were also seen at VE and PHC for 1,3-butadiene. Wind direction explained an additional 2% of the 1,3-butadiene variability at NI, 4% at Bay, 12% at VE, 14% at PHC, and 20% at the NR site.

Acrolein did not correlate well with either wind speed or temperature at any of the sites. The strongest relationship for either of those variables was a r^2 of 0.16 for rush hour wind speed and NR acrolein. Taken together, wind speed and temperature explained 3% of the acrolein variability at PHC, 5% at VE, 6% at NI, 155 at Bay and 17% at the NR site. Wind direction explained an additional 4% of the variability at Bay, 6% at NI, 7% at NR and 16% at the VE site.

Toluene levels at all sites correlated much better with wind speed than with temperature. The combination of those factors explained 34% of the variability of toluene levels at NI, 36% at PHC, 38% at Bay, 39% at VE and 49% at NR. Wind direction explained an additional 3% of the toluene variability at PHC and VE, 4% at NI, 8% at NR and 9% at Bay.

Regression analyses of ethylbenzene and xylenes yielded similar results. Both of those VOCs correlated much better with wind speed than with temperature.at all sites. For ethylbenzene, wind speed and temperature together explained 18% of the variability at PHC, 33% at NI, 34% at Bay and VE and 46% at NR. Wind direction increased the percentage of the variability explained by 4% at VE, 6% and NI, 8% at NR, 15% at Bay and 18% at PHC.

Similarly, wind speed and temperature together explained 16% of the variability at PHC, 27% at VE, 30% at Bay, 32% at NI, 45% at NR, with wind direction increasing those percentages by 3% at VE, 5% at NI, 6% at NR, 18% at Bay and 20% at PHC.

Wind direction played a much bigger role in ethylbenzene and xylene levels at the PHC and Bay sites than at the other sites. As discussed above, levels of those pollutants at the PHC site are actually higher when the site is upwind than downwind of the highway. The relatively high additional contribution of wind direction to the r^2 for ethylbenzene and xylenes for that site is further evidence that there is a significant source of those pollutants east of the monitor.

Wind direction also contributes substantially to the r^2 value for the Bay site. As with PHC, easterly winds were associated with higher concentrations of those pollutants at that site. However, since the Bay site is downwind of the highway under those conditions, the association with wind direction may reflect an impact of highway emissions. However, since there are other potential sources east of that site, including a large scrap metal processing facility in the port area directly across the highway from the site, it is not possible to definitively link the association between ethylbenzene and xylene levels and easterly winds at that site with highway emissions.

As discussed above, the contribution of wind direction to the coefficients of determination for the other pollutants are smaller, except for benzene at the NR site and 1,3-butadiene at the VE, PHC and NR sites. The highway is a likely source of those pollutants.

3-Hour Average VOC Samples.

As discussed previously, 3-hour VOC samples were taken during the morning rush hour at the study sites on five days between December 27, 2017 and the end of March. The purpose of these samples was to determine whether mobile source VOC levels at the sites were significantly higher than 24-hour average levels during that time period, which is associated with high traffic and poor air dispersion conditions.

Since 24-hour samples were not taken concurrently with the 3-hour samples, the 3-hour sample results were compared to the concentrations in 24-hours on other days between December 15, 2017 and March 31, 2018, as shown in Figures 18-23. In most cases, VOC concentrations in the 3-hour samples were within the range of the levels measured in the 24-hour samples.

Levels of ethylbenzene and xylenes were elevated in the December 27, 2017 3-hour sample at the Bay site. The reason for these elevations is not clear, but they do not appear to be associated with I-95, since the site was not downwind of the highway during that sampling period. Levels of BC and PC were not elevated on that day.

In the February 15, 2018 NI 3-hour sample, levels of all of the study VOCs except acrolein were on the high end of or slightly higher than the range of 24-hour concentrations measured. The site was downwind of the highway for much of that day (winds between SE and SW). PC and BC were not abnormally elevated on that day.

V. Particle Count (PC) and Black Carbon (BC) Results- Fixed Monitors

BC and PC were measured continuously at the five study sites from April 1, 2017 through March 31, 2018. The distributions of BC and PC concentrations measured at the study sites and comparison sites during that period are shown in Figure 23. Concentrations of both BC and PC at the NR site were approximately twice as high as those at the other study sites, while concentrations at the UL comparison site, which is approximately 0.5 miles from I-95 and 0.5 miles from the Bay site, were less than half those measured at the study sites.

Average weekday and weekend BC and PC concentrations by time of day are shown for each site in Figures 24-29. At all of the study sites, average weekday concentrations of both of the pollutants peaked during the morning rush hour period and remained considerably higher than weekend levels throughout the daytime hours. In contrast, BC and PC levels at the UL comparison site were only slightly higher on weekdays than on weekends, even during the morning rush hour period.

BC and PC levels at the Bay site peaked later (8:00 – 10:00 AM) than at the other study sites, which tended to be highest between 6:00 and 8:00 AM (see Figures 30 and 31). As shown in Figure 32, average PC levels at the Bay site were lower than those at the NI site, which is also west of I-95, throughout the day. BC levels at those sites, however, showed a very different pattern; average BC levels were higher at the Bay site than at the NI site from 7:00 AM to 3:00 PM. Possible reasons for these observations are discussed below.

Health Effects of Exposure to PC and BC

PC primarily measures ultrafine particles (UFP), which are particles with diameters less than or equal to 0.1 μm. Mass-based particulate matter measures, such as those used to determine compliance with the USEPA's National Ambient Air Quality Standard (NAAQS) for $PM_{2.5}$ (particulate matter with diameters less than or equal to 2.5 μm), are dominated by larger, heavier particles. However, PC monitors count the number, rather than the mass, of particles and, since there are far more particles in the UFP range than in larger size categories, PC is essentially a measure of UFP.

Since UFP are so small, inhaled UFP easily migrate throughout the body. Exposure to UFP has been linked to respiratory and cardiac health effects and to brain inflammation. Children and people with compromised respiratory systems, such as asthmatics, are at particular risk for those effects. UFP are also or particular concern because particles in that size range tend to be enriched in toxic species, and, due to a higher surface area to size ratio, those toxics are more bioavailable in UFP than in larger particles.

A 2015 study by the California EPA concluded that both UFP and $PM_{2.5}$ levels contribute to heart disease mortality. Certain constituents of UFP, including copper, iron, other metals, and elemental carbon, were particularly strongly associated with death from heart attacks.[1]

Recent animal toxicological studies have provided strong evidence of the effect of UFP exposure on inflammation of the nervous system, as well as more limited evidence of connections between UFP exposure and neurodegeneration, Alzheimer's disease-related pathology, and behavioral effects. Experimental animal studies also provide evidence that pre- and post-natal UFP exposures are linked to behavioral effects, altered neurotransmitters, neuroinflammation, and morphologic changes.

Health benchmarks for UFP have not yet been derived, largely because of the difficulty in quantifying exposures that change rapidly with time and distance. In the absence of health benchmarks, this report focuses on the factors that are associated with elevated PC levels, with the aim of minimizing future UFP exposures.

BC is measured as an indicator of diesel particulate matter (DPM). Particulate matter emitted by diesel engines is composed of black carbon particles and a variety of organic compounds, including polycyclic aromatic hydrocarbons, benzene, formaldehyde, acetaldehyde, acrolein, and 1,3-butadiene. Diesel exhaust also contains gaseous pollutants, including volatile organic compounds and oxides of nitrogen (NO_x). Inhaled DPM can deposit in the deepest regions of the lungs, which are most susceptible to injury.

Several agencies have evaluated the toxicity of DPM. The California Air Resources Board (CARB) classified DPM as a toxic air contaminant, based on an observed relationship between diesel exhaust exposure and lung cancer and other adverse health effects. The World Health Organization's International Agency for Research on Cancer (IARC) lists diesel engine exhaust as "carcinogenic to humans," based primarily on evidence from occupational studies that links exposure to DPM with lung cancer induction and death from lung cancer.

The USEPA derived an Inhalation Reference Concentration (RfC) of 5 $\mu g/m^3$ for diesel exhaust, measured as DPM, based on pulmonary inflammation and histopathology. CARB adopted a chronic REL for DPM at the same level as the RfC and derived a cancer potency factor for DPM. Based on that cancer potency factor, a lifetime exposure to 0.003 $\mu g/m^3$ DPM would be associated with a one in one million risk. CARB estimates that lifetime exposures to DPM are associated with 520 excess cancers per million people in California, as well as significant increases in cardiopulmonary death, cardiovascular and respiratory hospitalizations, and respiratory emergency room visits.[2]

[1] Ostro B, et al, Associations of Mortality with Long-Term Exposures to Fine and Ultrafine Particles, Species and Sources: Results from the California Teachers Study Cohort, Environmental Health Perspectives 123(6):549, June 2015.

[2] CARB web page "Overview of Diesel Exhaust & Health." https://ww2.arb.ca.gov/resources/overview-diesel-exhaust-and-health

Since DPM contains a variety of components, in addition to BC, and ambient BC originates from sources in addition to diesel engines, it is not appropriate to directly compare BC levels measured in the Rhode Island study with the USEPA and CARB health benchmarks for DPM. However, it is worth noting that BC levels measured at all study sites were more than 200 times higher than the concentration of DPM associated with a one-in-one million risk, derived from the CARB cancer potency. As with PC, this report focuses on the factors associated with elevated BC levels, with the aim of minimizing future UFP exposures.

Factors Affecting BC and PC Concentrations at Study Sites

Wind direction, wind speed, temperature and traffic-related parameters all impacted the concentrations of BC and PC at the study sites. The relative importance of those factors varied by site and parameter, as discussed below.

The maps in Figures 33 and 34 show the locations of the study sites relative to I-95. Graphs of average BC and PC concentrations at each study site by wind direction are superimposed on those maps. Those graphs show that average concentrations of both PC and BC at each site are higher when the site is downwind of I-95.

This effect is further demonstrated in Figure 35, which compares average BC and PC concentrations at the PHC and Bay sites, which are on opposite sides of the highway, by wind direction. When winds had a westerly component, concentrations of both BC and PC were higher at the PHC site, which is east of I-95, than at the Bay site, which is west of the highway. The reverse was true when winds had an easterly component.

The wind direction graphs were produced by processing BC, PC, wind speed and wind direction data with the Nonparametric Wind Regression program developed by Jay Turner at Washington University in St. Louis. That program uses a Gaussian kernel to produce smooth pollutant concentration curves by wind direction with error bars. Graphs produced using this program are useful for identifying sources of elevated pollutant levels.

Figures 36 and 37 show average weekday concentrations of BC and PC, respectively, by wind speed, as measured at UL and at the sites. Average BC concentrations were lower with higher UL wind speeds. The relationship between BC levels and the surface wind speeds measured at the sites is less clear. PC also decreased with increasing UL wind speed, but the decline was less substantial than for BC. The relationship between PC concentrations and site wind speeds is not clear.

BC and PC levels also appear to be associated with temperature, as shown in Figure 38. BC levels tended to be higher with higher temperatures. The opposite was the case with PC; concentrations of that pollutant declined with rising temperatures. Note, however, that wind speed and temperature are not completely independent factors, since wind speeds tend to be higher in cooler months (see Figure 5). The results of regression analyses that looked at the relationship between temperature and wind speed measured at UL and at the sites with BC and PC concentrations are shown in Tables 8 and 9 and graphically in Figure 39.

Table 8 Meteorological Parameters and BC Levels – Coefficients of Determination (r^2)

	UL Wind Speed	Site Wind Speed	UL + Site WS	Temp	WS + Temp
Bay	0.05	0.01	0.07	0.01	0.07
Niagara	0.24	0.15	0.24	0.06	0.27
Prov Health Ctr	0.15	0.04	0.15	0.06	0.18
Vernon	0.15	0.06	0.17	0.01	0.17
Near-Road	0.13	0.01	0.14	0.06	0.18

Table 9 Meteorological Parameters and PC Levels – Coefficients of Determination (r^2)

	UL Wind Speed	Site Wind Speed	UL + Site WS	Temp	WS + Temp
Bay	0.03	0.00	0.05	0.06	0.13
Niagara	0.09	0.05	0.09	0.04	0.15
Prov Health Ctr	0.01	0.03	0.03	0.20	0.24
Vernon	0.01	0.00	0.04	0.25	0.30
Near-Road	0.03	0.01	0.06	0.23	0.30

BC correlated most strongly with UL wind speed at all sites. That correlation was highest at the NI site ($r^2 = 0.24$) and lowest at the Bay site ($r^2 = 0.03$). The wind speeds measured at the sites and temperature contributed relatively little to the total coefficient of determination for BC and meteorology.

For PC, temperature was by far the most important factor for the PHC, NR and VE sites (temperature r^2 of 0.20, 0.23 and 0.25, respectively). Wind speed contributed and additional 0.04 – 0.07 to the total coefficient for PC and meteorology at those sites. The picture was different for the Bay and NI sites. The correlation between temperature and PC was far lower at those sites than at the other sites, as was the total coefficient of determination for the three meteorological parameters with PC.

The relationship between levels of PC and BC and wind speed and temperature was further demonstrated by comparing the average concentrations of those pollutants by time of day in the warmer and cooler months. As shown in Figure 5, the difference between average temperature in the warmer months and the cooler months is virtually constant throughout the day. Wind speed, however, peaks later in the day in the summer than in the winter. Although average wind speeds are considerably higher in the cooler months than in the warmer months during much of the day, wind speeds in warmer and cooler months are virtually equal in hours 16 – 18 (4:00 – 6:00 PM local time) due to the difference in the seasonal diurnal patterns.

Therefore, if levels of a pollutant are strongly impacted by wind speed, we would expect that the average levels of that pollutant in the warmer and cooler months would be more similar in the late afternoon, when wind speeds are similar in the two seasons, than at other times of the day.

BC and PC concentrations by time of day for warmer and cooler months at the study sites and the UL comparison site are shown in Figure 40. For most of the day, BC concentrations at the sites tended to be higher in warmer than cooler months. However, for most sites, that difference was much less pronounced in the late afternoon than at other times of day. In some cases, concentrations in the two seasons were virtually equal during that time period.

This was not the case with PC. Concentrations of PC at all sites were substantially higher in the cooler than the warmer month throughout the day and are, therefore, more likely to be primarily influenced by temperature, rather than wind speed. These patterns are consistent with the regression analysis discussed above, which showed a stronger association with wind speed than temperature for BC, while the reverse was true for PC.

That difference may be partially due to the mechanisms that produce and reduce the concentration of the particles measured by the BC and PC monitors. BC is largely associated with particles that are directly emitted by mobile and stationary source combustion processes and is a mass-based measurement (mass of BC per volume of air). Concentrations of BC decrease mainly by dispersion, the dilution of the pollutant-laden air with cleaner air. Higher winds increased the rate of dilution. In addition, higher wind speeds are associated with a less stable atmosphere, so vertical dilution is also greater when higher wind speeds are increased.

Since higher wind speeds increase dispersion rates and wind speeds tend to be higher in the cooler months, it makes sense that average BC levels would be lower with cooler temperatures. However, combustion emissions tend to increase when temperatures are cold, both because of increased heating-related combustion, including wood burning, and because engines do not function as efficiently when cold. Therefore, there are times and locations with higher BC levels during colder months.

The mechanisms associated with generation and reduction of ultrafine particles (UFP), the particulate species measured by PC, are more complicated. In addition to direct emissions, UFP are formed in the atmosphere by condensation of pollutant gases or vapors around microscopic particles, reactions that can be facilitated by cooler temperatures. As with BC, levels of UFP are reduced by dilution with clean air. However, UFP levels are reduced by other mechanisms as well. As discussed previously, PC is a number-based metric (number of particles per volume of air), rather than a mass-based metric like BC. When the tiny particles collide, they stick together, or agglomerate, into larger particles, reducing the number of particles measured by the PC monitors. Warm temperatures provide the particles with more energy, increasing the likelihood of collisions and, therefore, increasing the rate of agglomeration. It makes sense, then, that, at some locations and under some atmospheric conditions, temperature would have a major effect on PC levels, causing PC levels to be higher in the cold months than when it is warmer.

As discussed above, the relationships between wind speed and temperature and BC and PC levels varied somewhat from site to site. For instance, at the Bay site, neither BC nor PC correlated well with either wind speed or temperature. The PC-temperature correlation was highest at the VE, NR and PHC sites; temperature accounted for 25%, 23% and 20%,

respectively, of the variability in PC levels at those sites. The sites with the highest correlation between BC and wind speed were NI and VE, with wind speed accounting for 24% and 17% of the BC variability at those sites, respectively. NI was the only site at which PC correlated better with wind speed than temperature

RIDEM obtained truck traffic and total vehicle traffic count and vehicle speed data measured at several sites along I-95 from the RI Department of Administration, Office of Statewide Planning. There are traffic monitoring sites close to the NI and VE sites that are representative of the traffic at those sites. However, the traffic monitors with sufficient usable data which are closest to the NR, Bay and PHC sites likely underestimate the traffic at those sites.

Figure 41 shows the locations of the nearest traffic monitors and the NR study site. Traffic from the Rte. 6-10 Connector merges with I-95 NB between the NB traffic monitor and the NR study site and, on I-95 SB, the exit ramp to 6-10 is located between the NR site and the traffic monitor. Therefore, in both directions, traffic coming from or going to Rte. 6-10 that pass the NR monitor would not be counted by the traffic monitor. A traffic monitor located north of the NR site would be more representative of traffic at that site, but data were collection at that traffic monitoring location was minimal.

Similarly, as shown in Figure 42, the onramp from I-195 WB onto I-95 SB is just north of the Bay site, between that site and the nearest traffic monitor. Therefore, the I-195 traffic entering I-95 SB that passes the Bay site is not counted by the traffic monitor. This issue does not apply to NB traffic, because there are no exit or entrance ramps between the Bay site and the traffic monitor in the NB direction.

Since there are no exit or entrance ramps between the Bay and PHC sites, the same traffic monitor can be used to represent traffic at that location, with the caveat identified above concerning the undercounting of the SB traffic at the study sites. However, the PHC is immediately north of the Thurbers Avenue exit and may be affected by truck traffic entering and exiting at that site. Therefore, traffic data from both a traffic monitor south of the exit (labelled PHC 1) and the monitor near the Bay site were used in the evaluation of the PHC PC and BC results.

Figures 43 and 44 show diurnal patterns of average total traffic and truck traffic counts, respectively on weekdays and weekends at the five traffic sites used in the analysis of the PC and BC data. Average hourly speeds are shown in Figure 45. Note that RIDEM does not have sufficient quality assurance/quality control data for those measurements to have confidence in site-to-site or NB to SB comparisons of counts. However, the patterns of the diurnal traffic variations measured by all of the traffic monitors are similar. Weekday counts of both truck and total traffic were high throughout the day, with peaks during the morning and afternoon rush hours, while counts on weekends gradually increased until midday and then fell off through the afternoon hours. Thus, it appears that there is likely sufficient internal consistency in the measurements for them to be useful in evaluating site-specific traffic impacts.

Figures 46 and 47 compare average BC and PC levels, respectively, in hours with high and low total vehicle and truck traffic counts. The low hours were hours with traffic counts at the

representative traffic monitor for that site that were at least one standard deviation below the mean, while the counts for the high traffic hours were at least one standard deviation higher than the mean. Both BC and PC were higher at each site in the hours with high total and truck traffic counts than for the hours with low traffic counts.

Figure 48 shows average BC and PC levels at the site in hours with low and high traffic speeds. No relationship between the pollutant levels and average traffic speeds was evident. Note, however, that this simple look at traffic variables does not take into account the relationships between those variables. For instance, at all sites truck counts and total vehicle counts correlated strongly with each other (r^2 values were between 0.69 and 0.96 for NB travel and between 0.79 and 0.86 for SB travel). Diurnal patterns of traffic and meteorological parameters further complicate the interpretation of the data.

A multivariate regression analysis was conducted to evaluate the association between meteorological and traffic factors and BC and PC levels at the study sites and the UL comparison site. The results of this analysis are shown graphically in Figure 49. Wind speed and temperature together accounted for between 7% and 27% of the variability in BC levels. The highest association between BC and those meteorological parameters was at the NI site and the lowest at the Bay site. As discussed previously, wind speed was more strongly associated than temperature with BC levels.

For PC, temperature and wind speed together accounted for between 13% and 30% of the variability in pollutant levels. As with BC, PC levels at the Bay site correlated more poorly with those meteorological parameters than at the other sites. The highest correlations between those parameter and PC were at the NR and VE sites. As discussed previously, temperature correlated more strongly than wind speed with PC levels at all of the sites except for NI.

Of the traffic parameters, truck traffic counts correlated best with both BC and PC levels. When truck traffic count was added to the meteorological factors in the multivariate analysis, the coefficient of determination (r^2 value) increased by 0.04 – 0.17 for BC and 0.09 – 0.16 for PC at the study sites. Therefore, truck traffic accounted for an addition 4 – 17% of the variability in hourly BC levels and 9- 16% of PC levels. Total traffic and speed factors were then added to this analysis but, in most cases, those factors did not significantly increase the r^2 value.

As discussed above, the multivariate analysis showed that wind speed and temperature, in combination, explained only 7% of the BC variation at the Bay site, while those factors were associated with 17 – 27% of the variability at the other sites (see Table 8). This may explain why average BC levels at the Bay site were essentially equal in the warmer and cooler months for all hours of the day while, at the other sites, BC levels were higher in the warmer months than in the cooler months for most of the day (see Figure 40). Note that wind speeds are, on average, higher in the cooler months than in the warmer months, as shown in Figure 5.

The lower association of wind speed and BC at the Bay site may also explain, at least in part, why BC levels tend to peak later in the morning (8:00 – 10:00 AM) at Bay site than at the other sites, which peaked between 6:00 and 8:00 AM (see Figure 30). As shown in Figure 6, wind speeds tend to increase during the morning hours, and that increase in wind speed acts to reduce

BC levels, even though emissions continue to be high during that time period. The reduced impact of wind speed at the Bay site would be consistent with a later peak in BC levels at that site.

As discussed above, average PC levels at the Bay site were lower than those measured at the NI site, which is also west of I-95, throughout the day, while average BC levels were substantially higher at the Bay site than at the NI site from 7:00 AM to 3:00 PM (see Figure 32). This effect may also be related to the weaker association between wind speed and BC levels at the Bay site than at the NI site. Note that, the r^2 value for the relationship between BC levels and wind speed at the NI site (0.24) was more than three time higher than that value at the Bay site (0.07). Wind speed tends to be higher during the daytime hours and would have a more substantial effect on NI BC levels than on the BC levels at the Bay site.

The reason for the weaker association between wind speed and BC levels at the Bay site is not clear. Surface wind speeds measured at that site were lower than at the UL site but as high or higher than at the other study sites. Note, however, that the buildings in the area appear to funnel winds so that WSW winds predominate.

VI. Spatial Variability Measurements

As discussed above, in addition to the BC and PC fixed site monitors, BC and PC were measured monthly with portable instruments at 3-4 locations near each fixed site and two additional sites, Williams Park (RWP), which is west of I-95, directly across the highway from the Niagara site, and the Doric Park (Doric) in Cranston, which is east of I-95.

From March through June 2017, PC was measured using a TSI Model 3781 Particle Counter, an instrument that is designed primarily for fixed site monitoring. In July 2017, RIDEM obtained a TSI Model 3007 hand-held instrument, which is better suited for portable monitoring. On July 20, 2017, side-by-side measurements were taken with the two instruments at all of the spatial variation study locations.

As shown in Figure 50, the TSI 3007 readings correlated well with, but were consistently lower than, the TSI 3781 measurements ($r^2 = 0.86$). One reason for this difference is that the TSI 3781 detects particles that are as small as 6 µm, while the lower particle size limit for the 3007 unit is 10 µm. On average, the 3007 readings were 63% of those measured with the 3781 (range 39% - 92%). Therefore, the analysis will present the 3781 PC readings for March – July 2017 and the 3017 readings for July 2017 – March 2018 separately.

Spatial variability of BC was measured using side-by-side MicroAeth portable aethalometers. As shown in Figure 51, those readings correlated well ($r^2 = 0.89$) and were essentially equal. Portable instrument measurements were collected at each sampling location for approximately ten-minute periods and the reported values were the average of the measurements over that period.

Approximately 15% of the 10-minute BC average concentrations recorded were negative values Note that instantaneous measurements with aethalometers almost always include negative numbers that are inherent to the operation of the equipment. For that reason, aethalometer measurements are generally not reported for time periods shorter than one hour. Data processing programs can help reduce the occurrence of the negative values associated with the operation of the equipment if shorter averaging times are desired.

In addition, aethalometers sometimes record negative readings when BC levels are very low. Since, as shown in Figure 51, the negative values were almost always were recorded by both MicroAeth units at the same time, it appears that those values correspond to intervals with very low concentrations and were treated as such in the analysis of the MicroAeth data in this report.

For most sites, one portable equipment monitoring location was close to the fixed monitoring station and the two additional monitoring locations were approximately 300 and 500 feet further away from the highway. If the highway is the primary source of the pollutant at a site, concentrations of BC and PC measured with the portable equipment would tend to be higher on days that the site was downwind of the highway than on days that it was upwind. In addition, on the days that the site was downwind, the portable monitoring location closest to the highway should have the highest level, with concentrations dropping off with distance from the highway.

For two of the sites, portable readings were taken on both sides of the highway, providing further information about the impacts of highway emissions.

When concentrations on days when a site is downwind of the highway were highest at the location nearest the highway and dropped off with distance but were still higher at the most distant location on days that the site was downwind of the highway than on upwind days, it appeared that the highway impact extended at least as far as the distance to that location, approximately 500 feet. Those concentration patterns were observed at several of the sites. In many cases, the patterns associated with PC were clearer than the BC patterns. In addition, for some sites, other sources, e.g. major city streets, also appear to have a significant effect on the pollutant concentrations...

Figures 52- 63 show the spatial monitoring locations and the PC and BC levels measured with the portable equipment at those locations. The results are divided into days when the site was downwind of and days that it was upwind of the highway. Due to the mid-study change in the instrument used to measure PC, the PC graphs are further divided into results measured by the TSI 3781 and the results from the TSI 3007. The following are observations about the portable BC and PC results.

- At the Bay site, portable equipment measurements were taken near the monitoring shelter, approximately 40 feet from I-95, (Bay – A) and at locations (Bay-B and Bay-C) approximately 280 and 500 feet from I-95, respectively (see Figure 52). As shown in Figure 53, the PC concentrations at all three of the Bay locations tended to be higher when the site was downwind of I-95 (wind with easterly component) than when the site was upwind (westerly component). This is an indication that the impact of highway emissions extended at least as far as the Bay-C location, a distance of approximately 500 feet. On each of the four days that the Bay site was downwind of I-95, PC concentrations at Bay-A (the location nearest the highway) were higher than those at the Bay-B and C.

  On nine of the 12 sampling days, the PC levels measured at the site most distant from the highway, Bay-C, were higher than those at Bay-B. This is likely because Bay-C measurements were taken on the corner of Bay Street and Eddy Street, a highly traveled city roadway. It appears from this result that Bay-C PC levels were impacted by both I-95 and street traffic. Note that Bay-C is next to a day care center.

  The spatial variation of BC at the Bay site is more difficult to interpret. BC concentrations at Bay-A, the location closest to the highway, were consistently higher when the site was downwind of the highway than when it was upwind. However, BC measurements at Bay-B and Bay-C were more variable. The BC concentration at Bay-B was particularly elevated on December 28, 2017. The wind was from the west that day, so the site was not downwind of the highway. However, the field technician noted that a truck was idling near the Bay-B location during that sampling period. It is likely that local sources near Bay-B, which in an industrial area, and Bay-C, which is on a busy street, impacted the BC levels measured at those locations on other days as well.

- At the PHC site, the PHC-A monitoring location was close to the monitoring shelter, which is approximately 100 feet east of and 30 feet lower than the highway. The PHC- B portable monitoring location was due north of PHC- A, approximately 130 feet east of I-95, and the PHC-C and D locations were taken at points along a line east extending east from PHC-B, approximately 330 and 530 feet from I-95, respectively (see Figure 54).

  As shown in Figure 55, on five of the seven sampling days that the PHC site was downwind of I-95 (westerly wind component), PC levels were highest at PHC-A and decreased with distance from the highway (PHC- A> PHC-B > PHC-C > PHC-D). On the other two downwind days, PC levels at PHC- B were higher than those at A. Note that PHC- A and B are similarly distant from I-95. This result further verifies the impact of highway emissions on PC levels at the PHC site, even though is 30 feet lower than I-95 and is separated from the highway by a steep treed bank.

  It appears that truck traffic on Allens Avenue, a busy street next to the PHC- D location, also significantly impacts the PC levels measured in that area. On the three portable monitoring days when the wind direction had an easterly component (site not downwind of I-95), PC levels at the PHC-D location on Allens Avenue were higher than at the PHC-B and PHC-C locations, which are closer to the highway. On two of those days, PC at PHC- D was also higher than at PHC- A. However, when the site was downwind of I-95 (westerly winds), levels at PHC-D tended to be lower than at all of the other locations, an indication that highway emissions were the predominant source of PC at all of the PHC monitoring locations under those wind conditions.

  The portable BC measurements at the PHC site were more variable. When the wind was from the east, BC levels, like PC levels, were highest at PHC-D, the location closest to Allens Avenue. On three of the seven days with west winds, the concentrations at one of both of the two locations closest to the highway, PHC-A and PHC-B, were higher than at the more distant locations. However, on the other four days that the site was downwind of the highway, BC levels were higher at PHC-C and/or D than at the sites closer to the highway. Assuming that the BC measurements are reliable, it appears that BC impacts from other sources in the area, e.g. trucks on Allens Avenue, are important even on days that the site is downwind of the highway.

- The portable sampling locations around the NR site included one location (NR-D) which is on the opposite (west) side of I-95 from the site and the other portable monitoring locations. NR-D is less than 30 feet from I-95 SB. NR-A readings were taken near the fixed NR site, which is within 5 feet of I-95 NB. NR-B readings were also taken very close to I-95 NB, approximately 330 feet north of NR-A. The NR-C monitoring location was west of NR-B, approximately 250 feet from I-95 NB (see Figure 56).

  As shown in Figure 57, PC levels were higher at the NR-A location, the location near the NR monitoring shelter, on eight of the 12 sampling days and were highest at NR-D, the location on the other side of the highway, on 3 of the days. Although there is some relationship between wind direction and spatial variability, relative concentrations on some of the sampling days are not consistent with expectations based on wind direction. This may be because three of the sampling locations (A, B and D) are extremely close to the I-95, and the topography and the heavy traffic in that area create a microenvironment. As discussed previously, diurnal patterns of

wind speeds at the NR site were very different from those at the other sites and did not correlate well with the wind speeds measured at the UL site (see Figure 6).

BC measurements at one or both of the two NR portable monitoring location nearest the highway (NR-A and NR-B) were higher than those at the other two locations on all days that the site was downwind of the highway. BC levels appeared to drop off quickly with distance. BC levels at the most distance location, NR-C, were very low (or negative) on most of the downwind days.

- At the VE site, portable monitoring was conducted at three sites at increasing distance from I-95. VE-A monitoring was conducted near the monitoring shelter, which is on a triangle of land bounded by on- and off- ramps from I-95 NB. The VE-A location was approximately 60 feet from I-95 NB, while the two other VE portable monitoring locations, VE-B and VE-C. were 190 and 360 feet, respectively, from the highway (see Figure 58).

  While VE PC levels measured with the portable equipment tended to be somewhat higher when the wind had a westerly component (site downwind of the highway), there was no clear pattern in the relative PC levels at the three VE locations (See Figure 59). This may be because, although the mobile monitoring locations are at increasing distance from the highway, all are adjacent to the on- and off- ramps or the road leading to the on- and off -ramps to the highway. It appears that traffic on and approaching those ramps, rather than on the highway itself, may be the dominant source of the PC measured by the portable equipment at this site.

  BC levels measured at the VE site did not show consistent patterns.

- The NI site is directly across I-95 from RWP and portable monitoring locations for those two sites were aligned along a straight line that stretched across the highway in a NW-SE direction, perpendicular to I-95. The NI-A, B and C monitoring locations were approximately 90, 300- and 500-feet NW of I-95 NB, while RWP-A, B and C were similar distances SE of I-95 SB (see Figure 60).

  The NI locations were downwind of the highway when winds had a southerly component, while the RWP wee downwind with a northerly wind. If the highway significantly impacted those sites, it would be expected that, when the wind has a northerly component, PC and BC levels would be highest at RWP- A, lower at RWP- B and C, and still lower at the NI sites. Conversely, with s southerly wind, PC and BC concentrations should be highest at NI-A, somewhat lower at NI-B and C, and lower still on the other side of the highway at the RWP locations.

  As shown in Figure 61, the PC measurements followed that pattern on many of the monitoring days. PC levels at NI-A were higher than at any of the other NI or RWP locations on almost every monitoring day when the wind had a southerly component and RWP-A tended to be highest on days with a northerly wind. On many days with south winds, NI- A PC was higher than NI-B, which was in turn higher than NI-C, while all of the NI sites were considerably higher than the upwind RWP sites. Therefore, it appears that the highway PC impacts extend at least 500 feet (as far as NI-C) to the NW.

  With northerly winds, the pattern was more variable. On November 28, 2017, the wind was from the NW and PC levels at all of the RWP locations were highly elevated, with RWP-A levels

higher than at the other two RWP locations and all RWP locations considerably higher than at the upwind NI sites. PC levels at all RWP sites were also somewhat higher than those at the NI locations on some of the other days with northerly winds. This indicates that, on some days, the highway impacts also extended approximately 500 feet SE, to the location of RWP-C. However, that was not always true. On some of the days that RWP was downwind of the highway, levels at that location were similar to those at the upwind sites, so it appears that the highway impact did not extend as far as RWP-C on those days. BC levels showed similar patterns.

Note that, unlike the locations around the NI site, there are trees on the RWP side of the highway between the highway and the monitoring locations. That may explain the reduced spatial extent of highway impacts on that side of the highway.

- At Doric Park, Doric-A, B and C measurements were taken along straight line, approximately 50, 230 and 530 feet west of I-95 SB, respectively (see Figure 62). Since wind direction was not measured at that site, it was difficult to definitely link the relative PC concentrations at those locations to highway emissions. As shown in Figure 63, on three days, April 11, 2017, November 30, 2017 and March 29, 2018, PC levels at Doric-A were elevated relative to measurements at the other Doric locations. The Doric-A PC levels were also among the highest levels observed at any of the any of the monitoring sites on those days. On those days, wind directions at the NI site, the nearest fixed monitoring site, had an easterly component, indicating that the Doric site was likely downwind of I-95. On two of those days, April 11, 2017 and March 29, 2018, PC levels were also somewhat elevated at Doric-B, but were much lower at Doric-C. Therefore, it appears that the extent of the highway impacts on those days was less than 530 feet, the distance from I-95 to Doric-C.

  BC levels at the Doric site mirrored the PC readings. BC levels were high at the Doric-A location on the three days with high PC readings and tended to drop off with distance from the highway. Therefore, it appears that there are significant PC and BC impacts at the side of Doric Park closest to the highway on some days, but those levels tend to drop off with distance and do not tend to be elevated on the other side of the park. Note that the basketball courts are on the side of the park closest to the highway. Note also that there are some trees between the highway and the basketball courts, but a much thicker patch of trees between the basketball courts and the rest of the park, which may reduce the spatial extent of the highway impacts at this location.

VII. Mid-Term and Long-Term Objectives

The terms of the Community-Scale grants stipulate that the Final Report must document how the study has addressed its Mid-Term Outcomes and must discuss progress towards addressing Long-Term Outcomes. The following is a discussion of those Outcomes.

Mid-Term Outcomes

- *Using study data to understand the impacts of highway emissions at sensitive receptors located near I-95 in the Providence metropolitan area and the factors that affect those impacts*.

  As discussed in the body of this report, the pollutant concentration data collected, along with meteorological measurements at the study sites and the RI NATTS site and traffic data supplied by the RI Department of Administration, were analyzed to characterize highway impacts at the sensitive receptors near the monitoring sites and to identify the factors that influence those concentrations.

- *Disseminating that information to the public so that affected parties and community organizations have accurate information on which to base actions.*

  The conclusions from this study will be presented at a meeting of the Providence Health Equity Zone in February 2019. The RIDOH Asthma Program will present asthma hot spot data at that meeting. Additional presentations will be scheduled in the future.

- *Developing recommendations concerning mitigation procedures for existing sensitive receptors, where applicable and for siting of future sensitive receptors*;

  The results of the spatial monitoring studies indicate that impacts from traffic extend at least 500 feet from the highway at locations where there are few obstructions. Clear impacts from highway emissions were seen at the Providence Health Center site, even though it is at an elevation approximately 30 feet lower than and down a treed embankment from the highway. Therefore, it is clear that proximity to the highway should be an important consideration when siting sensitive receptors in areas near the highway, even when the location is not level with the highway. More specific recommendations will be developed for situations as they emerge.

- *Developing recommendations for future and long-term monitoring*;

  A community group has requested that monitoring be continued at the PHC site RIDEM will work with community groups and the RIDOH to determine what types of monitoring would be possible and informative at that and other sites.

- Providing data to the Rhode Island Department of Health (RIDOH), health researchers, other states, and other interested parties.

  All data have been input into an Access database and will be made available to researchers and other interested parties on request.

Long-Term Outcomes:

- *Reducing exposures of members of the public to pollutants from highway vehicles.*

  RIDEM and RIDOH are committed to disseminating the results of this study to members of the public and to other policy makers and stakeholders. It is our hope that the increased awareness of elevated pollutant levels near busy roadways will lead to decisions which, where possible, inform the siting of sensitive receptors and limit the amount of time that people, particularly children and people with underlying medical conditions, spend in the near-road environment.

- Reducing ambient levels of air pollutants in the near-road environment.

  Monitoring with portable equipment in this study verified the impact of trees or other barriers in ameliorating the spatial extent of vehicle impacts, RIDEM and RIDOH will use those data to argue for such barriers. However, significant reduction in ambient levels of air pollutants near roadways requires the continued reduction of vehicular emissions, especially emissions from diesel vehicles.

.

VIII. Conclusions and Recommendations

This Final Report presents the findings of Rhode Island's Community Scale Monitoring Project. RIDEM collected BC, PC, VOC, wind direction and wind speed data at five sites near I-95 for a one-year period beginning on April 1, 2017. BC and PC were also measured with portable monitors at 3-4 locations around the five fixed sites and two additional sites once per month during the study period in order to better understand the factors that contribute to spatial variability of those pollutants.

The Findings presented in this report include the following:

- On average, concentrations of BC and PC at the study sites, which are in urban areas near I-95, were more than twice as high as those at the State's NATTS site at the Urban League, which is in a similar neighborhood approximately 0.5 mile from the highway. BC and PC at the Near-Road site, which is immediately adjacent to I-95, were approximately twice those at the other study sites.
- BC and PC levels were highest under the following conditions: (1) during weekday morning rush hour periods, (2) when the sites were downwind of I-95, (3) when wind speeds were low, and (4) when traffic counts were high. BC levels tended to be higher with higher temperatures, largely because wind speeds are lower in the warmer months. PC levels tended to be higher in cooler temperatures.
- It was clearly demonstrated that highway emissions impact BC and PC levels at all of the sites, including the Providence Health Center, even though that site is 30 feet below the level of the highway. Emissions from other sources also appear to contribute to levels of certain VOCs, as well as black carbon and ultrafine particles, at that location and at the Bay Street location.
- Monitoring with the portable equipment demonstrated that, at some sites, impacts of highway emissions on ambient PC levels extend at least 500 feet from the highway. The presence of trees appears to reduce the spatial extent of those impacts. Traffic on city streets also contribute significantly to PC levels at some of the sites.
- VOCs emitted by mobile sources, including components of gasoline (BTEX compounds) and combustion products like 1,3-butadiene, were highest at the Near-Road site and were higher at the other study sites than at the comparison sites, including the Rhode Island NATTS site, which is approximately 0.5 miles from I-95. Levels of two of the BTEX compounds, ethylbenzene and xylenes, were elevated at the Providence Health Center site relative to the other study sites and the comparison sites. Based on wind direction data, it appears that the source of those elevated levels is east of the site. Cars in the health center's parking lot may contribute to those levels, as may sources at the port, which is east of the site.

Based on those findings, RIDEM recommends the following:

- Proximity to highways and other major roadways should be considered in all decisions considering siting of sensitive receptors.
- For existing sensitive receptors within 500 feet of a highway or near a major roadway, the following steps should be taken to minimize exposures to highway-related pollutants:
    - Located outdoor play areas as far from the highway as possible
    - Plant trees and/or install other barriers to ameliorate the spatial extent of highway impacts
    - Limit the time that people, particularly children, spend near the highway, e.g. by using parks for outdoor recreation that are not near the highway
    - Design air handling systems such that infiltration of air pollutants into buildings is limited to the extent possible
- Education about air pollutant levels near highways and other busy roadways and the consequences of exposures to those pollutants is essential for minimizing those exposures, especially for children and people with asthma and other respiratory diseases.
- Future land use planning should consider the proximity of facilities associated with considerable truck traffic, as well as stationary sources of pollutants, to neighborhoods and other sensitive receptors.
- Continuing efforts to reduce emissions from motor vehicles, particularly diesel vehicles, are essential.
- RIDEM and RIDOH will work with community groups to determine what, if any, additional monitoring studies are necessary to further aid in the understanding of air pollutant levels in the State and the sources of those pollutants.

Figure 1. Location of Monitoring Sites

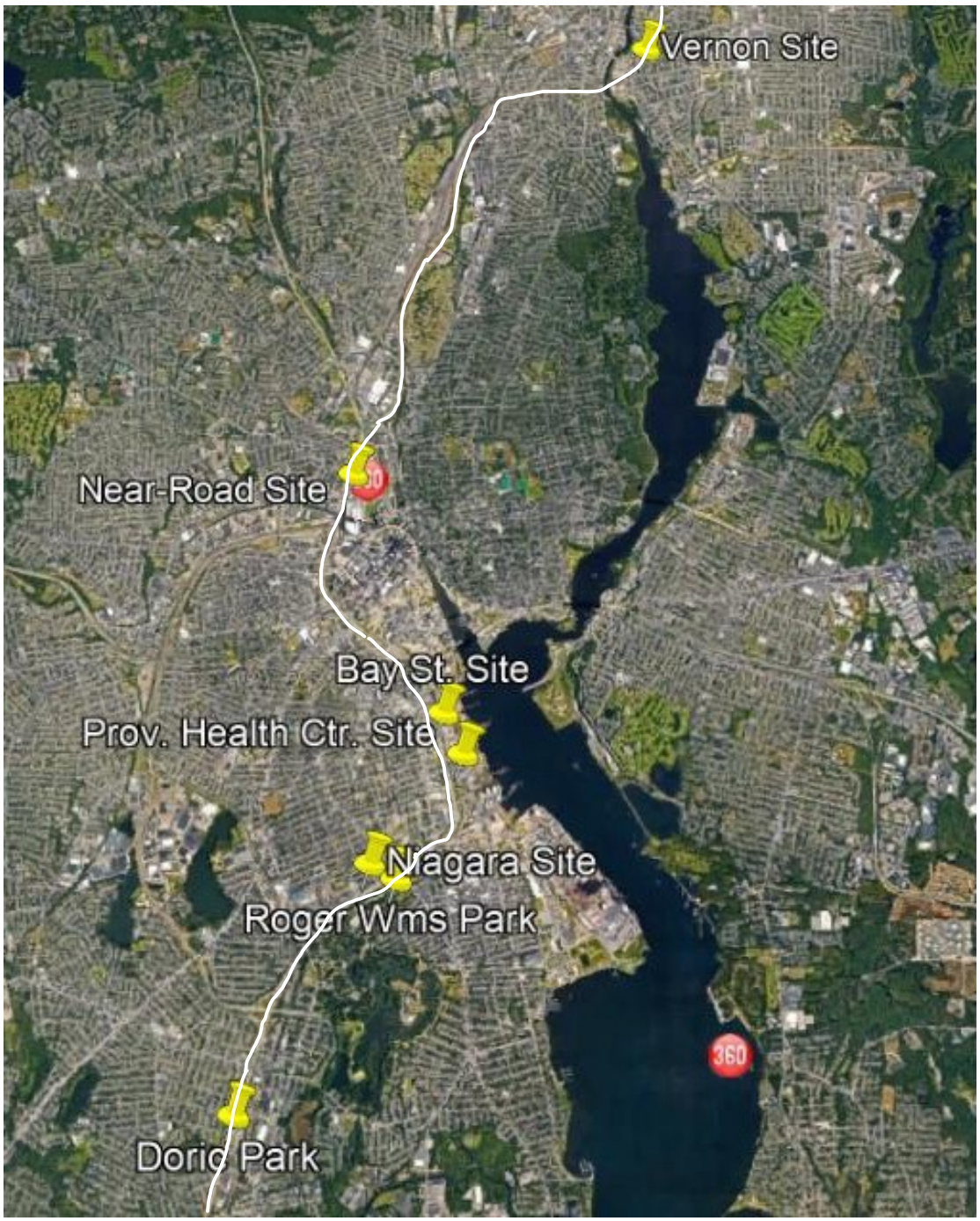


Figure 2. Wind Direction Frequencies Measured by Urban League Elevated Sensors and Surface Sensors at Study Sites

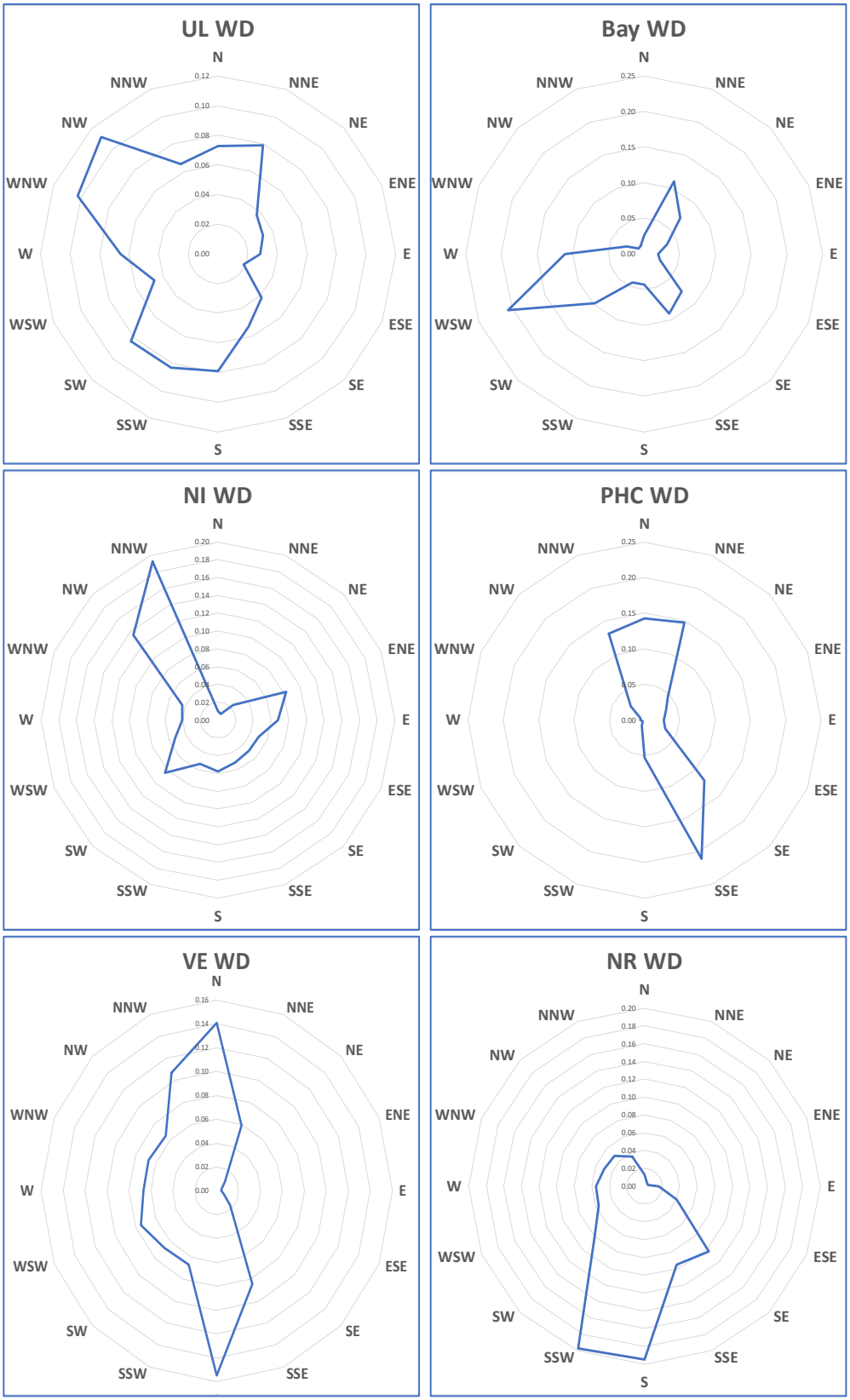


Figure 3. Seasonal Differences in Wind Direction Frequency at UL Site

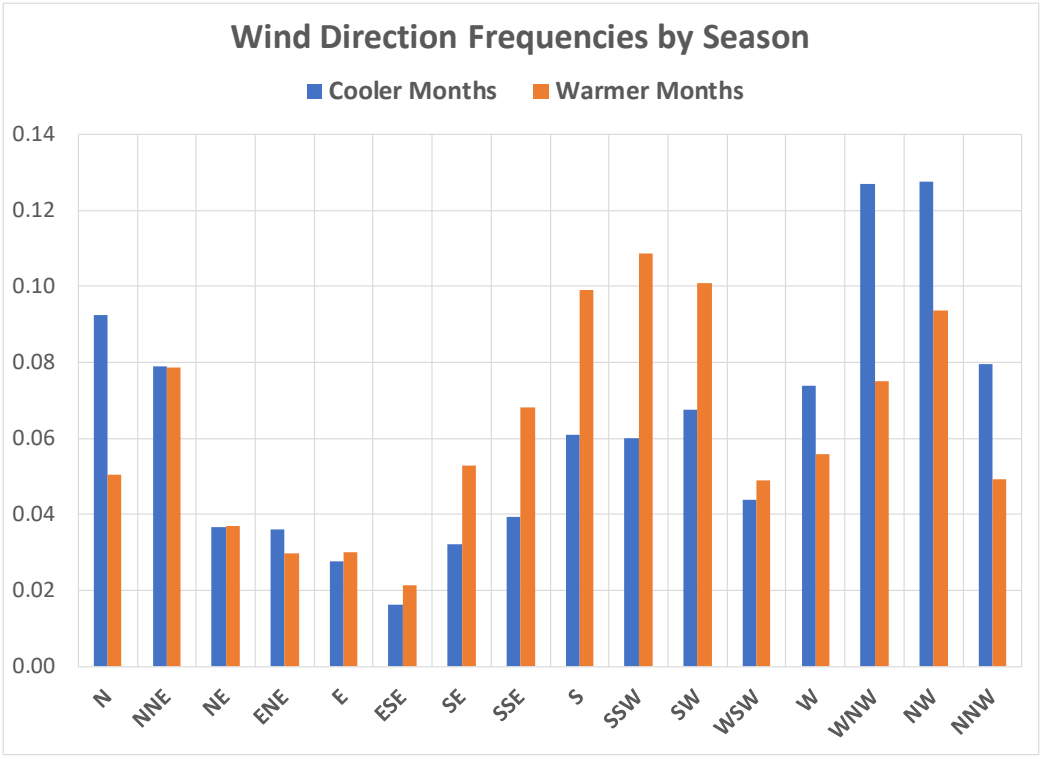


Figure 4. Comparison of Wind Speeds Measured at Urban League and Study Sites

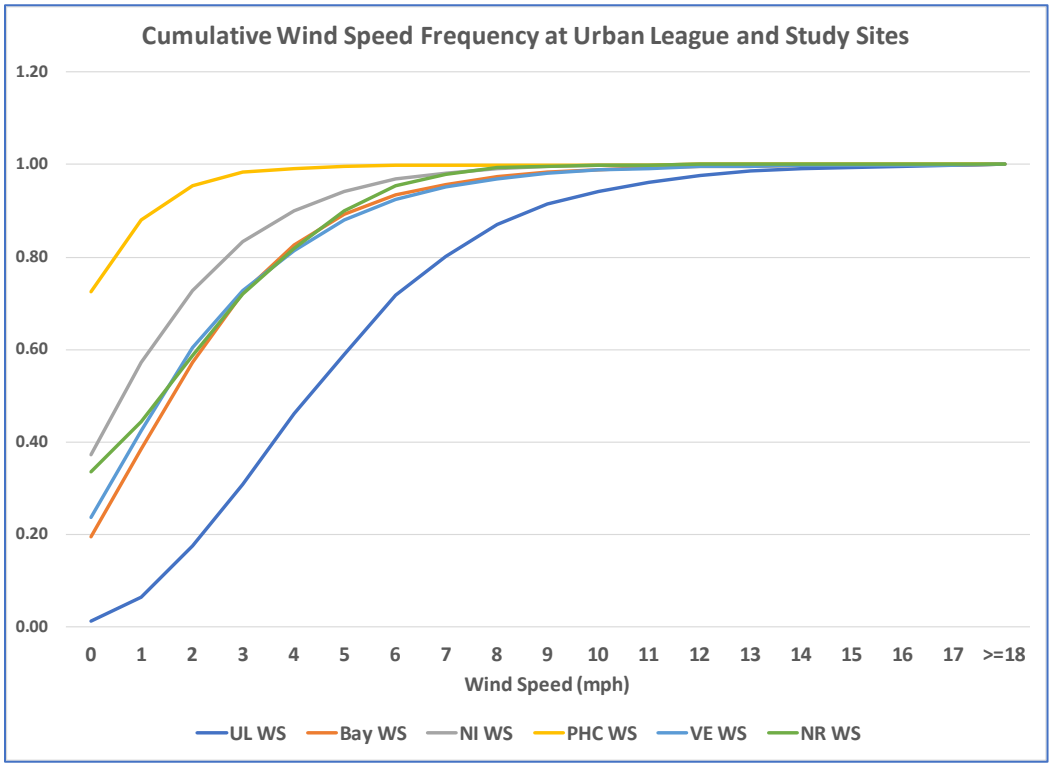


Figure 5. Diurnal/Seasonal Patterns of Urban League Wind Speeds and Temperatures

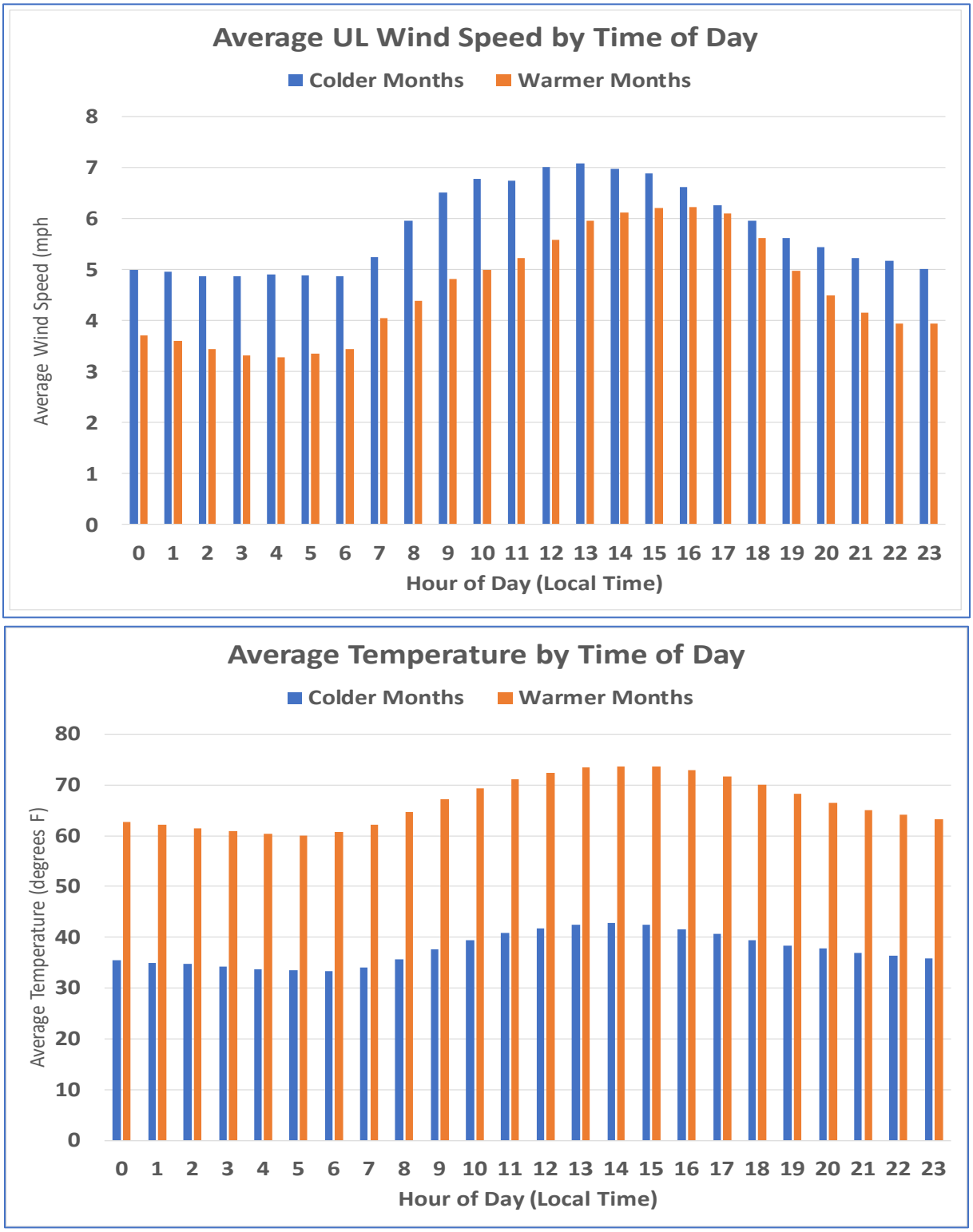
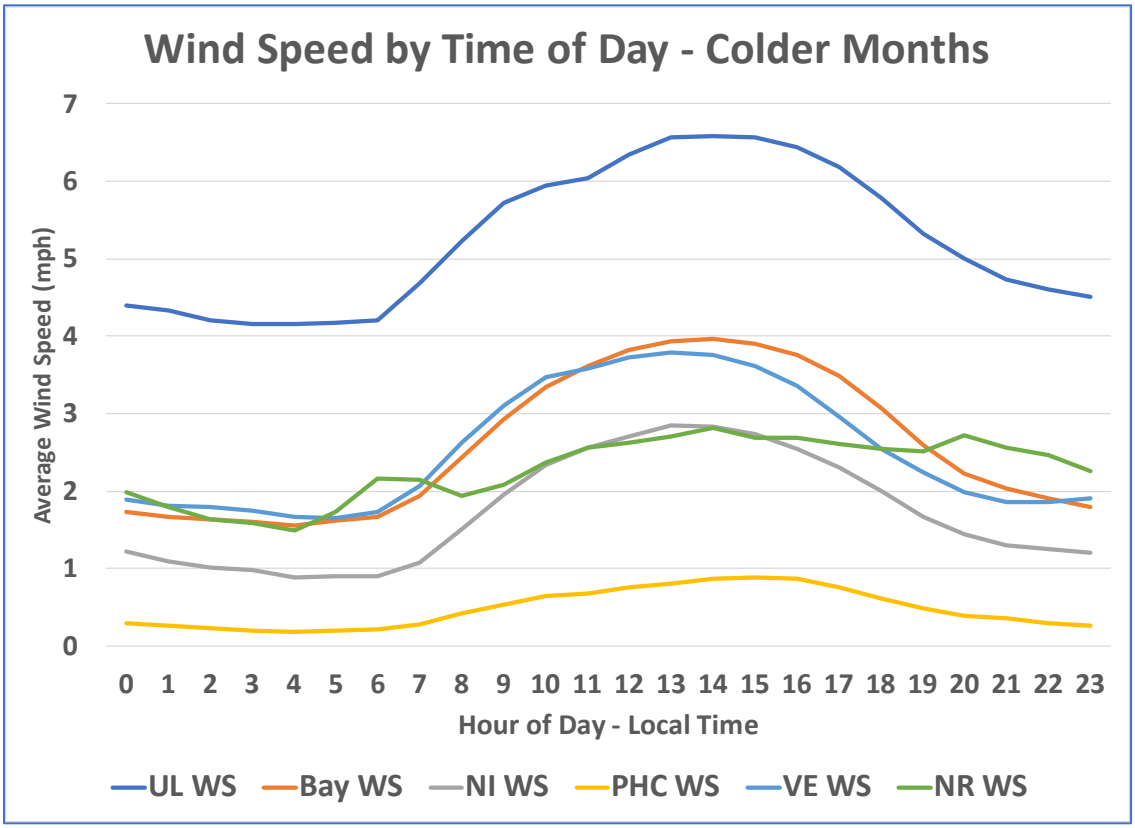


Figure 6. Diurnal/Seasonal Patterns of Wind Speeds at UL and Study Sites



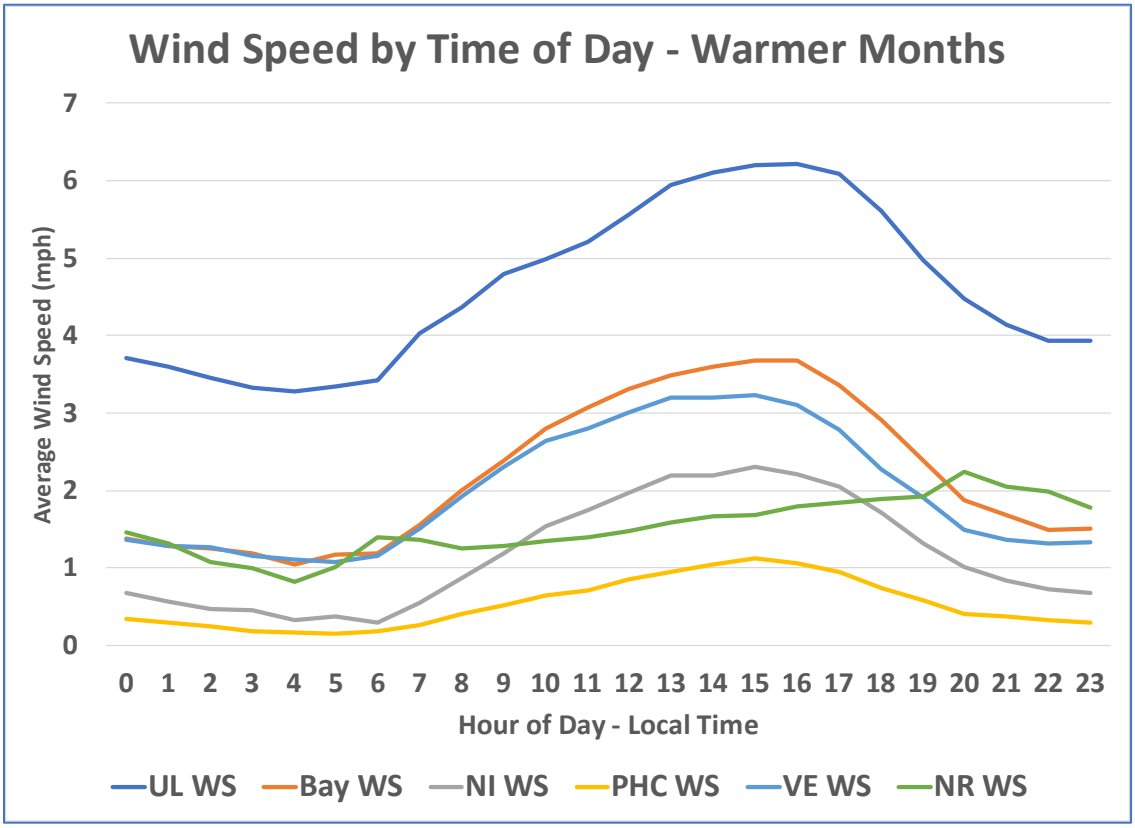


Figure 7. BTEX Compound Concentration Distributions

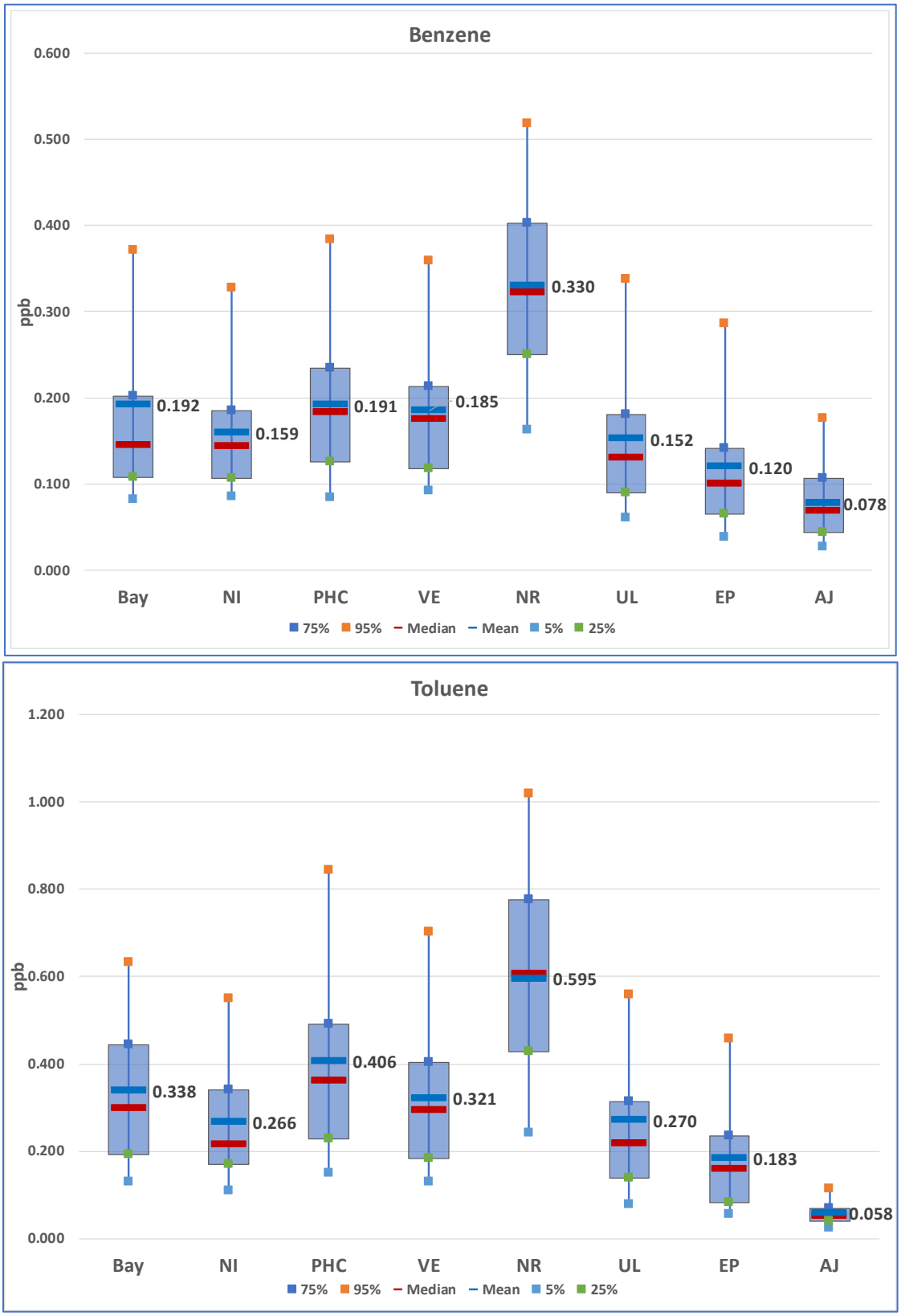
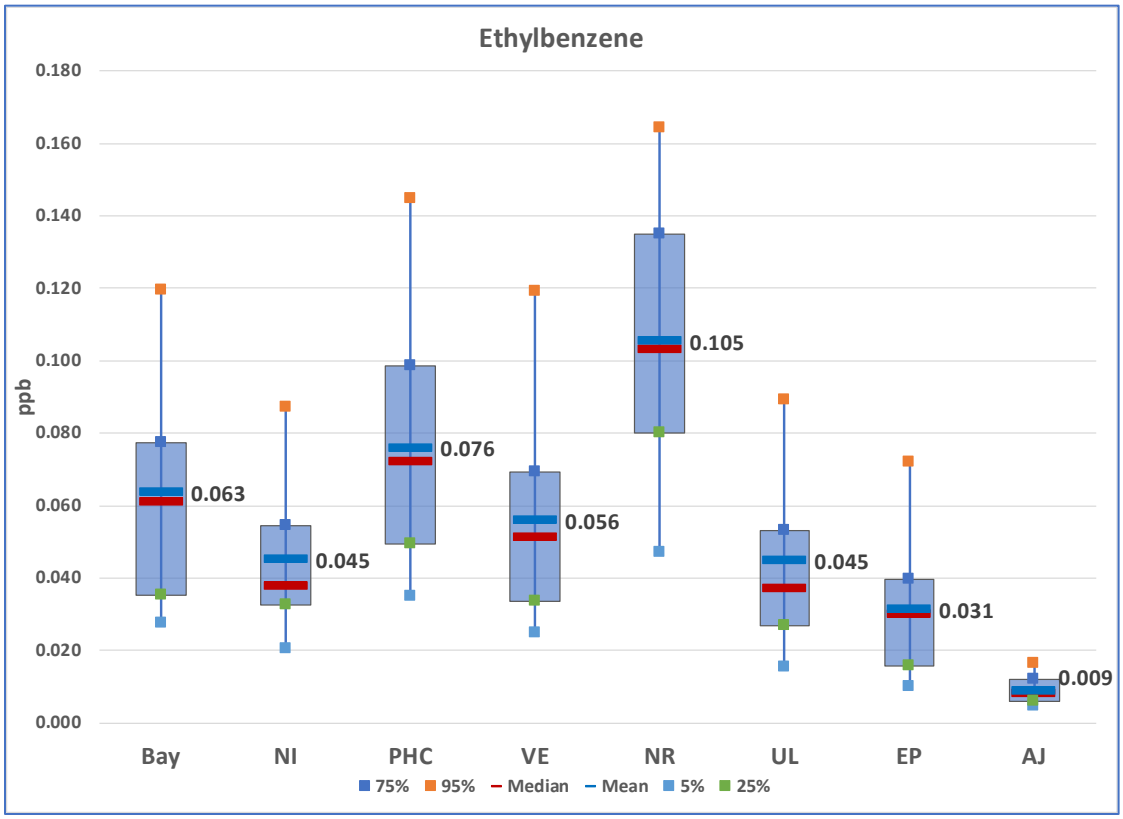


Figure 7 (cont.) BTEX Compound Distributions



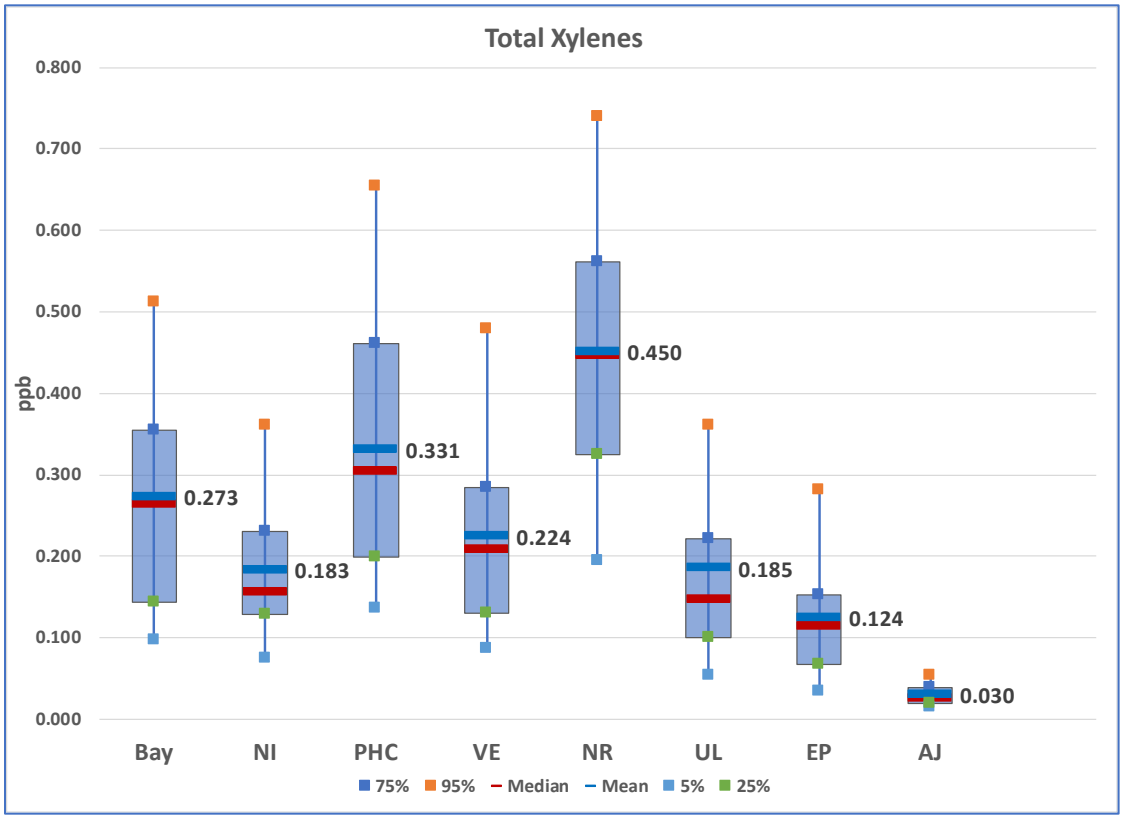
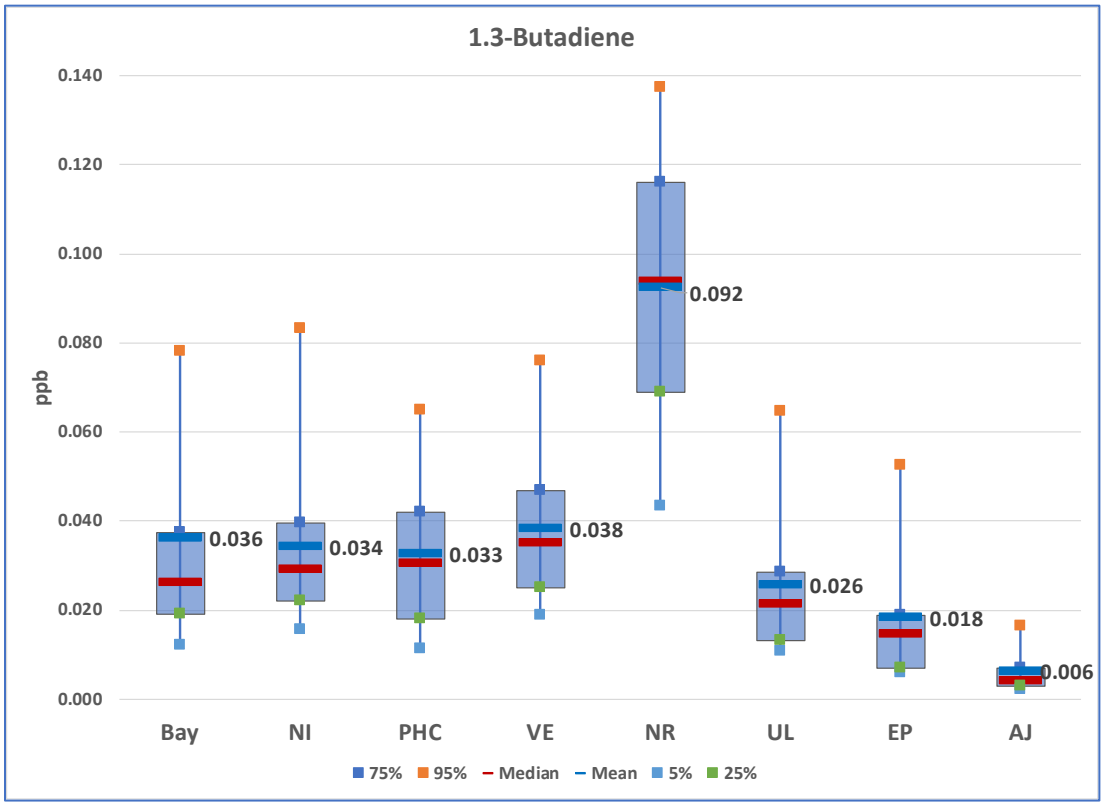


Figure 8. VOC Concentration Distributions for Other Components of Combustion Exhaust



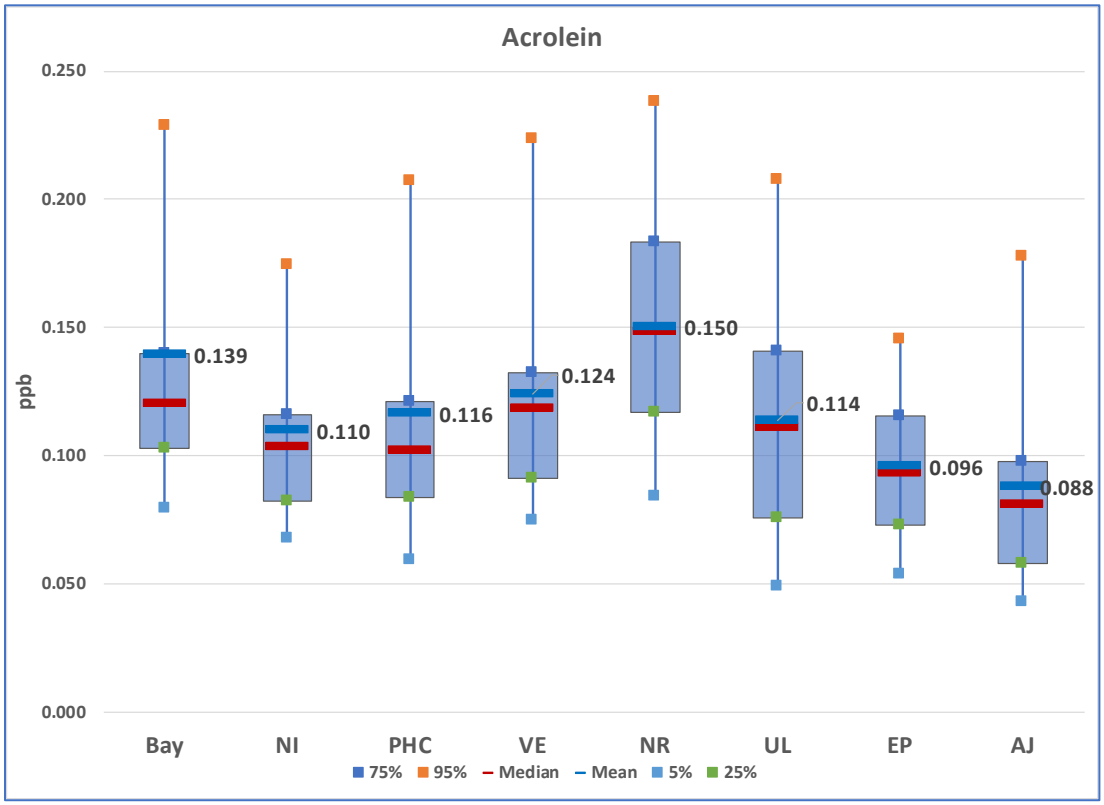


Figure 9. Benzene, 1,3-Butadiene and Acrolein at Bay, Niagara and Prov. Health Ctr

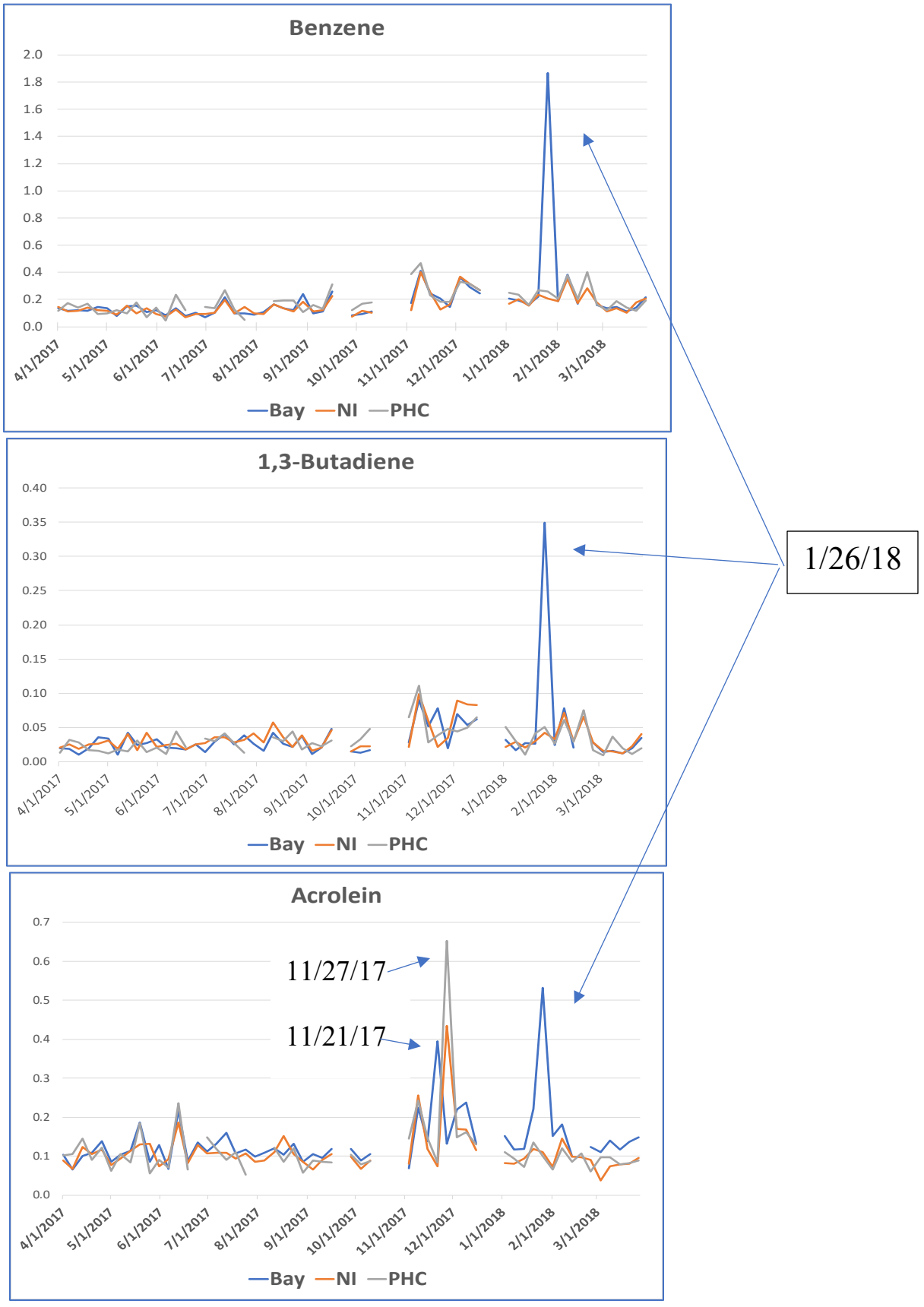
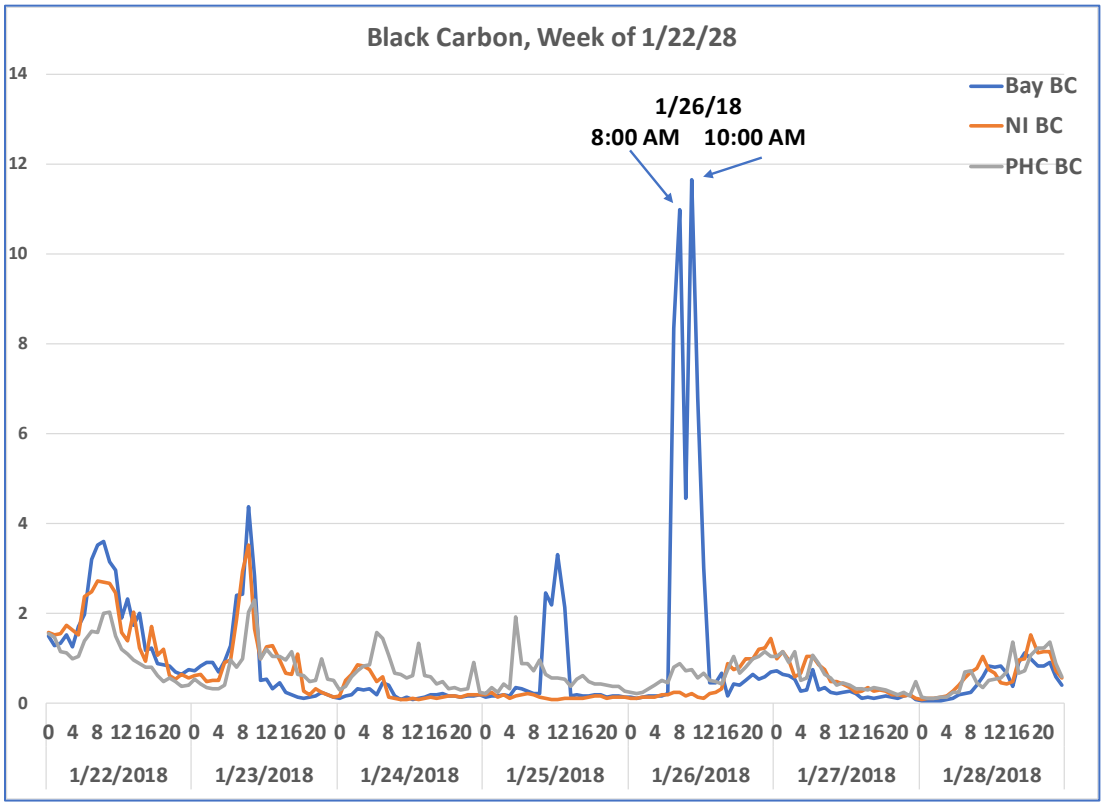


Figure 10. – PC and BC, Week of 1/22/18



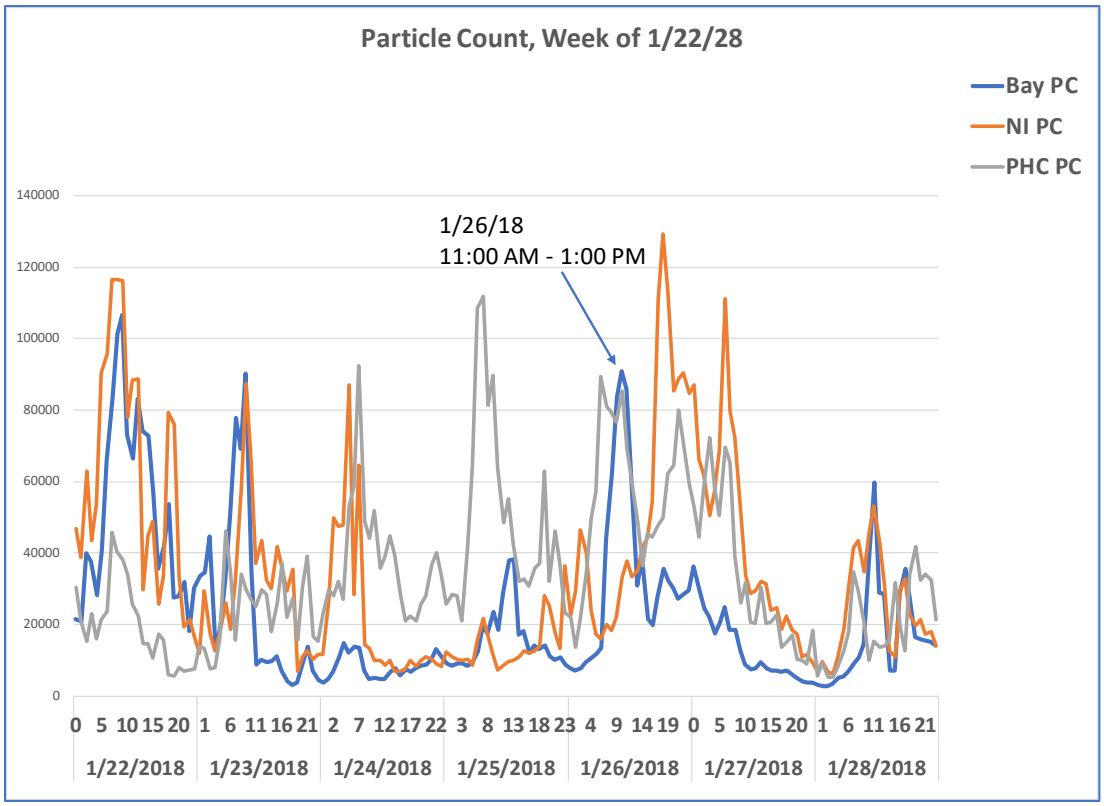
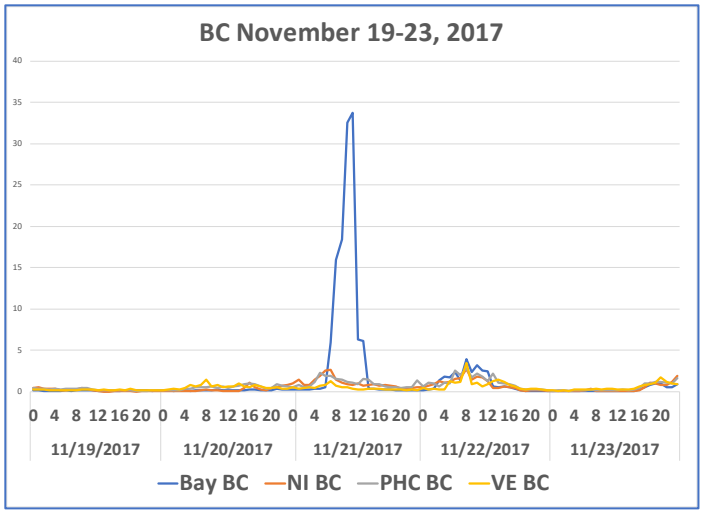
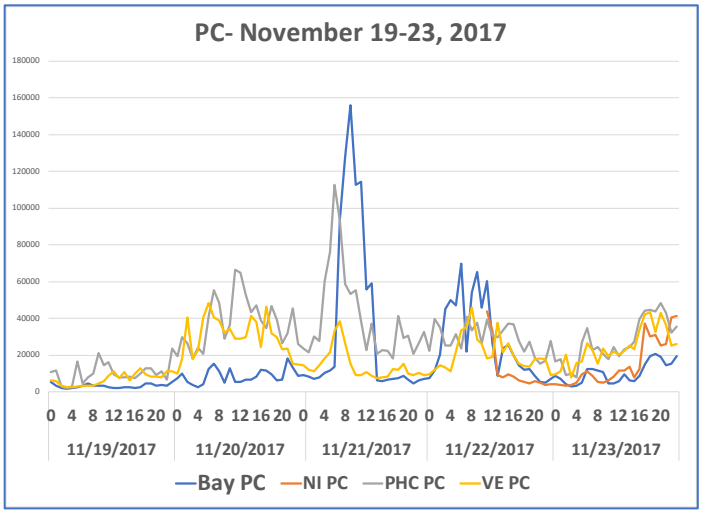
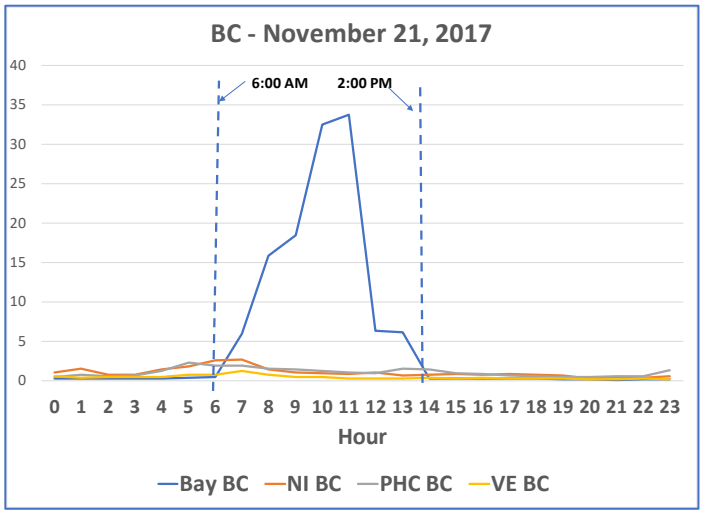


Figure 11. – PC and BC, November 21, 2017







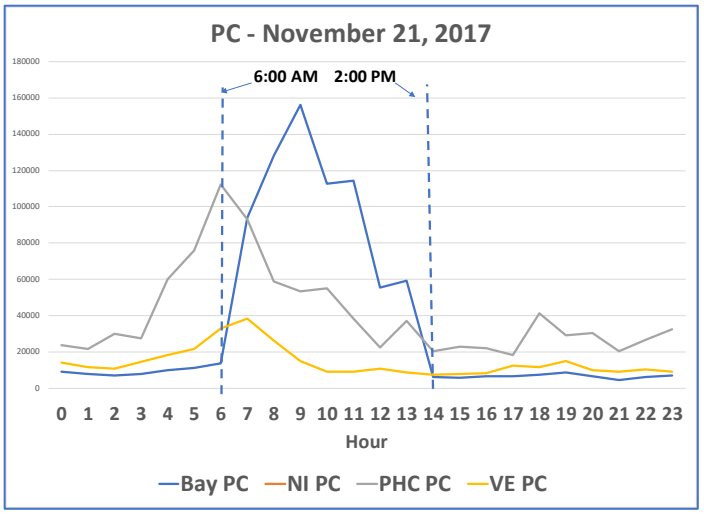


Figure 12. Average 24-Hour VOC Concentrations on Days with High and Low Average Wind Speeds

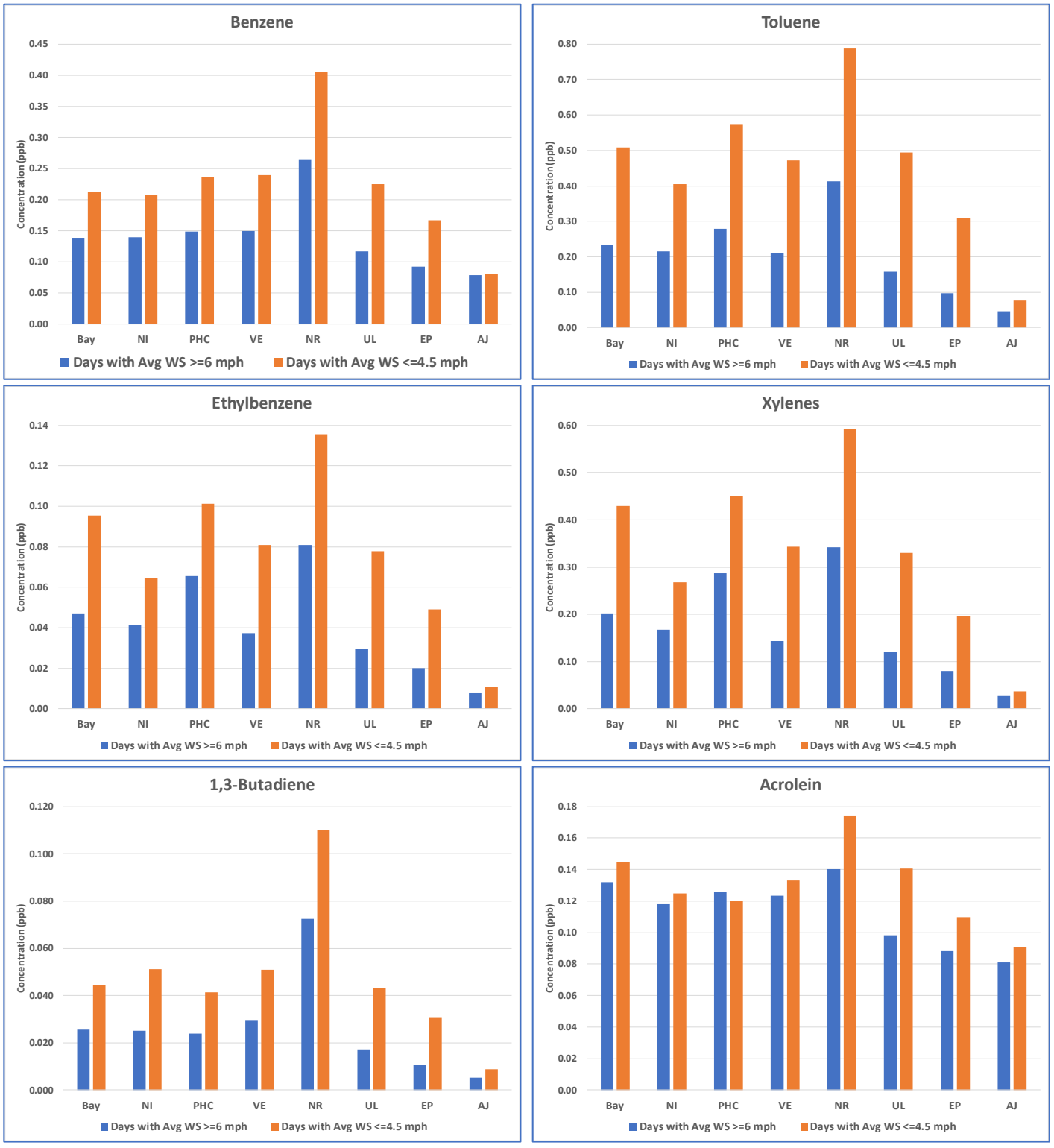
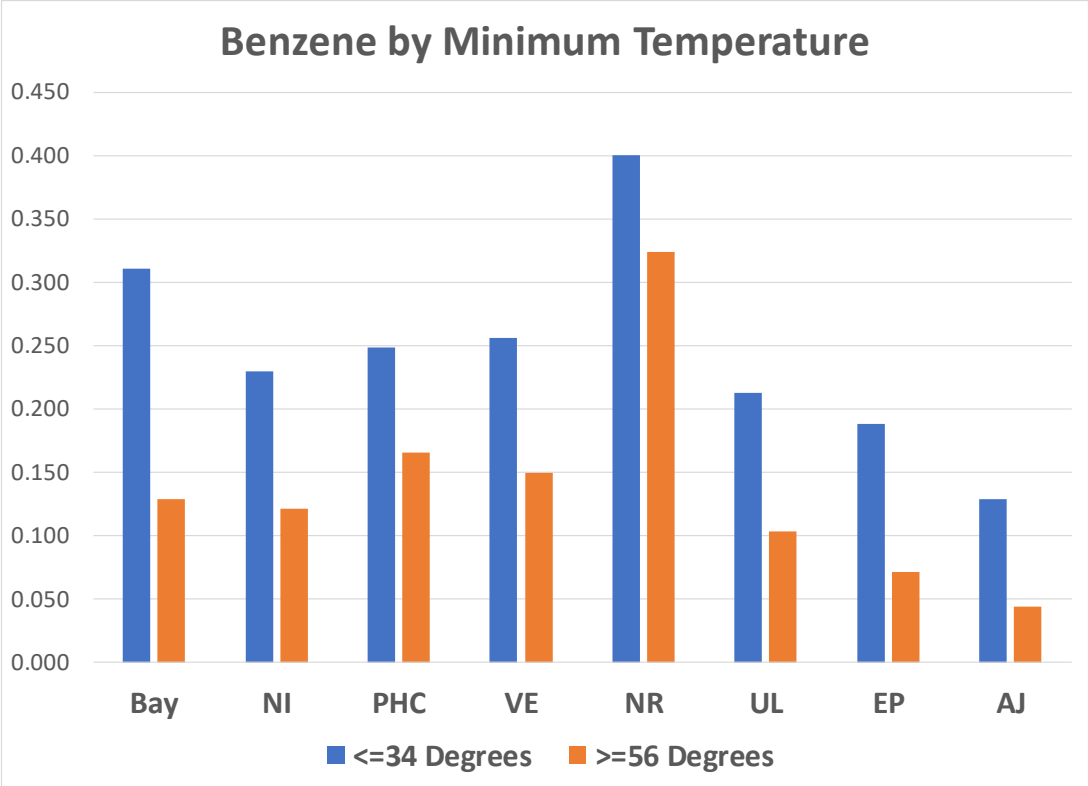


Figure 13. Average 24-Hour Benzene and 1,3-Butadiene Concentrations on Days with High and Low Minimum Temperatures During Morning Rush Hour



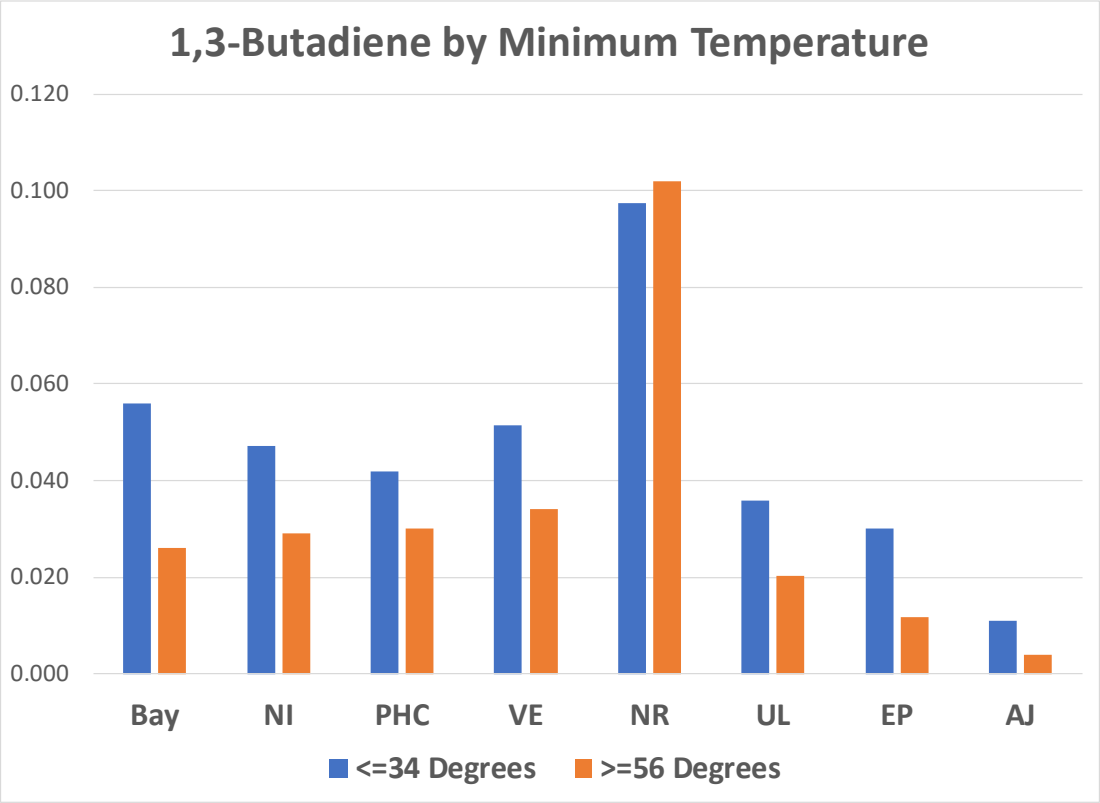
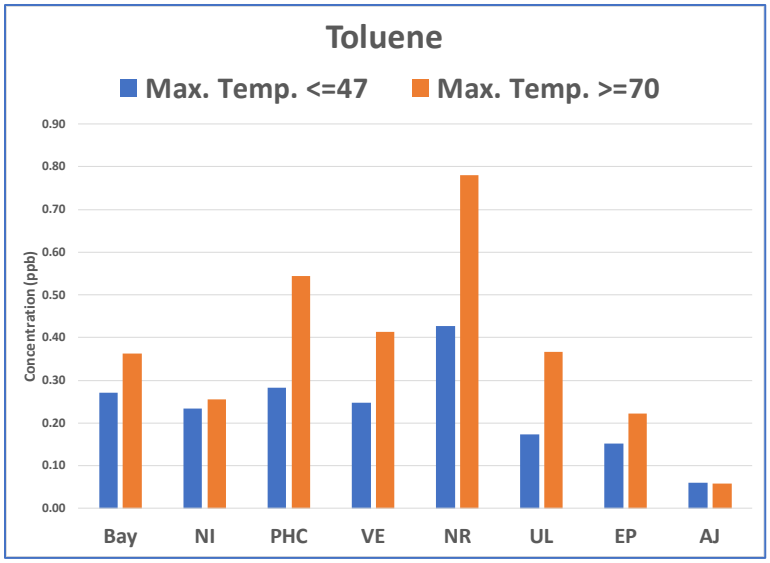
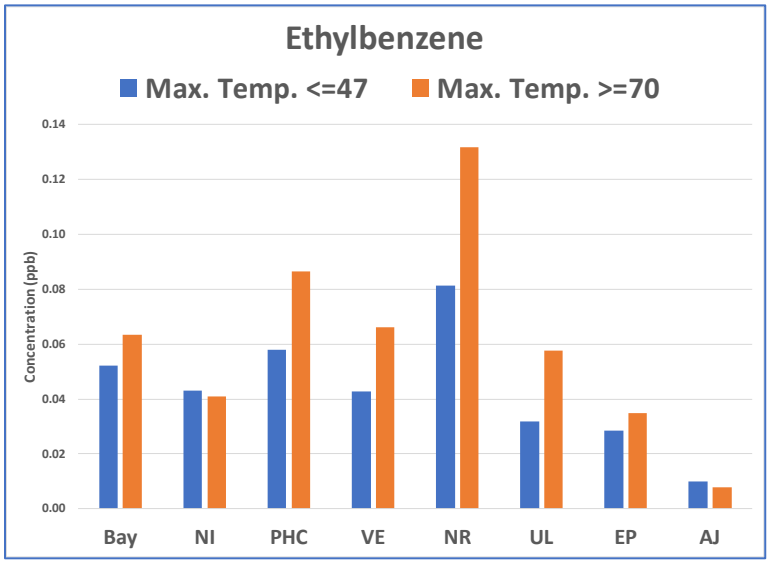


Figure 14. Average 24-Hour VOC Concentrations of Toluene, Ethylbenzene and Xylenes on Days with High and Low Maximum Temperatures





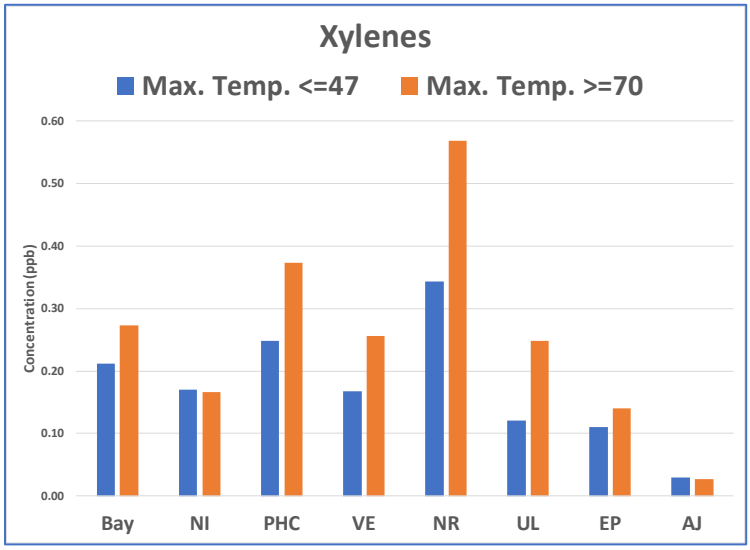
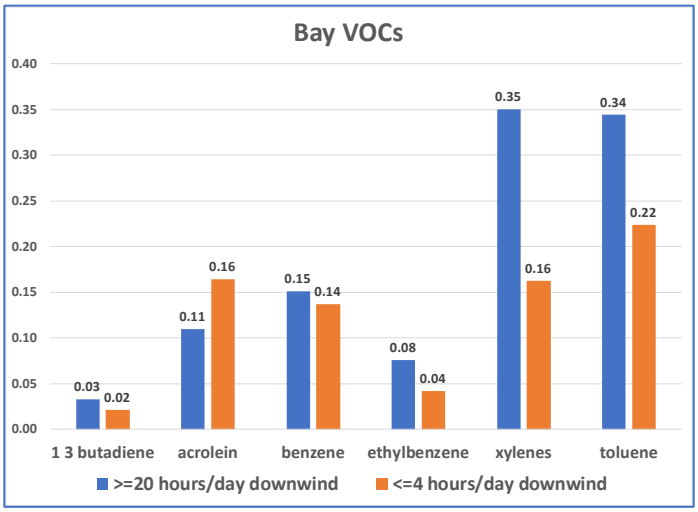
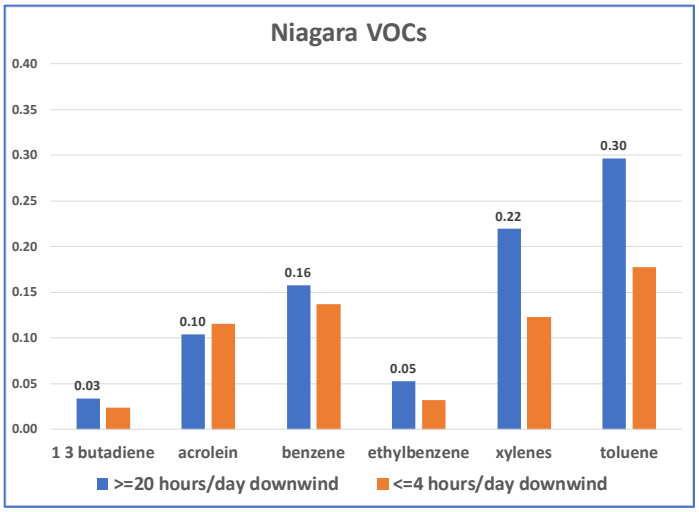
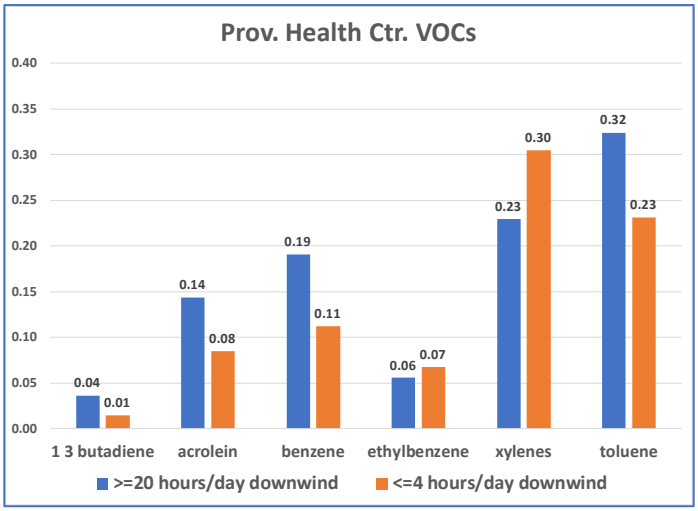
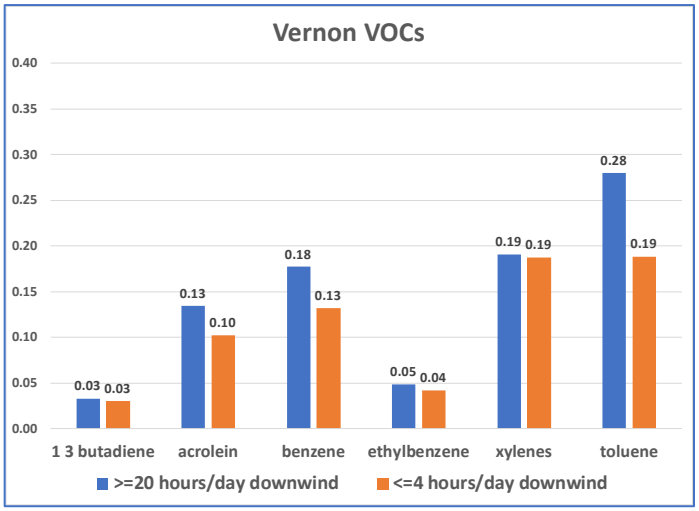


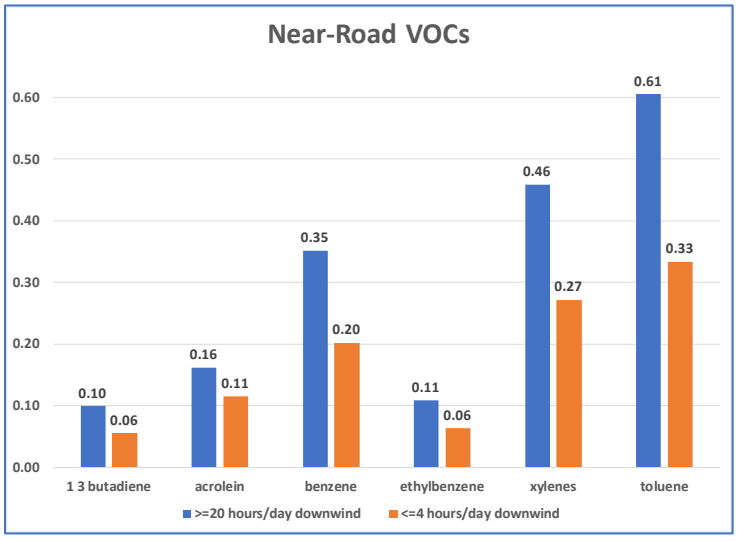
Figure 15 – Average VOC Concentrations at Study Sites by Number of Hours/Day Site Was Downwind of I-95





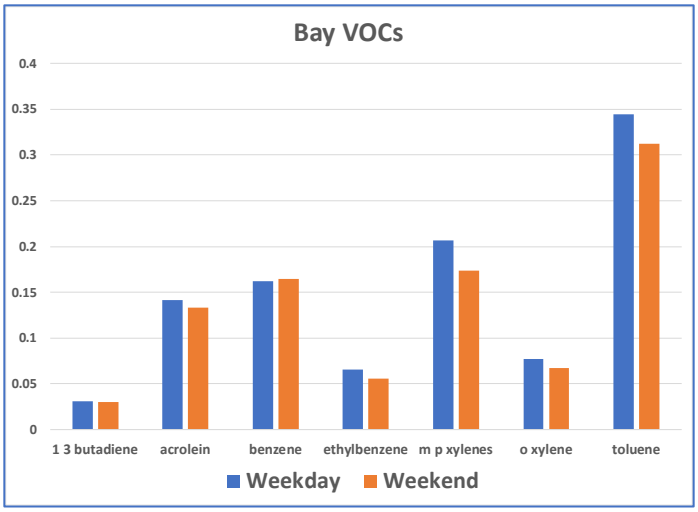


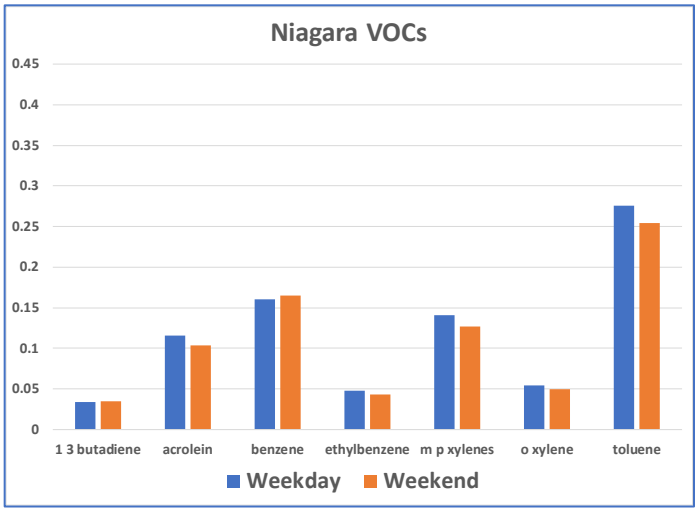


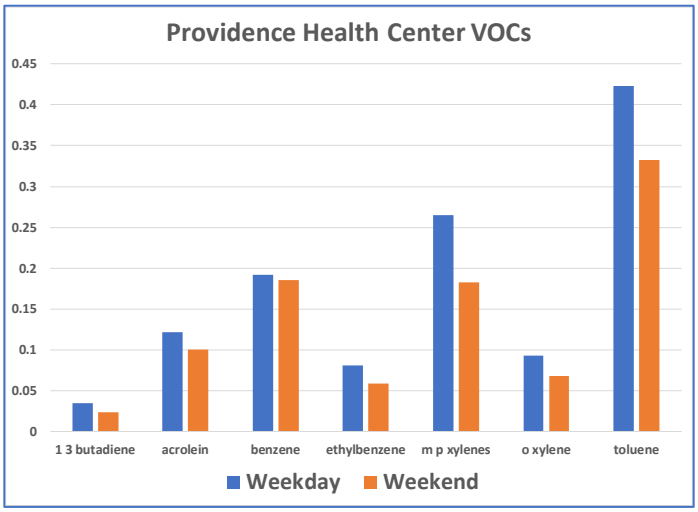


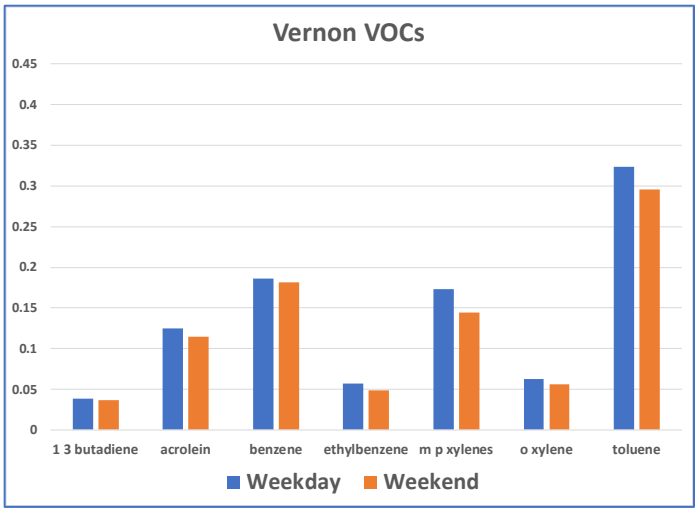
Note that the scale in the Near-Road graph is different from the other graphs because concentrations are considerably higher at this site than at the other sites

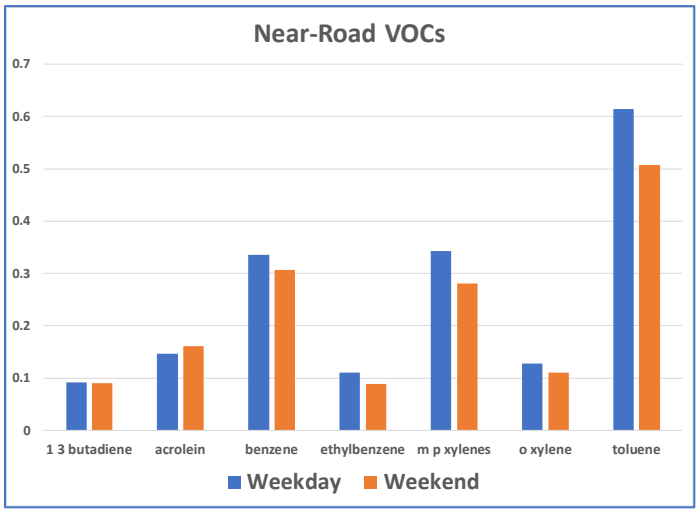
Figure 16 – Average VOC Concentrations at Study Sites on Weekdays and Weekends











Note that the scale in the Near-Road graph is different from the other graphs because concentrations are considerably higher at this site than at the other sites

Figure 17 – Average VOC Concentrations at Comparison Sites on Weekdays and Weekends

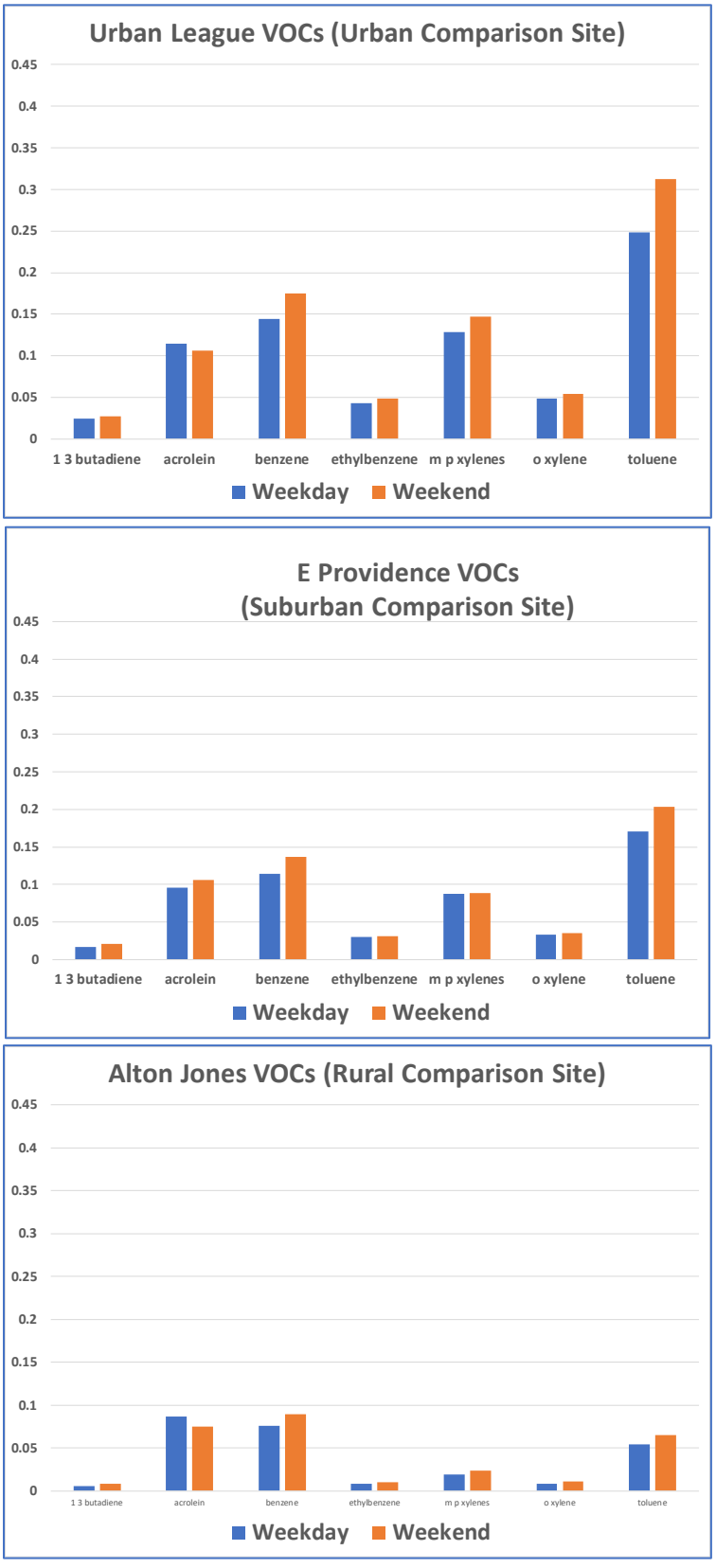
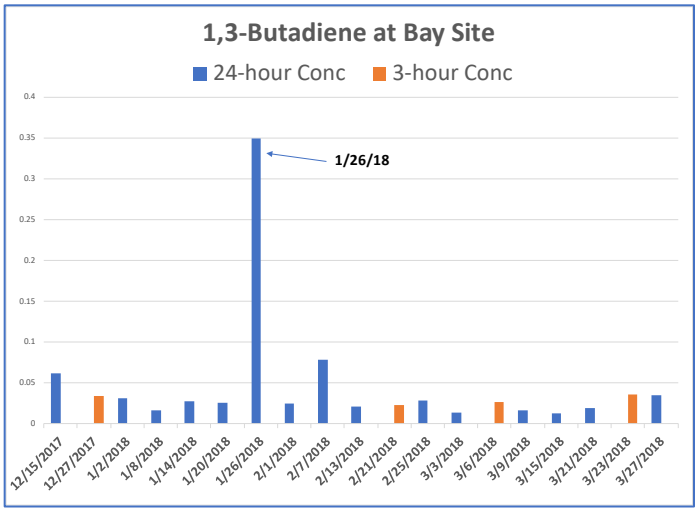
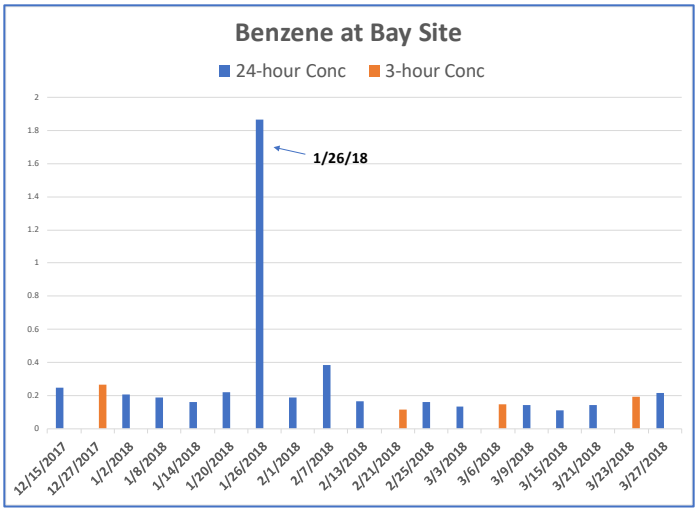
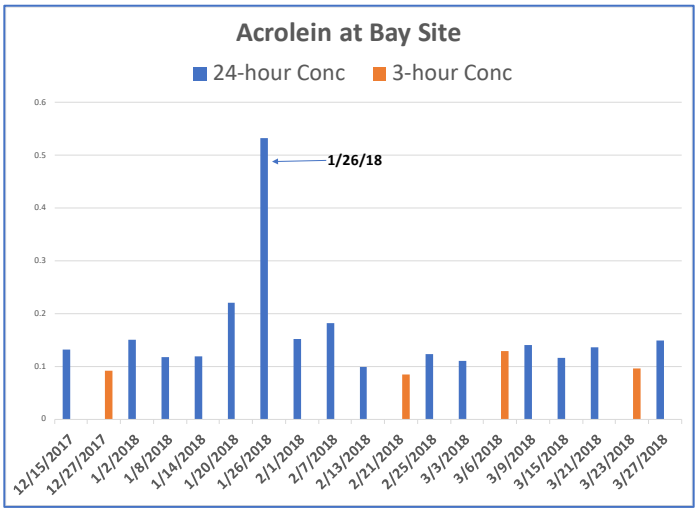
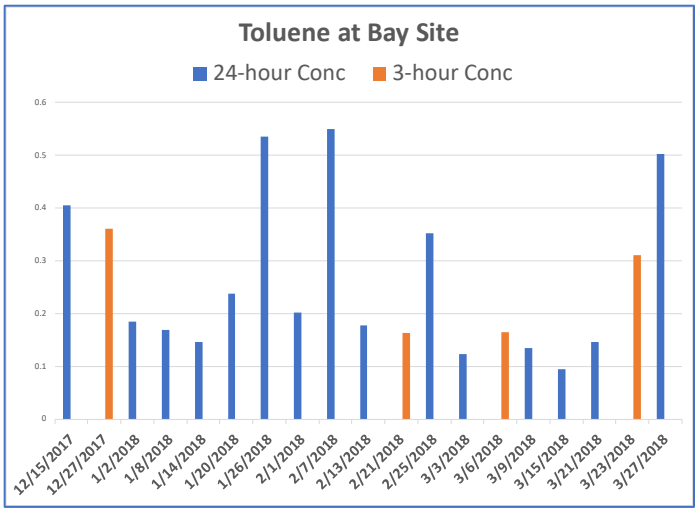


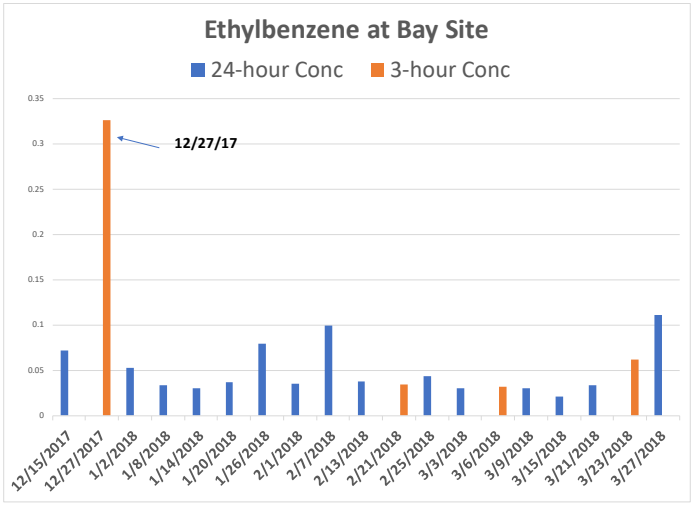
Figure 18. 3-Hour and 24-Hour VOCs at the Bay Site











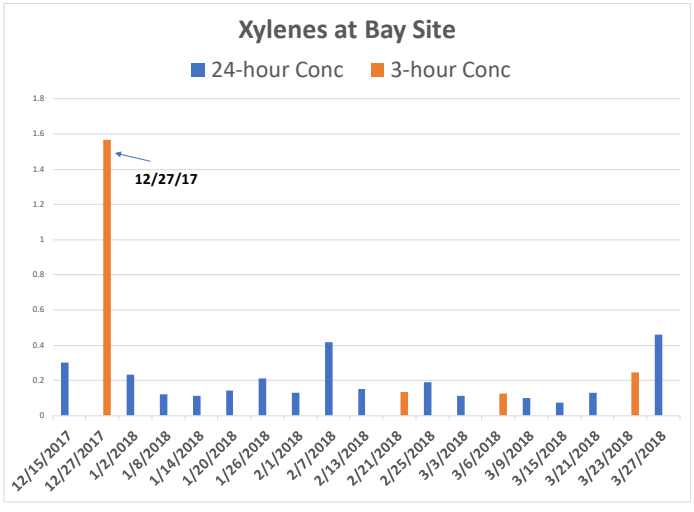


Figure 19. 3-Hour and 24-Hour VOCs at NI Site

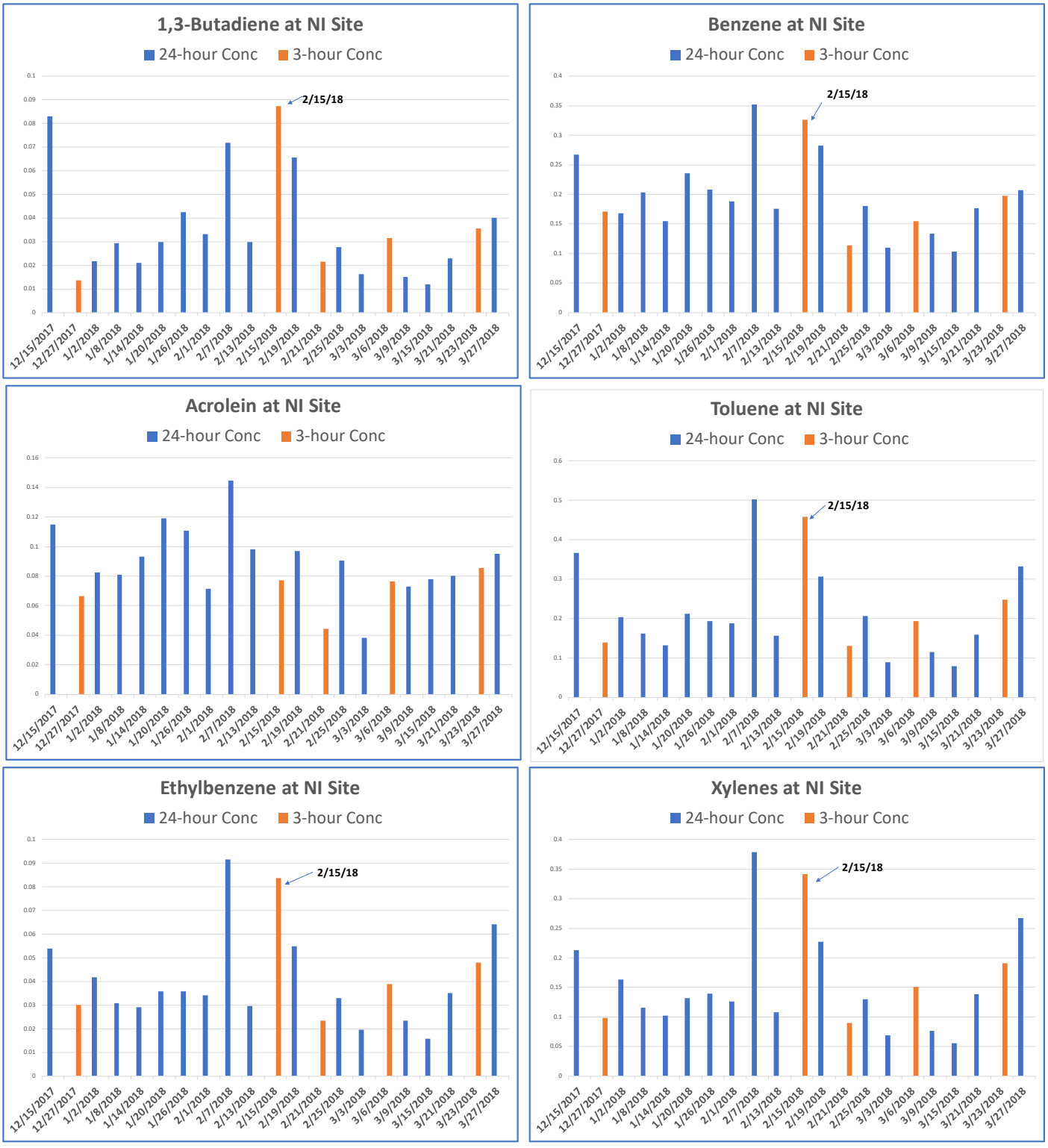


Figure 20. 3-Hour and 24-Hour VOCs at PHC Site

Figure 21. 3-Hour and 24-Hour VOCs at VE Site

Figure 22. 3-Hour and 24-Hour VOCs at NR Site

Figure 23. Black Carbon & Particle Count Concentration Distributions

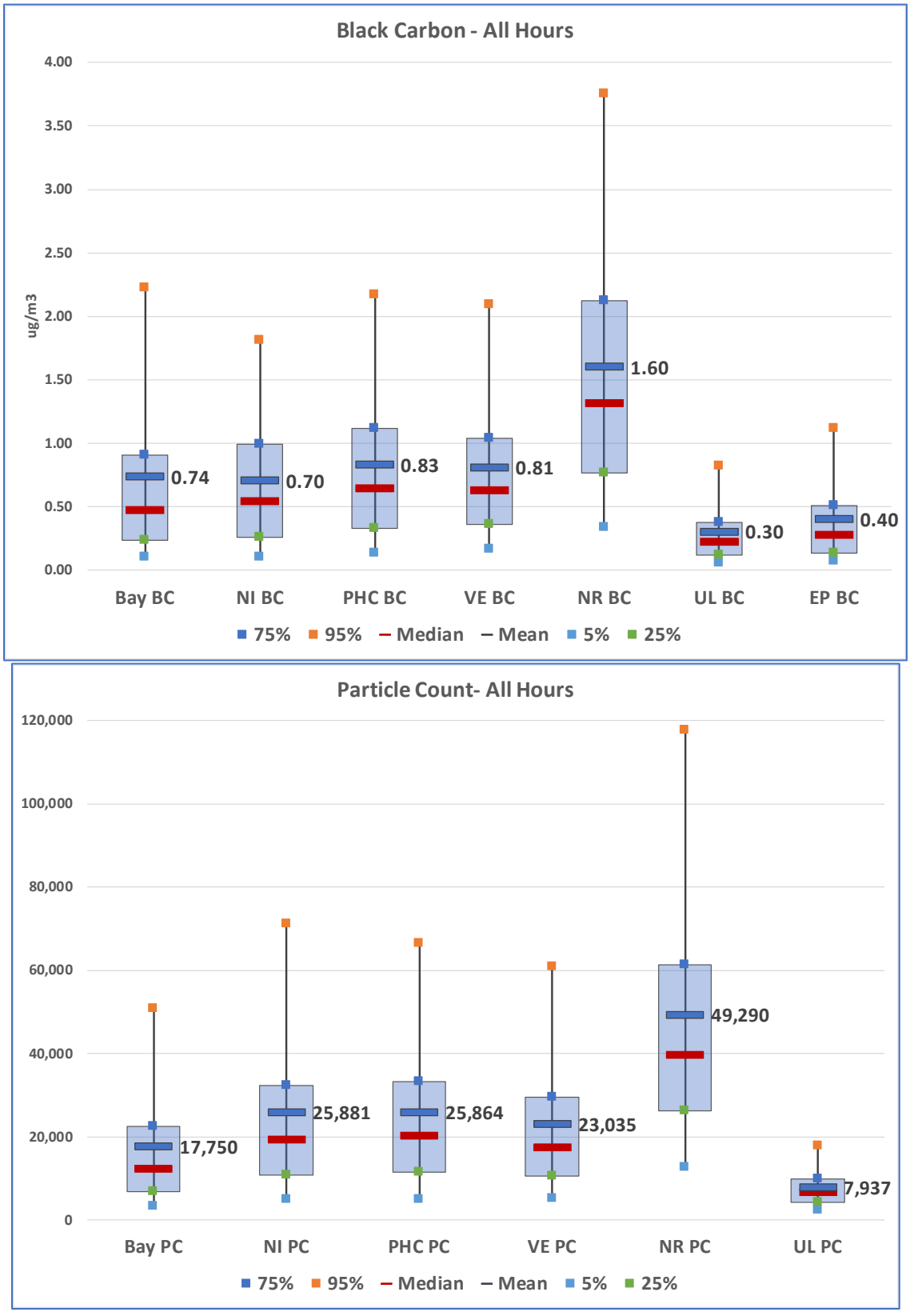


Figure 24. Bay site Ave. Weekend/Weekday Black Carbon & Particle Count by Time of Day

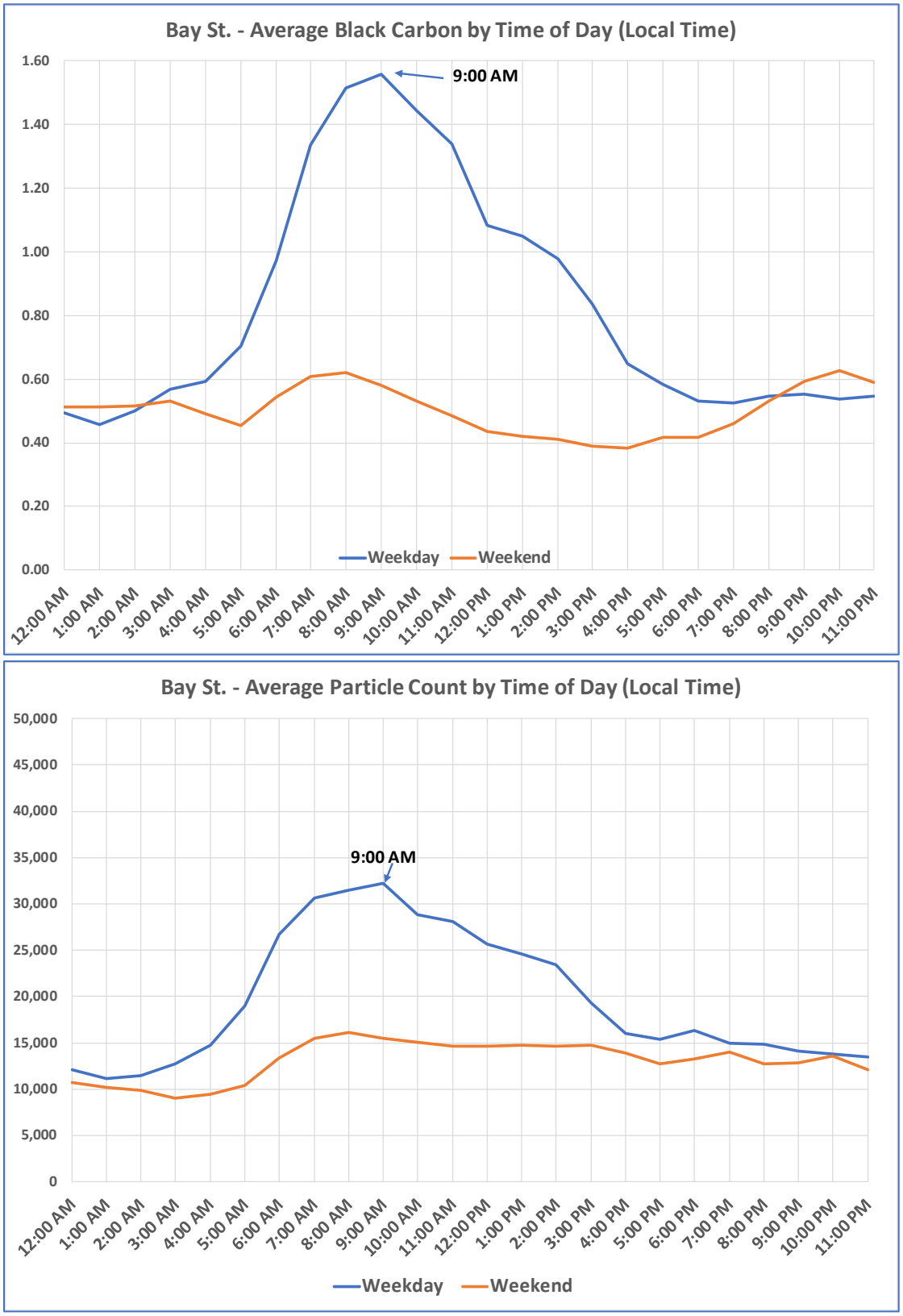


Figure 25. Niagara Weekend/Weekday Black Carbon & Particle Count by Time of Day

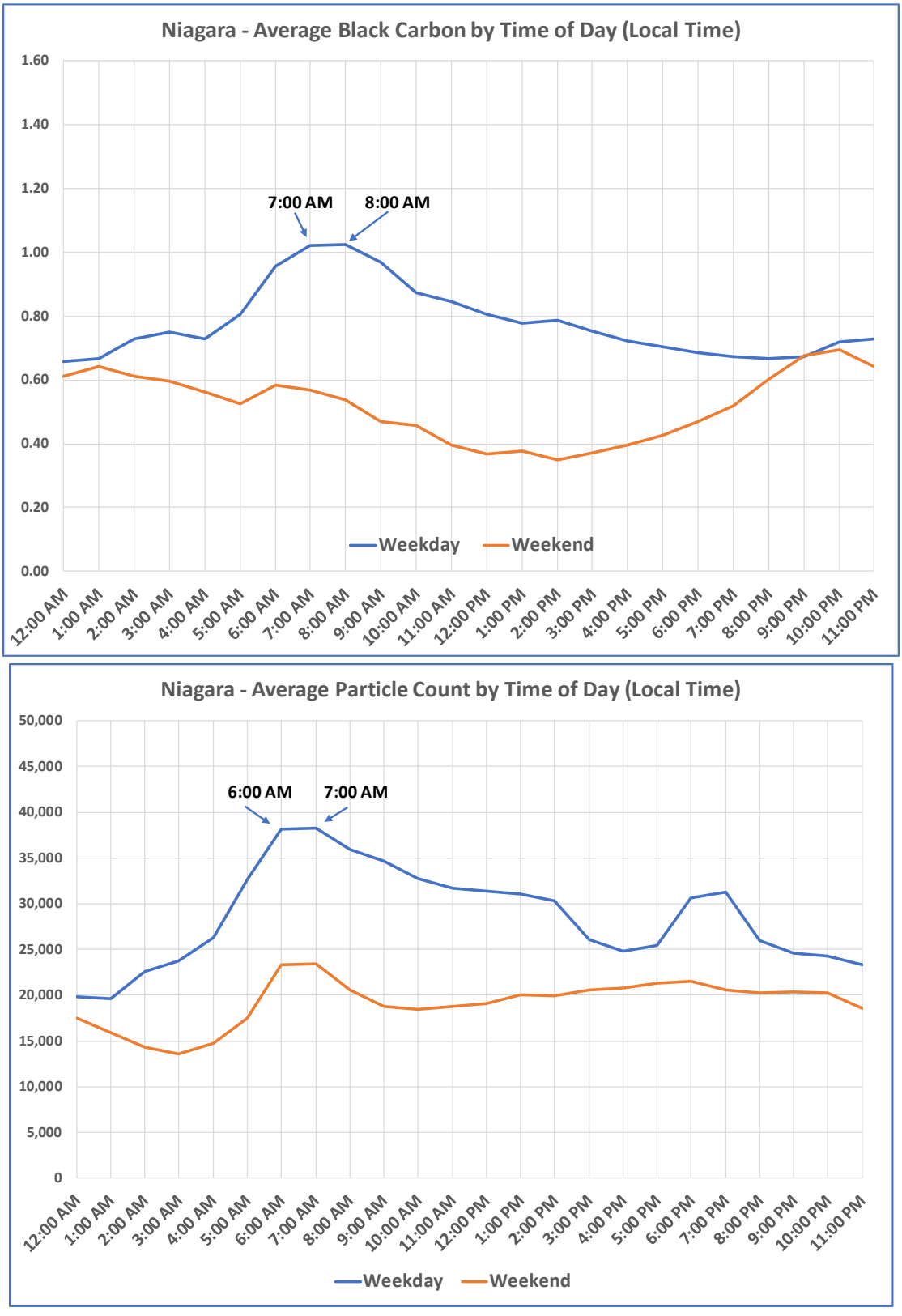


Figure 26. Providence Health Center Average Weekend/Weekday Black Carbon & Particle Count by Time of Day

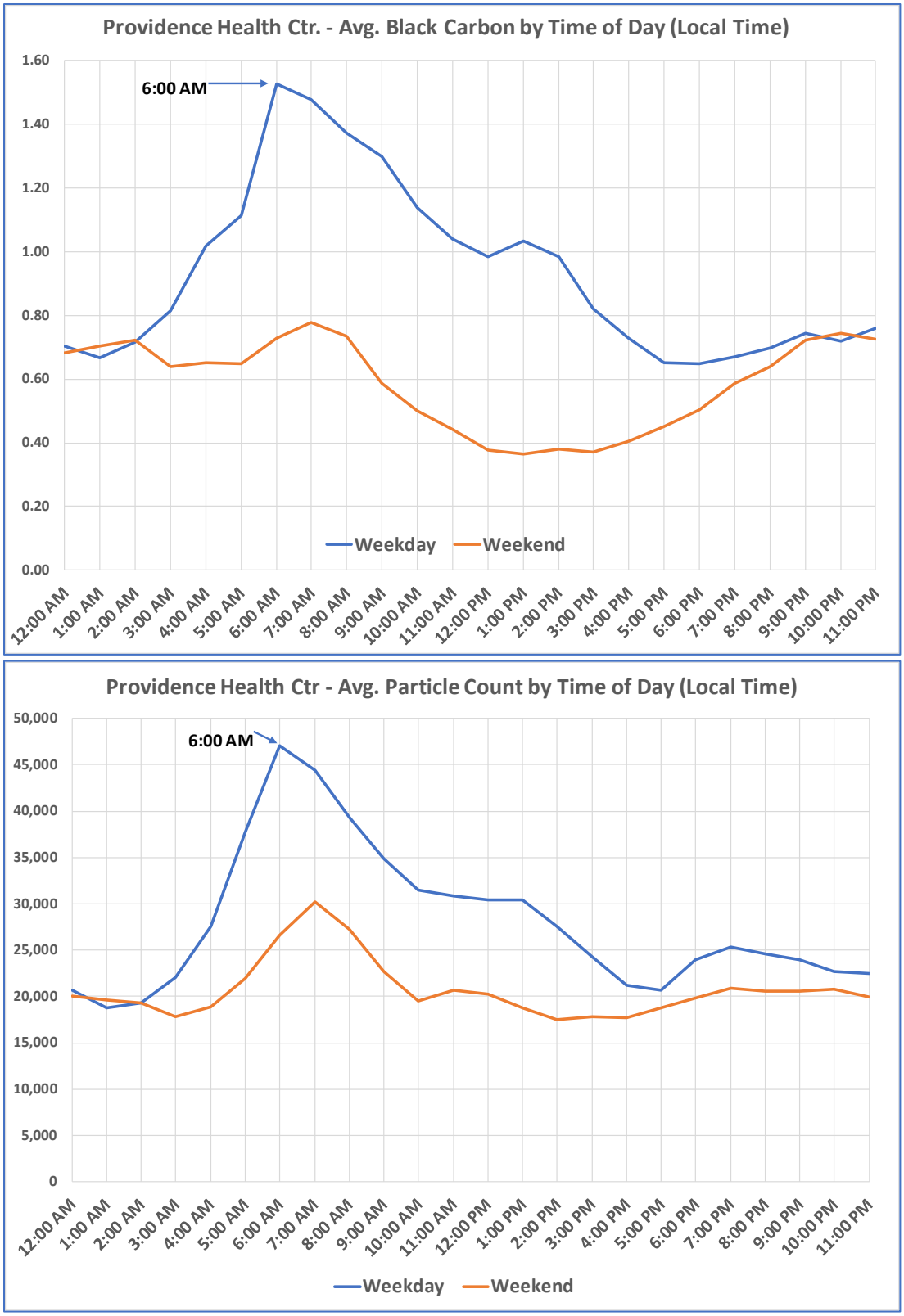


Figure 27. Vernon Average Weekend/Weekday Black Carbon & Particle Count by Time of Day

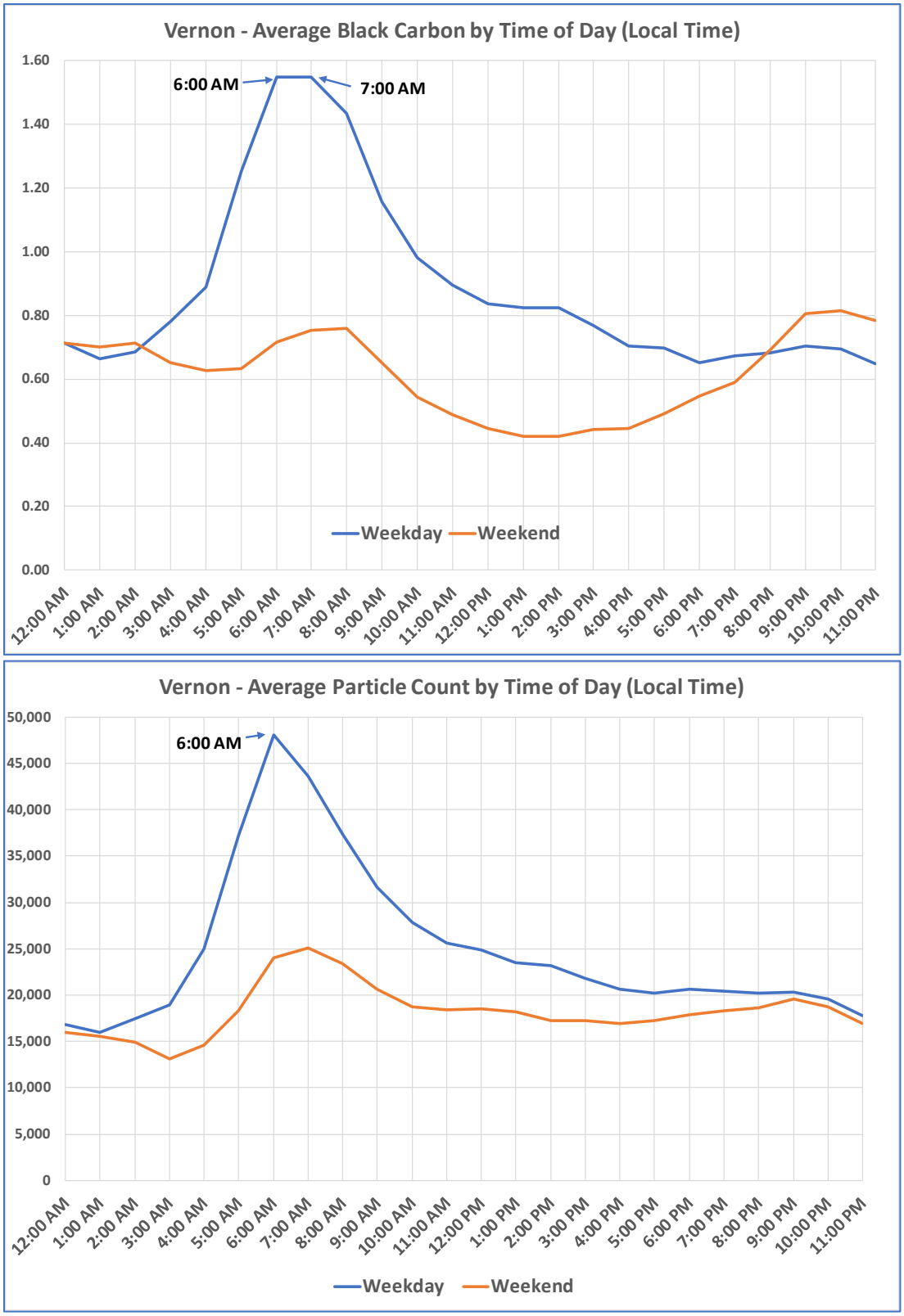


Figure 28. Near-Road Site Average Weekend/Weekday Black Carbon & Particle Count by Time of Day

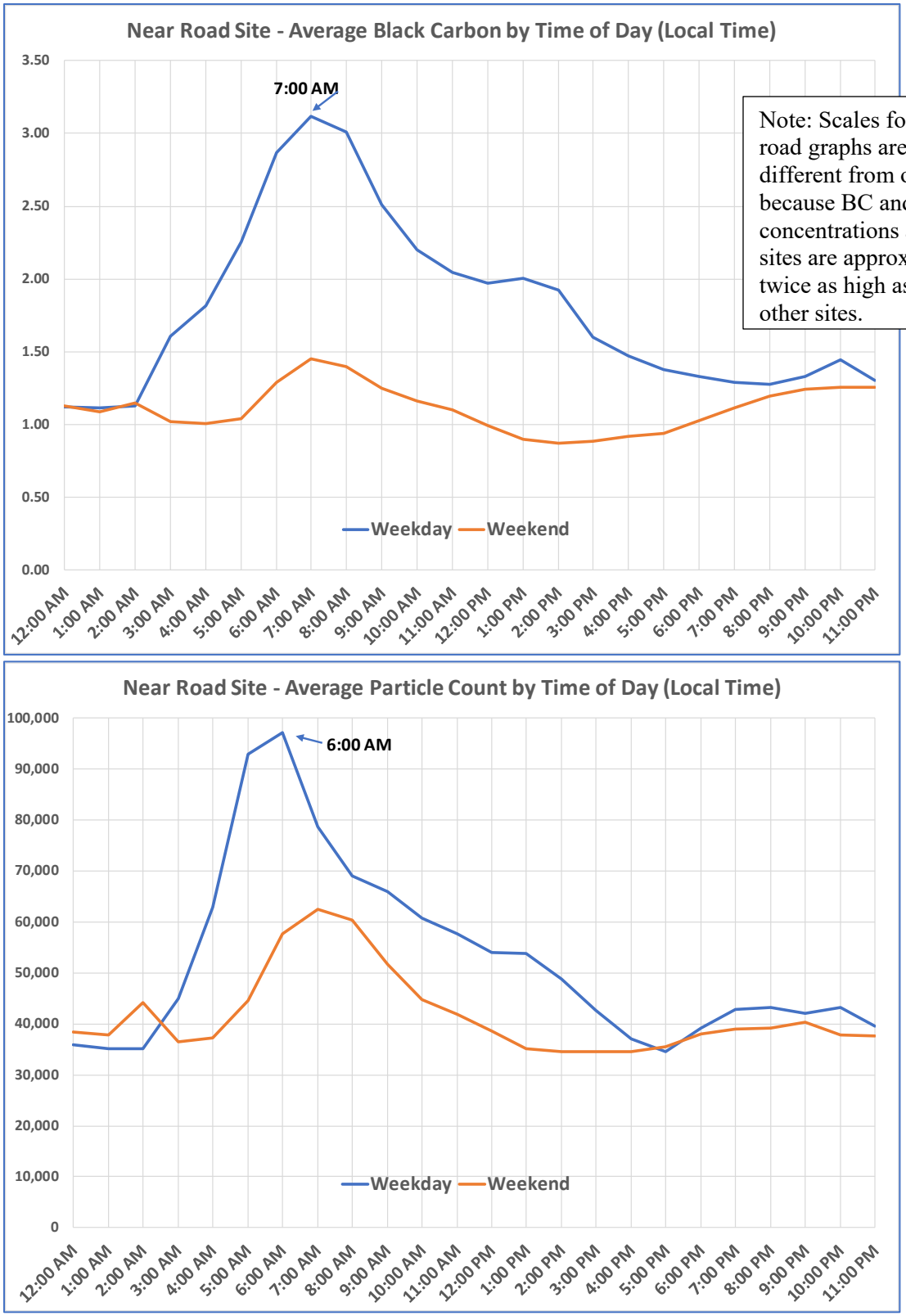


Figure 29. Urban League Comparison Site Average Weekend/Weekday Black Carbon & Particle Count by Time of Day

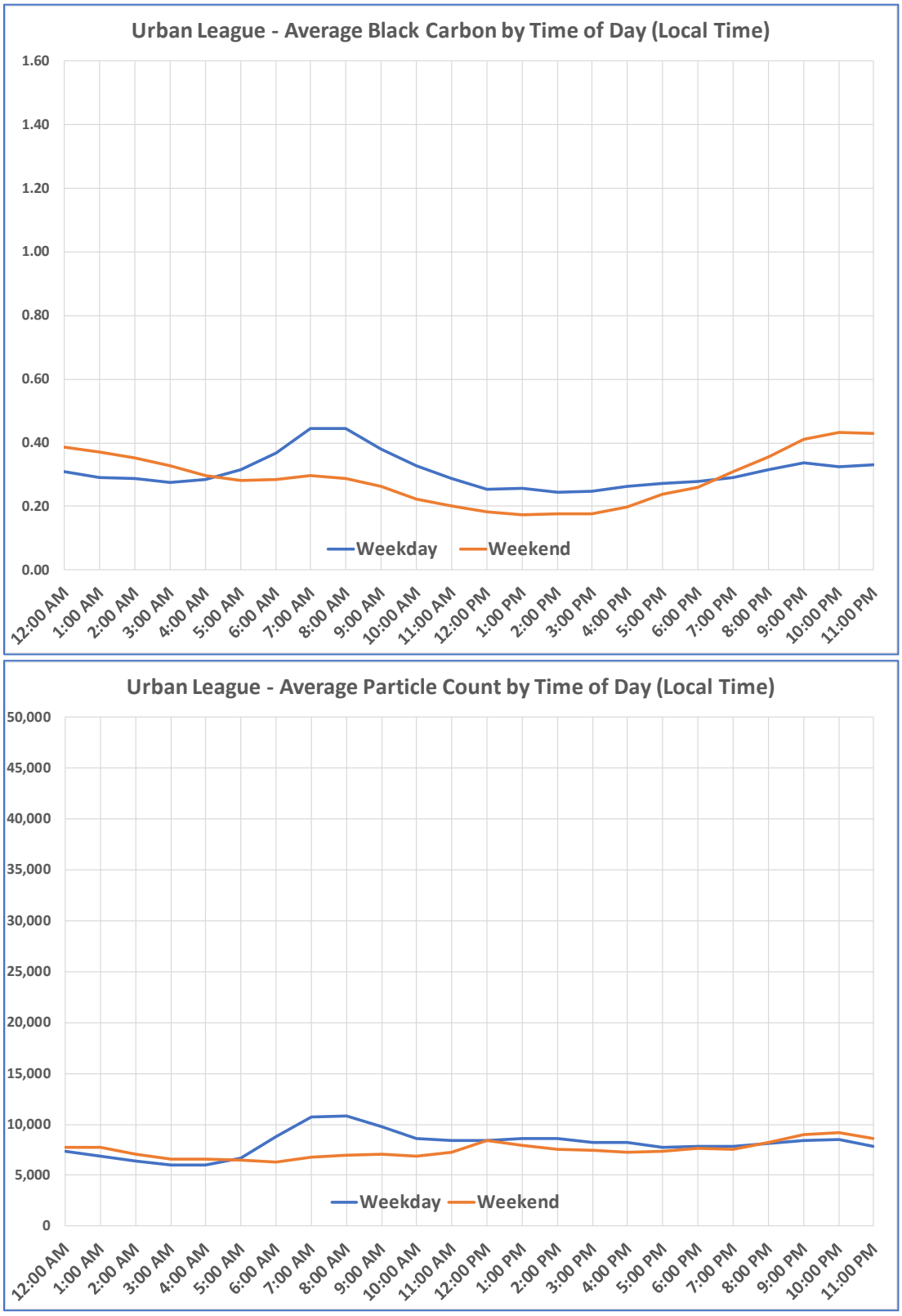
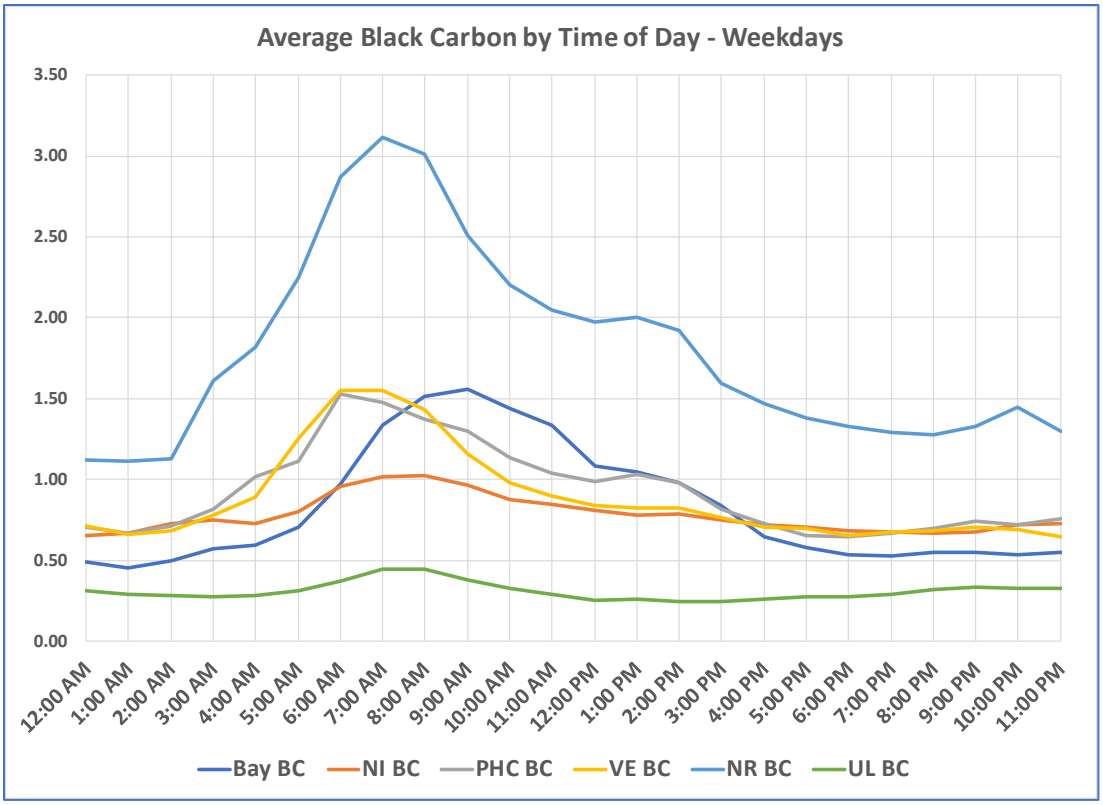


Figure 30. Average BC on Weekdays and Weekends by Time of Day at Study and Comparison Sites



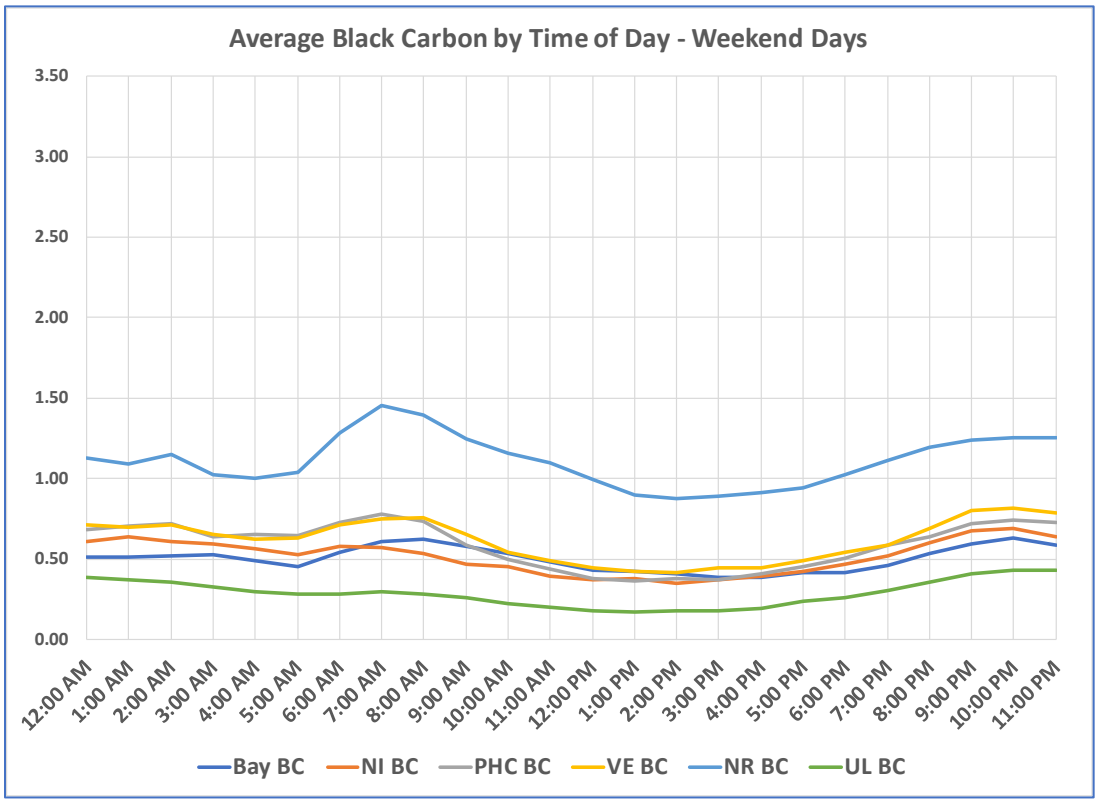


Figure 31. Average PC on Weekdays and Weekends by Time of Day at Study and Comparison Sites

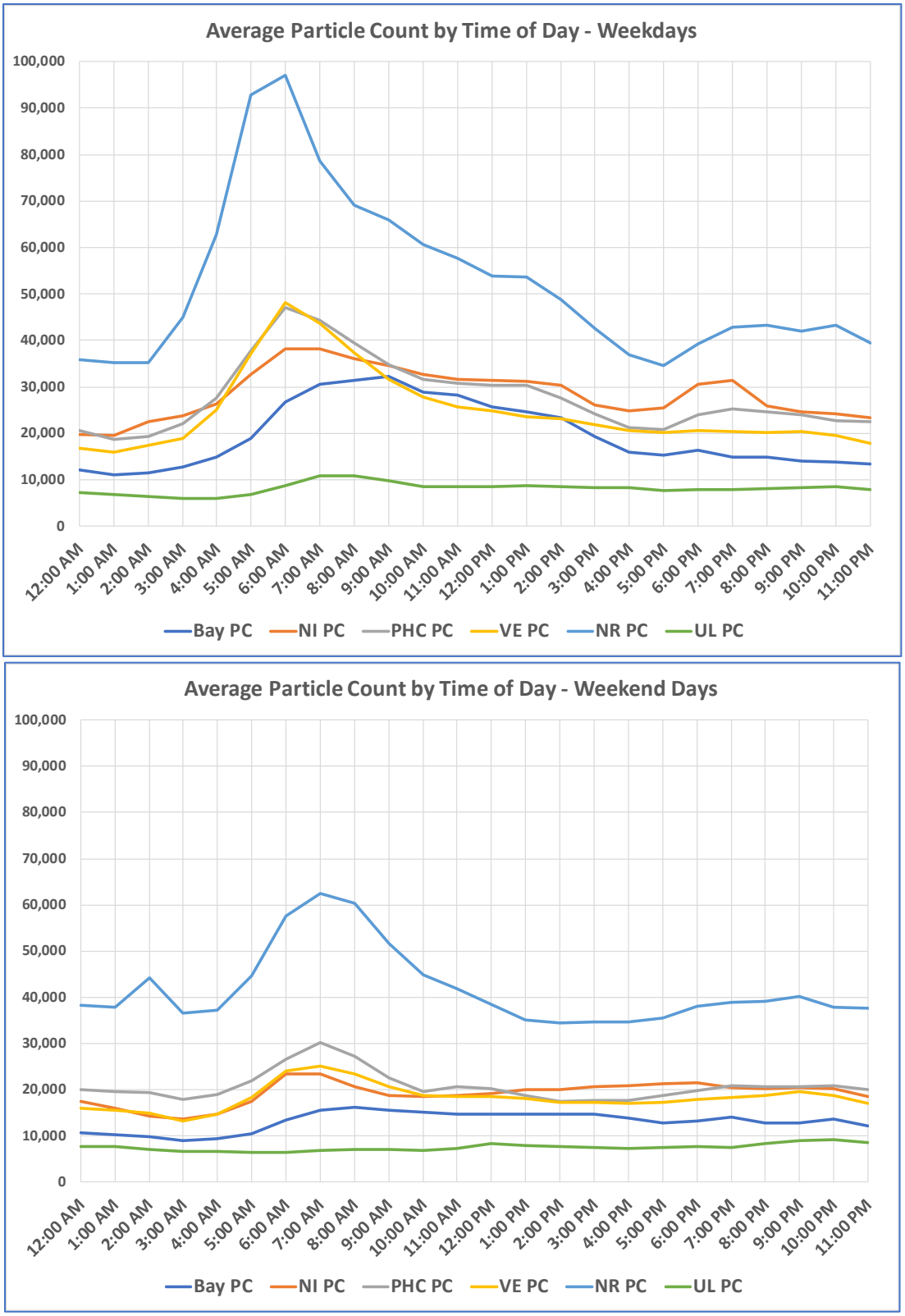
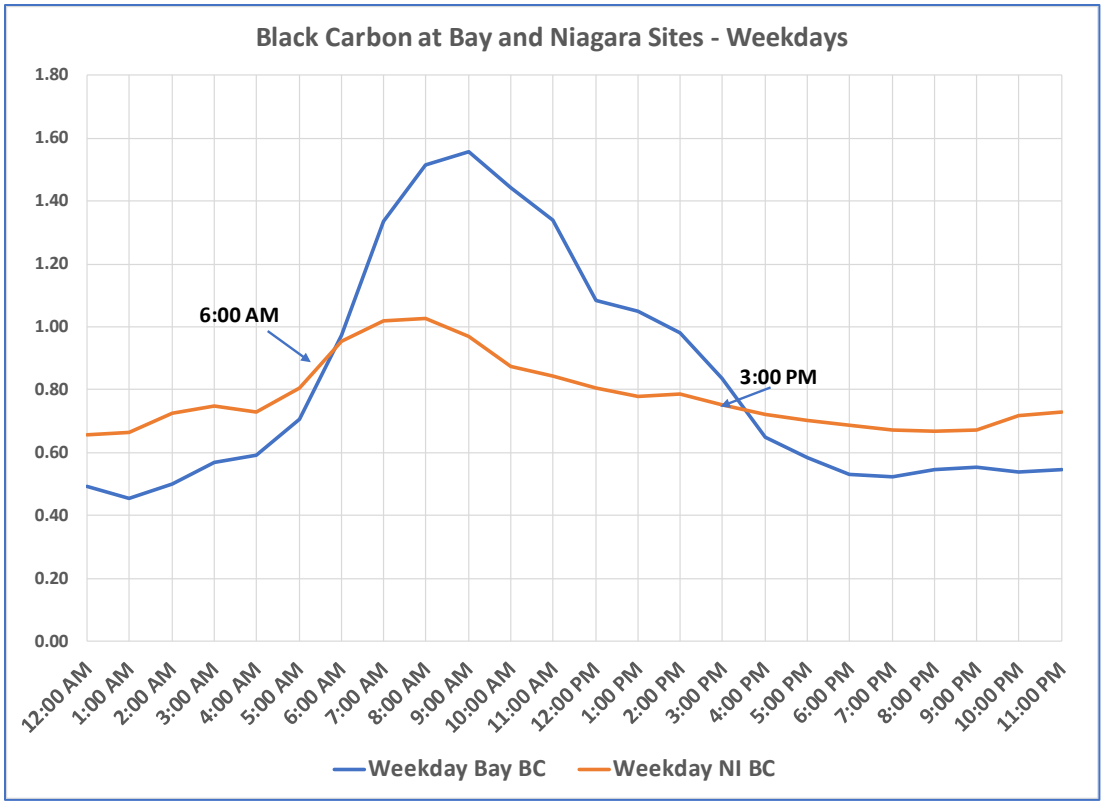


Figure 32. Diurnal Weekday BC and PC Patterns at Sites West of I-95 (Bay Street and Niagara Street)



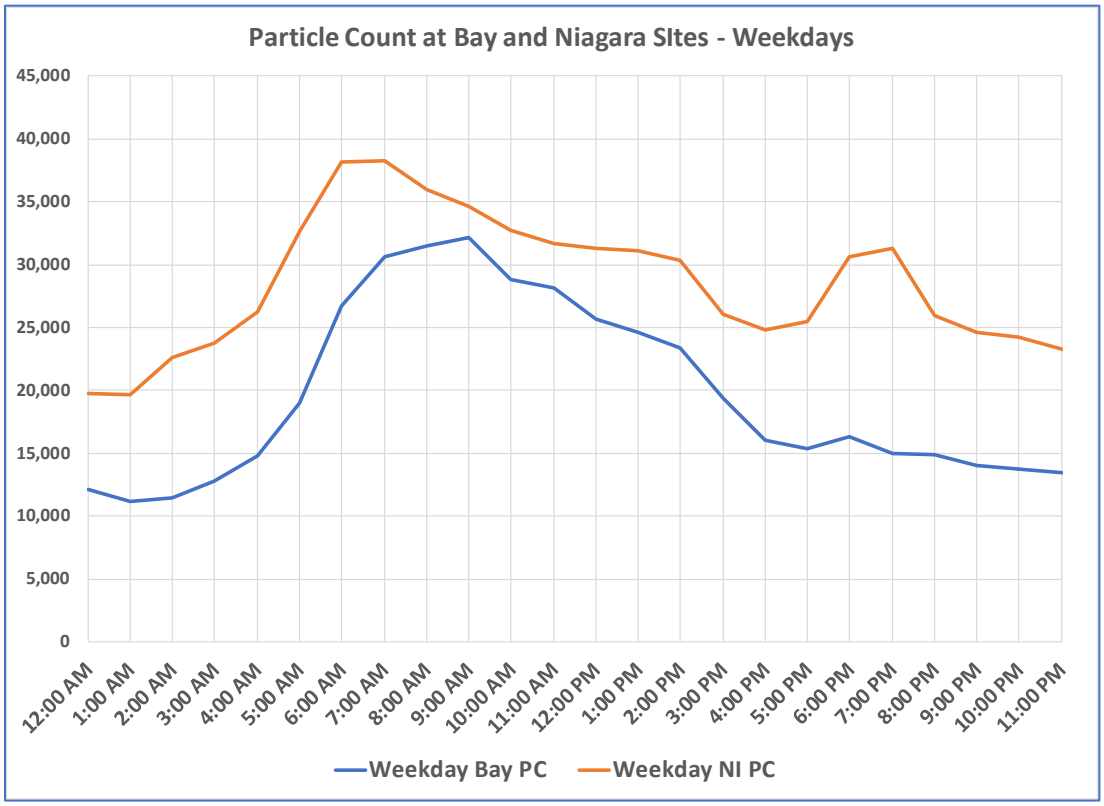


Figure. 33. Average BC and PC at Bay, Prov Health Ctr and Niagara by Wind Direction

Figure 34. Average BC and PC at Vernon and Near-Road Sites by Wind Direction

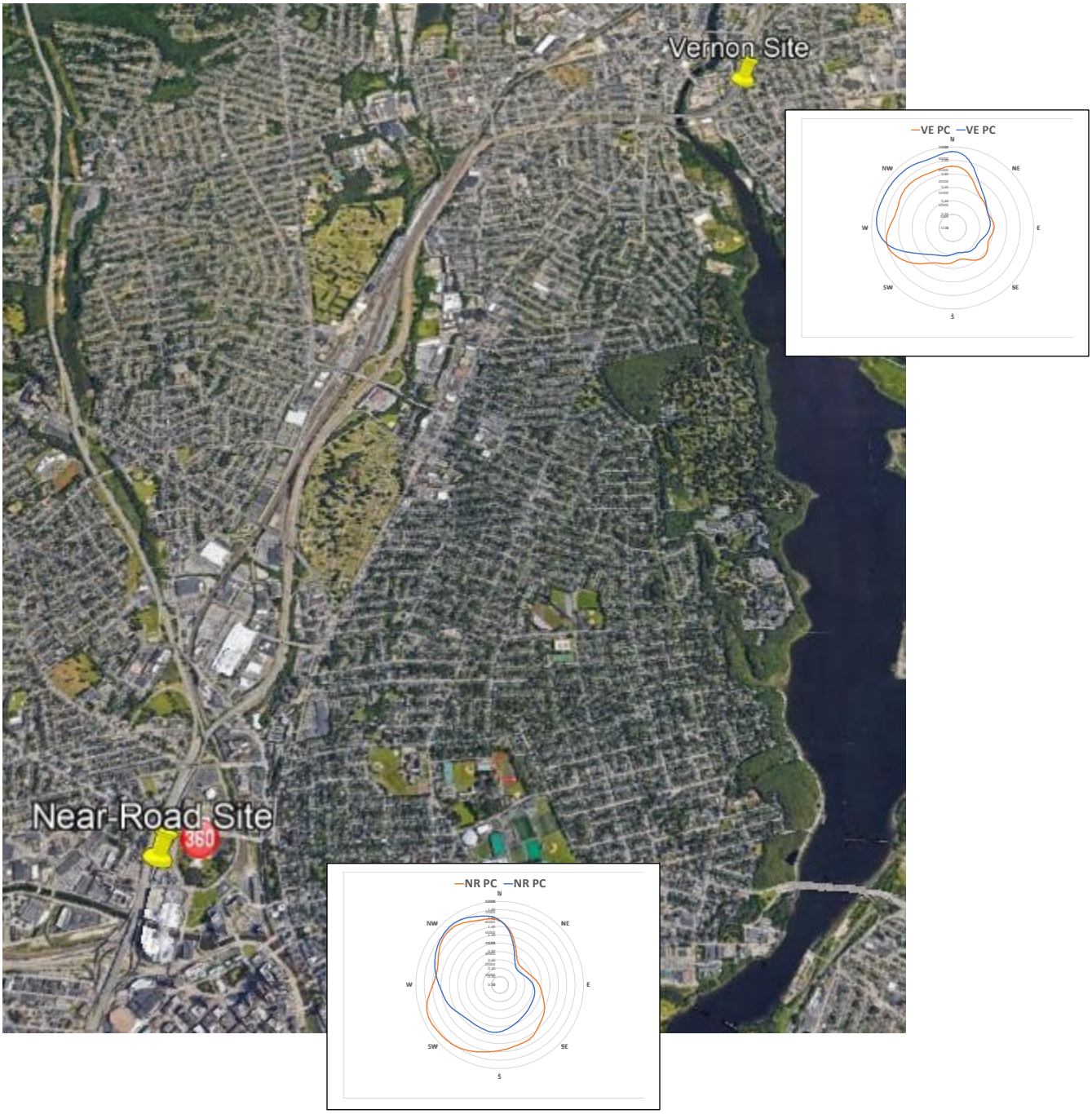


Figure 35. Average BC and PC at PHC and Bay Sites by Wind Direction

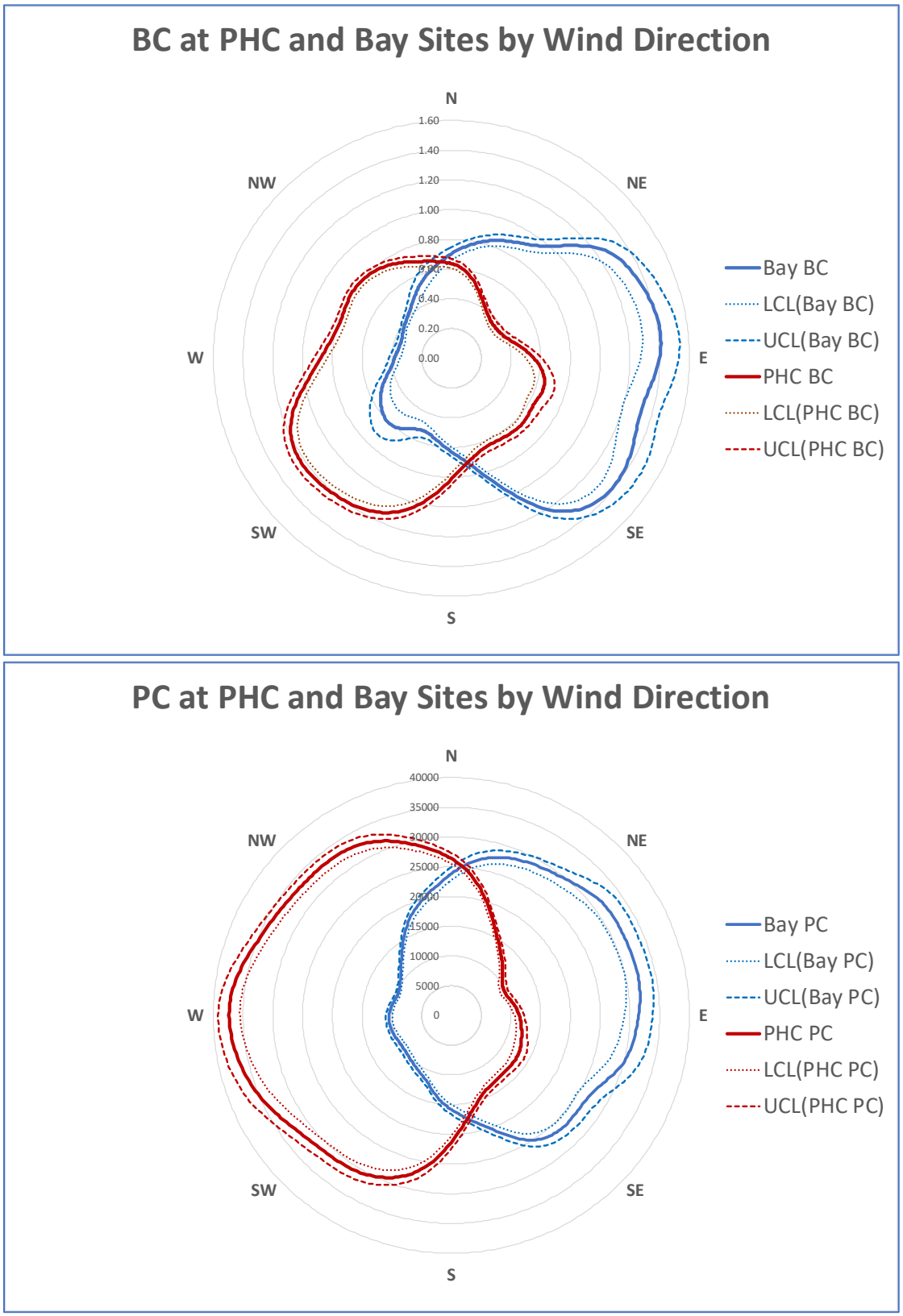
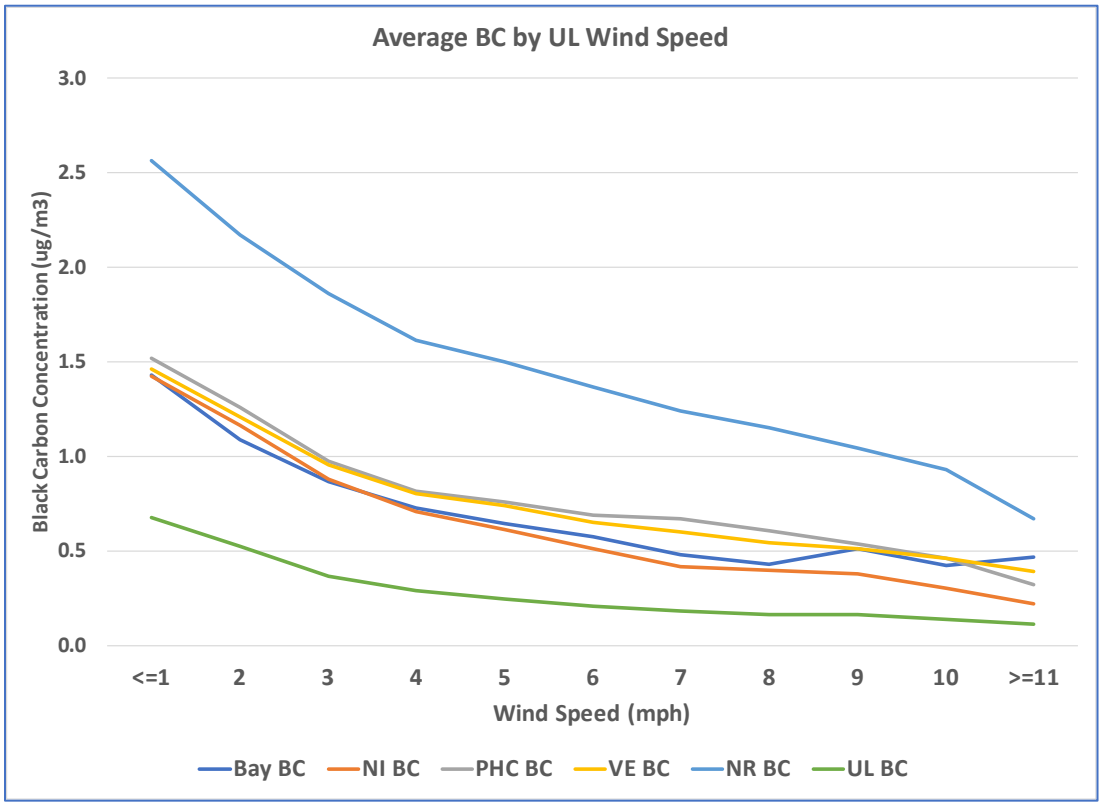


Figure 36. Average Weekday Black Carbon Levels by Wind Speeds Measured at UL and Sites



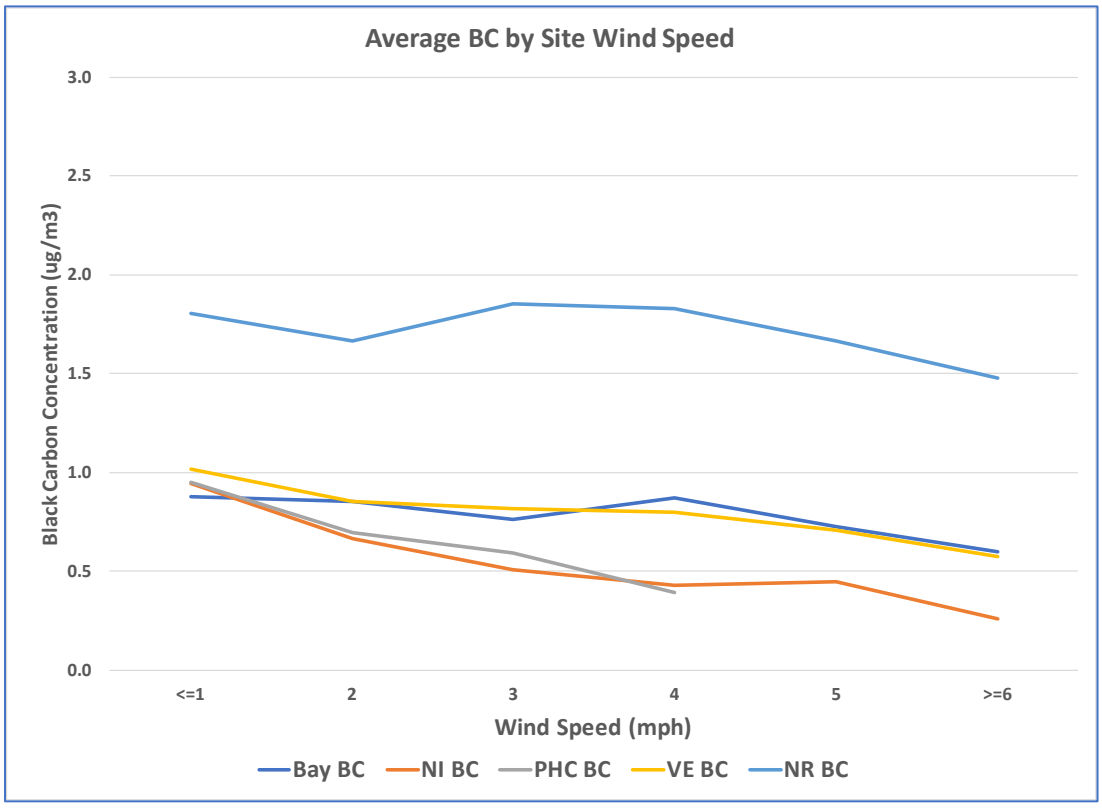
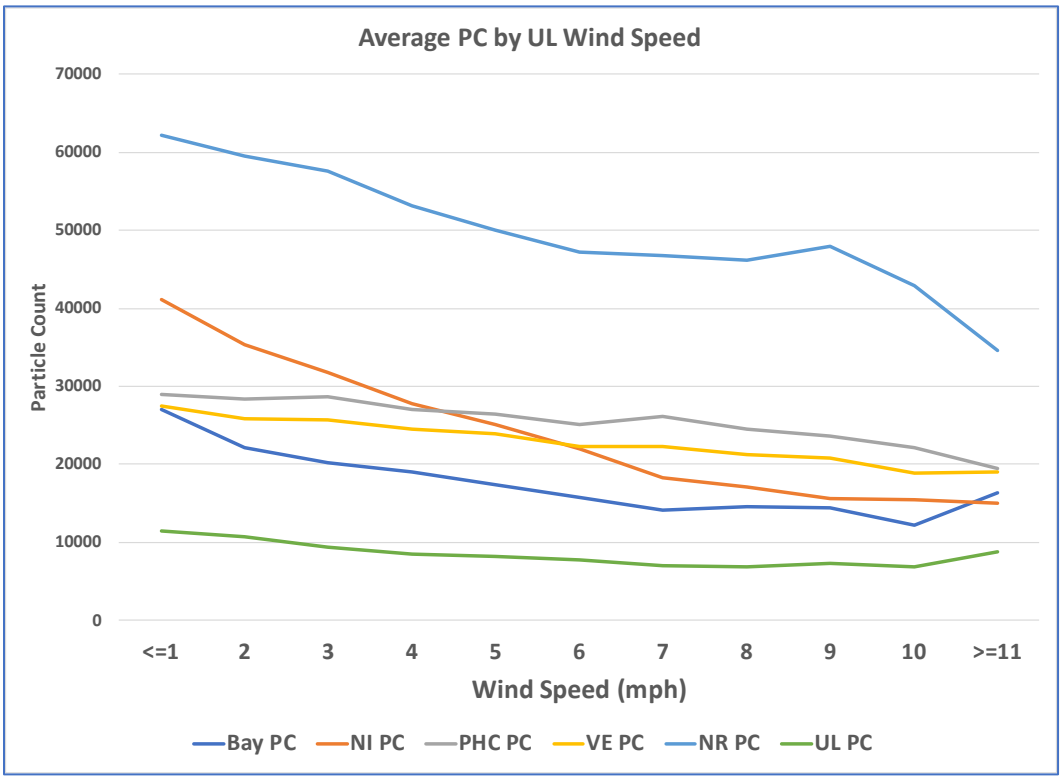


Figure 37. Avg. Weekday Particle Count by Wind Speeds Measured at UL and Sites



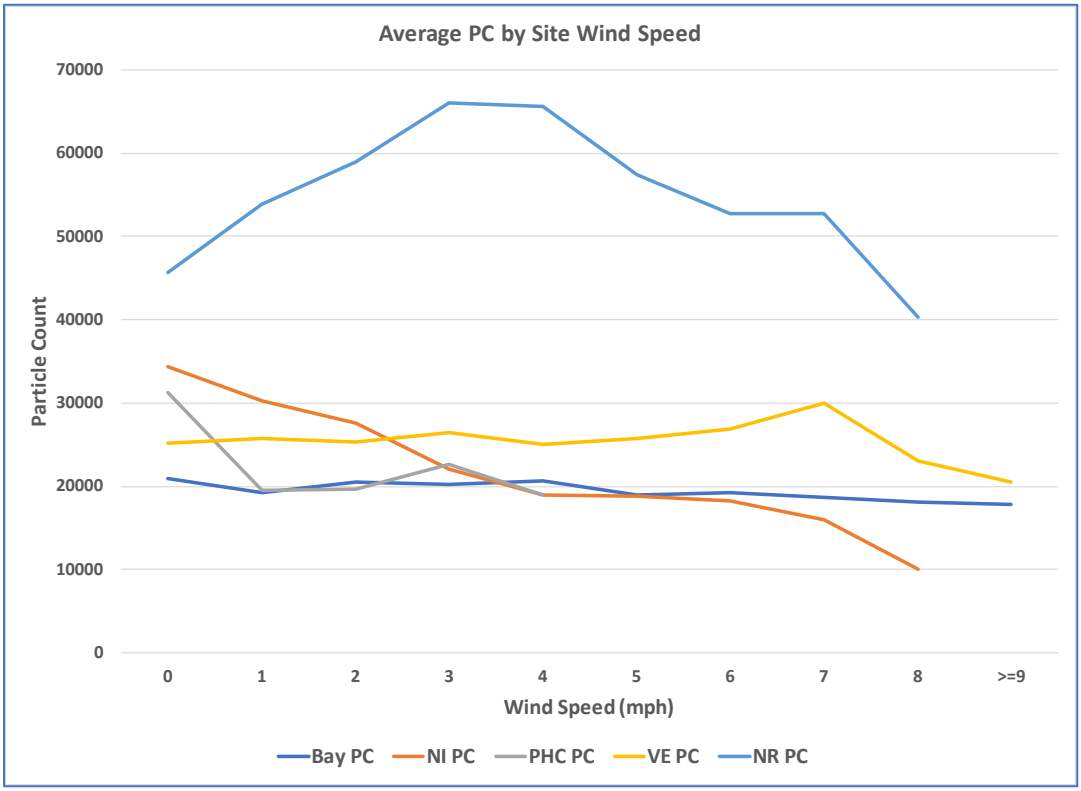


Figure 38. Black Carbon and Particle Count by Temperature

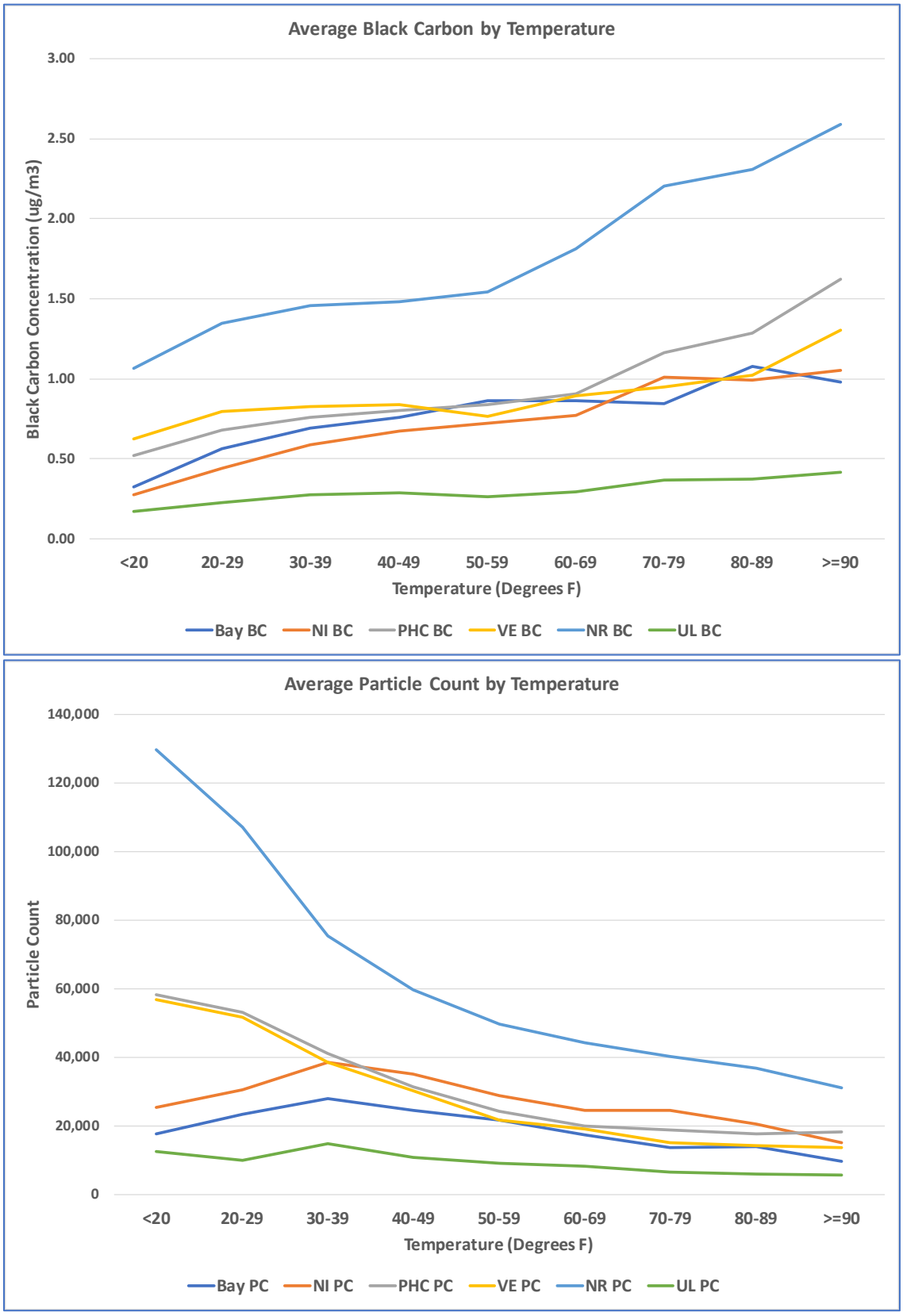


Figure 39. Wind Speed and Temperature Regression Against BC and PC

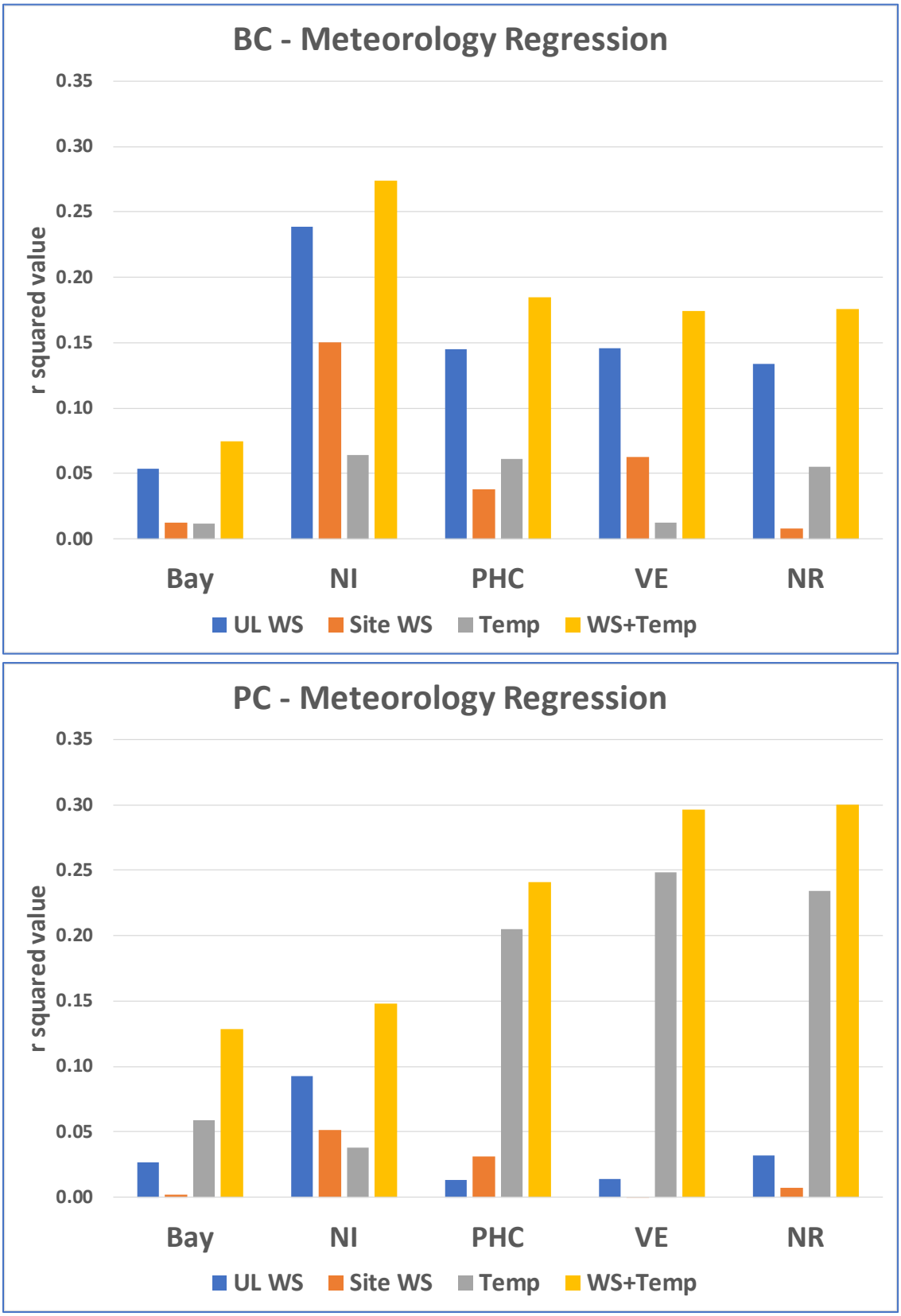


Figure 40. PC and BC by Time of Day – Warm and Cold Months

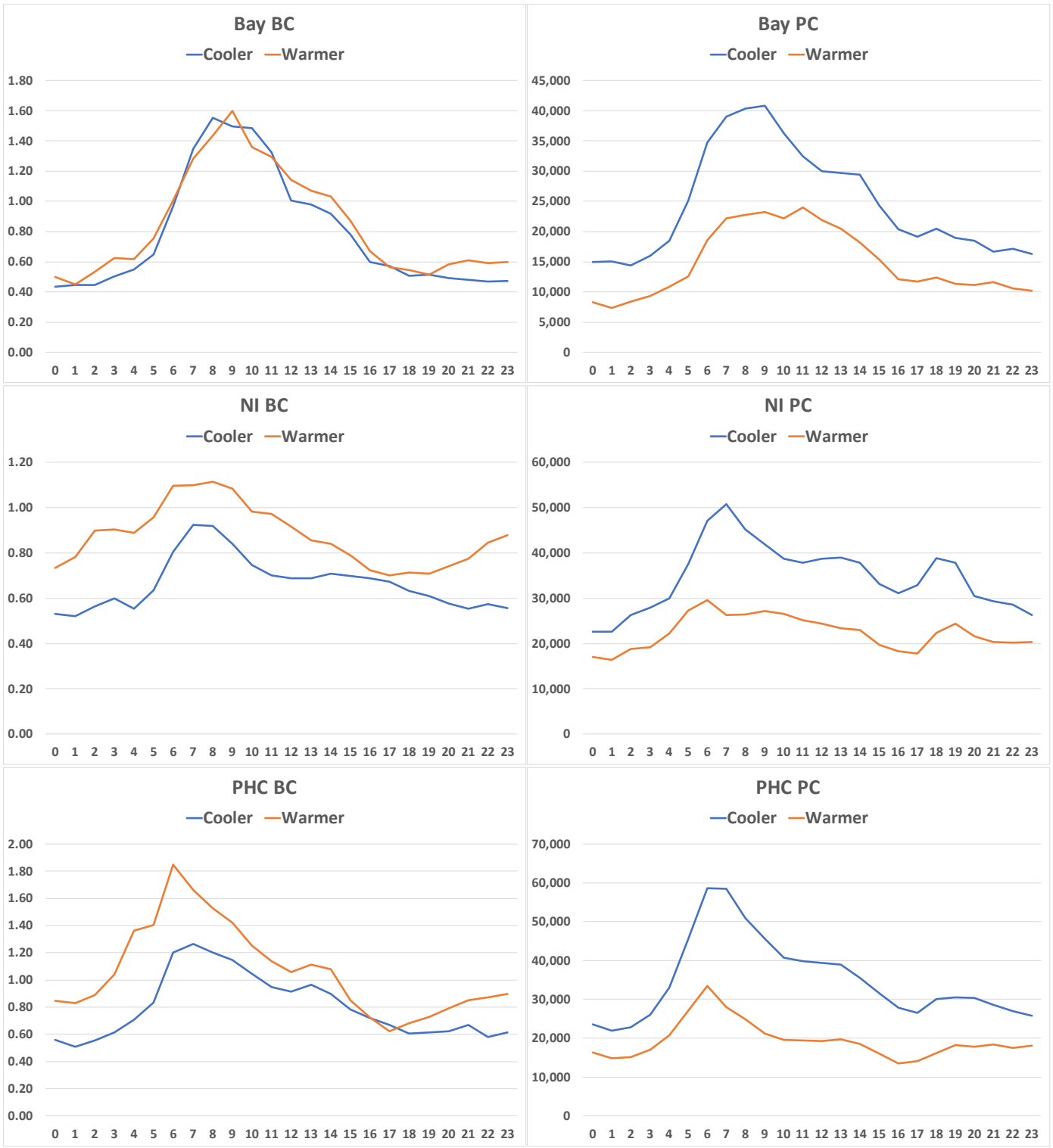


Figure 40 (cont.) PC and BC by Time of Day – Warm and Cold Months

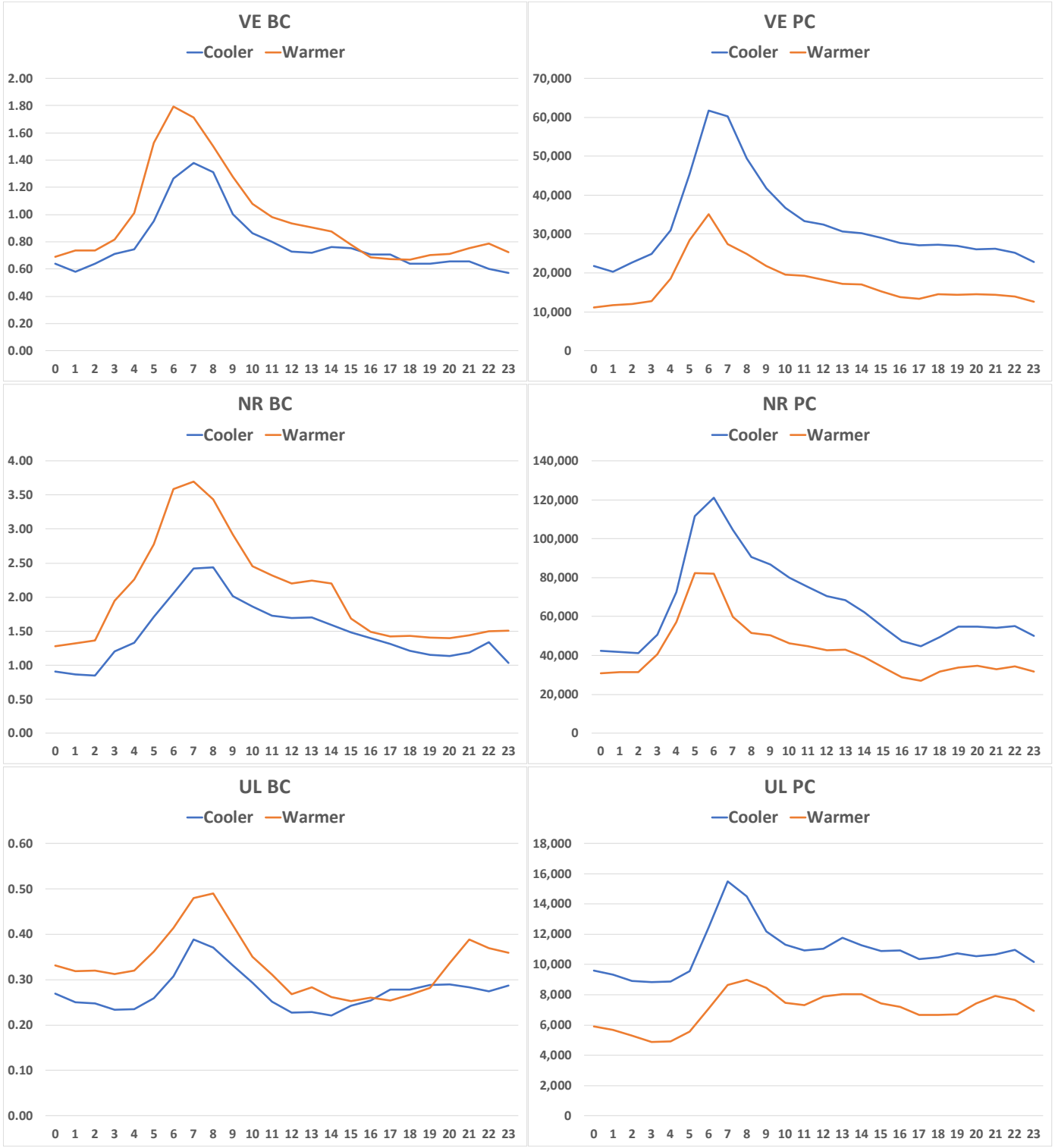


Figure 41. Location of Traffic Monitor Near Near-Road Site

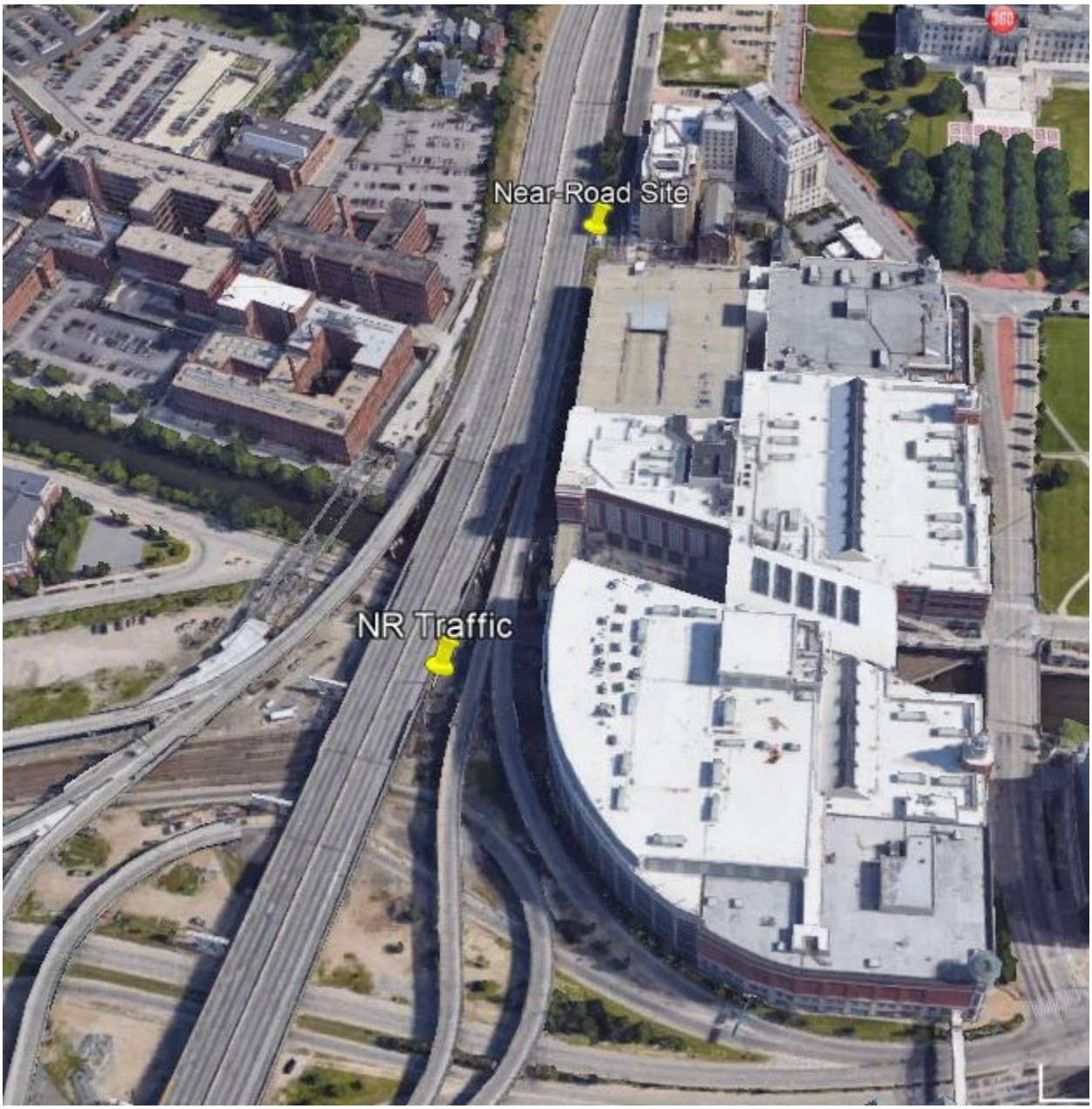


Figure 42. Location of Traffic Monitors Near Bay and Prov. Health Ctr. Sites

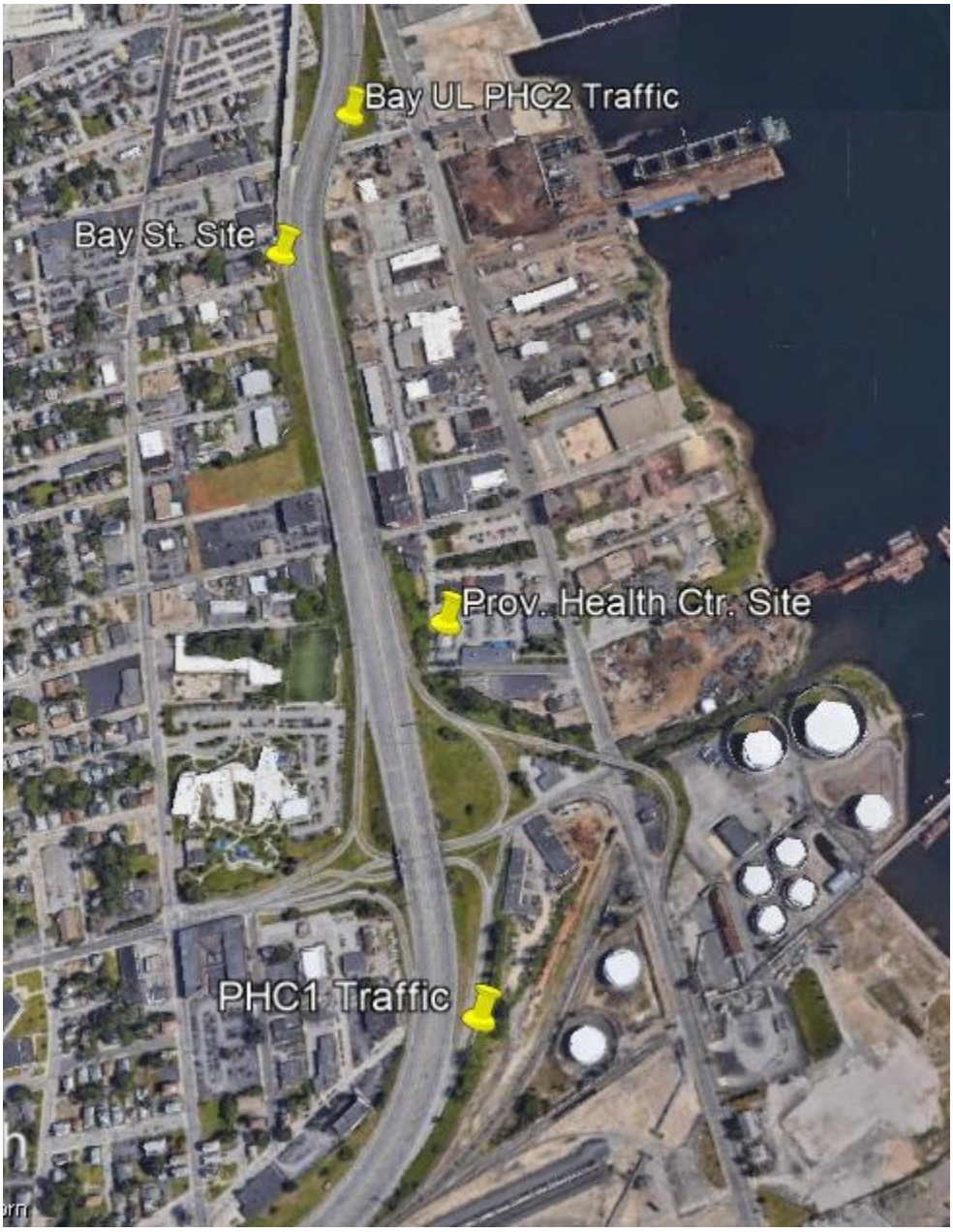


Figure 43. Average Hourly **Total Traffic** Counts by Local Time Hour

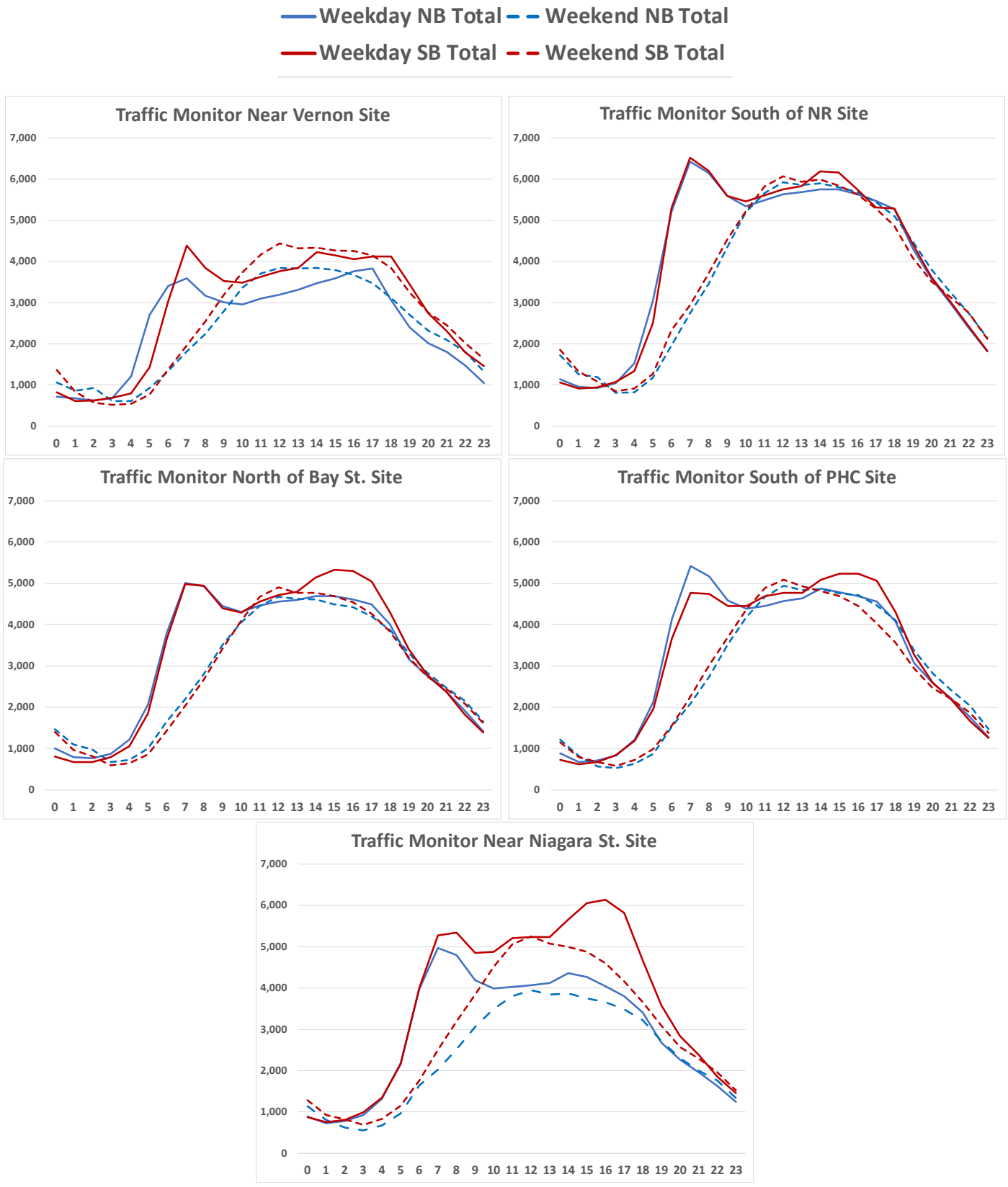


Figure 44. Average Hourly **Truck Traffic** Counts by Local Time Hour

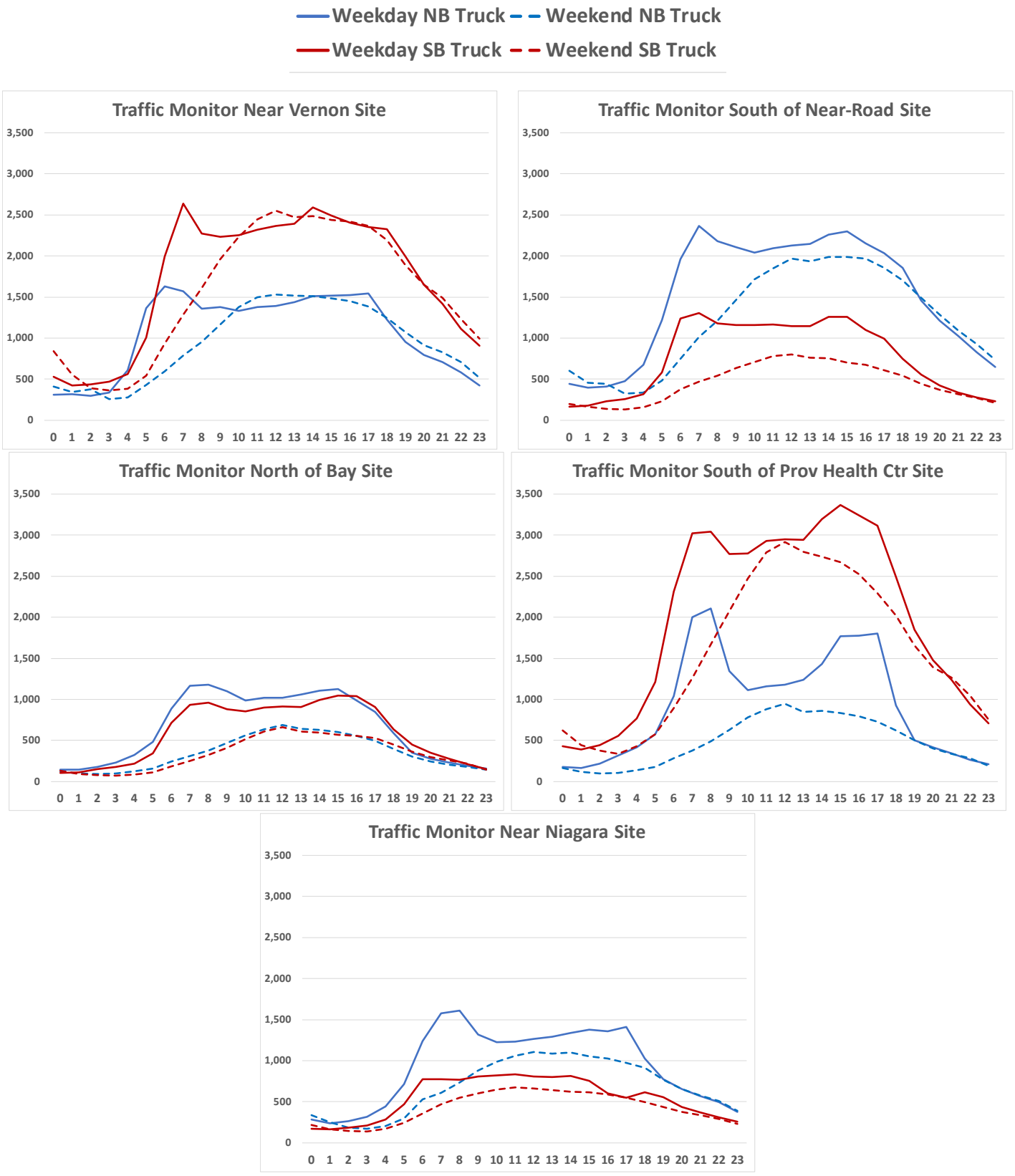


Figure 45. Average Hourly **Traffic Speeds** by Local Time Hour

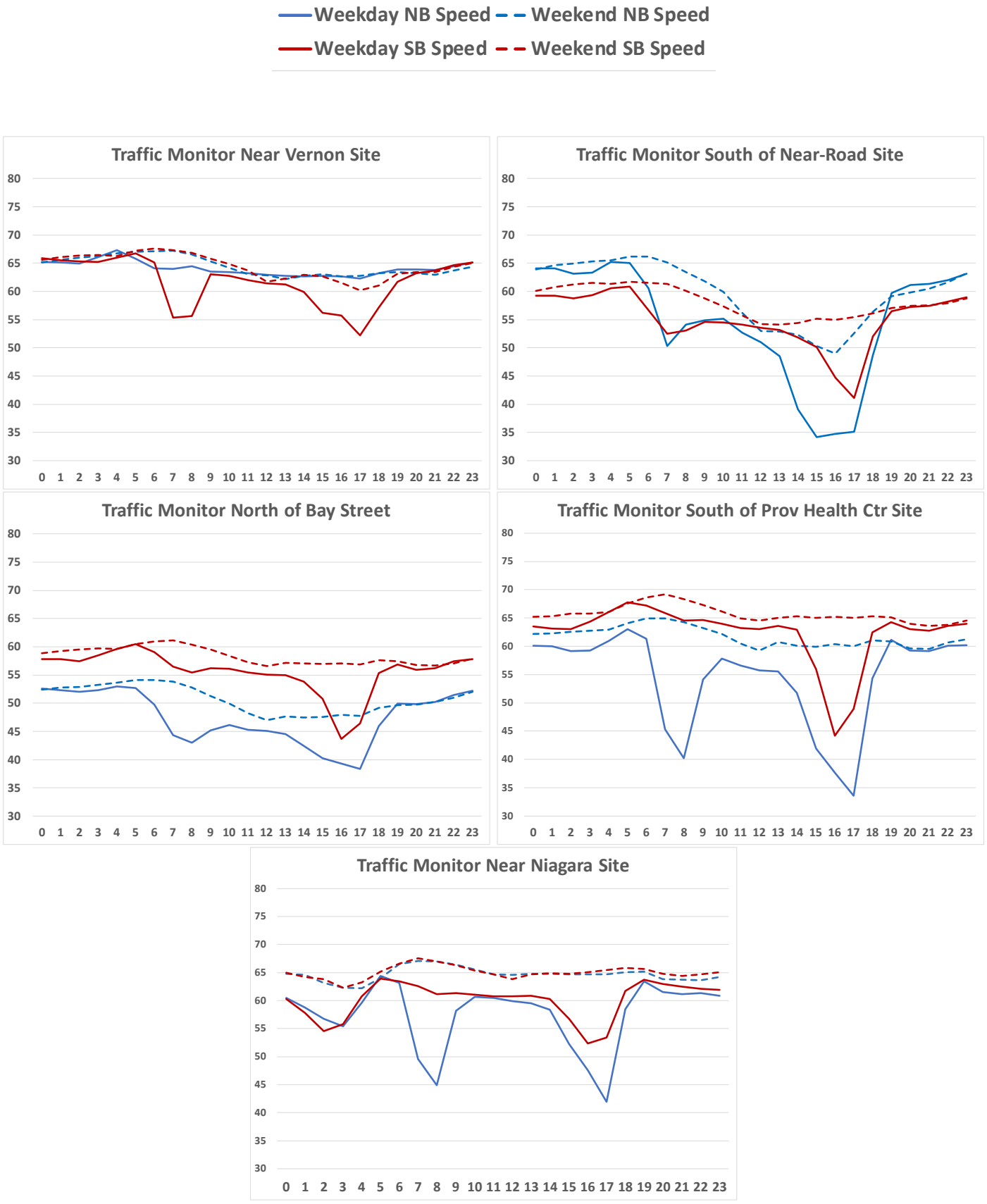


Figure 46. Average Black Carbon Levels in Hours with High and Low Truck and Total Traffic Counts

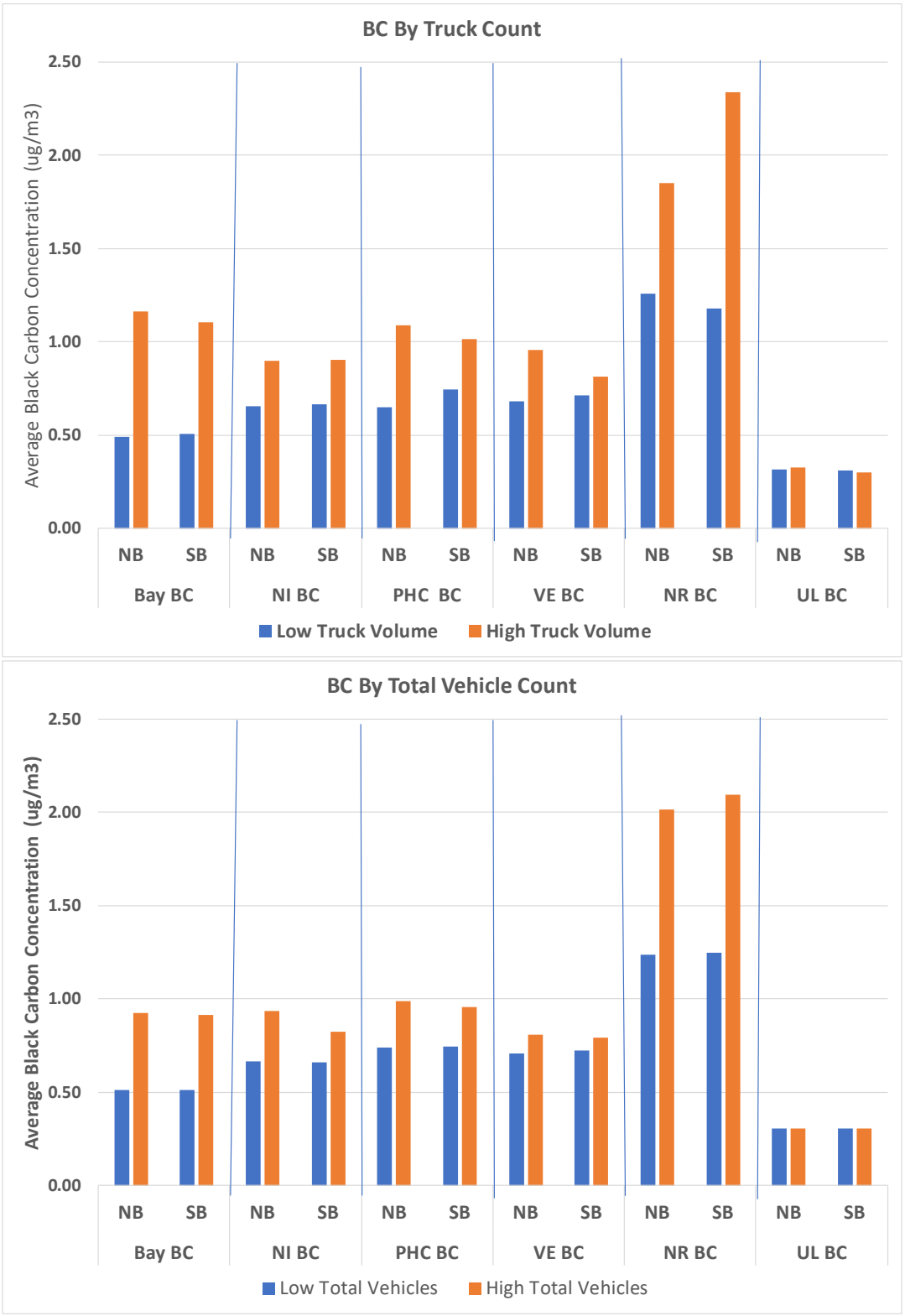
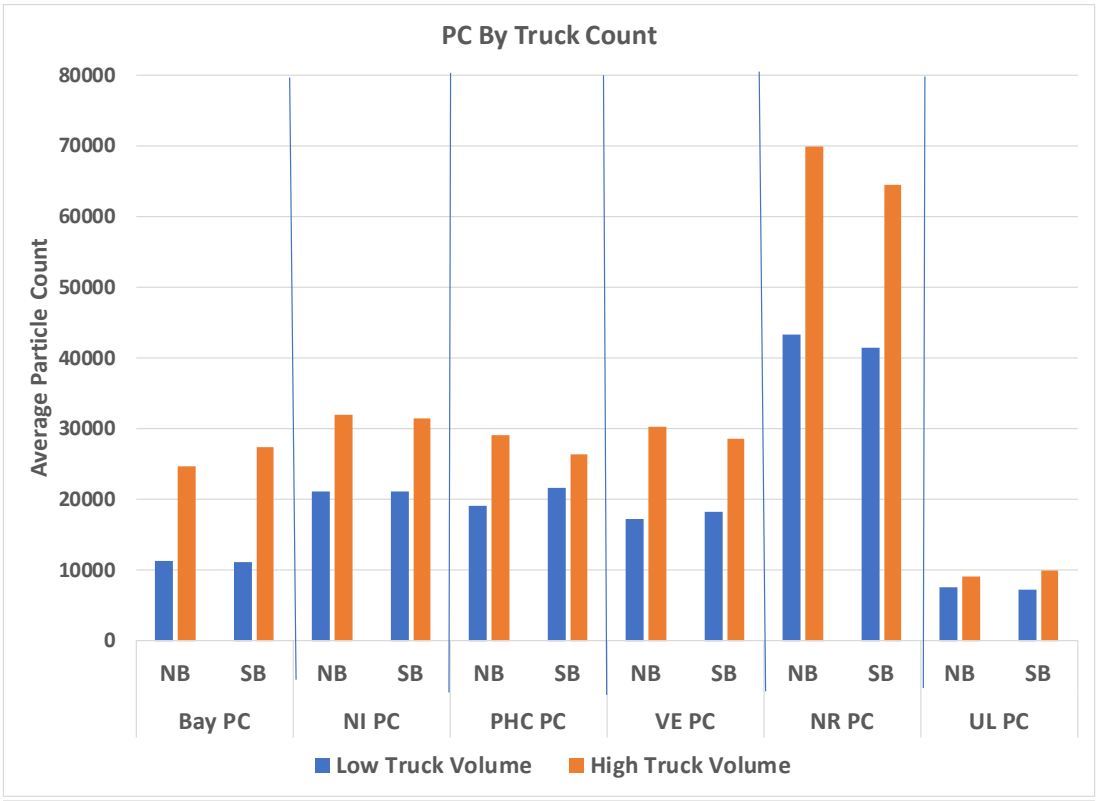


Figure 47. Average Particle Count in Hours with High and Low Truck and Total Traffic Counts



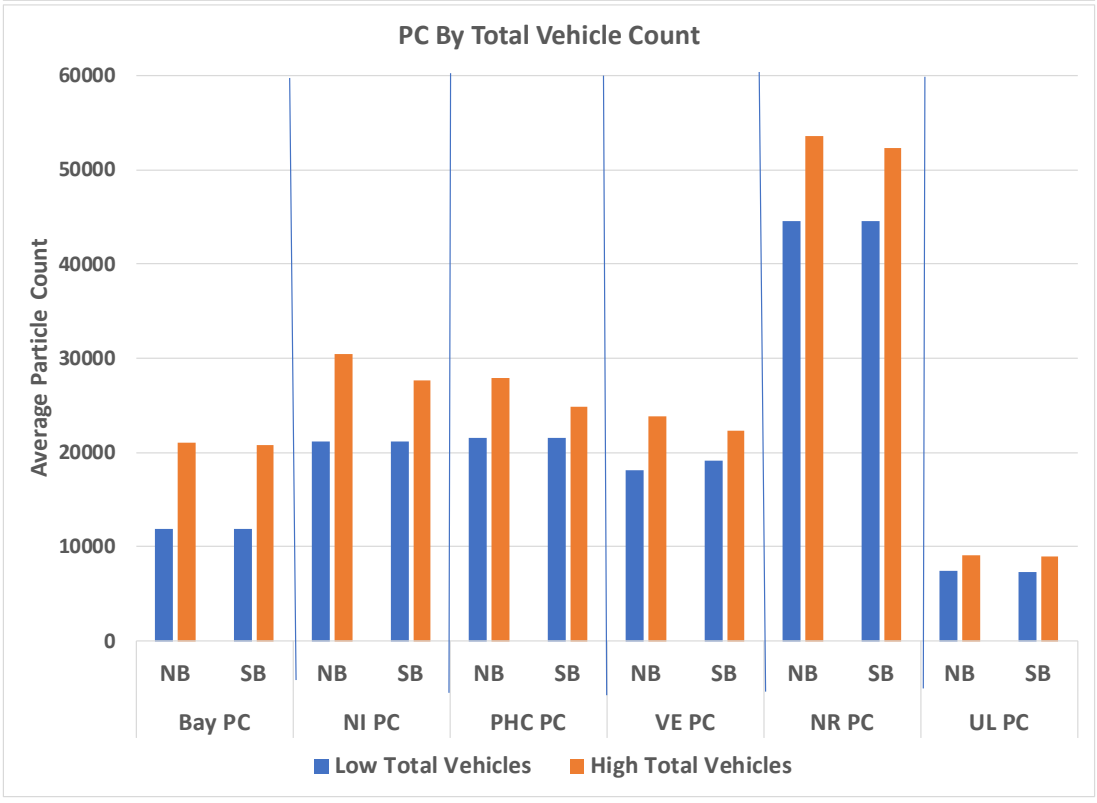
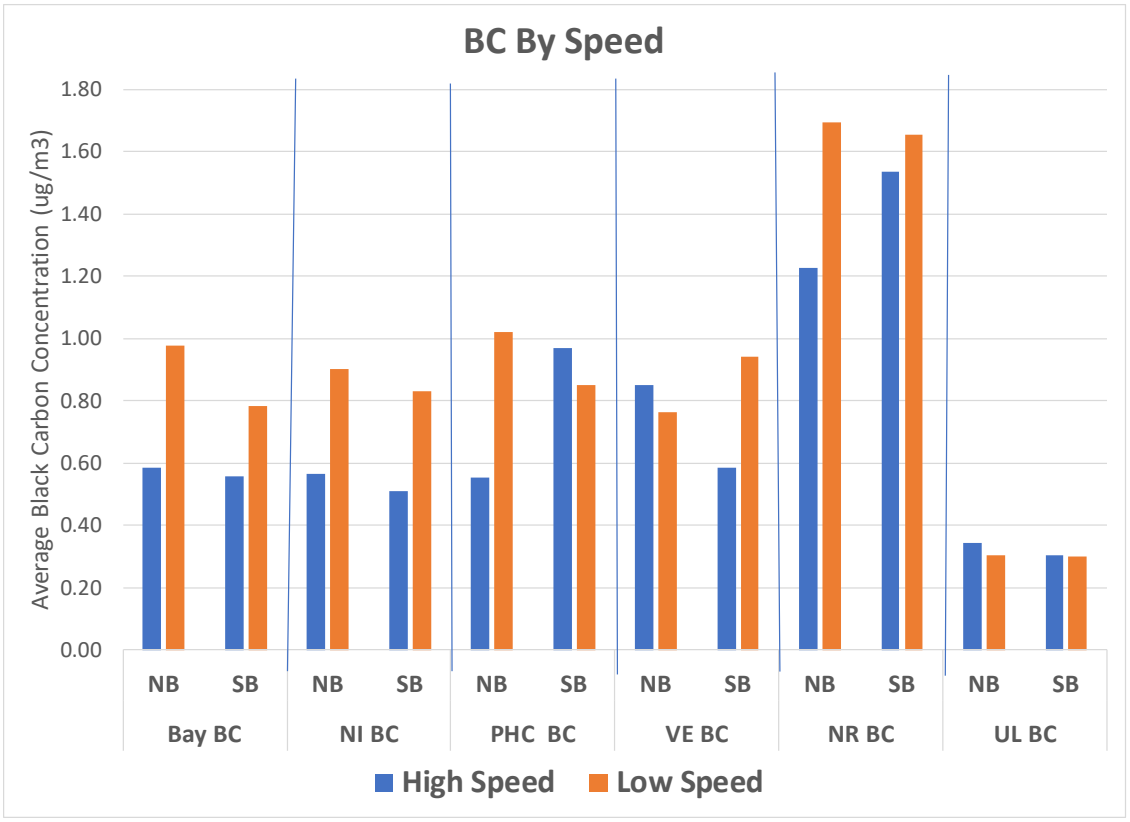


Figure 48. Average Black Carbon Concentrations and Particle Counts in Hours with High and Low average Speeds



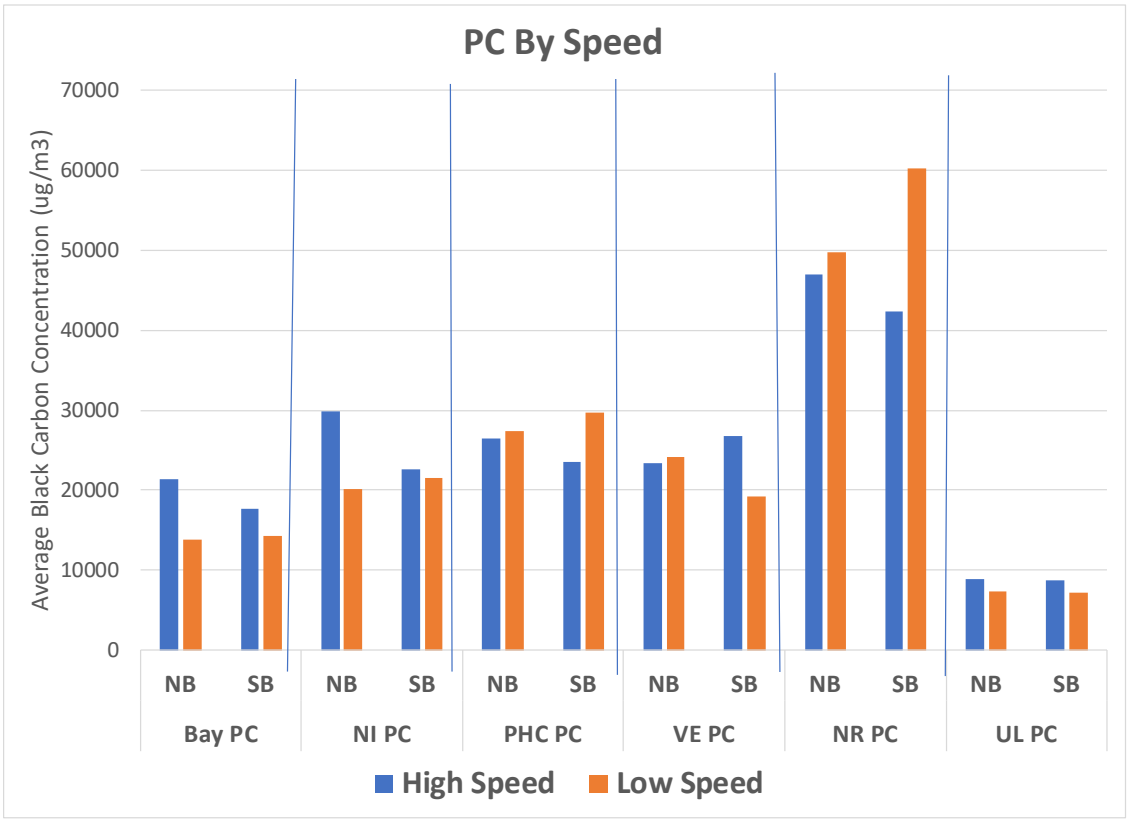


Figure 49. Meteorological and Traffic Factor Associations with PC and BC Levels

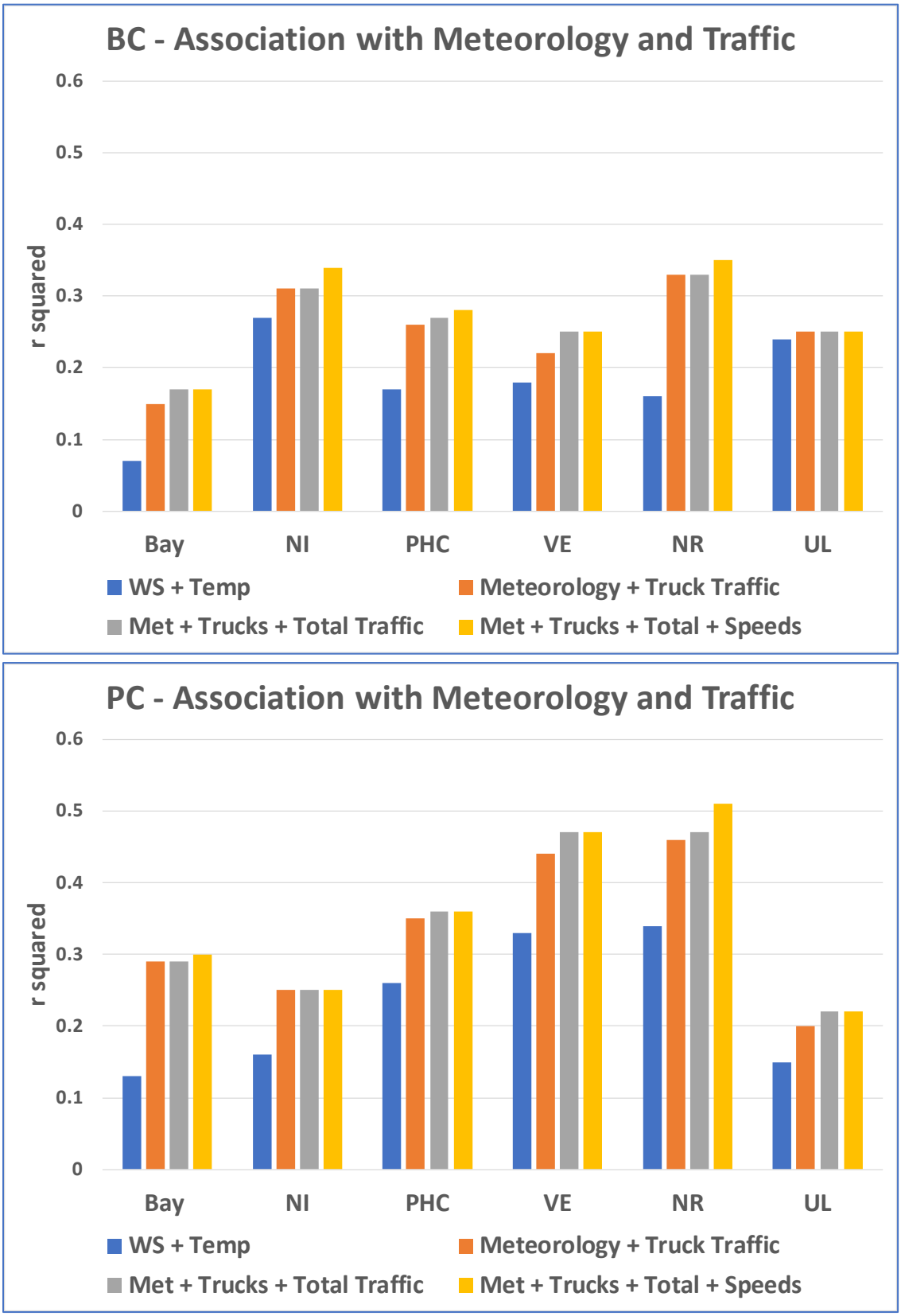
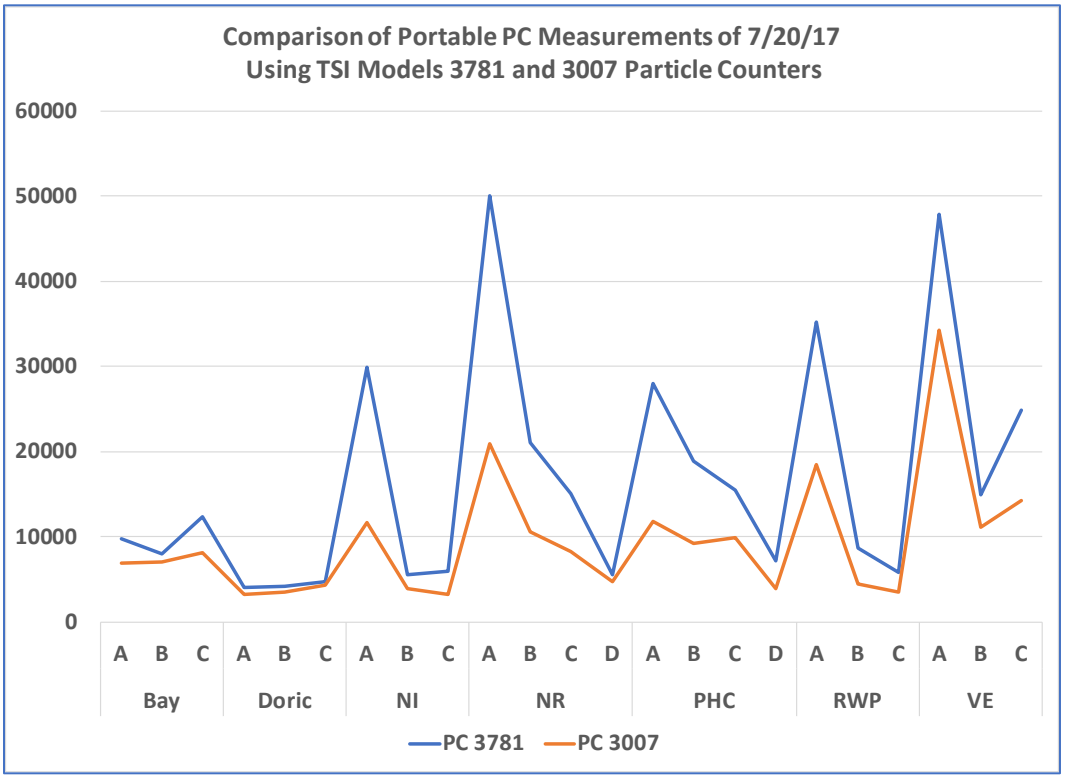


Figure 50. Comparison Measurements with the TSI Model 3781 Particle Counter Used to Study Spatial Variation in March – July 2017 and with the TSI Model 3007 Used July 2017 – March 2018



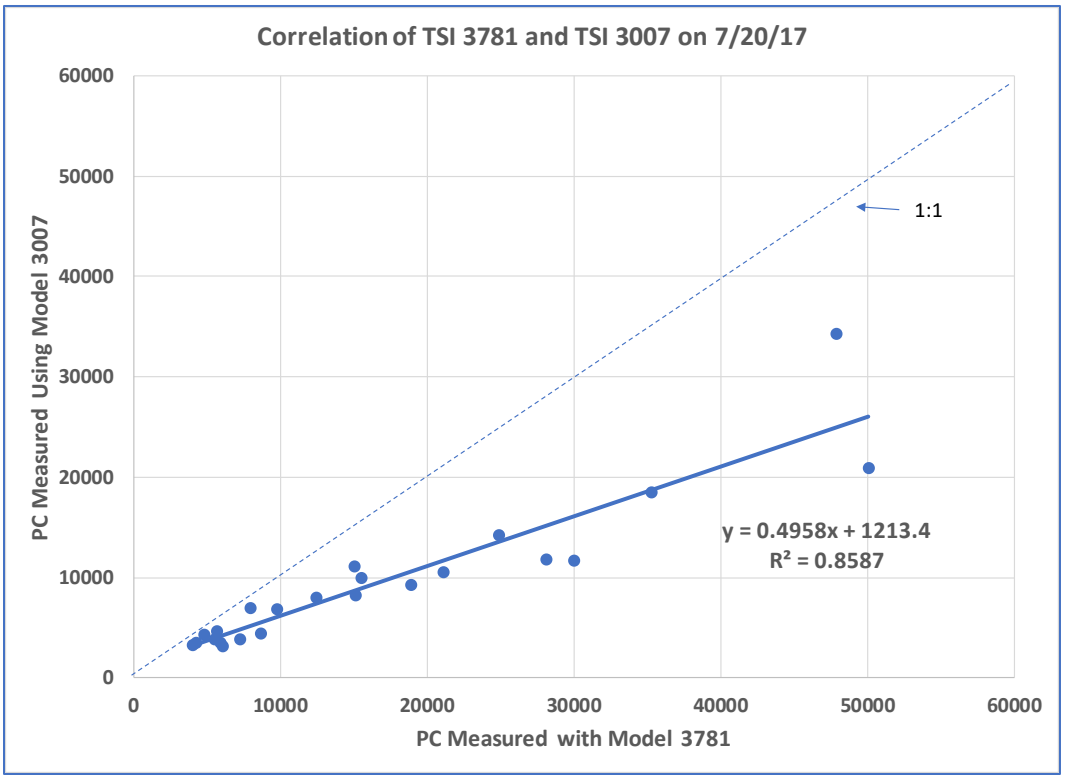
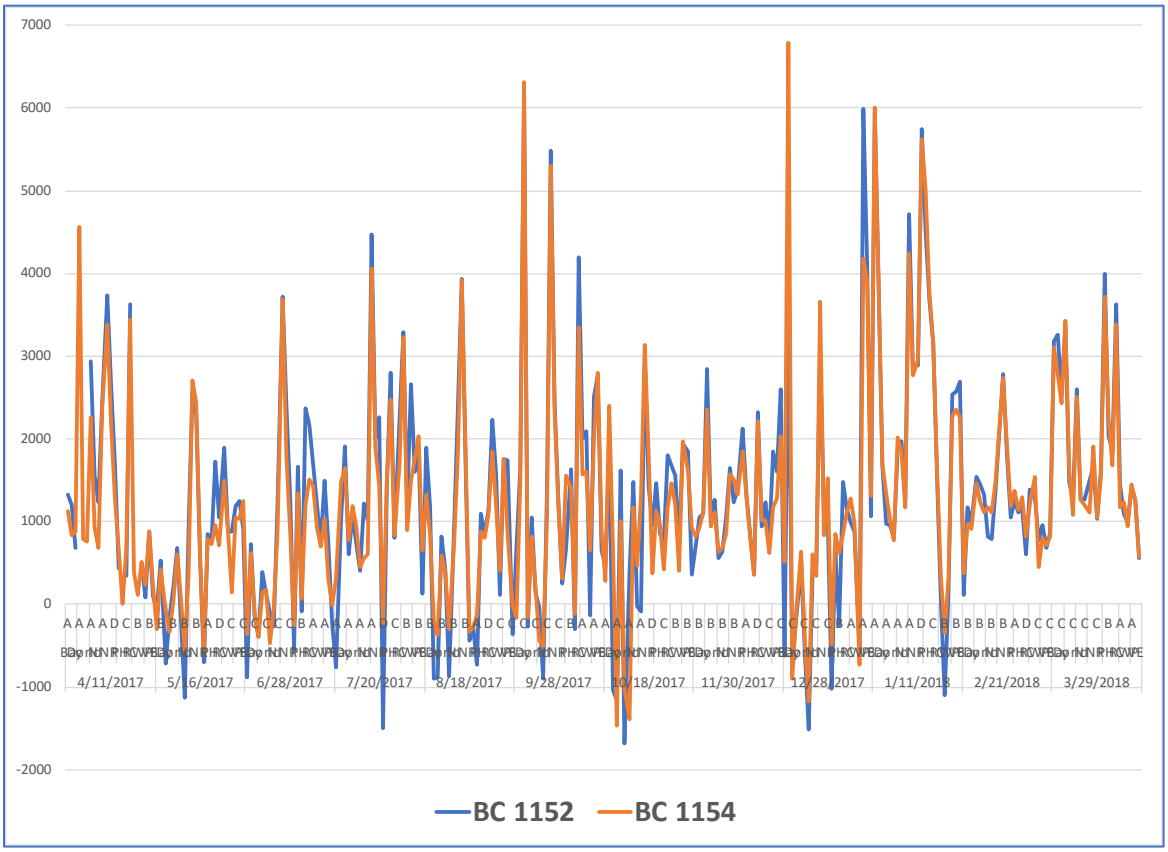


Figure 51. Comparison of Two Portable Aethalometers Used to Study BC Spatial Variability



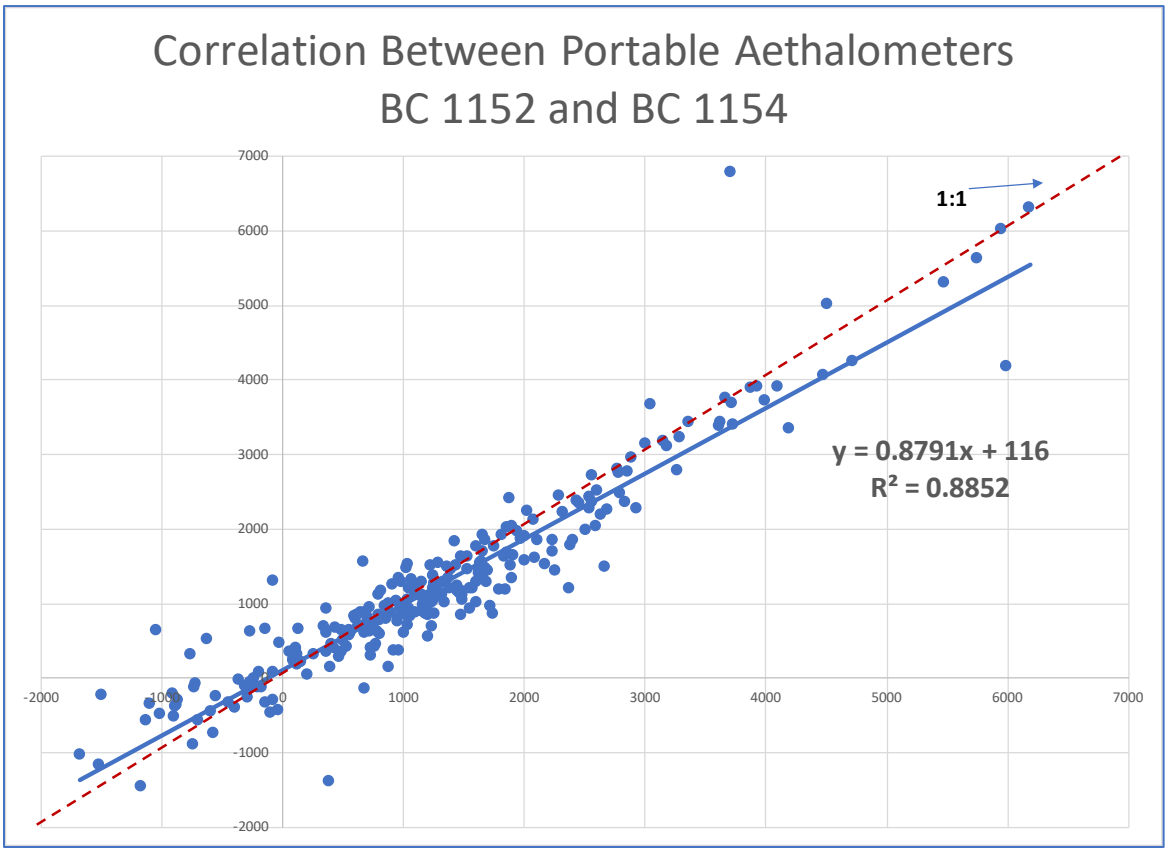


Figure 52. Bay St. Spatial Variation Study Monitoring Locations

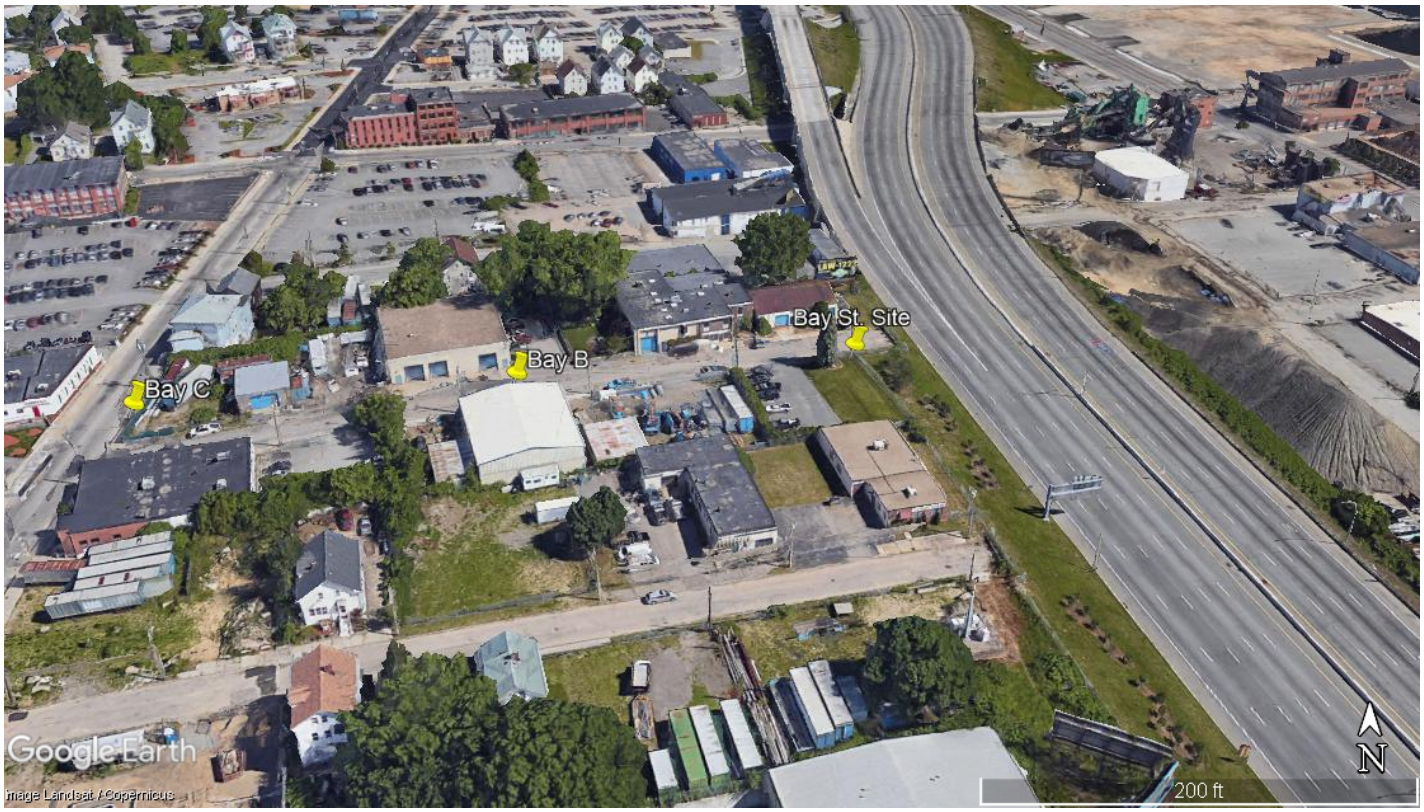


Figure 53. Bay St. Spatial Variation Study Results

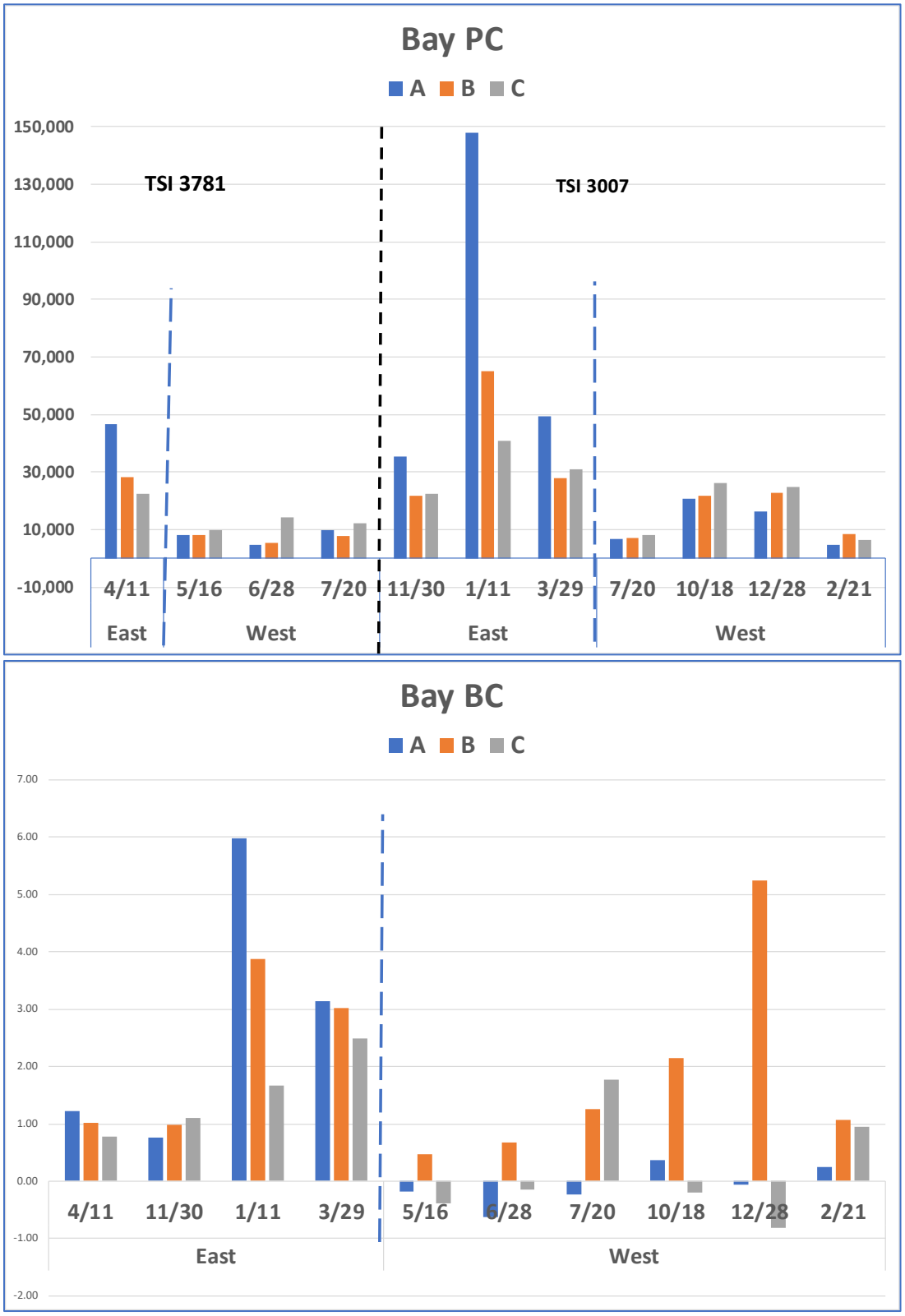


Figure 54. Providence Health Center Spatial Variation Study Monitoring Locations

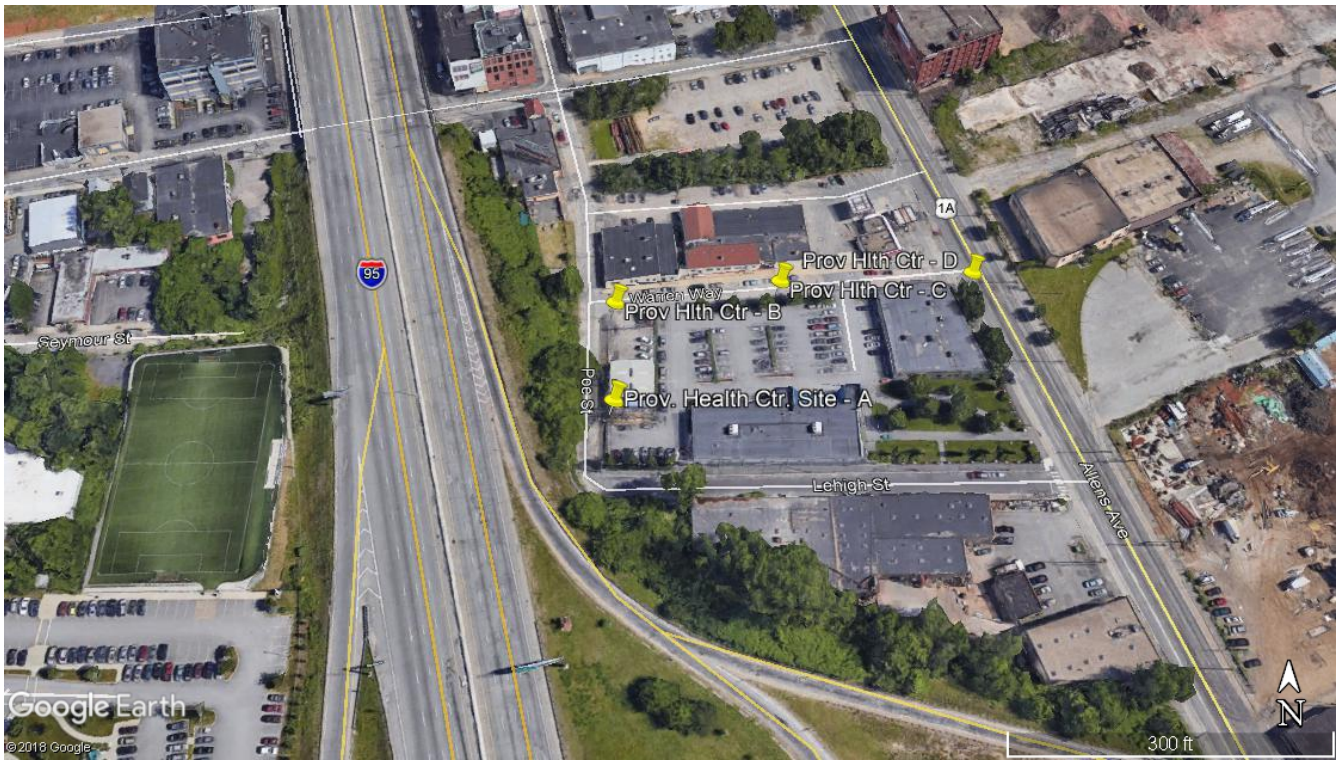


Figure 55. Providence Health Center Spatial Variation Study Results

Figure 56. Near-Road Site Spatial Variation Study Monitoring Locations

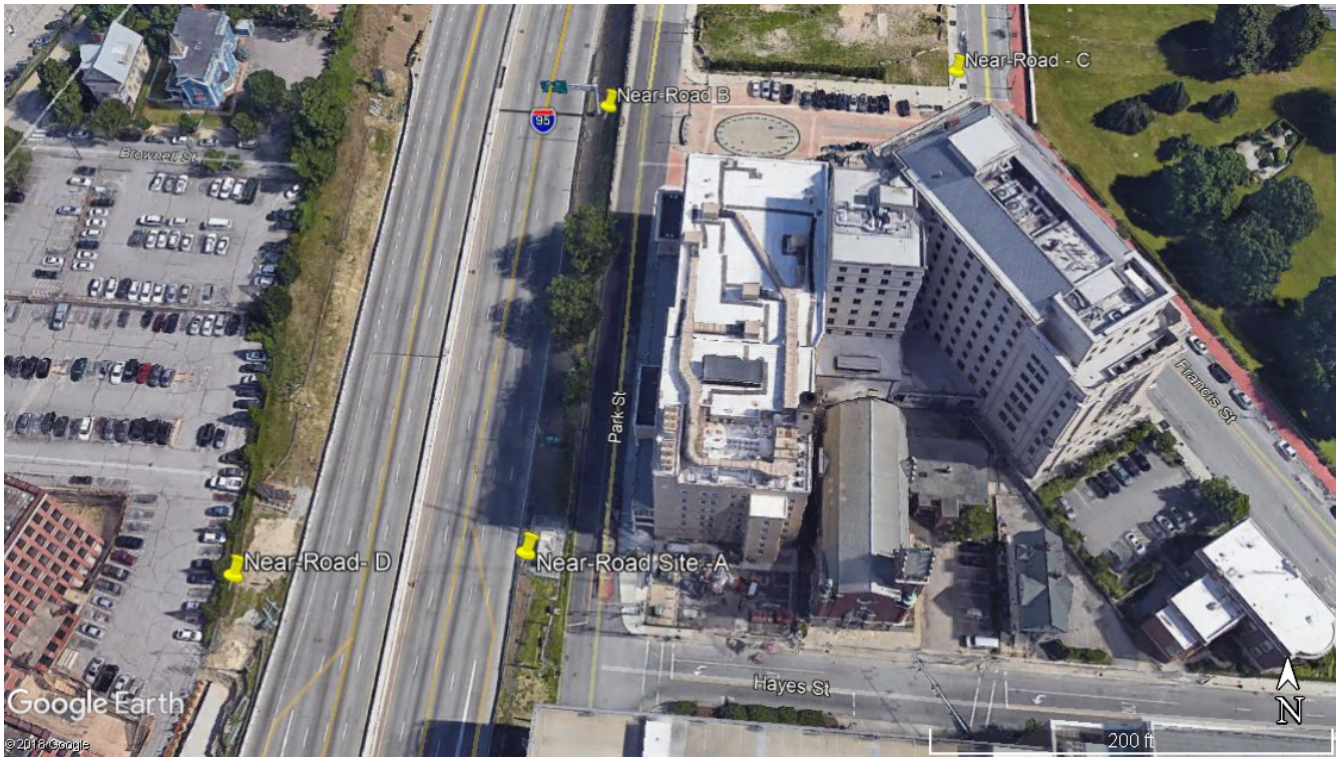


Figure 57. Near-Road Site Spatial Variation Study Results

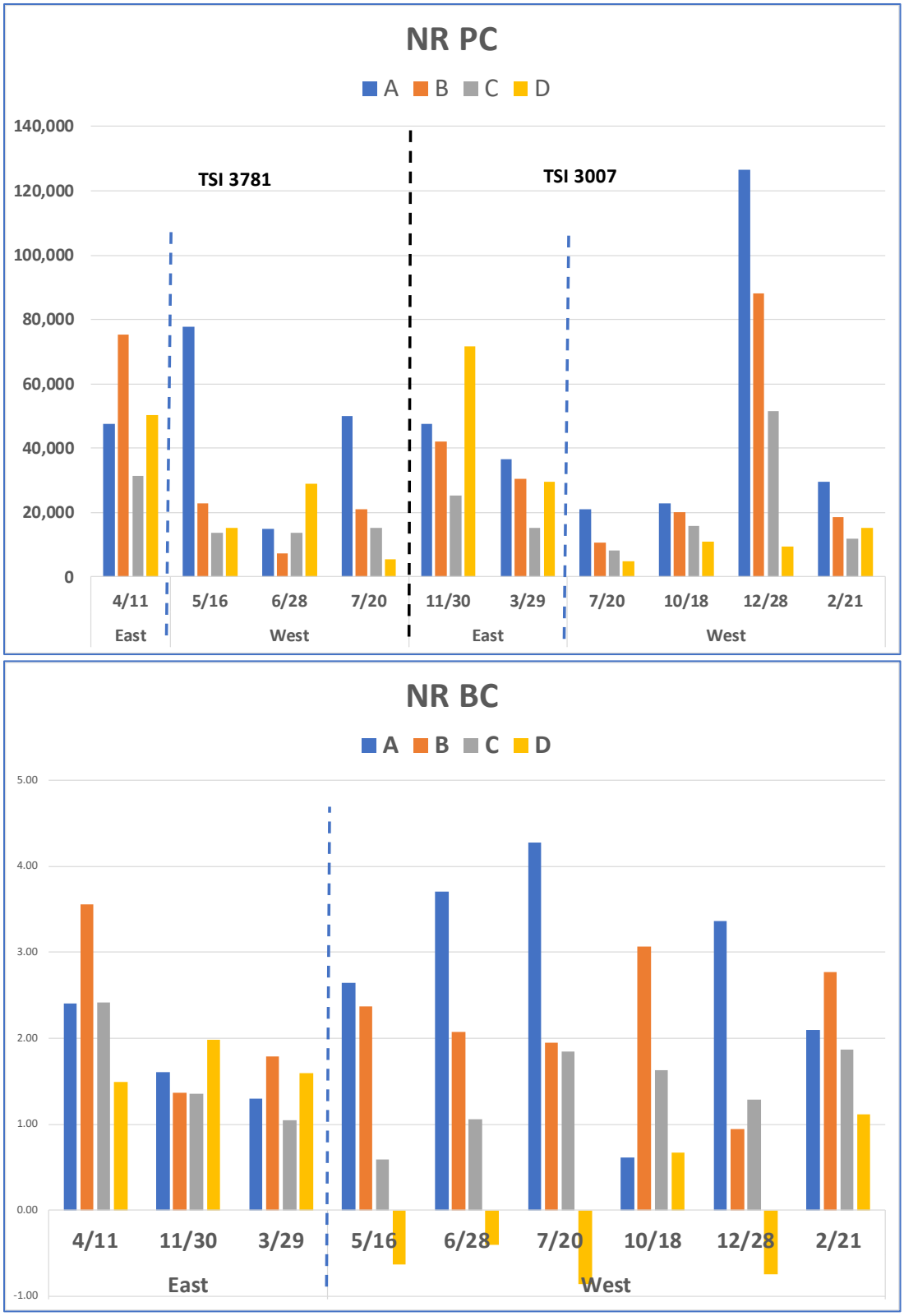


Figure 58. Vernon Site Spatial Variation Study Monitoring Locations

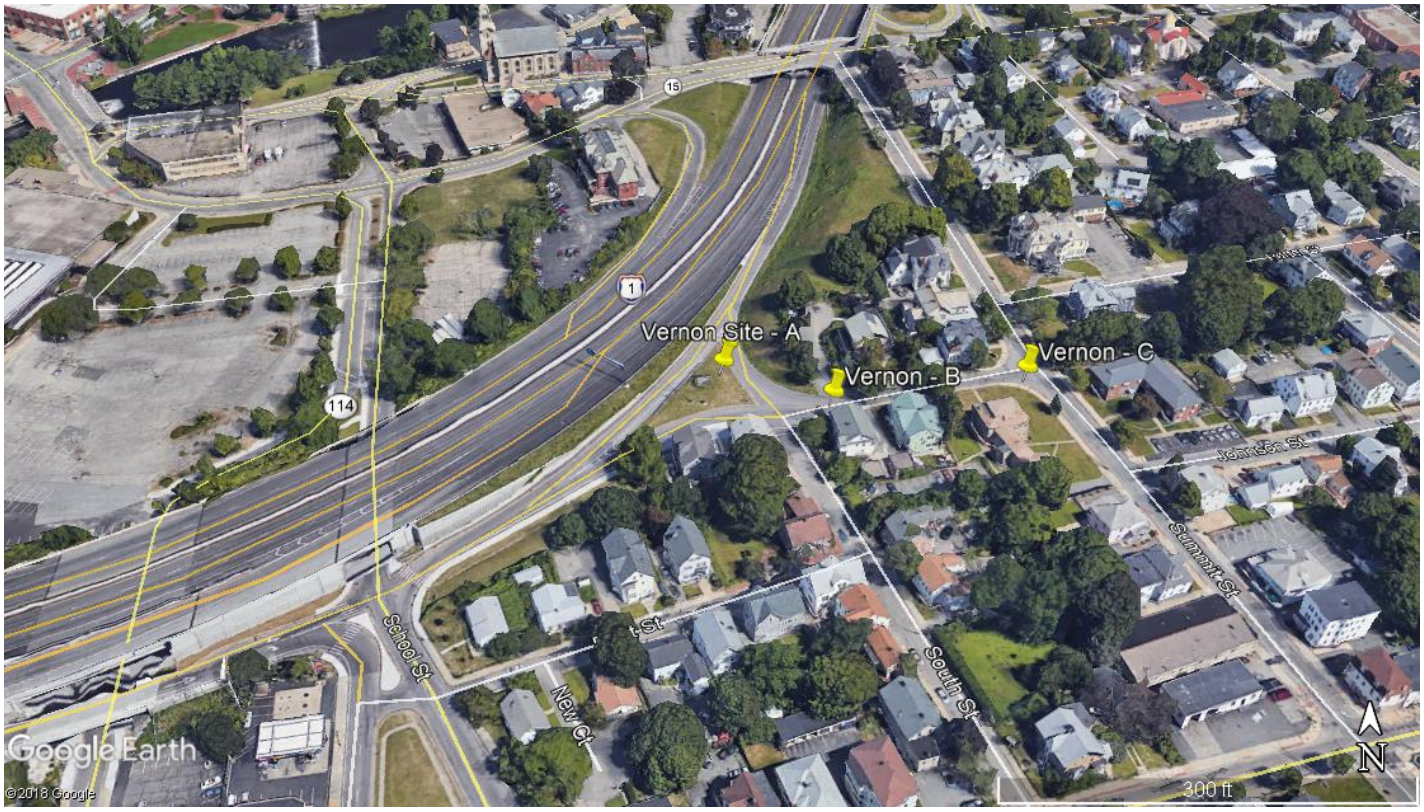


Figure 59. Vernon Site Spatial Variation Study Results

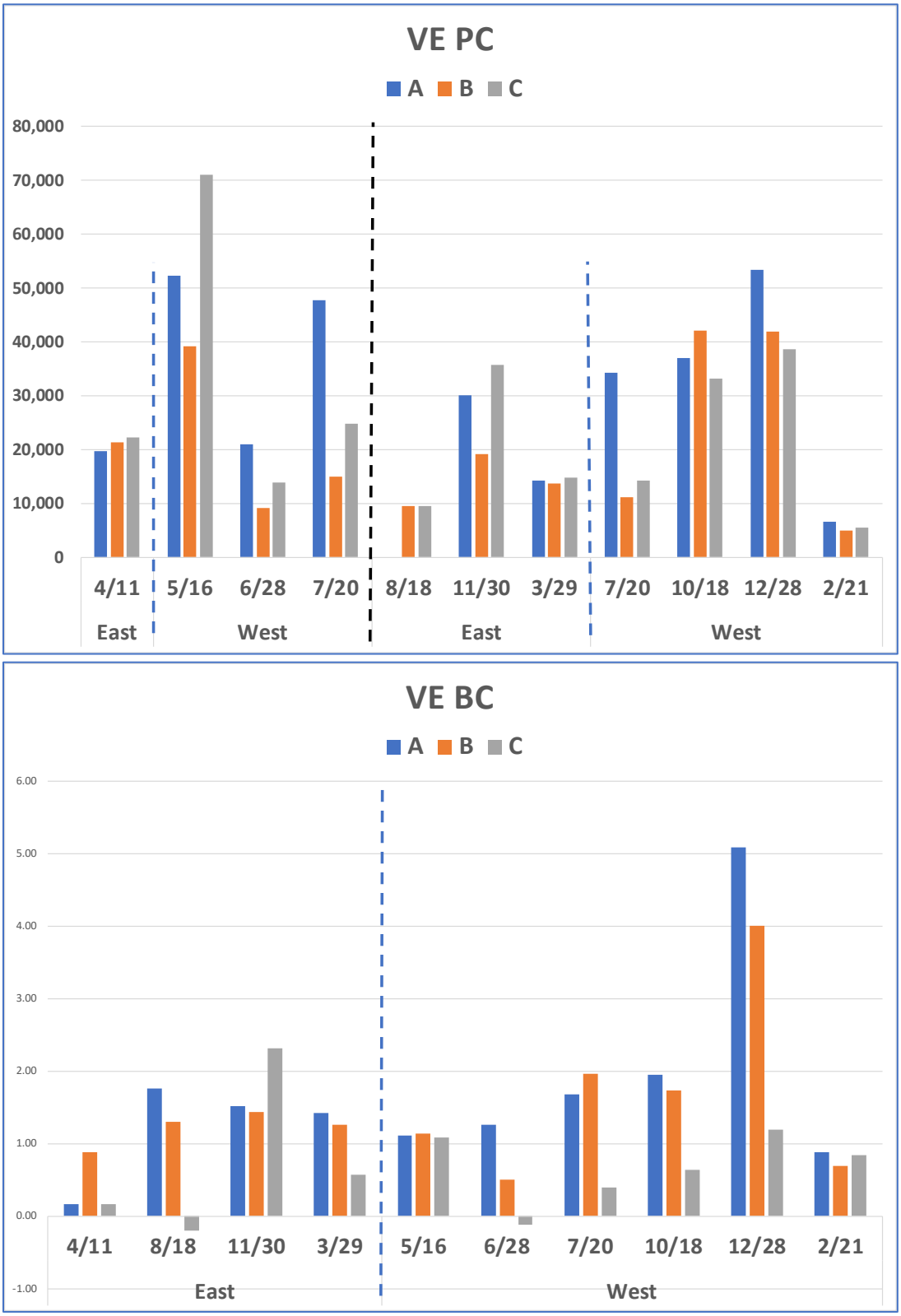


Figure 60. Niagara and Roger Williams Park Spatial Variation Study Monitoring Locations

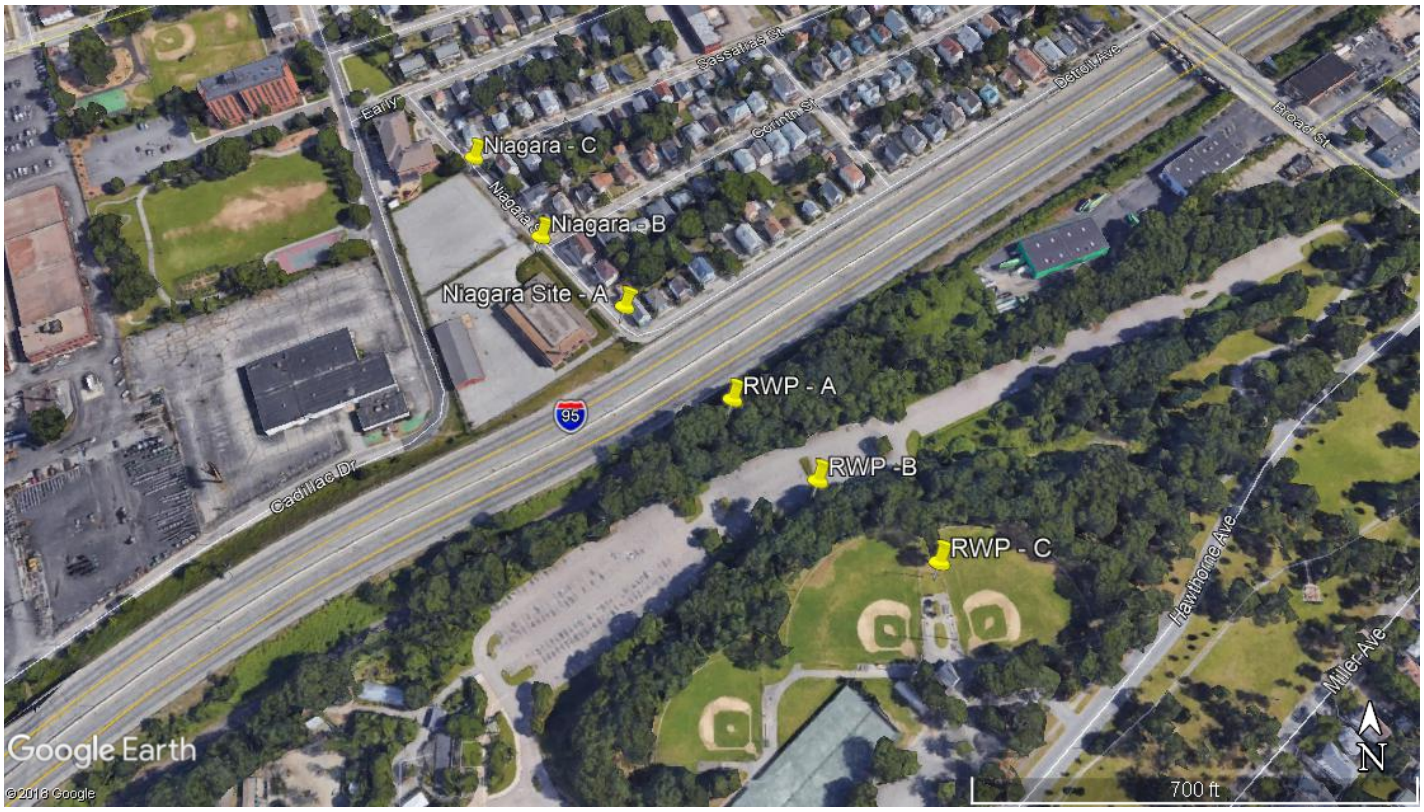
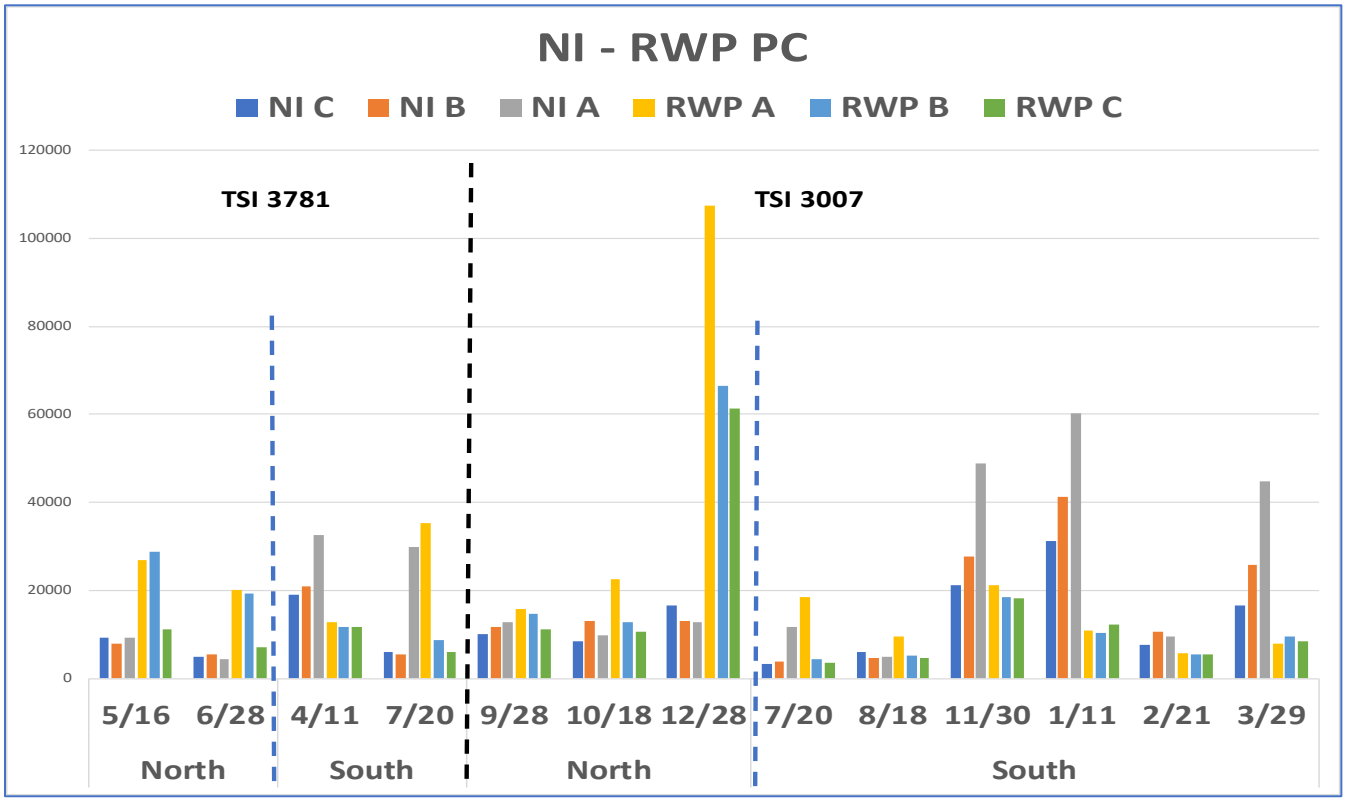


Figure 61. Niagara and Roger Williams Park Spatial Variation Study Results



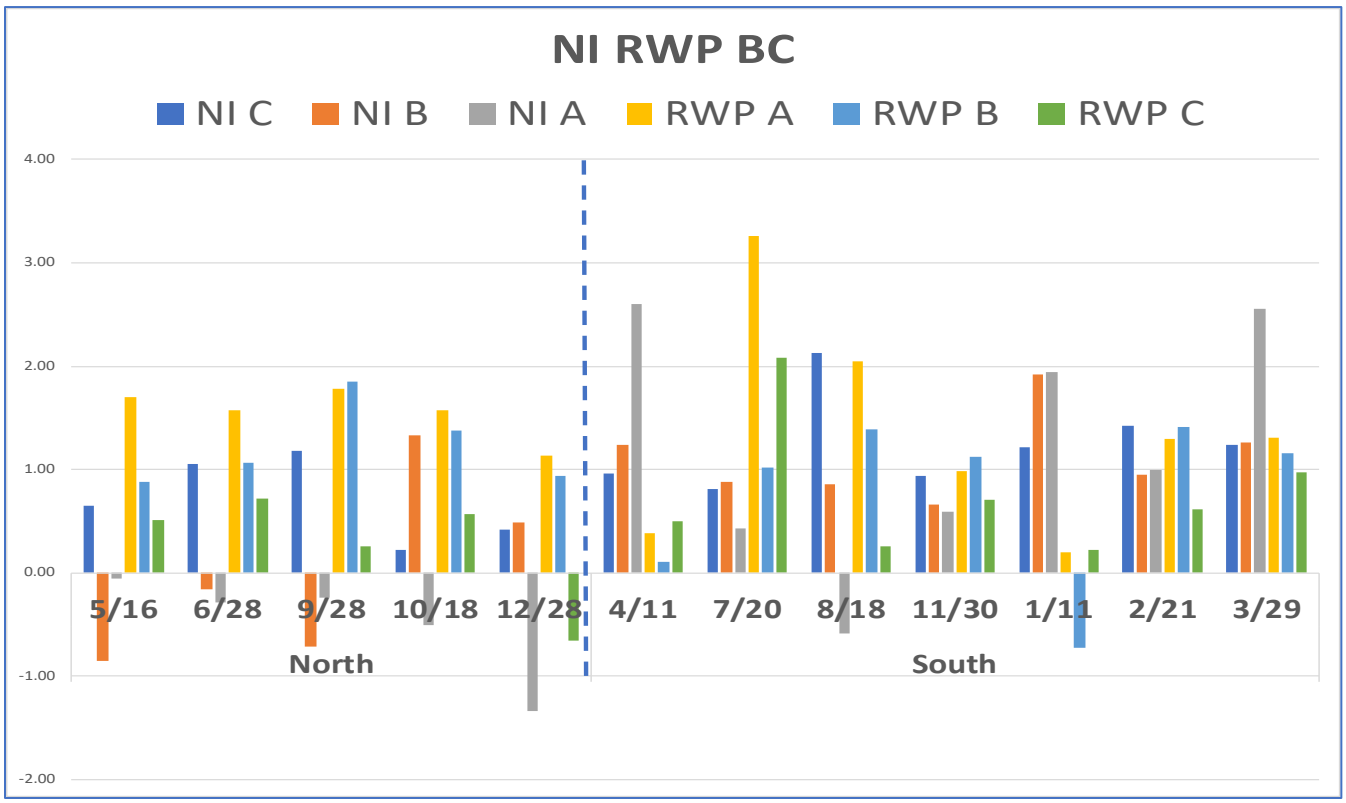


Figure 62. Doric Spatial Variation Monitoring Locations

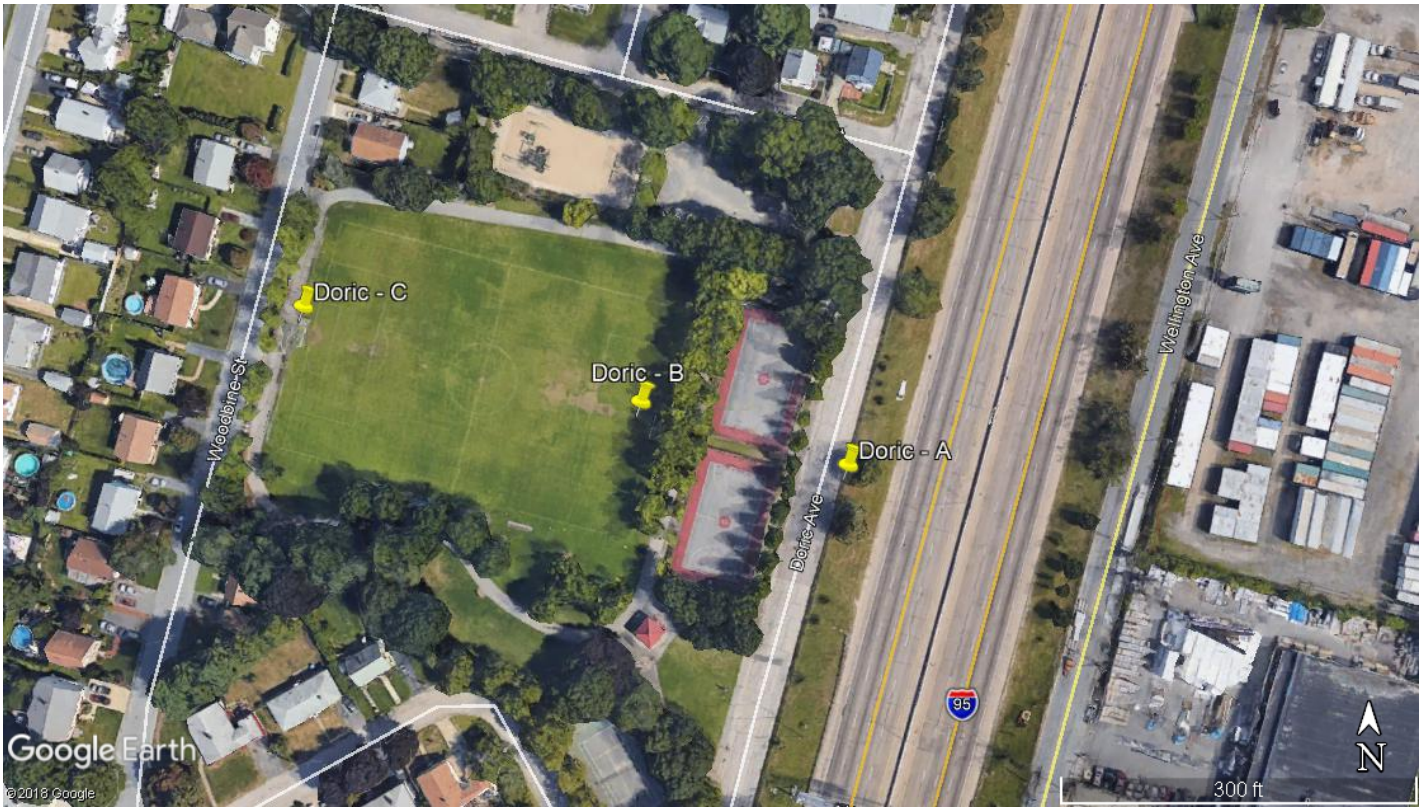


Figure 63. Doric Spatial Variation Monitoring Study Results