Testing of Cavity Attenuation Phase Shift Technology For Siting Near-road NO_2 Monitors

FINAL PROJECT REPORT

by

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Sponsorship
WSDOT

for
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In cooperation with US Department of Transportation-Research and Innovative Technology Administration (RITA)

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Technical Report Documentation Page

1. Report No. 2013-S-UW-0053	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Testing of Cavity Attenuation Phase Shift Technology for Siting Near-road NO2 Monitors		5. Report Date 8/31/2015
		6. Performing Organization Code
7. Author(s) Timothy Larson and Mengyu Cai		8. Performing Organization Report No.
9. Performing Organization Name and Address		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. DTRT12-UTC10
12. Sponsoring Agency Name and Address Pacific Northwest Transportation Consortium (PACTRANS) University of Washington More Hall 112, Box 352700 Seattle, WA 98195-2700 (List matching agency name and address)		13. Type of Report and Period Covered Research: 7/30/2013-8/31/2015
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Recent research has identified the public health importance of air pollution exposures near busy roadways. As a result, the Environmental Protection Agency (EPA) significantly revised its Nitric oxide (NO2) air quality standard in 2010. The current regulatory focus has shifted from assessment of longer-term (annual average) NO2 concentrations measured at locations away from busy roads to shorter-term (1-hour average) concentrations measured at locations near busy roads. Even though EPA has developed extensive guidelines for siting traditional air quality monitors that are located relatively far from roads, their siting guidance for near-road NO2 monitors is not yet officially established. Therefore this project proposes to test a more direct approach to siting near-road NO2 sampling locations using a state-of-the-art NO2 monitor that is no more expensive than traditional EPA chemiluminesce-base monitors, is much more readily deployed on a mobile platform, and can ultimately be used as the regulatory monitor at the official sampling location.

17. Key Words Data and Information Technology; Highways; I15: Environment		18. Distribution Statement No restrictions. Copies available from PACTRANS: www.pactrans.org	
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages	22. Price

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List of Abbreviations

PacTrans: Pacific Northwest Transportation Consortium
WSDOT: Washington State Department of Transportation
QUIC: Quick Urban & Industrial Complex Dispersion Model
CALINE: California Line Source Model
CAPS: Cavity Attenuation Phase Shift
ESRL: Earth System Research Laboratory
WBAN: Weather Bureau Army Navy

Chapter 1 Executive Summary

1.1 General Background

Recent research has identified the public health importance of air pollution exposures near busy roadways. As a result, EPA significantly revised its NO_2 air quality standard in 2010. The current regulatory focus has shifted from assessment of longer-term (annual average) NO_2 concentrations measured at locations away from busy roads to shorter-term (1-hour average) concentrations measured at locations near busy roads. Given the potential importance of understanding both near-road and on-road NO_2 exposures in built-up urban areas, additional monitoring approaches are needed that are relatively user-friendly, specific to NO_2 rather than general oxides of nitrogen, and sufficiently flexible to be deployed at both near-road locations over time as well as on busy freeways over both time and space.

1.2 Key Methodology

The CAPS NO_2 analyzer is a robust and sensitive instrument that can be deployed in a mobile mode for further characterization of near road monitoring sites and for assessment of relevant on-road concentrations. We operated the instrument on a movable platform (a Toyota Prius) equipped with GPS to identify position at the corresponding concentration. The platform was operating either in a stationary mode or a moving mode. In the moving mode, the ratio of the one-minute average NO_2 values from the mobile platform to the corresponding hourly values at a fixed site were computed as a means to adjust for temporal variation primarily between sampling days. The stationary mode consisted of sampling over a 25 to 30 minute period at designated fixed locations near a major roadway. The upwind/downwind differences from samples taken in the stationary mode within the same hour were further compared with roadway dispersion models.

1.3 Major findings and their implications

We observed NO2 concentrations within 60 meters of a busy urban freeway (I-5 in Seattle) that were between 5 and 30 ppb higher on average downwind of the freeway compared with immediately upwind at a nearby location. More generally, we observed concentrations on I-5 were between 7 and 35% higher than at these near-road sites, consistent with the few previous studies on this subject. This latter finding has potentially important implications for understanding short-term NO2 exposures to the general population and how those exposures relate to near-road regulatory monitoring data.

We plan to submit a paper on the results of this project for publication in a journal and also to present these results to the air-monitoring group at the Washington State Department of Ecology as they begin to interpret data from their newly established NO_2 monitor near I-5 in Seattle.

Chapter 2 Introduction

Recent research has identified the public health importance of air pollution exposures near busy roadways. As a result, EPA significantly revised its NO_2 air quality standard in 2010. The current regulatory focus has shifted from assessment of longer-term (annual average) NO_2 concentrations measured at locations away from busy roads to shorter-term (1-hour average) concentrations measured at locations near busy roads. A near-road monitoring network is being deployed by EPA in major metropolitan areas, and is about a year old at the time of this report, with additional sites coming online. The guidelines for siting such monitors do not directly address the representativeness of such monitors with respect to short-term exposures to NO_2 within the population, especially to exposures during commuting.

Our goal with this study was to explore the feasibility of deploying the CAPS monitor on a mobile platform to obtain information about NO_2 concentrations in an urban area, specifically both on and near a major urban freeway. We deployed the NO_2 monitor on a movable platform in November and December of 2013 as a way to assess NO_2 concentrations both near and on a busy freeway located in a complex urban environment. These short-term mobile platform measurements were made in conjunction with existing NO_2 measurements from a fixed-site regulatory monitor that is by design located some distance away from the roadway. We also deployed this same platform in a stationary mode near the freeway and compared these near-road measurements to traditional roadway dispersion models.

Chapter 3 Literature Review

Living near a busy roadway is clearly an important factor that can increase outdoor NO_2 concentrations near residences (HEI, 2010; Karner et. al., 2010). A number of studies also point to the potential importance of on-road, in-vehicle exposures during commuting hours (HEI, 2010), although all of these studies reported NO_x concentrations rather than NO_2 values (Fruin et. al., 2008; MacNaughton et. al., 2014; Zhu et.al., 2008; Fujita et. al., 2011). The EPA has issued a technical guidance document for near-road NO_2 monitoring (EPA, 2012). However that document is focused on siting near road monitors rather than assessing the relationships between near-road and on-road NO_2 concentrations. There are only a few studies to date that have looked at the relationship between immediately near-road versus on-road NO_2 levels (Bell and Ashenden, 1997; Cape et. al., 2004; Monn et.al., 1997). In addition, these studies reported concentrations that were time averaged over at least a one-week period. To our knowledge, there are no studies that attempt to measure this relationship at shorter-term averaging times.

Chapter 4 Study Site/Data

4.1 Study Site

The study area is shown in Figure 4.1. Sampling on the I-5 freeway occurred between NE 65th Street and I-90. Mobile platform measurements were also taken in areas of downtown Seattle near I-5. In these locations, the platform was either moving or was stationary at specific locations near I-5. Additional stationary platform measurements were also made near the intersection of I-5 and SR520 (see Figure 4.1). The location of the regulatory, area-wide NO_2 monitor at Beacon Hill operated by the Washington State Department of Ecology is also shown.

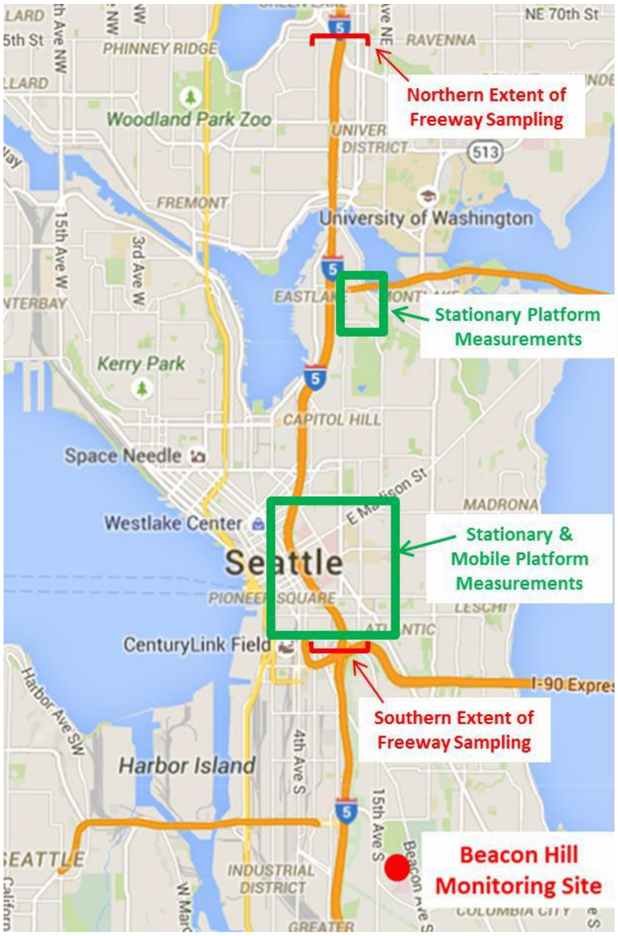

Figure 4-1 Study Area and Sampling Locations

4.2 External Data

We obtained meteorological data for the relevant sampling periods from the National Weather Service. These were used to assess the sampling period versus the values over the entire year. They were also used as necessary inputs to the dispersion modeling that was done as part of the data analysis. We used appropriate hourly wind direction and wind speed values based upon National Weather Service data from nearby Boeing Field (National Climatic Data Center WBAN Station ID # 24208). We also used information on mixing height based on input data from Sea-Tac airport taken from the ESRL Radiosonde Database (http://esrl.noaa.gov/raobs).

Wind Roses for the study period as well as for the entire year of 2013 are shown in Figure 4.2. There was a relatively small percentage of calms during the study period (2.7%) compared with the year as a whole (~14%). It is important to point out that the wind direction during our study period was such that measurements made on the east side of I-5 were predominantly upwind of that source, whereas measurements made on the west side of I-5 were predominantly downwind. This is the more typical wind pattern in the summer. The relative frequency of wind speeds less than 2 meters per second was also higher during the study period compared with the year overall. At these low wind speeds, the concept of “upwind” versus “downwind” is less clear and pollution can travel in the nominally upwind direction (c.f. Snyder et. al. , 2013)

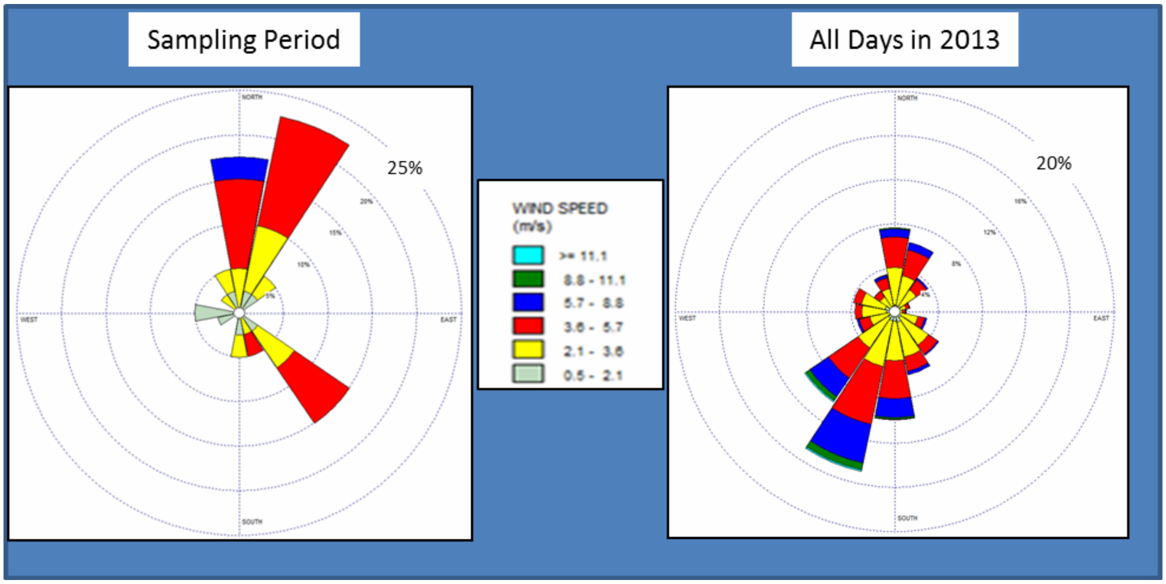

Figure 4-2 Wind Roses for Sampling Period and for all hours of 2013. Data from Boeing Field.

We also obtained hourly NO_2 data at the Beacon Hill Site operated by the Washington State Department of Ecology. The monitor location is shown in Figure 4.1. This data was used to adjust the mobile platform measurements to account for temporal variability across the entire study region.

One of the dispersion models, the Quick Urban Industrial Complex (QUIC) model, requires additional information on building profiles. The shapefiles for building outlines and arterials for the study area are available from the database of City of Seattle. Since the projection system in QUIC is UTM and the unit is meter, the first step was to project the building outlines and arterials to UTM (NAD_1983_HARN_UTM_Zone_10N for Washington State). The buildings in City Builder were geo-referenced once the Origin XY coordinates are set. In addition, information about the building height is obtained from the Google Earth and some other websites (such as http://www.emporis.com). In order to put the building heights in shapefiles, they were manually edited in tables. Then the buildings were then imported to QUIC City Builder successfully.

As additional input to the dispersion models, the emissions of NOx and NO_2 directly from the interstate were computed using emission factors from the EPA MOVES model for King County restricted roadways for 2012. We assumed daily and peak hourly traffic counts of 6,000 and 8,000 vehicles/hour, respectively, which is representative of the two mobile air monitoring periods and also is the peak daily traffic count on this section of I-5 (TDAD database, UW ITS Research Program) shown in Figure 4.3 below.

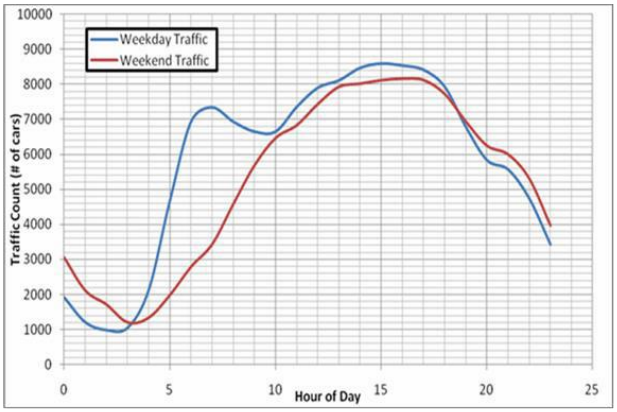

Figure 4-3 Average traffic counts along I-5 within the study region

Chapter 5 Methods

5.1 NO_2 Platform Measurements

One-second average concentrations of NO_2 were measured on a moving platform using a Cavity Attenuation Phase Shift (CAPS) monitor (Aerodyne Research Inc., Billerica, MA). The monitor relies on absorption of blue laser light at 450nm in a mirror cavity (see Figure 5.1A). It is essentially free of interferences from other compounds although there are minor interferences from dicarbonyl species. This particular model instrument has been shown to agree very well with the EPA equivalent NO_2 monitoring method ($R^2 > 0.99$; Kebabian et al, 2008). It has a 0.06 ppbv detection limit at an averaging time of 10 seconds. The van, the air sampling inlet, and the CAPS analyzer location in the van is shown in Figure 5.1B. Simultaneous GPS location information was also obtained, allowing us to plot the NO_2 measurements on a map.

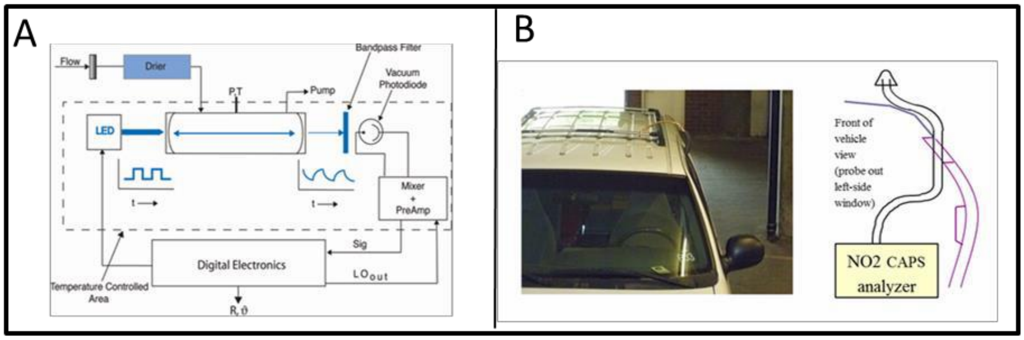

Figure 5-1 A) Schematic of the CAPS NO2 Monitor showing typical laser signal entering and exiting the sensor cavity; B) Toyota Prius with sampling inlet tube and schematic of analyzer location inside vehicle.

5.2 Platform Sampling

Measurements were taken during November and December of 2013. All measurements were made during afternoon rush hour to avoid the effect of temporal variations due to rapidly changing morning mixing depth that can obscure the spatial patterns. The Platform was operating either in a stationary mode or a moving mode. The stationary mode consisted of sampling over a 25 to 30 minute period at designated locations on both the east and west sides of I-5 (see Chapter 5 for specific locations). In the moving mode, we computed the continuous 10-second average NO_2 value and assigned the GPS location at the middle of the 10 second interval. Stationary measurements were made at locations near I-5 just north of I-90 as well as near I-5 and SR520 (see Figure 4.1 for general sampling locations).

5.3 Data Analysis

5.3.1 Concentration Ratios

The ratio of the one-minute average NO_2 values from the mobile platform to the corresponding hourly values at the Beacon Hill site were computed as a means to adjust for temporal variability. The day to day variation was significantly larger than the hour to hour variation within a day as shown in Figure 5.2. Therefore we did not attempt to smooth the Beacon Hill values within a given day prior to computing the ratios.

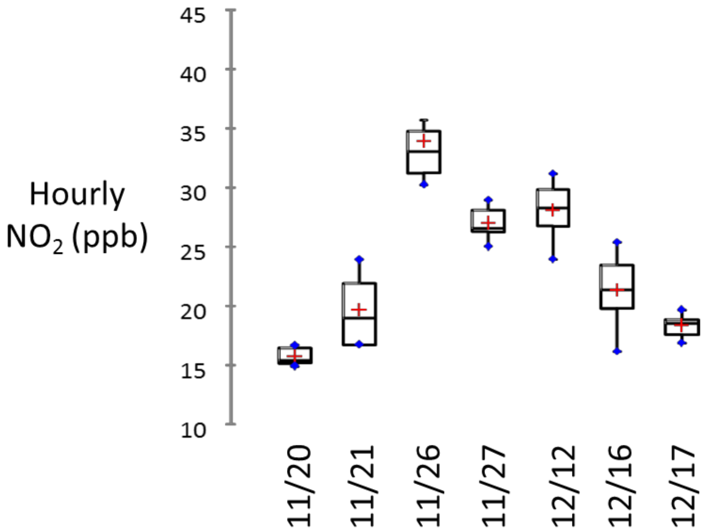

Figure 5-2 Hourly NO2 concentrations at Beacon Hill during the study period

5.3.2 Roadway Dispersion Models

We implemented the QUIC and CALINE dispersion models in this analysis to compare their predictions against the observed difference in the concentration between paired upwind/downwind stationary sites (see Chapter 5 for specific site locations). There was minimal time difference between sites within an upwind/downwind pair. Sampling was done over a 25 to 30 minute period at any one site, the platform moved to the other paired site within a few minutes, and then another 25 to 30 minute sampling period was initiated.

QUIC is a Lagrangian random walk dispersion model that includes both a mean wind field and flow separation regions due to both individual buildings as well as larger scale street canyons (Williams et.al., 2002). The current model is maintained by Los Alamos National Laboratory (see https://www.lanl.gov/projects/quic/open_files/QUICURB_UsersGuide.pdf for additional details on the model formulation, and http://www.lanl.gov/projects/quic/ for further information on the model implementation). QUIC accounts for the non-Gaussian distribution of downwind, polluted air parcels due to preferential capture within building wakes and thus for possible “hot spots” that are not predicted by traditional Gaussian dispersion models.

The area of interest containing the stationary sites is along the Interstate 5 in downtown Seattle, from Marion Street to S Dearborn Street. The focus of the study is on near-road NO_2 emissions from vehicles on I-5, thus only the buildings within two blocks from I-5 are considered in this study. The modeling area is 1200m*1200m. In the QUIC model, if the origin xy coordinates are set, QUIC-URB is able to load shapefiles into the City Builder. Since the projection system in QUIC is UTM and the unit is meter, the first step is to project the building outlines and arterials to UTM (NAD_1983_HARN_UTM_Zone_10N for Washington State). The buildings in City Builder will be geo-referenced once the Origin XY coordinates are set. The

QUIC model requires a single, overlying wind direction (specified by sector), an average wind speed at reference height, and an associated vertical wind speed profile. The effect of classic stability category on downwind dispersion of emission is less important than the flow disturbances created by nearby structures. Hourly dry bulb temperature is used as an input (ambient temperature) in the QUIC model. The wind profile in QUIC was selected as logarithmic. As for the roughness length z_0, 0.4 m was assumed, typical of urban areas.

To assess the variability in the wind direction over a given sampling period, the TD-6405 formatted 1-minute ASOS data is obtained through the National Climatic Data Center's (NCDC) website (ftp://ftp.ncdc.noaa.gov/pub/data/asos-onemin/) for Boeing filed (WBAN #: 24234). With the one-minute wind direction and wind speed, the vector-averaged wind directions and the variances of the wind directions were for each period of time the vehicle was conducting stationary monitoring. Then, the days with the variance of the wind directions to be less than 10 degree were selected for comparison with the hourly dispersion model predictions. Data taken on Nov 20th, Nov 21st, Nov 27th and Dec 17th 2013 met this criterion.

In the CALINE model, we implemented the plume volume molar ratio method (Hanrahan, 1999a,b) found that for these near-road sites, the conversion of NO to NO_2 is not significant compared with its direct emission. Therefore NO_2, was treated as an inert gas. The geometry of I-5 was represented by 5 straight line segments. The mixing zone width is set to be 60m based on the measurement from Google Earth and the link height is 1.7m. We assumed hourly traffic counts of 8000 vehicles/hour during the peak hours, which is representative of the two mobile air monitoring periods and also is the peak daily traffic count on this section of I-5 (TDAD database, UW ITS Research Program). The emission factor of NO_2 from MOVES was given as 0.37 grams per vehicle-mile.

Chapter 6 Results

6.1 Moving Platform 1-minute NO_2 Ratios

Figure 6.1 shows selected ranges of ratios in downtown Seattle during peak weekday commuting hours on seven afternoon periods in November and December of 2013. The low ratios (<1.0) are predominately on the east side of I-5, and the higher ratios (between 2 and 4) are predominately on the west side of I-5. This is consistent with the fact that the winds during these periods were such that the west side of I-5 was predominately downwind of the freeway and that the west side sampling locations included parts of the built-up downtown core.

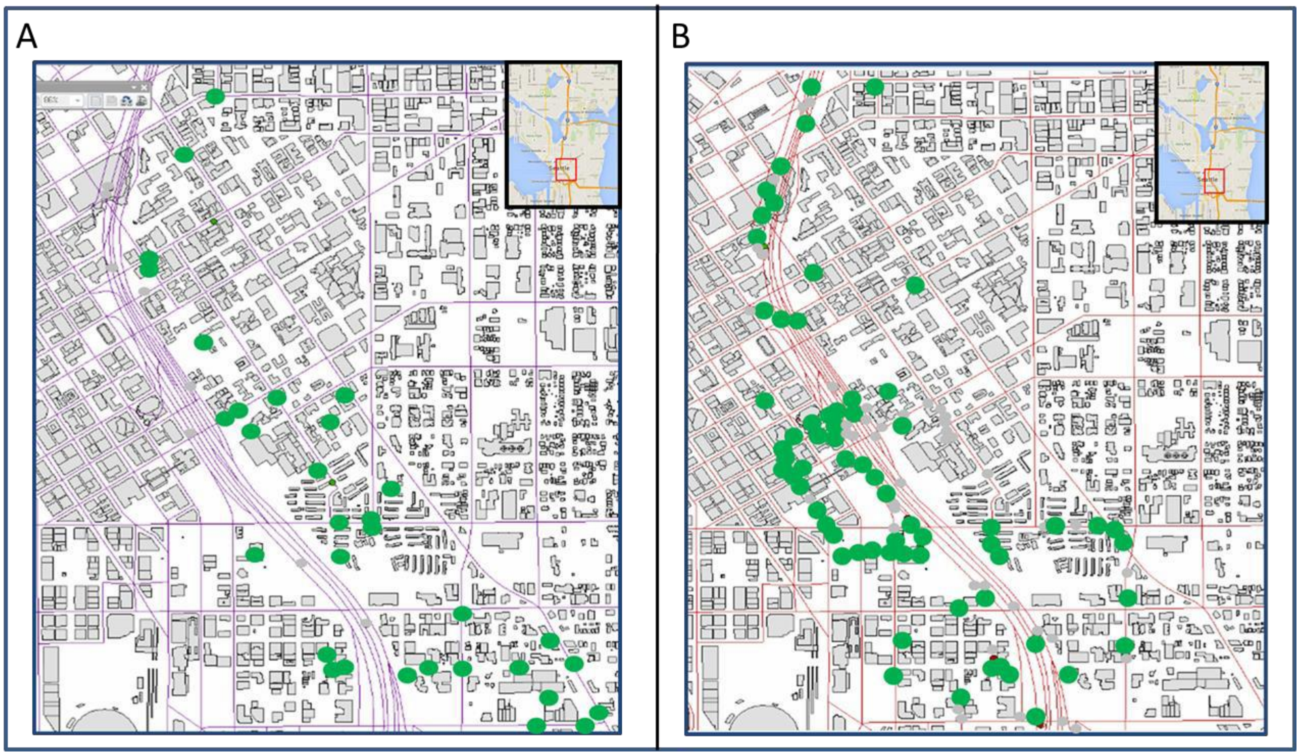

Figure 6-1 Ratios of 1-minute NO2 to the corresponding hourly Beacon Hill concentration: A) Values less than 1.0; B) Values between 2.0 and 4.0. Measurements were taken during peak weekday afternoon commuting times during November and December of 2013.

The proportion of high versus low ratios east and west of I-5 is shown in Table 6.1. Excluding the samples taken within 100 m of I-5, a simple Chi-squared test results in a p value < 0.0001, meaning that there is a link between the ratios somewhat removed from I-5 and the general location east vs. west of I-5. This is fairly obvious from simply looking at the maps in Figure 6.1. The p-value is the same if the near road sites are also included, but there are more sites near I-5 on the west side than on the east side, so this could potentially be a biased comparison.

Table 6-1 Proportion of samples with a given ratio by location

Ratio	West of I-5	East of I-5	Total
<1.0	0.056	0.389	0.444
2-4	0.361	0.194	0.556
Total	0.417	0.583	1.000

Figure 6.2 shows the ratios measured while driving *on* I-5 as compared with near I-5. The data are separated into three geographical regions of I-5 within the study area as shown in Figure 6.2A. The cumulative frequency distributions of the observed ratios are shown in Figure 6.2B where each regions distribution is compared with the overall distribution from all three

regions. As none of these distributions meets the test of normality, we assessed their pairwise differences using the non-parametric two-sample Kolmogorov-Smirnov Two-tailed test. None of the regional distributions differed from the overall distribution with p values of 0.28, 0.94 and 0.61 for the 'I-90 to Denny', 'Denny to Ship Canal' and 'North of Ship Canal' regions, respectively.

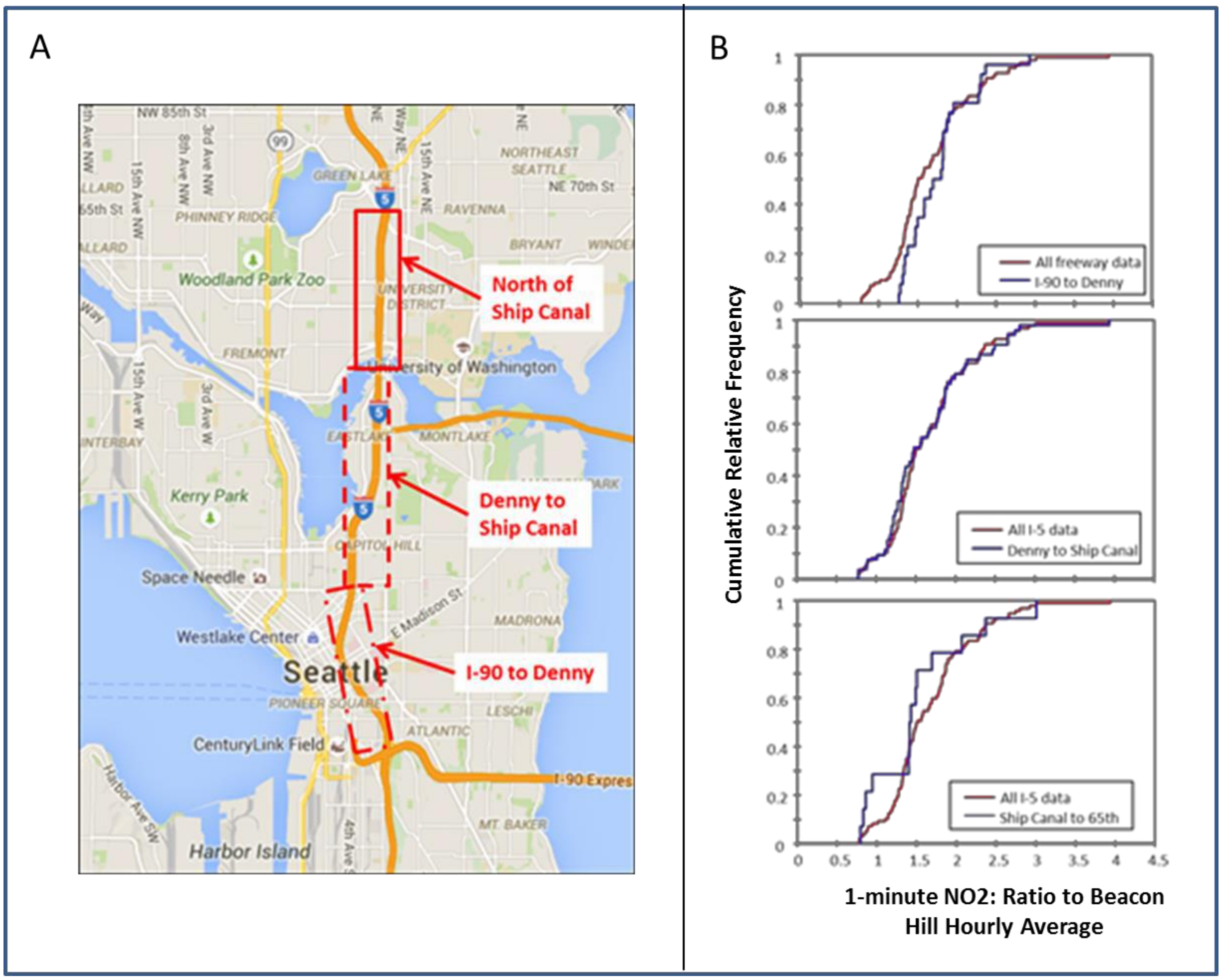

Figure 6-2 Distribution of NO2 ratios observed while driving on different sections I-5 during the study period.

6.2 Stationary Platform 1-minute NO_2 Ratios

The stationary sampling locations are shown in Figures 6.3A and 6.4A. The sites in Figure 6.3A are within 35 to 60 meters of I-5, whereas those in Figure 6.4A are between 90 and 120 meters from I-5. Figures 6.3B and 6.4B show the cumulative frequency distributions of the observed ratios at each site compared with the overall distribution observed on I-5 during the study period. Using the same Kolmogorov-Smirnov Two-tailed test, none of the stationary site distributions are the same as the I-5 distribution ($p < 0.0001$ in all cases). As expected, the near-road values are consistently lower than those observed on I-5.

The nearest sites to I-5 shown in Figure 6-3A had an average ratio of 1.39 versus an average of 1.67 for the on-freeway measurements. The ratio was therefore ~20% higher on the freeway than within 60 meters of the freeway. The two predominately downwind sites to the west of the freeway had an average ratio of 1.56 whereas the predominately upwind sites on the east side of the freeway had an average ratio of 1.22. Therefore the on-freeway values were ~ 7% higher than the downwind sites and ~ 35% higher than the upwind sites.

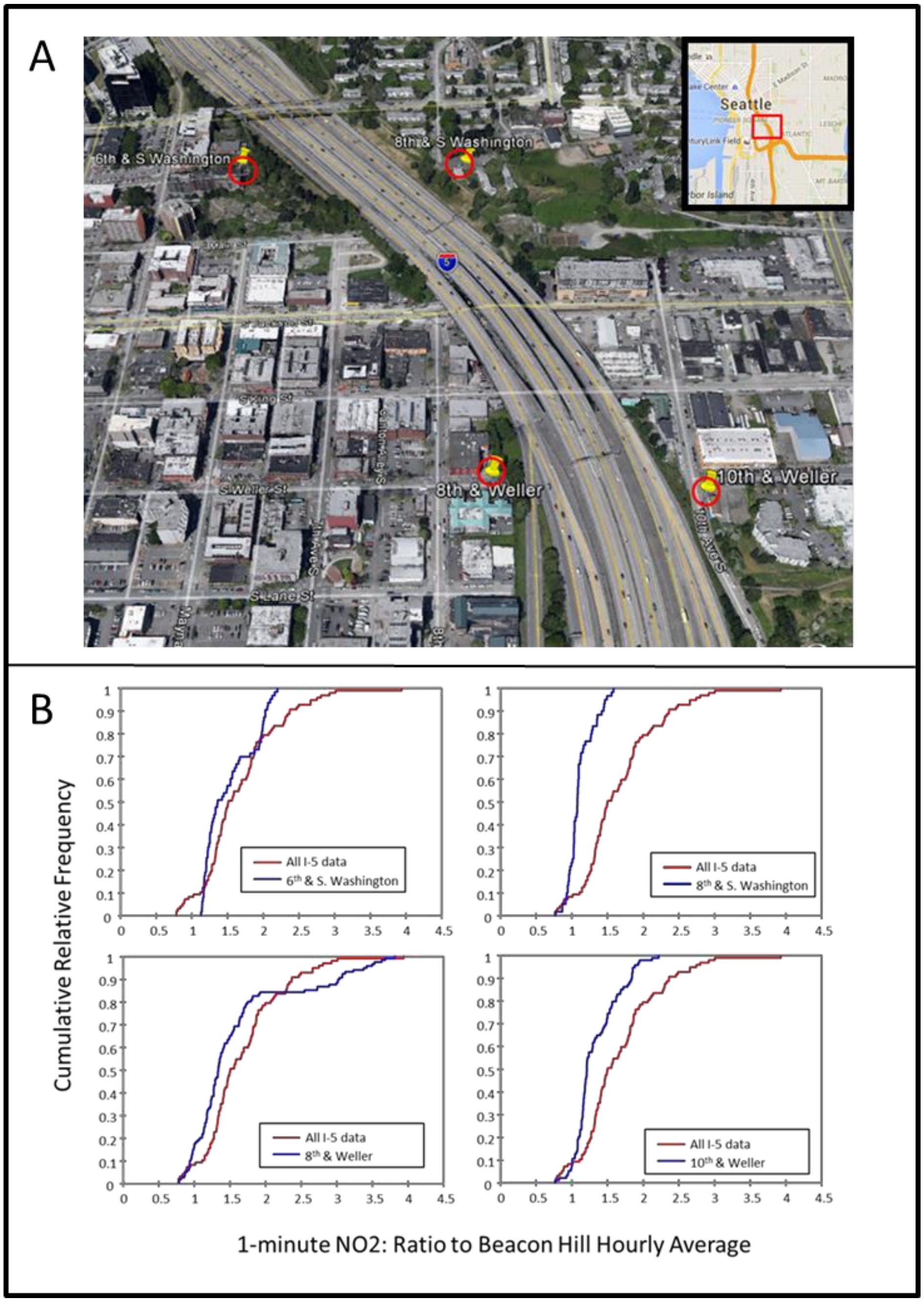

Figure 6-3 Location of stationary monitoring locations (A) and corresponding cumulative frequency distributions of the NO2 ratios compared with those on the I-5 freeway.

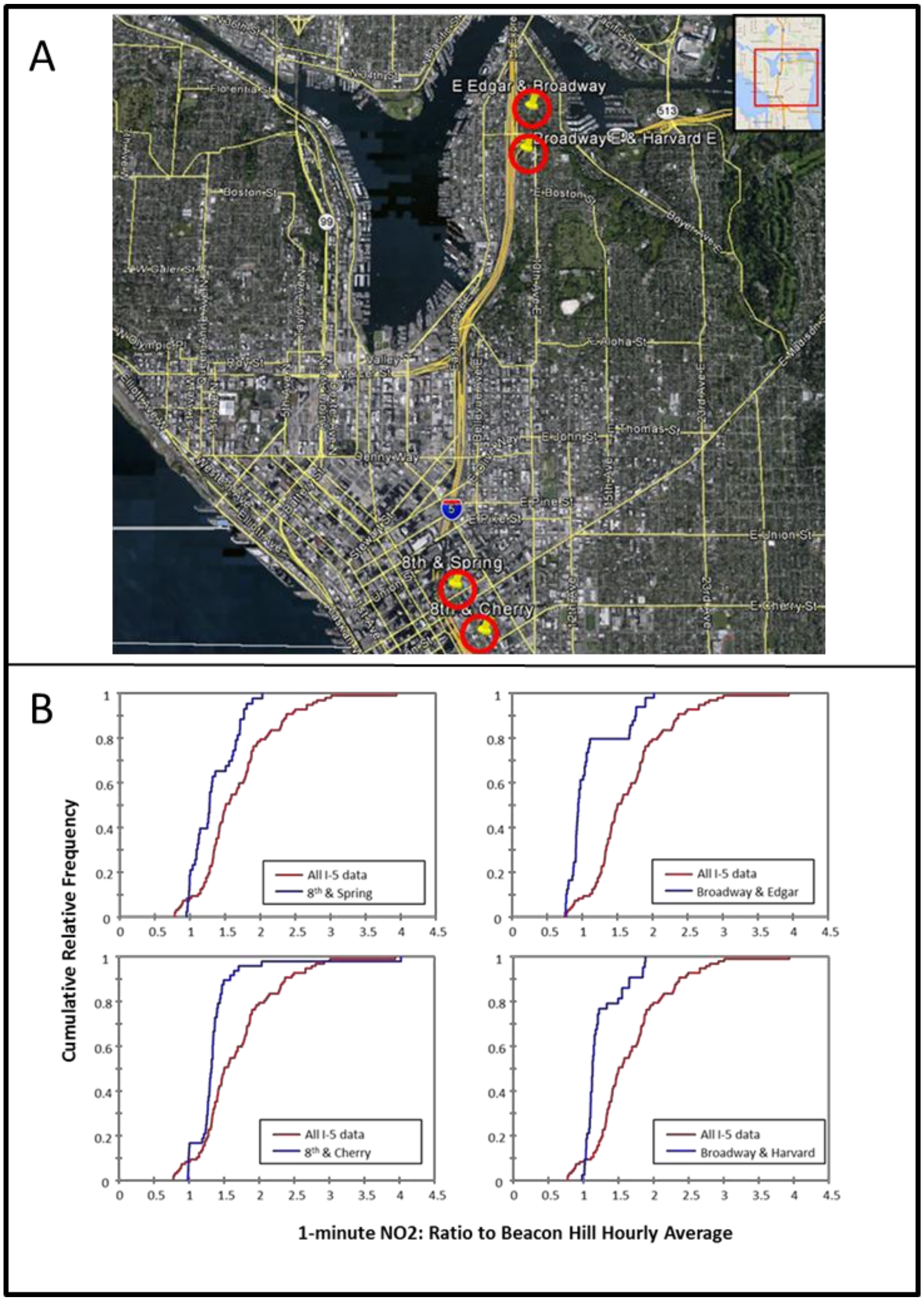

Figure 6-4 Location of stationary monitoring locations (A) and corresponding cumulative frequency distributions of the NO2 ratios compared with those on the I-5 freeway.

6.3 Dispersion Model Predictions

The upwind/downwind differences in the observed NO_2 concentrations at four of the stationary sites are shown in Figure 6.5 were computed and compared with the dispersion model predictions. The Weller St sites were one pair and the Washington St sites were the other pair. Four sampling days that met the steady wind direction modeling criterion described in Chapter 5. One of the upwind/downwind differences could not be computed due to missing data. Therefore there were seven observed upwind/downwind differences that were compared with the model predictions.

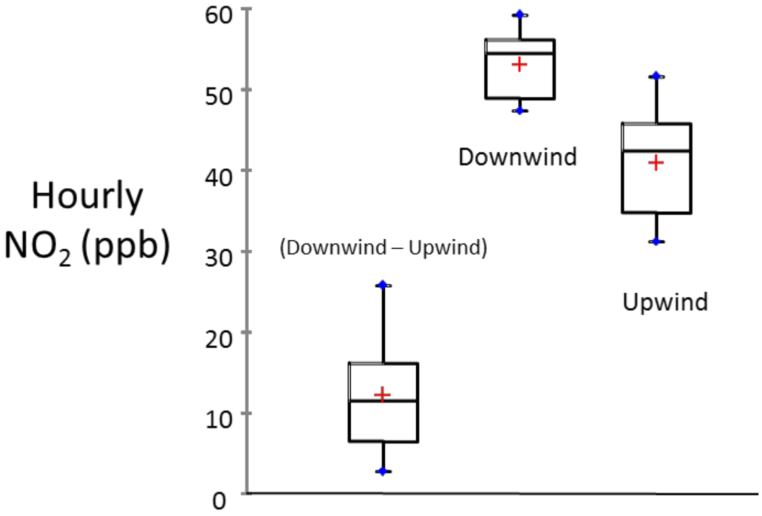

Figure 6-5 Boxplots of the observed NO2 Concentrations at the four Stationary Near-Road site shown in Figure 6.3A. The paired differences are also shown.

Figure 6.6 shows a scatterplot of the predicted downwind concentrations from both the QUIC and CALINE models versus the observed upwind/downwind differences. The CALINE model appears to do a bit better than QUIC, although this conclusion is tentative given the relatively small number of samples. However, it does appear that the QUIC model under-predicts the observations whereas the CALINE model appears to at least capture the mean difference across the four days.

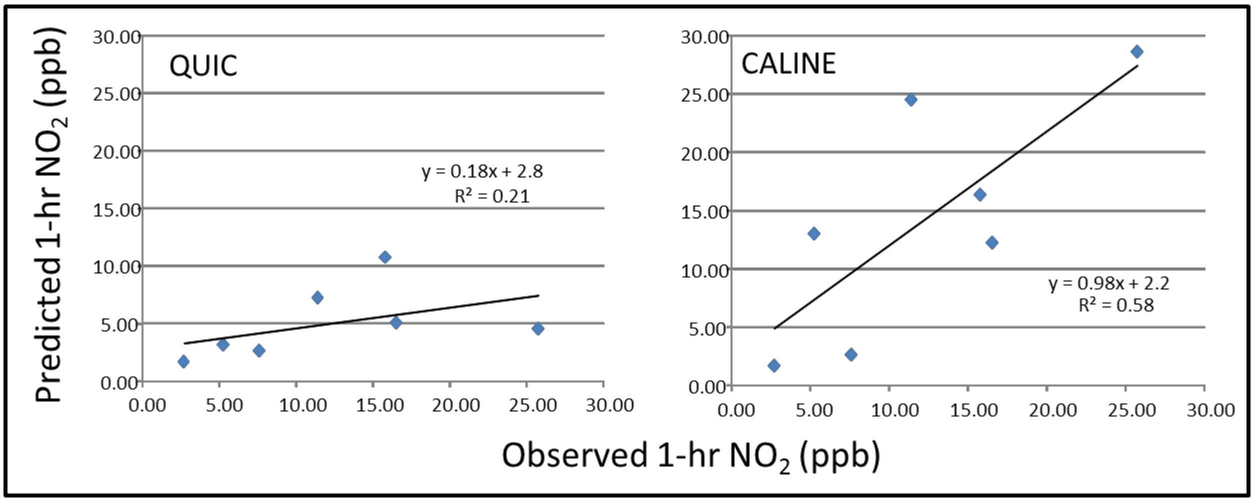

Figure 6-6 Predicted versus observed upwind/downwind differences at paired locations near I-5 south of downtown Seattle. Predictions are from the EPA California Line Source Model (CALINE) and the Quick Urban Industrial Complex (QUIC) model.

Chapter 7 Discussion and Implementation

7.1 Discussion of Findings

Our goal with this study was to explore the feasibility of deploying the CAPS monitor on a mobile platform to obtain information about NO_2 concentrations on and near a major urban freeway. We have demonstrated a simple way to combine the mobile platform's one minute average values and associated GPS derived locations with hourly measurements taken at an existing area-wide fixed site that is part of the traditional regulatory network. The resulting ratio of platform to fixed site values provides useful information on the spatial distribution of NO_2 near a freeway in a complex urban environment.

Given that regulatory fixed-site monitors can theoretically provide minute by minute concentrations in addition to hourly averages, it appears possible to improve this ratio method by using a moving one hour average at the fixed site that is centered about the relevant time of the mobile platform measurements. Even though the major temporal variability at the fixed site was between days, there was some within-day variability that could be captured better by such a moving average, thereby avoiding the inevitable abrupt transitions between discrete hourly values.

The mobile platform can be deployed in a given time period either by parking at a few fixed locations or by continuously moving. Both modes were explored in this study. The NO_2 concentrations observed in the continuously moving mode, when adjusted for temporal variability using a fixed site monitor, were able to clearly show consistently elevated values on the predominately downwind side of the freeway. These elevated values were observed west of and within approximately 200 meters of the freeway in the built-up downtown area and on both sides of the freeway in areas less built-up south of downtown but nearer to I-90. In contrast, consistently lower values were observed on east of downtown and of the freeway. However, it is difficult to isolate the specific impacts from the freeway with these measurements due to the complex interactions between emissions and urban form in the downtown areas. Some of the higher ratios in the downtown core could also be due to street canyon effects that amplifying emission impacts.

In contrast, deploying the mobile platform in a stationary mode by parking at a few fixed locations on both sides of the freeway can provide information on the specific contributions of the freeway to nearby locations. We have shown that paired upwind/downwind measurements taken in this stationary sampling mode, even though lasting for less than an hour at each location, can provide information on the contributions of the freeway to downwind NO_2 levels independent of upwind levels. Our measurements of this upwind/downwind difference ranged between ~5 and 25 ppbv during our sampling campaign, and were reasonably consistent with traditional dispersion model predictions for those sites near the freeway. The CALINE model was better able to predict the mean upwind/downwind difference than the seemingly more detailed QUIC model. This is due in large part to the fact that the QUIC model predicted impacts on the nominally upwind side of the road due to interactions of wind direction with near-road building footprints, whereas the simpler CALINE model did not by definition predict upwind impacts.

On-road NO_2 concentrations are equally as important to estimates of short-term exposures as are near-road levels. There are only a few studies to date that have looked at the relationship between immediately near-road versus on-road NO_2 levels (Bell and Ashenden, 1997; Cape et. al., 2004; Monn et.al., 1997). However, these studies reported concentrations that were time averaged over at least a one-week period. To our knowledge, there are no studies of this relationship at shorter-term averaging times. We have shown that such information can be readily obtained using the platform in a combination of moving and stationary modes. In our limited sampling campaign, we found that mean on-freeway values were about 7% to 35% higher than those observed at the downwind and upwind near road sites, respectively, reasonably consistent with the range of 15% to 35% previously reported in the previous studies cited above.

7.2 Technology Transfer Activities

We plan to submit a paper on the results of this project for publication in a journal and also to present our findings to the air monitoring group at the Washington State Department of Ecology.

Chapter 8 Conclusions and Recommendations

1. The CAPS NO_2 analyzer is a robust and sensitive instrument that can be used on a mobile platform to provide useful information about NO_2 concentrations near busy roadways as well as concentrations on busy freeways.

2. Fixed location measurements near a busy freeway of upwind/downwind differences paired in time ranged between 5 and 30 ppb and were in relatively good agreement with predictions from CALINE, a relatively simple roadway dispersion model.

3. Concentrations of NO_2 on the freeway were on average 7% to 35% higher than the downwind and upwind near road concentrations, respectively, and their respective cumulative frequency distributions also differed.

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