Characterization of Spatial and Temporal Variation of Ultrafine Particles in a Highway Tunnel

A thesis

submitted by

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ABSTRACT

Exposure to traffic-related air pollution has been linked to increased risks of cardiopulmonary disease, asthma, and reduced lung function. Ultrafine particles (UFP; aerodynamic diameter <100 nm) may contribute to these increased health risks. Previous tunnel studies have shown that UFP concentrations are highly elevated in poorly ventilated tunnels compared to open-air mixed roadways; however, little work has been done to characterize the seasonal and temporal variation of UFP in a roadway tunnel. The goals of this work were to characterize UFP and other pollutant concentrations along the length of an urban highway tunnel over the course of one year and more intensely during two wintertime days to analyze seasonal and daily trends. The study was done in the Thomas P. O'Neill Jr. Tunnel on Interstate 93 (I-93; >$1.5\text{x}10^5$ vehicles per day) in Boston, MA. Data was collected by driving the Tufts Air Pollution Lab (TAPL) – which measured particle number concentration (PNC, an indicator of UFP) in the 6 nm to 225 nm size range, as well as CO, NO, NO_x, $PM_{2.5}$, PAH, and black carbon – through the tunnel in each direction on 38 days distributed over one year (Sept 2010 – Sept 2011), and then 45 times in each direction over the course of two days (04:00 – 21:30) in January 2012. PNC was ~8-fold higher in the tunnel than on the highway outside during the 12-month monitoring campaign. In the northbound tunnel, the median PNC (particles/cm^3) was 2.5-times higher during the winter than the summer. Similar differences were observed in the southbound lanes. In January 2012, median PNC inside the tunnel was higher in the morning than evening. Results of this study could inform strategies for tunnel ventilation.

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1. INTRODUCTION

1.1 Health Problems Associated with UFP Exposure

Exposure to particulate air pollution has been linked to increased risks of cardiopulmonary disease, asthma, and reduced lung function (Brugge et al., 2007; Sioutas et al., 2005; Delfino et al., 2005). Ultrafine particles (UFP; aerodynamic diameter <100 nanometers) are a traffic-generated air pollutant that has been measured at elevated levels near major roadways. In-transit studies have linked UFP exposure during commuting to increased risks in healthy and health-compromised individuals (Svartengren et al., 2000; Larsson et al., 2007; Mills et al., 2007); however, to date relatively little research has been done to characterize UFP in a heavily-trafficked roadway tunnel environment.

1.2 Atmospheric Particles

UFP counts are typically very high in comparison to larger particles, but their small size results in a much smaller total mass (Janhall et al., 2006; Weijers et al., 2004; Finlayson-Pitts and Pitts, 2000). The National Ambient Air Quality Standards only regulate mass-based concentration for particles with a diameter less than 2.5 and 10 microns ($PM_{2.5}$ and PM_{10} respectively). These mass concentrations are dominated by larger particles and thus do not accurately account for UFP. As a result PM regulations may not have relevance for vehicle emissions (Zhu et al., 2006). Seasonal changes in relative humidity and temperature may impact vehicle combustion efficiency and photodegradation rates which can, in turn, affect aerosol particle size distribution (Finlayson-Pitts and Pitts, 2000). Kittleson et al. (2000) found that formation of new nuclei-mode particles (diameter 5-50) is enhanced during cooler ambient conditions since there is a stronger driving force for nucleation and growth of nanoparticles when the vapor pressures of condensable species are lower at lower temperatures.

1.3 Previous Research

In comparison to other roadway environments, highway tunnels are an environment where high concentrations of UFP occur (Gouriou et al., 2004; Westerdahl et al., 2005; Zhu et al., 2007; Fruin et al., 2008; Morawska et al., 2008; Knibbs et al., 2009). Vehicle composition, traffic volume, and traffic velocity have been shown to influence the UFP count in highway tunnels. The enclosed nature of tunnel systems limits the ability for exhaust plume dispersion to occur, causing accumulation of UFP along the length of tunnels. Longitudinal ventilation occurs in unidirectional tunnels when the traffic creates air flow that discharges from the distal end of the tunnel (Barrefors et al., 1996). In a tunnel with a steady flow of traffic, longitudinal ventilation causes pollutant concentrations to increase with distance (Cheng et al., 2009). Traffic speed and volume have been strongly correlated with pollutant emission rates at the exit of one-way tunnels (De Fre et al., 1994). Higher traffic volumes and lower traffic speeds result in higher pollution levels within and at exits of tunnels. This can lead to increased pollutant concentrations in areas located at either end of roadway tunnels as well as at outflows of tunnel ventilation systems.

Recent studies have measured and analyzed the effects of traffic volume and composition on in-tunnel UFP concentration using the mobile laboratory approach. These studies have shown that hourly heavy diesel vehicle volume (HDV) is a highly significant determinant of hourly median trip-averaged concentrations of UFP in tunnels (Westerdahl et al., 2005; Knibbs et al., 2009).

Seasonal monitoring has shown that UFP concentrations near highways are highest during the winter season and peak daily concentrations occur during the morning rush hour (Padro-Martinez et al.; Wang et al., 2010). Wang et al. conducted a study in Rochester (New York) from 2002 until 2009 in which they analyzed the seasonal UFP trends. They found that the lowest monthly average number concentration of 10-50 nm particles was in July and the highest in February. Wang et al. suggested that these trends could likely be explained by the formation of new nuclei-mode particles in colder ambient temperatures described by Kittelson et al. (2000) and less dilution from poorer mixing in wintertime (Kittelson et al., 2004; Wang et al., 2010; Zhu et al., 2004).

Commuter exposures to UFP and other traffic-related air pollutants on roadways are largely determined by air infiltration rates (Hammond et al., 2007; Rim et al., 2008; Knibbs and de Dear, 2010; Zhang and Zhu, 2010). In a 2009 study of six different automobiles operating under four distinct ventilation settings, Knibbs et al, observed that infiltration increased linearly with vehicle speed. Based on measurements in a tunnel, Knibbs et al. found that the proportion of tunnel-air UFP reaching the cabin varied from 0.08 when the ventilation system was recirculating air at the maximum rate to ~1.0 when the recirculation system was off.

1.4 The Problem & Objectives

Little work has been done to study the seasonal or diurnal variation of UFP concentrations in urban highway tunnels. The I93 Central Artery in project in Boston, Massachusetts has helped to decrease traffic congestion in the greater Boston area since its completion in 2005. With >10^5 vehicles traveling through the Thomas P. O'Neill Jr. Tunnel in each direction each day, a significant amount of traffic-related air pollution (TRAP) is being released within an enclosed environment.

The goal of this study was to characterize the seasonal and diurnal variation of UFP and other pollutants under different driving conditions in an urban highway tunnel located in Boston, Massachusetts. The objectives were to (1) measure traffic-related air pollutants while driving through the tunnel using the Tufts Air Pollution Lab (TAPL) over the course of a one year period and thereby capture the seasonal trends in pollution, (2) collect two days of data in January 2012 from 04:00 – 22:00 to measure and analyze the diurnal variation of UFP in the tunnel, and (3) measure in-cabin UFP and analyze infiltration rates and lag time into the cabin by collecting an additional data set inside of the TAPL during the January 2012 in-tunnel monitoring campaign. Results from this study on the seasonal and temporal trends in traffic-related air pollution may help to establish when worst case (highest concentration) scenarios are likely to occur.

This could help to inform strategies for tunnel ventilation. This study's results may also identify the need for additional studies that look more closely at the drivers of spatial and temporal pollutant trends in tunnels.

2. METHODS

2.1 Tunnel Location

The highway tunnel studied was the Thomas P. O'Neill Jr. Tunnel, the underground portion of I-93 located in Boston (Massachusetts, USA) that connects the Zakim Bridge over the Charles River to South Boston (Figure 1). The tunnel has been in operation since 2005. The tunnel consists of two unidirectional bores, each approximately 2.5 km in length. The operating speed in the tunnel is about 64 km/h when there is no traffic congestion.

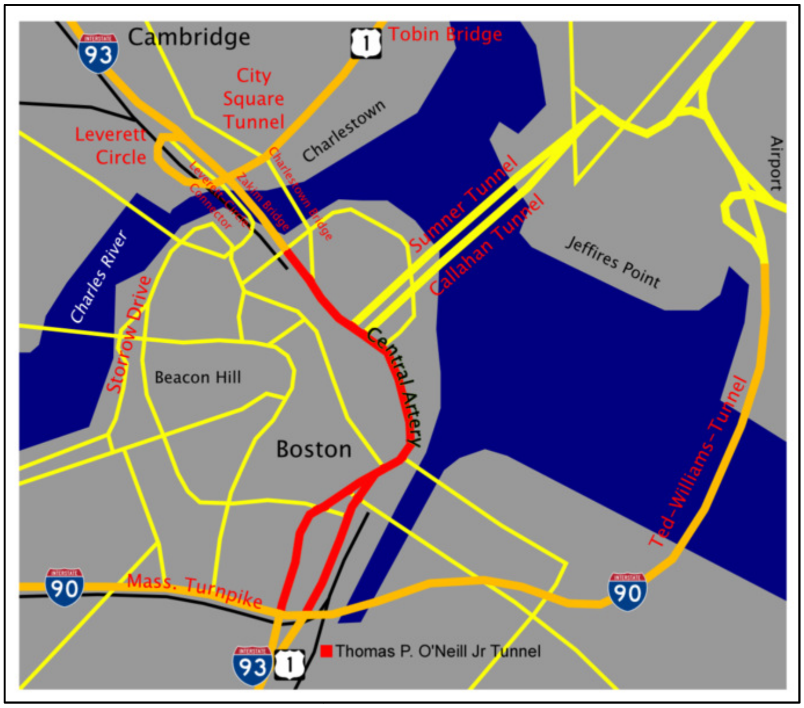

Figure 1. Aerial view of the Thomas P. O'Neill Jr. Tunnel (red) as part of the I-93 Central Artery located in Boston, Massachusetts.

Traffic counts from 2010 indicate that $>10^5$ vehicles per day travel in each direction through the tunnel. Figure 2 illustrates the layout of each bore, identifying approximate locations of on-ramps and exits, as well as indicating the number of lanes at a given location in the tunnel.

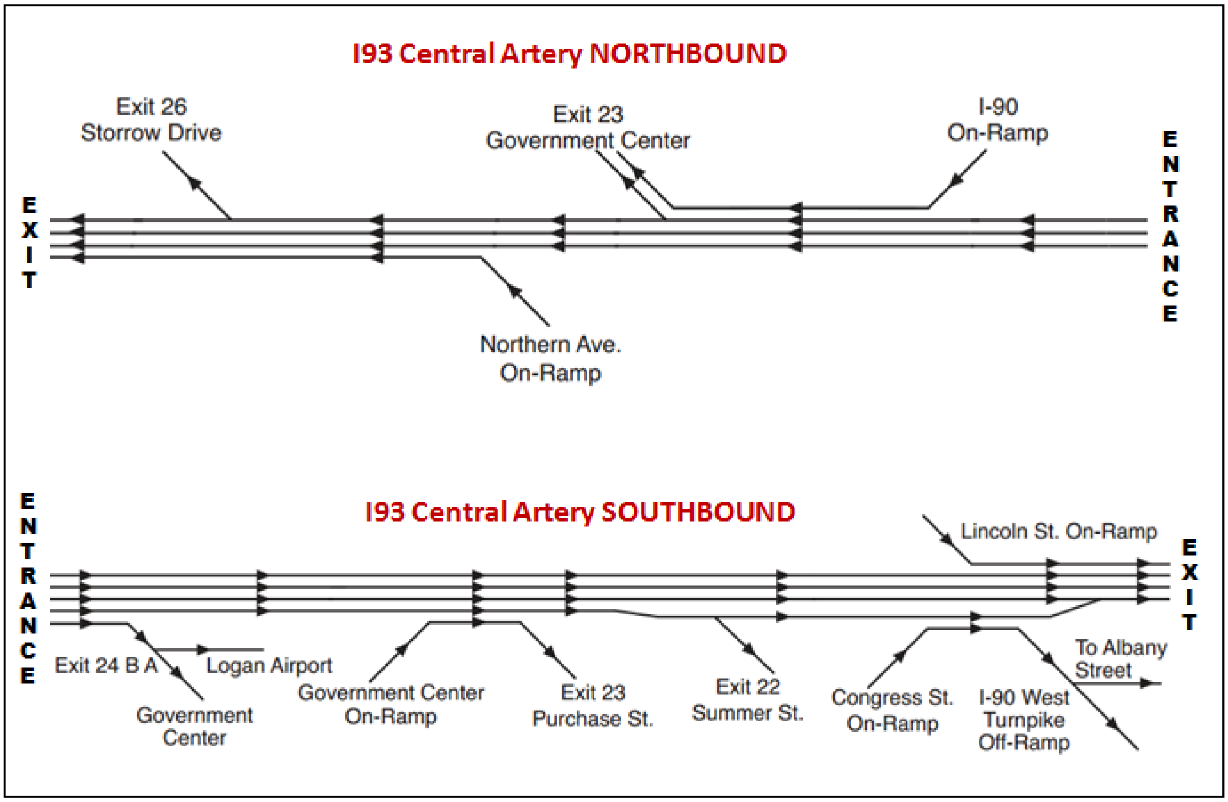

Figure 2. Schematic of traffic lanes within the Northbound and Southbound bores of the Thomas P. O'Neill Jr. Tunnel including all on ramps and exits (off ramps).

Table 1 more precisely describes the locations of on-ramps and exits.

Table 1. Locations of all on ramps and exits (off ramps) for the Thomas P. O'Neill Jr. Tunnel portion of the I-93 Central Artery.

Southbound Bore	**Distance (km)**
Entrance	0.00
Exit 24 (off ramp)	0.40
On ramp	0.76
Exit 23 (off ramp)	1.06
Exit 20 (off ramp)	1.45
On ramp	2.37
Exit	2.46
Northbound Bore	
Entrance	0.00
On ramp	0.39
On ramp	1.51
Exit 23 (off ramp)	1.53
Exit 26 (off ramp)	2.20
Exit	2.53

There is no mechanical ventilation system in operation for the Thomas P. O'Neill Jr. Tunnel; all ventilation occurs longitudinally, both at the main exit of each tunnel bore along I-93 and at each exit with off-ramps from within the tunnel (Massachusetts Turnpike Authority, 2006).

2.2 Seasonal Measurements

The Tufts Air Pollution Lab (TAPL) was used to collect data within the Thomas P. O'Neill Jr. Tunnel, and measurements were also made along the I-93 open-air highway for at least a distance of 400 m from the tunnel's main entrances and exits. The TAPL is equipped with rapid response instruments for measuring carbon monoxide, nitrogen oxides, $PM_{2.5}$, black carbon, particle-bound polycyclic aromatic hydrocarbons, and ultrafine particles (Table 2).

Table 2. Instruments used for data collection in the Tufts Air Pollution Lab (TAPL), including model/manufacturer, measurement reporting frequency, and pollutant description.

Pollutant(s)	*Instrument Model / Manufacturer*	*Measurement reporting frequency*
Ultrafine Particle Number Concentration (6-225 nm)	Condensation Particle Counter (CPC) Model 3775 / TSI	1 second
Polycyclic aromatic hydrocarbons (PAHs)	PAS 2000 / EcoChem Analytics	8 seconds
Particulate Matter Mass Concentration (<2.5 µm)	Model AM510 SidePak Personal Aerosol Monitor / TSI	1 minute
"Black" carbon aerosol particles	Aethalometer / Magee Scientific	1 minute
Carbon monoxide (CO)	48i – TLE / Thermo Fischer	10 seconds
Nitric oxide (NO), Oxides of nitrogen (NO_x)	42i / Thermo Fischer	10 seconds

All of these instruments were powered by two Honda EU2000i Companion Generators, housed in well-ventilated compartments on either side at the back of the TAPL. Separate gas and particle inlets were located on the roof of the TAPL, approximately 3 m off the ground and 5.5 m from the rear of the vehicle. Additional testing determined that self-sampling was most likely to occur when the wind was blowing from behind the TAPL and the wind speed exceeded the vehicle speed. These self-sampling simulation tests (June 2010) indicate that pollutant concentrations measured when self-sampling occurred were <12% of the pollutant concentrations measured inside of the Thomas P. O'Neill Jr. Tunnel during the summertime monitoring in 2010 and 2011. Additionally, in-tunnel measurements minimized the impact of both wind speed and direction, making it unnecessary to correct the data for self-sampling.

The CPC Model 3775 has an upper detection limit of 10^7 particles/cm^3. The measured values did not near or exceed this value during data collection within the Thomas P. O'Neill Jr. Tunnel. The manufacturer-stated precision is 10% at $<5\text{x}10^4$ particles/ cm^3 and 20% at $<10^7$ particles/ cm^3. The majority of the data set falls within the 20% particle concentration precision range. The low-flow mode (0.3 +/- 0.015 L/min) was used during data collection. The lag time between when the air entered the inlet on top of the TAPL and when the measurement was recorded by the CPC was ~8 s, and this was corrected for during the QAQC process. The CPC was zero checked and the flow rate was measured using a Bios Defender$^{\text{TM}}$ 500 Series prior to each use.

Monitoring was done on 38 different days between September 2010 and September 2011. One traverse of the southbound tunnel and one traverse of the northbound tunnel were completed on each day of data collection. Additional measurements were taken along the I-93 in Somerville, located just north of Boston, in order to compare in-tunnel and on highway pollutant concentrations. Collection of the data occurred at various times of day across all four seasons and was limited to only weekdays.

Average weekday daily traffic (AWDT) and hourly volumes for the I-93 Central Artery from 2010 were obtained from the Boston Region Metropolitan Planning Organization. This data set included averages at the tunnel entrance and exit along I-93 as well as after each on-ramp and off-ramp within the tunnel. The AWDT values ultimately used in analysis were weighted based on the times that data collection occurred and the hourly traffic counts for each of the tunnels. Additionally, a log book was kept to record observations within and near the entrance and exit of the tunnel, and in particular to note when large diesel vehicles were also in the tunnel.

2.3 Diurnal Measurements

A total of 45 runs of each tunnel were made on January 4, 2012 and January 5, 2012 to characterize wintertime diurnal variations. Over the course of the two days, traverses of each tunnel bore occurred approximately every 30 min from 04:00 to 10:30 and 15:00 to 21:30. The two days had similar meteorological conditions and represented typical midweek winter days in Boston. Meteorological data collected at Logan International Airport in Boston was obtained from Weather Underground, Inc. and was utilized to compare the conditions on the two days.

In addition to the suite of instruments used in the TAPL during the initial monitoring effort, a TSI CPC Model 3783 (diameter size range 7-3000 nm, reporting frequency 1 s) was used to measure the UFP concentration inside of the mobile lab. The CPC Model 3783 had an upper detection limit of 10^6 particles/cm^3. The measured values did not near or exceed this value during data collection within the TAPL while passing through the tunnel. The manufacturer-stated accuracy was 10% at 10^6 particles/ cm^3. The low-flow mode (0.6 +/- 0.06 L/min) was used during data collection, and the response time was <5 s. The CPC Model 3783 was zero checked and the flow rate was measured using a Bios Defender^{TM} 500 Series prior to each use.

2.4 Analysis

The data collected during September 2010 - September 2011 was divided into seasonal subsets for each tunnel. The data for all runs during a given season were compiled and placed into 400-m distance bins measured relative to the tunnel entrance. Igor Pro 6.2 Software was used to create box plots of the binned data for four different pollutants: Ultrafine Particles (reported as particle number count, #/cm^3), CO concentration (ppb) and NOx concentration (ppb). One set of box plots was created for the northbound tunnel and one set was created for the southbound tunnel, since traffic conditions were different in the two tunnels. The average weekday daily traffic patterns were also plotted to indicate how AWDT volume changed throughout the tunnel and to allow for a comparison to how ultrafine particle counts varied within the tunnel. In addition, data for individual runs were plotted as time-series in order to observe the change in PNC between the open air and in-tunnel environments.

Average PNC concentrations for each run on January 4, 2012 and January 5, 2012 were plotted versus time to analyze the daily temporal trends in ultrafine particle levels. In-cab PNC data was used to analyze infiltration into the TAPL during monitoring on January 5, 2012. Time series plots were created to compare tunnel air and in-cab PNC as well as to estimate the lag time between the two measurements. The data sets were processed in two different ways. First, both the tunnel air and in-cab counts were normalized to their respective values at the tunnel entrance to show how the magnitudes changed over time. Second, both data sets were normalized to the tunnel air value at the tunnel entrance to compare the magnitudes of the tunnel versus in-cab PNC. Box plots for each tunnel were created for the morning data set as well as the evening data set.

Spearman Correlation Coefficients (ρ^2) for the data from January 4, 2012 and January 5, 2012 were calculated for all of the pollutants measured by the TAPL as an additional data quality assurance measure.

3. RESULTS & DISCUSSION

During the 12-month monitoring campaign, data was collected on 37 out of the 38 trips in each tunnel bore. There were equal numbers of runs through the northbound (n=37) and southbound (n=37) bores, representing 2.46 h and 2.15 h of data collection in each tunnel, respectively. The average trip duration was 3 min 29 s in the northbound direction and 3 min 59 s in the southbound direction. The longest trip (25 min 3 s) was recorded in the southbound tunnel during evening peak traffic conditions on June 16, 2011. Run lengths were defined as the sum of the tunnel length plus 400 m on either end, resulting in a total distance of 3.2 km, of which 2.4 km (75%) was within the tunnel (the run times reported herein include the time to travel the additional 400 m at each end of the tunnel bores). Table 3 displays the seasonal breakdown of data collection.

Table 3. Seasonal breakdown of monitoring duration in the Thomas P. O'Neill Jr. Tunnel during the September 2010 – September 2011 monitoring campaign.

Northbound Tunnel

Season[1]	Fall	Winter	Spring	Summer	*Total*
Runs	10	9	12	6	*37*
Total Duration	41 m 23 s	28 m 35 s	43 m 42 s	15 m 15 s	*129 m*

Southbound Tunnel

Season[1]	Fall	Winter	Spring	Summer	*Total*
Runs	10	9	12	6	*37*
Total Duration	36 m 58 s	29 m 37 s	43 m 28 s	37 m 35 s	*148 m*

[1] Fall = 09/24/10 to 12/21/10; Winter = 12/22/10 to 03/20/11; Spring = 03/21/11 to 06/21/11; Summer = 09/01/10 to 09/23/10 and 06/21/11 to 09/23/11

On January 4, 2012 and January 5, 2012 45 runs of the tunnel were made in each direction. Twenty-two runs were completed through each bore on January 4, 2012, and 23 runs were completed through each bore on January 5, 2012. Since average in-tunnel concentrations were calculated to analyze the daily temporal trends, the run length was defined as only the 2.4 km within each tunnel for this portion of the data set. Run durations were shorter than in the year-long monitoring campaign (~75% of the duration defined in the September 2010 – September 2011 data set). On January 4, 2012, 81 min 45 s was spent in the tunnel, and 79 min 30 s was spent in the tunnel on January 5, 2012. The average run duration (from tunnel entrance to exit) was 1 min 49 s on January 4, 2012 and 1 min 46 s on January 5, 2012. The longest recorded trip during these two days was 3 min 3 s and occurred in the southbound bore during peak traffic conditions the morning of January 5, 2012.

In-cab PNC measurements were also collected on January 4 and 5; however, a change was made on the second day of monitoring. On January 5, the windows of the TAPL were opened for approximately one minute between each tunnel run to ensure the cabin was fully flushed and residual PNC would not accumulate across subsequent runs. For this reason, only the January 5, 2012 data is used for the infiltration analysis. The vehicle used as the Tufts Air Pollution Lab (TAPL) is manufactured by Chevrolet (2002). When the vehicle is moving, the flow-through ventilation system supplies outside air to the inside of the vehicle through the front air inlet grilles at the base of the windshield and exhausts out the rear air exhaust valve after passing through the cabin. When the heater is running, as was the case during this monitoring campaign, the system supplied additional outside air through the same vents. The ventilation system did not have a recirculation feature; therefore, the cabin was being continuously refreshed with outside air, thus creating the potential for a worst-case scenario for UFP infiltration. Air vents are located at the front of the cab, approximately 1 m from the location where the inlet to the CPC 3781 was located inside the TAPL.

In addition to UFP concentrations, the TAPL collected data on the CO, NO, NO_2, NOx, PAH, BC and $PM_{2.5}$ concentrations (PAH, BC, and $PM_{2.5}$ data are included in the appendix) within the tunnel during monitoring on the two January 2012 days. Table 4 displays the spearman correlation coefficients for the various pollutants measured in the northbound tunnel bore on the morning of January 5, 2012 from 04:00 until 10:00. Ten-second averages of the data were used to account for the varied reporting frequencies of the instruments. Stronger correlations were evident as expected between combustion exhaust products, such as PNC and NO, while a weaker correlation was observed between PNC and $PM_{2.5}$. Bold blue font indicates that the value is higher than the same statistic calculated from a data set collected within 50 m of I93 in Somerville, located just north of Boston (Padro-Martinez et al.).

Table 4. Spearman correlation coefficients for data collected in the northbound tunnel on the morning of January 5, 2012 from 04:00 until 10:00.

	CO	NO	NO$_2$	NO$_x$	PAH	PM$_{2.5}$
PNC	**0.585**	0.644	**0.55**	0.651	**0.617**	**0.372**
CO		**0.779**	**0.564**	**0.781**	**0.533**	0.337
NO			**0.624**	**0.993**	**0.759**	0.164
NO$_2$				**0.694**	**0.393**	**0.812**
NO$_x$					**0.739**	0.15
PAH						**0.19**

3.1 In-tunnel UFP concentration

Figure 3 displays a PNC time-series plot for the northbound tunnel measured on March 2, 2011. Median PNC was 3.7x10^5 particles/ cm^3 and 2.6x10^5 particles/ cm^3 in the southbound and northbound bores, respectively. The median PNC measured on I-93 in Somerville was 3.7x10^4 particles/cm^3 in both the southbound and northbound directions. Thus, the median in-tunnel PNC levels were higher than median on-highway PNC levels in Somerville by a factor of ~10 in the southbound direction and ~7 in the northbound direction. Overall median PNC on I-93 in Somerville was 3.7x10^4 particles/ cm^3, and overall median PNC in both tunnels was 3.0x10^5 particles/ cm^3 (higher by a factor of ~8). The median urban background PNC in Somerville during this same period was ~1.8x10^4 particles/cm^3 (Padro-Martinez et al.).

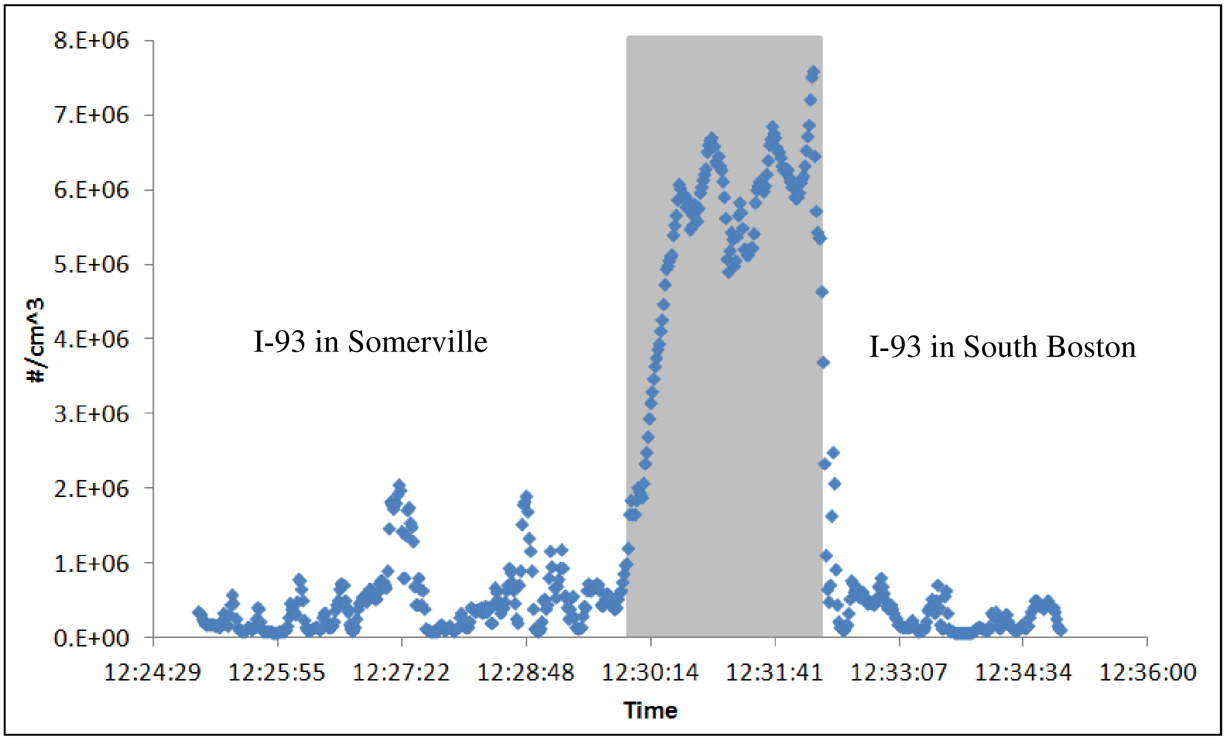

Figure 3. UFP concentration time-series plot of one run of the northbound tunnel on March 2, 2011. The area highlighted in gray indicates when the TAPL was inside of the tunnel. Traffic speed was consistent along I-93 and through the tunnel during this monitoring period.

3.2 Seasonal Variation

Figures 4 and 5 display the seasonal breakdown of the PNC data during the 12-month campaign for the northbound and southbound bores, respectively. The top portion of each figure also displays the change in traffic volume at different locations throughout each bore based on the weighted average weekday daily traffic counts from 2010 (Boston Metropolitan Planning Organization).

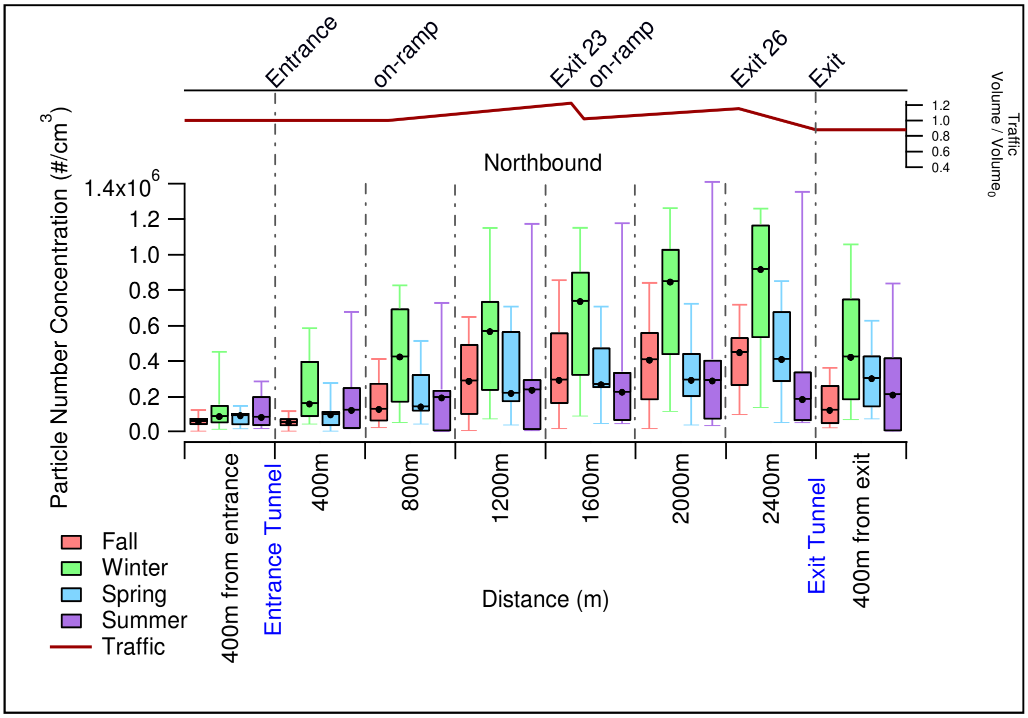

Figure 4. Seasonal box plots of PNC versus distance in the Northbound bore of the Thomas P. O'Neill Jr. Tunnel during the September 2010 – September 2011 monitoring campaign including average weekday daily traffic counts.

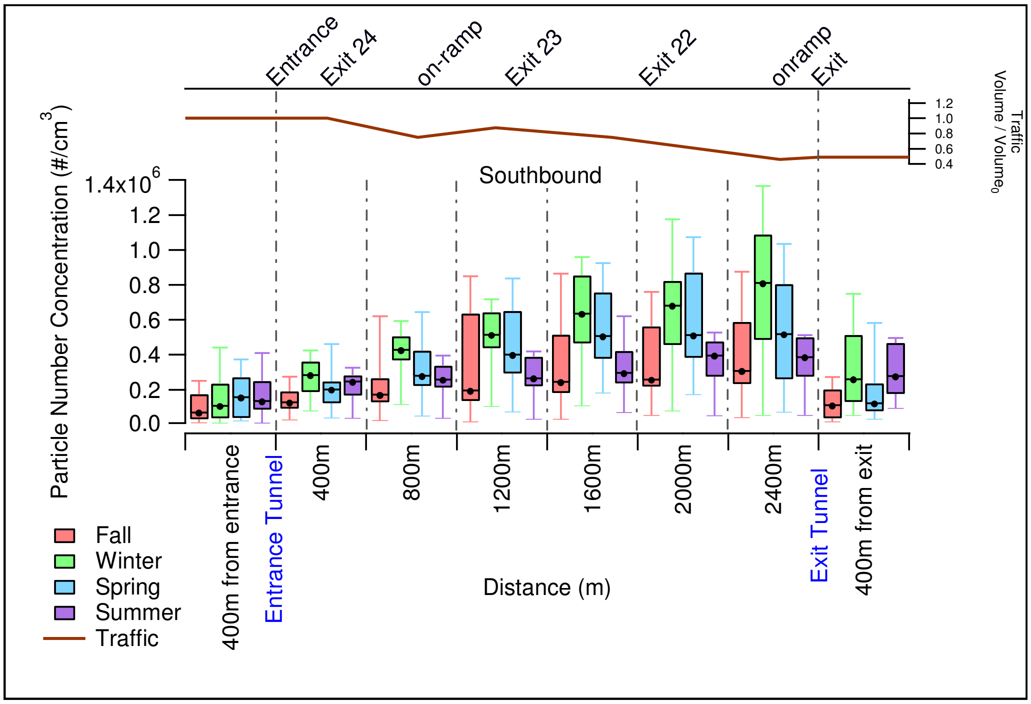

Figure 5. Seasonal box plots of PNC versus distance in the Southbound bore of the Thomas P. O'Neill Jr. Tunnel during the September 2010 – September 2011 monitoring campaign including average weekday daily traffic counts.

In both bores, PNC levels measured by the TAPL were significantly higher during the winter months than during the summer months. In the northbound bore, the median in-tunnel PNC measured was $4.5\text{x}10^5$ particles/cm^3 during the winter and $1.8\text{x}10^5$ particles/cm^3 during the summer. Similarly, the median PNC measured in the tunnel's southbound bore was $4.4\text{x}10^5$ particles/cm^3 during the winter and $2.1\text{x}10^5$ particles/cm^3 during the summer. Colder ambient temperatures, which result in a stronger driving force for nucleation and the formation of nanoparticles, and minimal mixing during the winter months may account for this seasonal variation in PNC levels within the tunnel. The formation of ammonium nitrate as a secondary pollutant in lower temperatures may also be contributing to the observed trends. Drewnick et al. (2004) and Weimer et al. (2006) studied aerosol composition in New York City during the summer 2001 (duration = 36 days) and winter 2004 (duration = 30 days), respectively. Both studies found that average ammonium concentrations were 1.7 µg/m^3, but the average nitrate concentration during the summertime study was only 0.68 µg/m^3 and the wintertime concentration of nitrate was 2.6 µg/m^3 based on Weimer's study. The increased formation of nitrate, driven by the accelerated reaction of ammonia and nitric acid in colder temperatures, may help to explain the season trends observed in our study (Schneider and Voigt, 2011). Previous studies have noted similar seasonal trends in near-highway UFP concentration (Wang et al., 2010; Padro-Martinez et al., 2012; Hussein et al., 2005).

The binned data displays the increase in PNC with distance in the tunnel across all seasons and for each tunnel direction. The wintertime median PNC increased by a factor of ~10 in the northbound bore and ~8 in the southbound bore between the entrance and the exit of the tunnel. The traffic plots indicate that the overall traffic volume increases within the northbound tunnel and decreases within the southbound tunnel, which may help to explain the larger increase in PNC levels recorded in the northbound tunnel.

CO and NOx concentrations measured throughout the year-long data set were also analyzed for seasonal trends. Figures 6 through 9 display the binned data in a similar format to the PNC box plots.

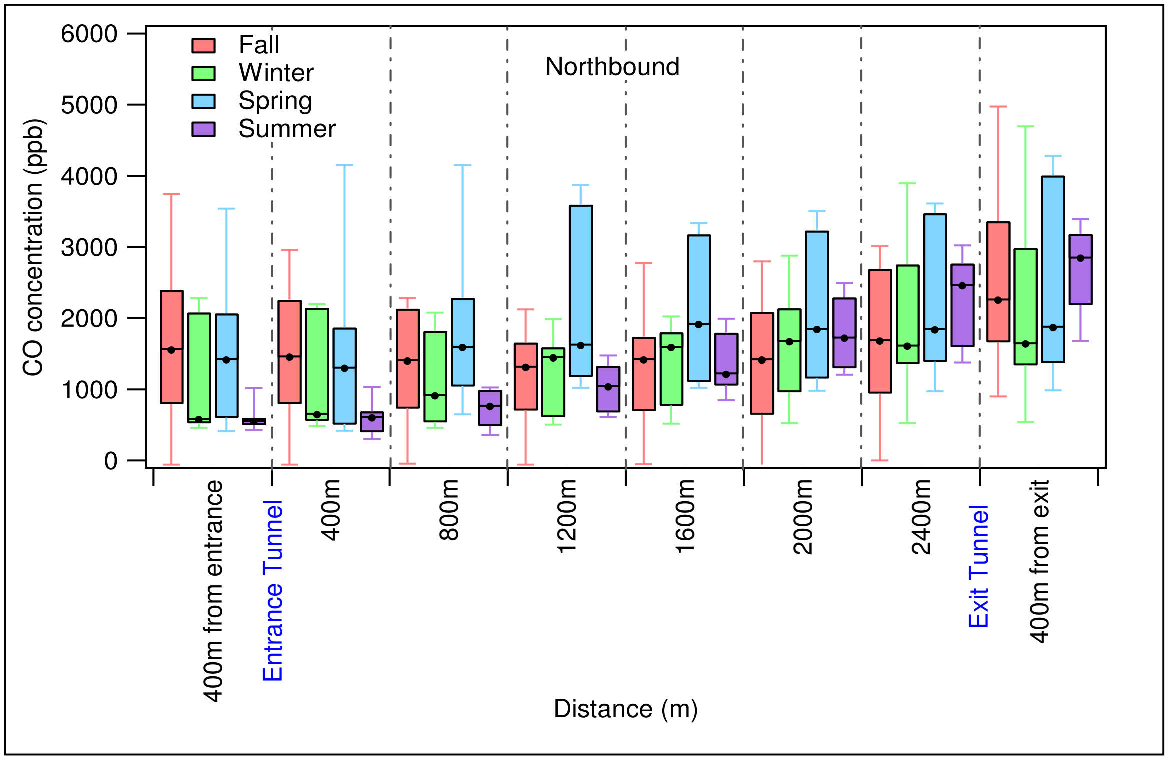

Figure 6. Seasonal box plots of CO concentration versus distance in the northbound bore of the tunnel during the September 2010 – September 2011 monitoring campaign.

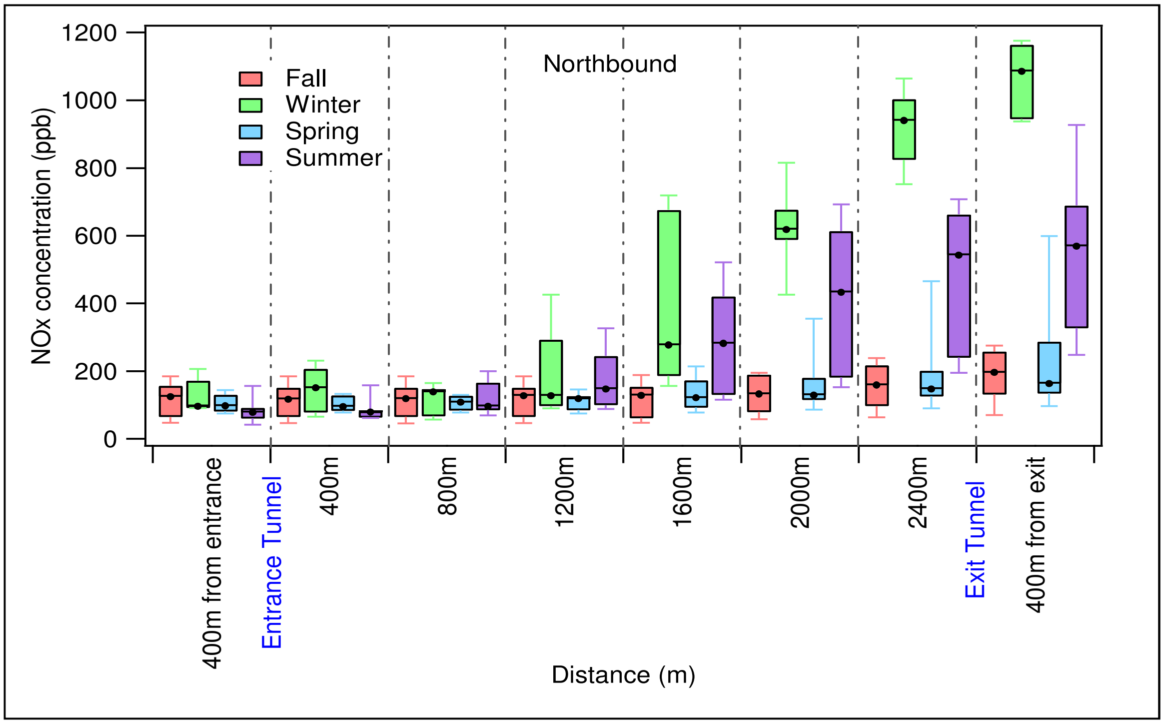

Figure 7. Seasonal box plots of NOx concentration versus distance in the northbound bore of the tunnel during the September 2010 – September 2011 monitoring campaign.

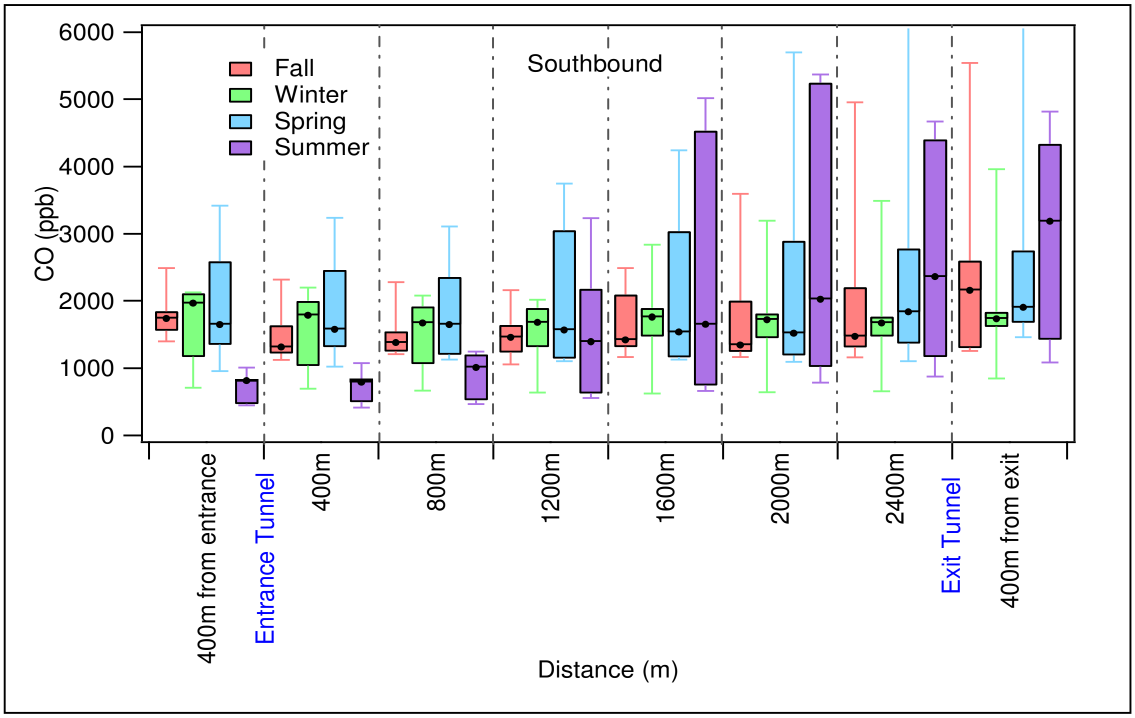

Figure 8. Seasonal box plots of CO concentration versus distance in the southbound bore of the tunnel during the September 2010 – September 2011 monitoring campaign.

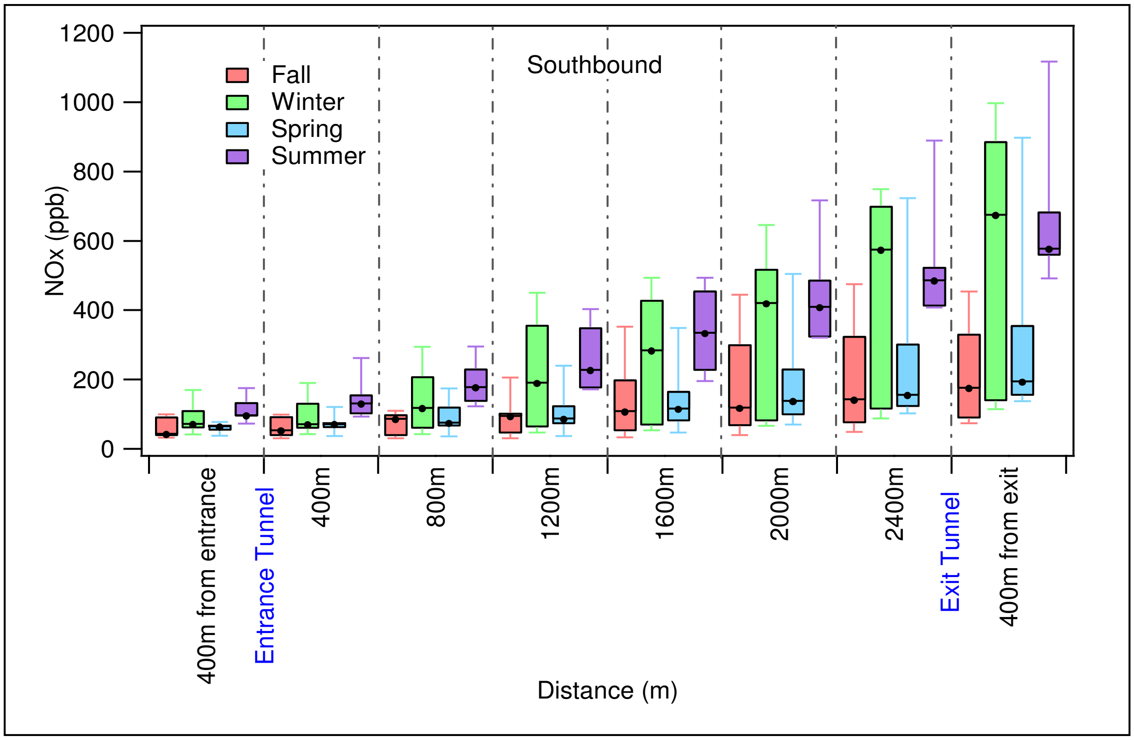

Figure 9. Seasonal box plots of NOx versus distance in the southbound bore of the tunnel during the September 2010 – September 2011 monitoring campaign.

3.3 Influence of HDVs on PNC in-tunnel

Although it was not possible to obtain precise and accurate data on the heavy diesel vehicle (HDV) patterns within the tunnel, the log book used inside of the TAPL served as a means to observe the proximity of HDVs during in-tunnel monitoring. Figure 10 displays six runs of the southbound tunnel which all occurred on different days (in fall and winter) between 05:15 and 05:30. Each spike identified in the November 5, 2010 data set represents the presence of an HDV within close proximity (3-5 m) of the TAPL inside of the tunnel.

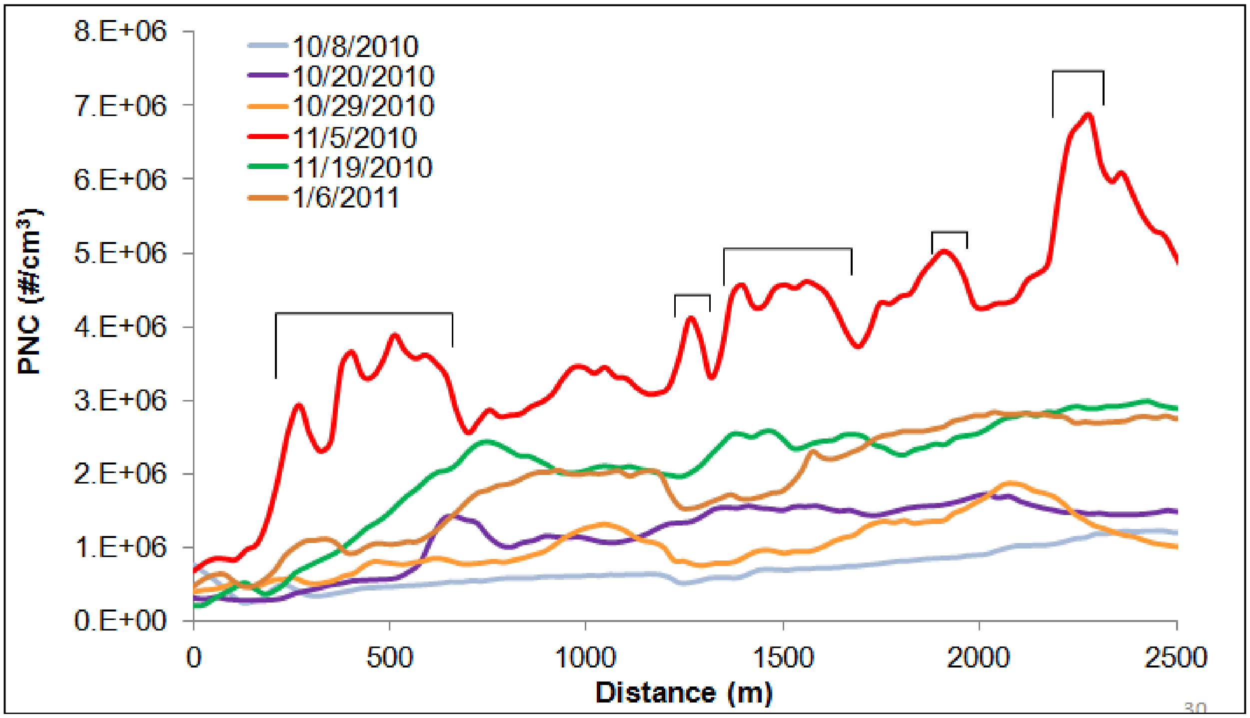

Figure 10. PNC versus distance in the tunnel (m) for six runs of the southbound bore of the Thomas P. O'Neill Jr. Tunnel. All runs occurred between 05:15 and 05:30. HDVs within close proximity to the TAPL are identified on the plot for November 5, 2010.

During this run the TAPL was following two diesel-emitting trucks shortly after entering the tunnel; midway through the tunnel, the TAPL was passed by a tractor-trailer followed by a construction vehicle and then a school bus; and shortly before the exit of the tunnel was passed by another diesel-emitting truck. The large change in UFP concentration resulting from the presence of each HDV is consistent with the findings of previous studies that looked at the impact of traffic fleet composition on in-tunnel UFP (Knibbs et al., 2010).

3.4 Diurnal Variation in PNC

On January 4, 2012 the median PNC measured in the tunnel was 5.6x10^5 particles/cm^3 (18 runs) during the morning (04:00 – 10:30) and 3.5x10^5 particles/cm^3 (26 runs) during the evening (15:00 – 21:30). The morning PNC on January 5, 2012 was also higher than later in the day, with median values of 3.8x10^5 particles/cm^3 (22 runs) and 3.1x10^5 particles/cm^3 (24 runs), respectively. Figures 11 and 12 display the average PNC for each run of the tunnel on each of the two days and for both the northbound and southbound tunnels.

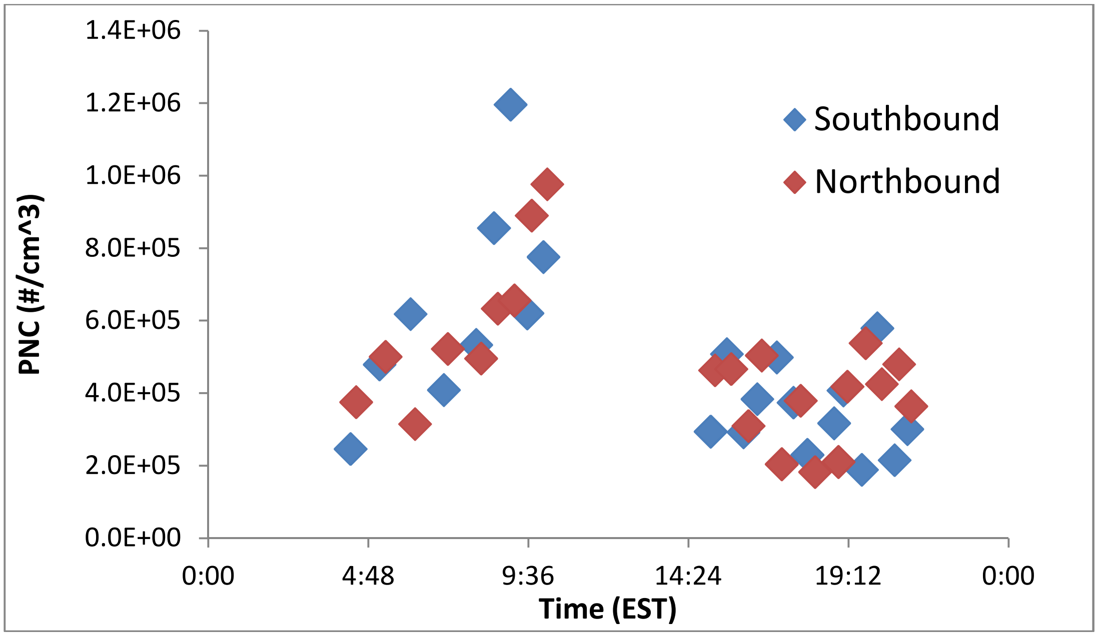

Figure 11. Average PNC for each run of the tunnel for all of the runs completed on January 4, 2012.

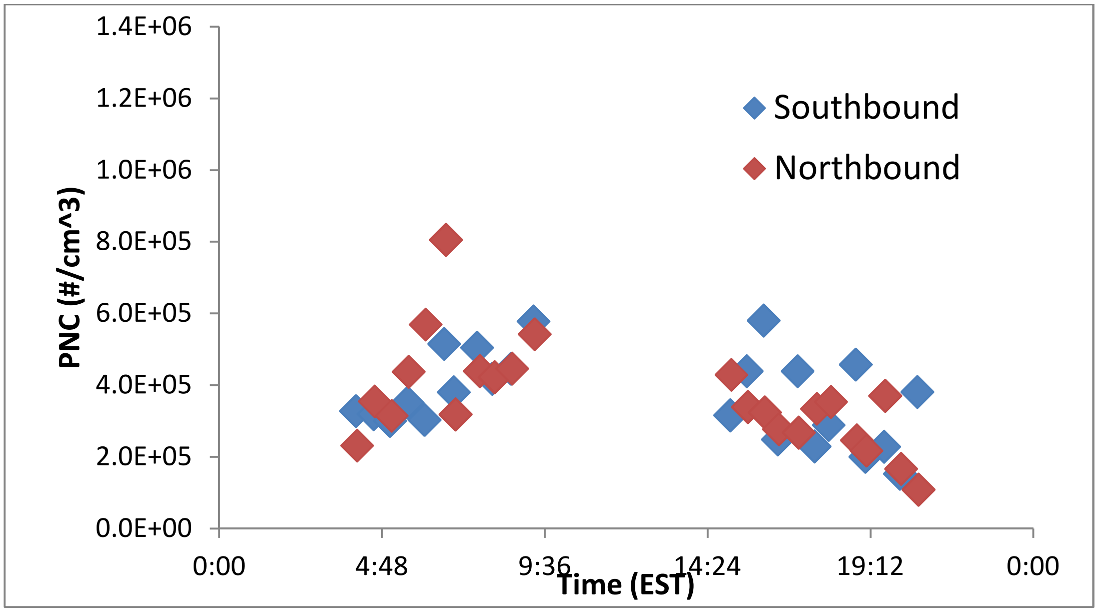

Figure 12. Average PNC for each tunnel run for all of the runs completed on January 5, 2012.

Colder temperatures and less mixing during the morning hours may help to explain the higher PNC during the morning monitoring as opposed to the evening monitoring. Previous near-highway studies also indicate that peak daily PNC occurs during morning rush hours (Wang et al., 2010). The average temperature on Wednesday, January 4, 2012 was -7°C and the average temperature on Thursday, January 5, 2012 was 0°C. The average wind speed was 12 mph on both days, and the average relative humidity was 44% on Wednesday and 48% on Thursday. Figure 13 displays additional meteorological information for the two January days.

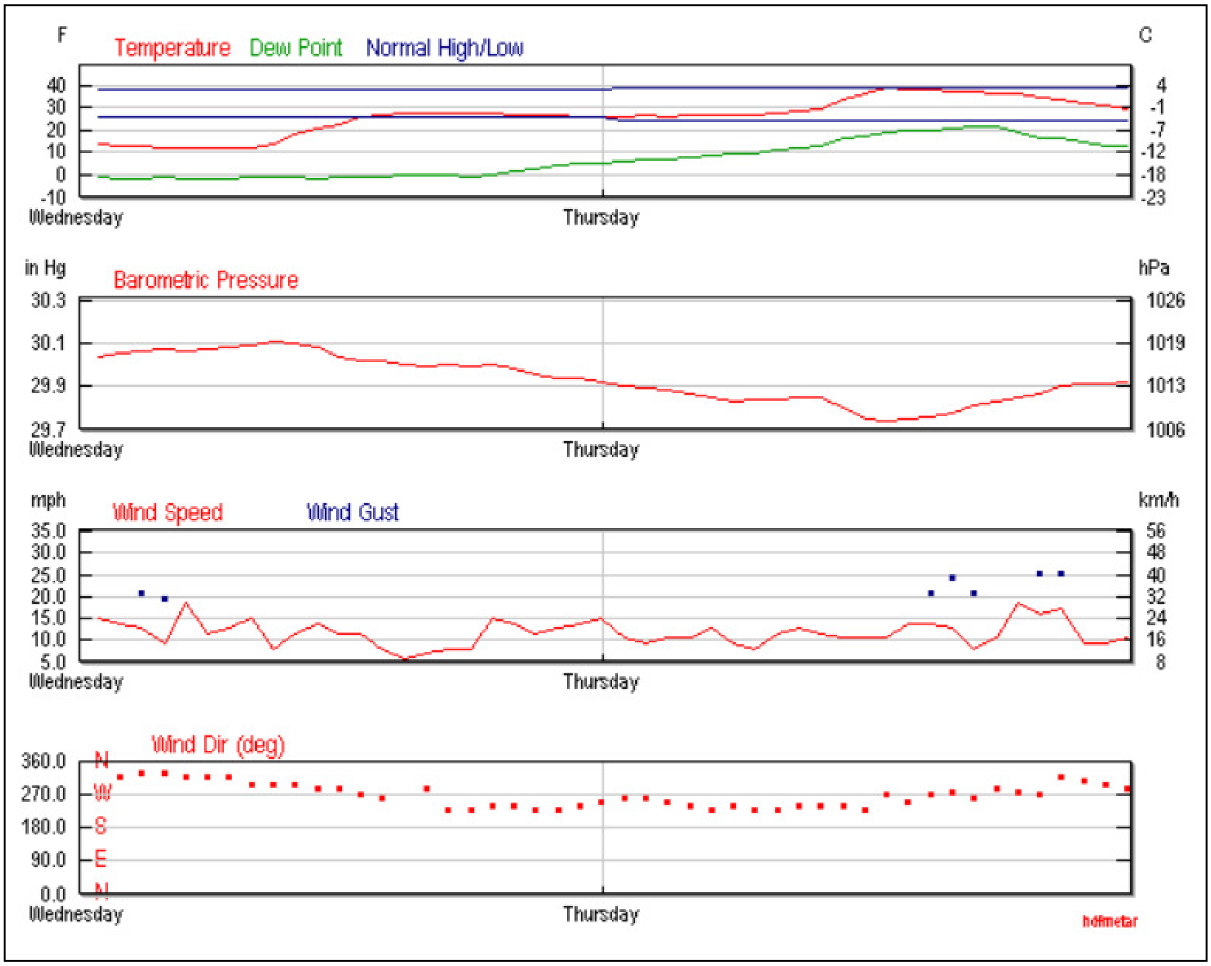

Figure 13. Meteorological data recorded at Logan International Airport located in Boston, Massachusetts on Wednesday, January 4, 2012 and Thursday, January 5, 2012 (Weather Underground, Inc).

The colder temperatures on January 4, 2012 may help explain the higher UFP concentrations recorded in the tunnel as compared with the following day. Average HDV counts (5 min reporting frequency) on January 4, 2012 were 5 in the southbound tunnel and 11 in the northbound tunnel during morning monitoring. Evening average HDV counts were 7 and 5 on the same day for the southbound and northbound tunnels, respectively. Average HDV counts on January 5, 2012 were relatively similar: average morning HDV counts (5 min) were 5 in the southbound and 13 in the northbound tunnel, while evening values were 6 and 5 in each tunnel (MassDOT).

3.5 In-cab Measurements

The median PNC of tunnel air at the entrance to the southbound tunnel during the morning of January 5, 2012 was 2.4×10^5 particles/cm^3. The median in-cab PNC measured at the same location was 3.4×10^4 particles/cm^3, or about a 1:7 ratio relative to the tunnel air. The median PNC measured outside and inside the TAPL in the evening hours at the southbound tunnel entrance were 1.7×10^5 particles/cm^3 and 4.7×10^4 particles/cm^3, respectively (about a 1:4 ratio of air inside the TAPL relative to tunnel air). Figures 14 and 15 display the PNC for in tunnel-air versus in-cab concentrations at different locations in the southbound tunnel. The concentrations for both data sets were normalized to the PNC in the tunnel air at the entrance to the tunnel for each run.

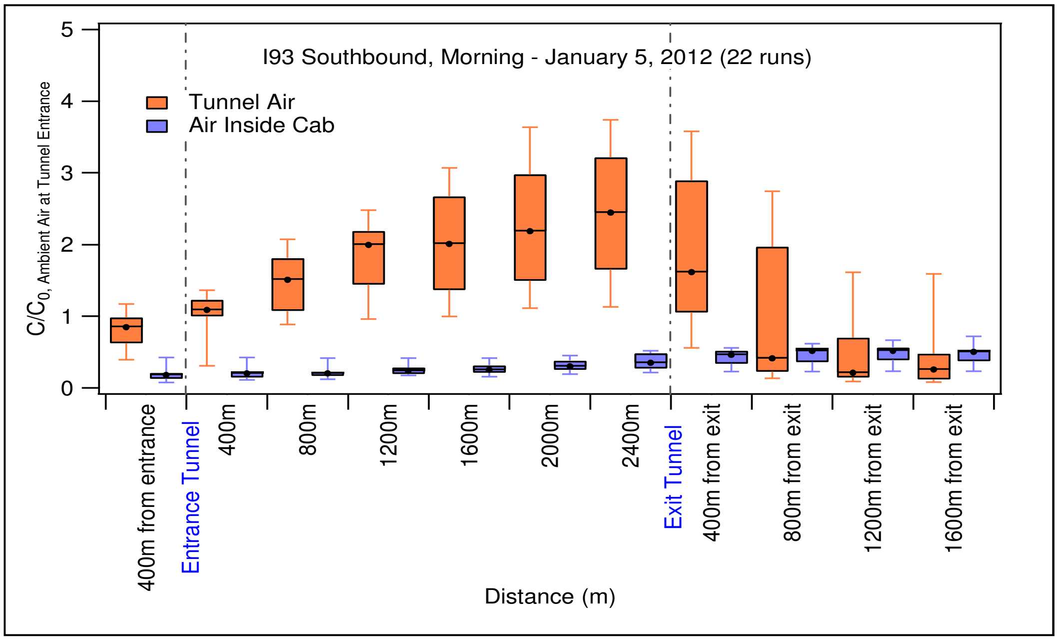

Figure 14. Box plots of tunnel air and in-cabin PNC (normalized to the tunnel air PNC at the tunnel entrance) versus distance in the southbound bore on the morning of January 5, 2012.

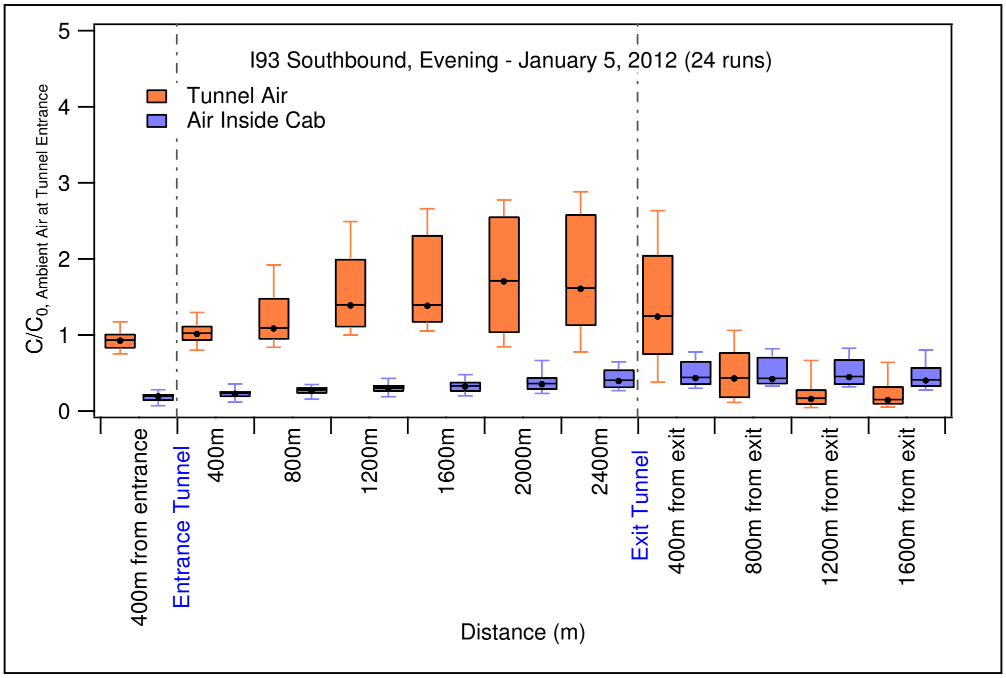

Figure 15. Box plots of tunnel air and in-cabin PNC (normalized to the tunnel air PNC at the tunnel entrance) versus distance in the southbound bore on the evening of January 5, 2012.

These figures illustrate (1) the difference between the PNC in the tunnel air versus in the cab of the TAPL and (2) the delay that occurs between the observation of peak concentration measurements of the tunnel air and peak concentrations measured inside the TAPL. Maximum PNC of tunnel air occurred at 2000-2400 m right before the tunnel exit, while maximum in-cab UPF concentrations occurred in the bin 800-1200m past the tunnel exit along I-93 Southbound. Figures 16 and 17 display the tunnel air and in-cab UFP concentrations normalized to their respective values at the southbound tunnel entrance.

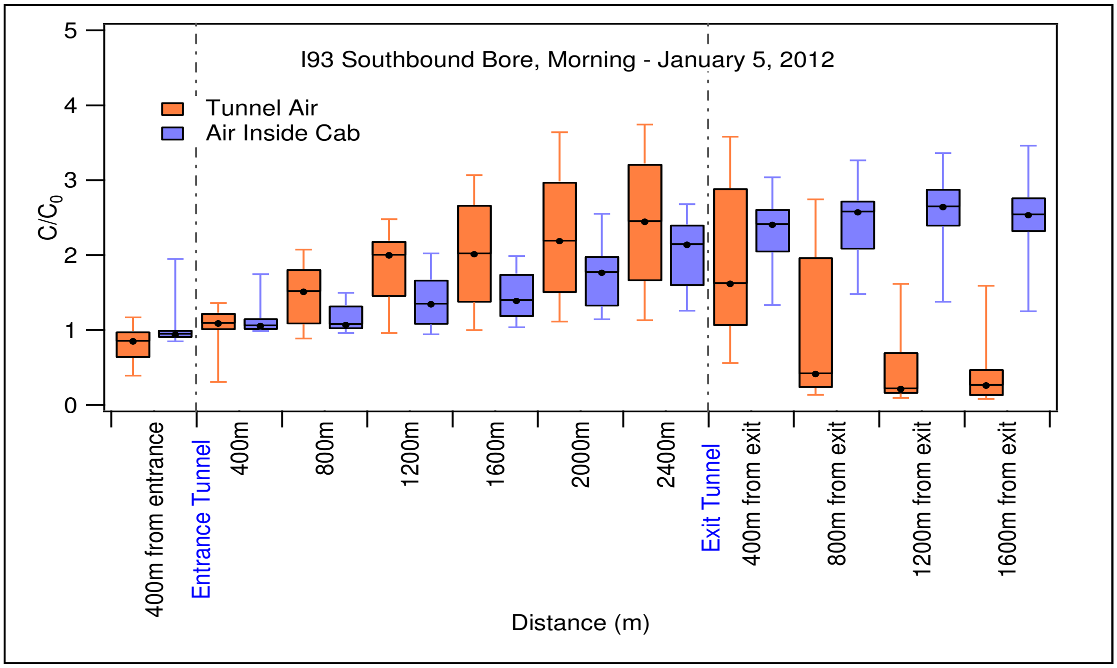

Figure 16. Box plots of tunnel air and in-cabin PNC (each normalized to their respective PNC at the tunnel entrance) versus distance in the southbound bore on the morning of January 5, 2012.

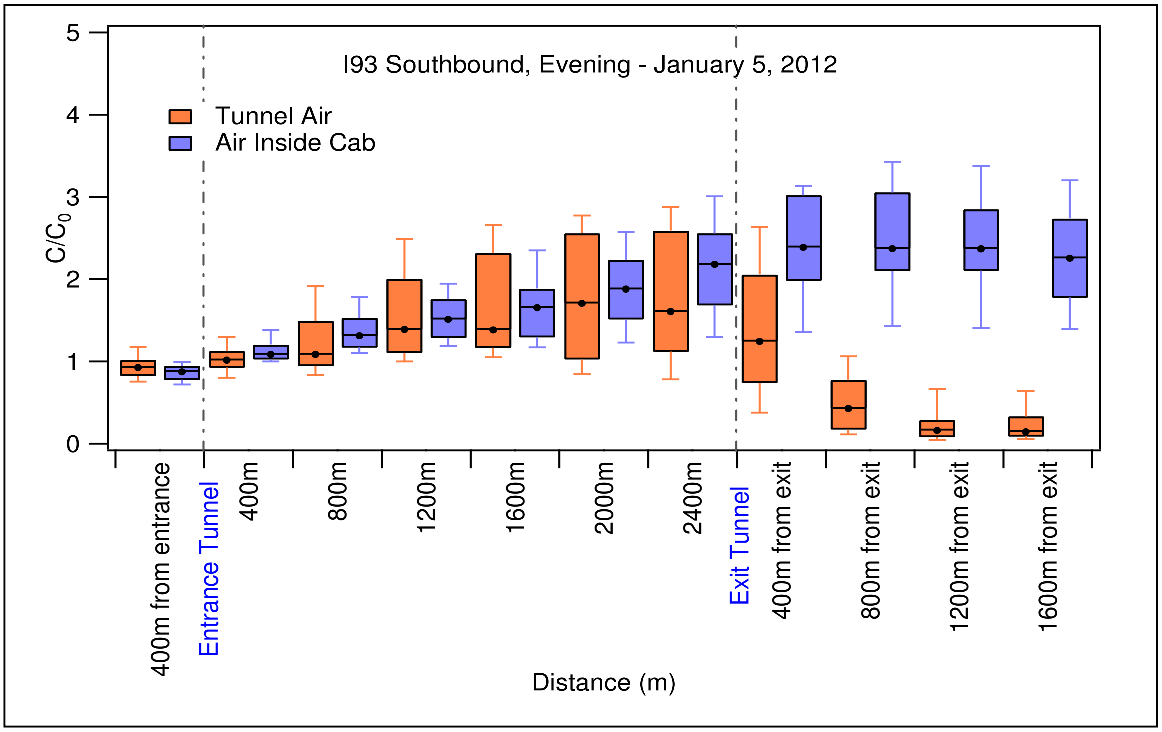

Figure 17. Box plots of tunnel air and in-cabin PNC (each normalized to their respective PNC at the tunnel entrance) versus distance in the southbound bore on the evening of January 5, 2012.

During the morning monitoring, the peak average in-tunnel air PNC was 2.5x the level at the tunnel entrance, and the peak average in-cab PNC was 2.6x the level at the tunnel entrance. Results from the evening monitoring showed an increase by a factor of 1.8 for the in-tunnel PNC and 2.4 for the in-cab PNC. The lag in peak measured UFP concentration for a given run can also be observed in Figures 16 and 17. The ventilation system in the TAPL does not have a recirculation feature. The infiltration rate could be expected to be as high as ~1.0 if the windows were open, and as low as 0.08 if there was a recirculation feature (Knibbs et al., 2011). Although no recirculation feature is in place in the vehicle, UFP may be deposited within different portions of the heating and ventilation system, causing the PNC to be ~80% lower inside of the TAPL.

3.6 Summary

Tables 5-7 display a summary of the monitoring results from the entire study.

Table 5. Summary of results from September 2010 – September 2011 monitoring campaign in the Thomas P. O'Neill Jr. Tunnel.

	Northbound	**Southbound**
Winter median PNC (#/cm^3)	4.5×10^5	4.4×10^5
Summer median PNC (#/cm^3)	1.8×10^5	2.1×10^5
Ratio Winter Entrance : Exit	11:1	8:1
In-tunnel median PNC (#/cm^3)	3.7×10^5	2.6×10^5
On-highway median PNC (#/cm^3)	3.7×10^4	3.7×10^4
Ratio In-tunnel : On-highway	10:1	7:1
Urban Background PNC (#/cm^3)[1]	1.8×10^4	

[1] from Padro-Martinez at al., 2012

Table 6. Summary of PNC in the Thomas P. O'Neill Jr. Tunnel on January 4th and 5th, 2012.

Date	**Morning PNC (#/cm^3) (04:00 – 10:30)**	**Evening PNC (#/cm^3) (15:00 – 21:30)**
1/4/12	5.6×10^5	3.5×10^5
1/5/12	3.8×10^5	3.1×10^5

Table 7. Summary of outside versus in-cabin PNC in the tunnel on January 5, 2012.

Jan 5th		**Morning**	**Evening**
Outside PNC at tunnel entrance (#/cm^3)		2.4×10^5	1.7×10^5
In-cabin PNC at tunnel entrance (#/cm^3)		3.4×10^4	4.7×10^4
Outside PNC ratio	Tunnel entrance: peak concentration	2.5	1.8
In-cabin PNC ratio	Tunnel entrance: peak concentration	2.6	2.4

3.7 Comparison to other tunnel studies

Table 8 displays the median PNC measured in other tunnel studies, all of which utilized mobile monitoring with the exception of Larson et al. (2007). The concentration for this study was higher than all others than Knibbs et al. (2009), which measured UFP in a tunnel that was 1.6 km longer than the Thomas P. O'Neill Jr. Tunnel. The difference in length likely accounts for the higher median PNC because more accumulation is able to occur over a greater distance. Given the high volume of traffic flow through the I-93 tunnel, it is not unexpected that the median PNC would be relatively high in comparison to other tunnel studies.

Table 8. Median PNC from other tunnel studies for comparison.

Authors	**Location**	**Tunnel Length**	**Median PNC (#/cm^3)**
Knibbs et al., 2009	Sydney, Australia	4 km	1.7×10^6
Gouriou et al., 2004	Rouen, France	1.6 km	3.5×10^4
Larson et al., 2007	Stolkholm, Sweden	1.5 km	1.1×10^5
Lechowicz et al., 2008	Brisbane, Australia	0.5 km	4.1×10^4
This Study	Boston, MA, USA	2.4 km	3.0×10^5

3.8 Significance

No tunnel studies analyzing PNC and other traffic-related air pollutants have been completed in the Thomas P. O'Neill Jr. Tunnel to date. While many studies have looked at different determinants of UFP concentration within highway tunnels, none have specifically analyzed the seasonal or diurnal trends. Results from this study focus on determining the impact of seasonal and temporal factors on pollutant concentrations measured in the tunnel. In addition, this study may help to inform ventilation strategies for current and future tunnel systems. The results from this study raise questions that could be the basis for future research. More work could be done to identify the factors affecting seasonal and diurnal trends in UFP observed in the tunnel. A better understanding of the most significant factors could help to develop mitigation strategies to reduce UFP concentrations in the tunnel. Additionally, a more detailed analysis of seasonal and daily traffic patterns for both total volume and HDVs would help to determine whether traffic conditions play a significant role in the seasonal and temporal trends in TRAP levels observed in this study.

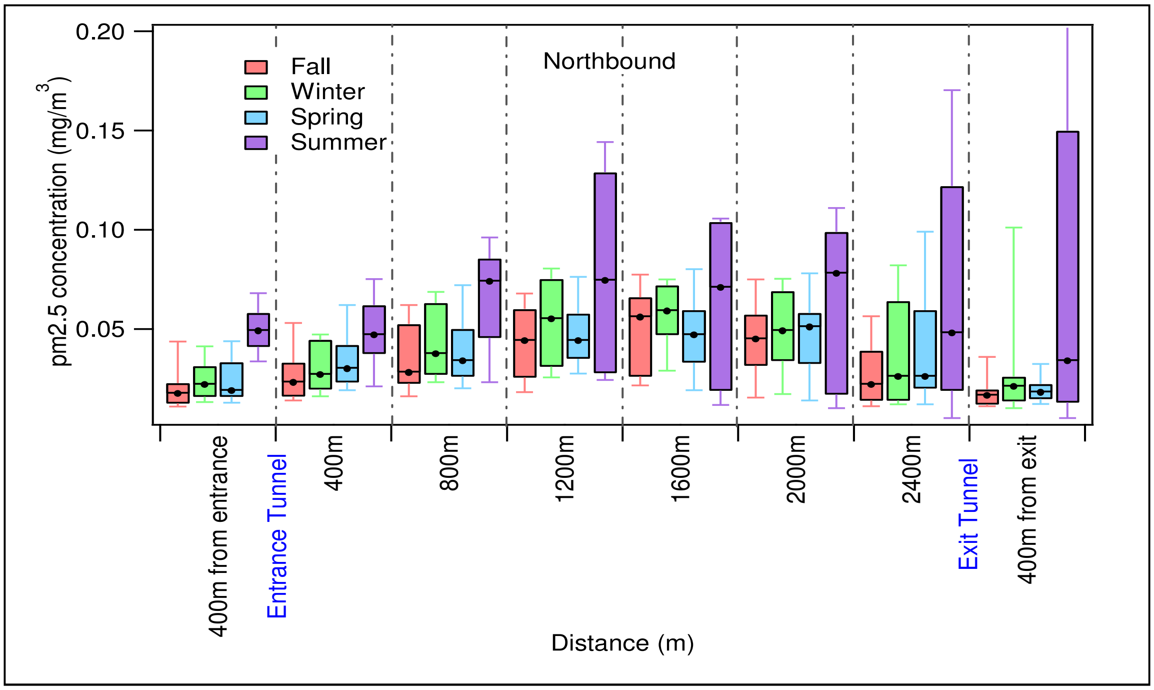

Figure A. Seasonal box plots of $PM_{2.5}$ concentration versus distance in the northbound tunnel during the September 2010 – September 2011 monitoring campaign. Note: this is a provisional data set that has not undergone rigorous QAQC.

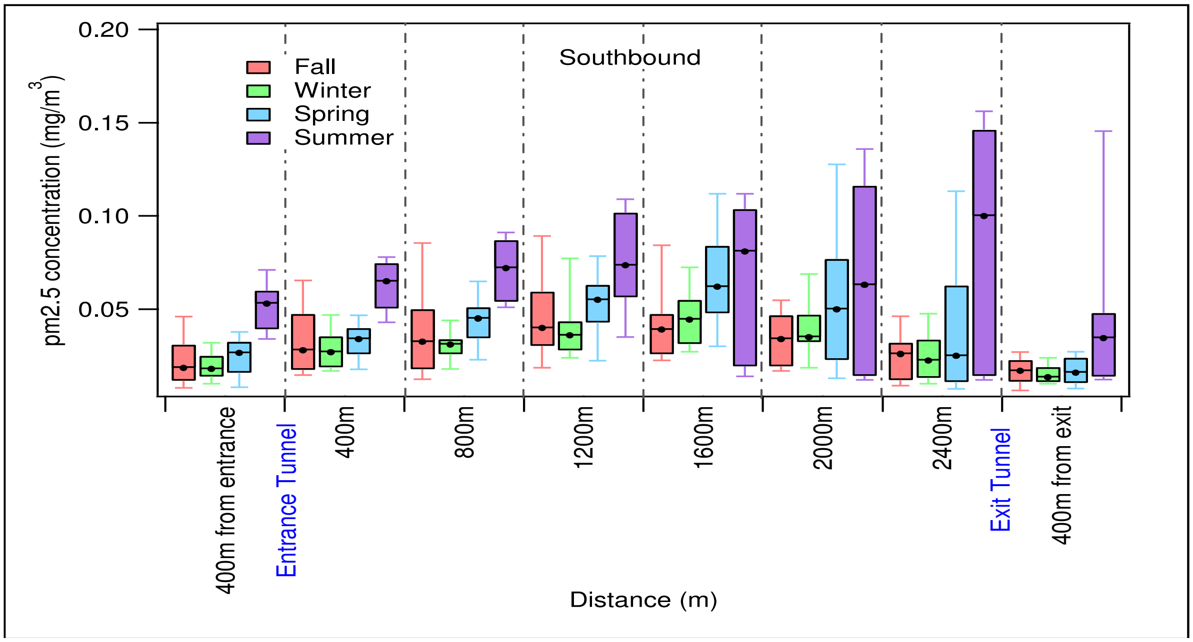

Figure B. Seasonal box plots of $PM_{2.5}$ concentration versus distance in the southbound bore of the tunnel during the September 2010 – September 2011 monitoring campaign. Note: this is a provisional data set that has not undergone rigorous QAQC.

Table A. Northbound Tunnel – Additional Pollutant Median Concentrations

Season	PAH (femtoamps)	Black Carbon (µg/m^3)
Fall	84	3600
Winter	110	5700
Spring	130	7400
Summer	200 (upper limit)	21000

Table B. Southbound Tunnel – Additional Pollutant Median Concentrations

Season	PAH (femtoamps)	Black Carbon (µg/m^3)
Fall	93	3600
Winter	130	6100
Spring	200 (upper limit)	9800
Summer	200 (upper limit)	15000

Table C. PAH Median Concentrations (femtoamps)

	Northbound	Southbound
January 4, 2012 morning	150	150
January 4, 2012 evening	120	100
January 5, 2012 morning	150	150
January 5, 2012evening	110	110

Table D. Black Carbon Median Concentrations (g/m^3)

	Northbound	Southbound
January 4, 2012 morning	8000	7400
January 4, 2012 evening	2800	2100
January 5, 2012 morning	3000	3900
January 5, 2012evening	no data	

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