Carbon Monoxide and Nitrogen Oxides Relationships Measured Inside a Roadway Tunnel and a Comparison with the Mobile 6.2 Emission Model Predictions

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ABSTRACT

This paper presents the results of a multi-year carbon monoxide (CO) and nitrogen oxides (NOx) monitoring program performed inside the 8,000 foot long Ted William Tunnel (TWT), which is part of the Central Artery/Tunnel (CA/T) Project in Boston, Massachusetts.

The monitoring program was performed in support of developing the CA/T Project's Operating Certification for the tunnel's ventilation system. Its objective was to measure tunnel operating levels for both pollutants, and to develop a statistical method using monitored CO levels as a predictor for estimating NOx levels for compliance demonstration with the Massachusetts State's 1-hour NO_2 Policy Guideline. The program measured in-tunnel CO and NOx levels on quarterly basis during 1997-1998 at the newly constructed TWT when only commercial traffic was permitted inside the TWT. The program was repeated during 2004 when the tunnel was open to general traffic use. An analysis of the measured levels and the relationship between the two pollutants using more than 20,000 hours of collected data is described in this paper.

The CO-NOx data proved that there is a good correlation between the two pollutants and that NOx levels can be predicted as a function of CO levels within the TWT. The comparison to the EPA MOBILE 6.2 Emission Factor Model predictions using all available project specific data indicated that the CO/NOx ratios matched very well for the summer seasons, but the large increases in CO winter emissions predicted by MOBILE 6.2 did not occur during the three years of data collection.

INTRODUCTION

The Ted William Tunnel (TWT) under Boston harbor opened to commercial and other authorized vehicles in December 1996. Subsequently, the TWT opened to general traffic on January 2003. Massachusetts Department of Environmental Protection (DEP) 1991 regulation 310 CMR 7.38 entitled "Certification of Tunnel Ventilation Systems in the Metropolitan Boston Air Pollution Control District" requires the filing of an Operating Certification which includes continuous tunnel emission monitoring, and must demonstrate that the ambient air quality resulting from operation of the ventilation system in question will be in compliance with the applicable National Ambient Air Quality Standards, and the DEP one-hour NO_2 Policy Guideline of 0.170 ppm in the areas affected by the project.

The project measured CO and nitrogen oxides (NO and NOx) levels inside the TWT for two-week periods every quarter during 1997-1998, and 2004. Data gathered during 1997-1998 provided an indication of the CO and NOx levels inside the TWT when only commercial and other authorized traffic were using the tunnel during the Early Opening Phase. A statistical analysis of the data was initially performed in 1999 to explore the possibility of using CO levels as a surrogate for predicting NOx levels. The results indicated that there was a good correlation between measured levels of NO, NOx and CO. Linear-regression models were then developed to predict in-tunnel NO and NOx levels based on measured CO levels. The results from the 1997-1998 emission monitoring program were presented by the same authors at the 1999 AWMA annual meeting (Paper #99-684).

The 2004 monitoring data reflects the current TWT conditions (general traffic use and today's vehicle technology) versus the 1997-98 conditions when the TWT was open to commercial traffic only with higher percentage of heavy vehicles. The new regression models based on the 2004 data are considered to represent the Full Opening traffic conditions.

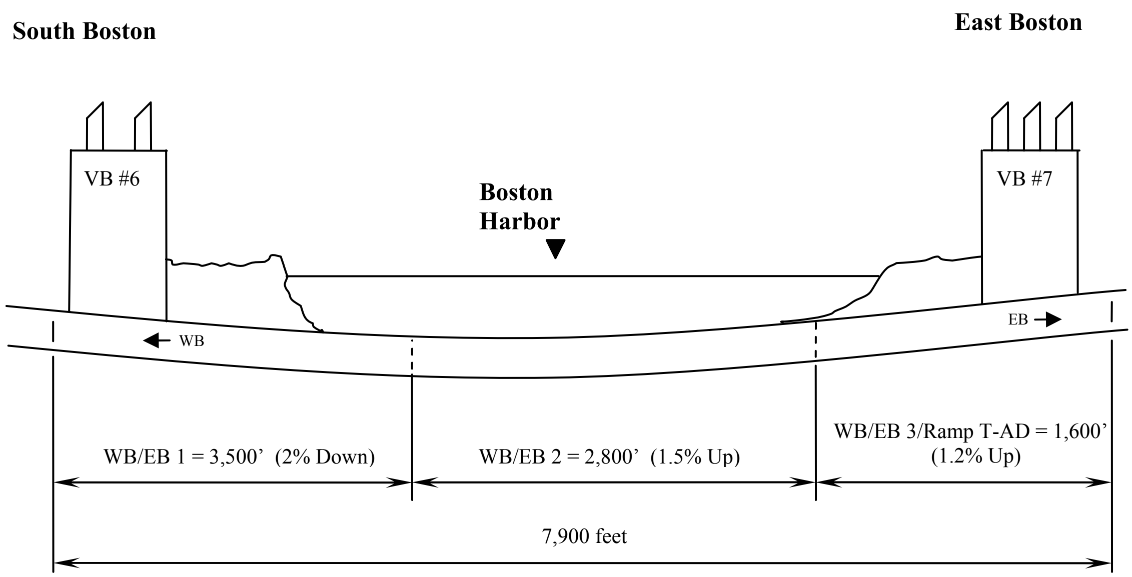
Since the CO/NOx ratios could also be determined using the EPA MOBILE 6.2 Emission Factor Model, a traffic data collection including vehicle classification (i.e., number of cars, light duty, and heavy duty trucks) was performed inside the TWT during January 2004 to be used as input to the MOBILE 6.2 Model.

TWT VENTILATION SYSTEM CHARACTERISTICS

The 7,900-foot long, four-lane TWT tunnel is ventilated by a full transverse system in which supply air is introduced to the tunnel from under the roadway, and the mixture of vehicular exhaust is extracted through the openings in the tunnel ceiling to a plenum located above the ceiling before being diverted up through the ventilation building's exhaust stacks. The ventilation system is divided into 7 ventilation zones. Two zones (EB-1 and WB-1) are associated with VB6 and five zones (EB-2, WB-2, EB-3, WB-3 and Ramp T-A/D) with VB7.

VB7, located in East Boston (Figure 1), serves the east sections of the TWT. These sections include I-90 Eastbound, I-90 Westbound, and Ramp T-AD. Both EB-2 and WB-2 zones are 2,800 feet in length with a 1.5 % upward gradient toward the east. Zones EB-3 and WB-3 are both 1,600 feet with a 1.2% upward gradient toward the east. Each plenum serves one ventilation zone. Six exhaust air stacks are fed by 2 plenums which serve I-90 Westbound, and eight exhaust stacks are fed by 3 plenums which serve I-90 Eastbound and Ramp T-AD.

Figure 1
Ted Williams Tunnel Profile



MONITORING PROGRAM DESCRIPTION

Location of Pollutant Sampling Points

The monitoring program continuously measured concentrations at each one of the VB7 ventilation zones.

Pollutant concentrations of CO, NO, and NOx were sampled at four monitoring locations as follows:

- two for I-90 Eastbound; one at each plenum for EB2 and EB3
- two for I-90 Westbound; one at each plenum for WB2 and WB3

Sampling Instrumentation

NOx concentrations were recorded using multiple chemi-luminescence gas analyzers (Model 42), manufactured by Thermo Environmental Instruments, Inc.

CO concentrations were recorded using non-dispersive infrared spectrometry analyzers (Model 48) also manufactured by Thermo Environmental Instruments, Inc.

Pollutant Sampling and Recording Methods

The monitoring system employed a "rake Probe" to gather the samples of NO, NOx and CO. The probe consisted of a length of one half inch Teflon or stainless steel tubing. Each of the probes had 8 equal distant holes drilled so that they allowed for sample collection along the entire width of the ventilation plenum. The probe was oriented so that the 8 holes were directed into the direction of flow of the source stream. Each probe was positioned during the initial testing so that the sample was representative of the emissions of the plenum.

During normal sampling, the monitoring equipment sampled from each vent location five minutes and then switched to the second location. In this manner, a one-hour average at each sample location would be comprised of six 5-minute averages.   During calibrations, the sample protocol was followed except that the time sequence was increased so that the calibration could be completed in a single cycle.

TRAFFIC DATA MONITORING

The total number of vehicles using the TWT from the eastbound and westbound roadways was recorded on an hourly basis by the Massachusetts Turnpike Authority during January 2004. Vehicle classification, i.e., number of cars, light duty trucks (SUVs and vans) and heavy duty trucks was obtained through manual reduction of the in-tunnel video recordings for selected hours.

The January 2004 westbound traffic volume during the peak AM and PM periods was about 2,200 vehicles per hour. Vehicle classification included at average 67% autos, 28% light-duty trucks (SUVs/vans) and 5% heavy-duty trucks. The eastbound direction had higher peak-hour traffic volumes of approximately 2,600 vehicles. Vehicle classification was similar, but heavy-duty trucks constituted 3% of the total volume. The night time traffic ranged from 500 to 1,100 vehicles per hour with a similar vehicle classification.

By comparison, the peak hour traffic volumes during 1997/98 were about half of the 2004 peak hour levels. In addition, the 1997/98 data had a higher percentage of heavy-duty trucks in the fleet with the average of 12-15%.

2004 MEASURED POLLUTANT LEVELS

Approximately 300 to 500 coincident hourly concentrations for CO, NO, and NO_x were measured at each ventilation zone of VB7 on a quarterly basis during 2004. In total, over 6,000 concentration measurements for each pollutant were collected. A summary of the average and maximum concentration levels measured at each two week monitoring period is provided in Table 1 for CO and Table 2 for NOx.

Table 1: 2004 CO Monitoring Levels (ppm)

Location Direction	January		April		August		October	
	Max	**Average**	**Max**	**Average**	**Max**	**Average**	**Max**	**Average**
TWT, WB zone 2	8.1	2.8	9.2	2.9	8.9	2.7	13.4	2.7
TWT, EB zone 2	10.1	4.0	11.9	4.2	**16.2**	4.0	13.7	3.7
TWT, WB zone 3	3.6	1.5	8.4	1.9	6.1	1.4	11.2	1.7
TWT, EB zone 3	11.1	**4.4**	**13.0**	**4.9**	14.6	**4.4**	**15.6**	**4.5**

Table 2: 2004 NO_x Monitoring Levels (ppm)

Location Direction	January		April		August		October	
	Max	**Average**	**Max**	**Average**	**Max**	**Average**	**Max**	**Average**
TWT, WB zone 2	--	0.647	1.471	0.604	1.395	0.504	1.624	0.464
TWT, EB zone 2	1.758	0.910	2.018	**0.973**	**1.959**	0.758	1.593	0.672
TWT, WB zone 3	1.080	0.374	1.672	0.357	0.921	0.289	1.598	0.257
TWT, EB zone 3	**2.267**	**1.185**	**2.075**	**0.973**	1.726	**0.761**	**1.749**	**0.696**

The average hourly CO levels (at each ventilation zones) ranged from 1.4 ppm to 4.9 ppm. The maximum measured concentration was 16.2 ppm. The average quarterly CO levels for all four ventilation zones were between 3.1 and 3.5 ppm.

The variation of CO levels between summer and winter was within 4%. This was an unexpected finding, since it was anticipated that CO levels in winter would be much higher than in summer.

The average hourly NOx levels ranged from 0.257 ppm to 1.185 ppm. The maximum measured concentration was 2.267 ppm. The average winter NOx levels were approximately 30% higher than the average summer levels. This was within the expected range of variation.

The average NO component ranged from 83 to 93% of NOx. The lower range was always at the westbound entrance zone, which is affected by ambient air dragged into the tunnel by the moving vehicles, and has a higher component of NO_2. The NO component for EB3 zone (eastbound tunnel exit zone) varied from 91 to 93%, which is within the expected range measured in previous studies.

These measurements also revealed that the uphill sections of the tunnel had significantly higher levels of CO, NO, and NOx. These results confirm the well-documented facts in the literature that vehicle emissions increase significantly during accelerations.

In order to determine the influence of ambient pollutant levels on the exhaust data, pollutant levels were also measured at the air intake of VB7 during all 2004 monitoring periods. The average CO level at the air intake ranged from 0.3 ppm to 0.8 ppm with a maximum recorded value of 0.9 ppm; and the average NOx level ranged from 0.03 ppm to 0.07 ppm with a maximum recorded level of 0.103 ppm. These air intake levels were between 5 and 10% of the levels measured at the exhaust plenums for CO and NOx.

DATA ANALYSIS AND RESULTS

Statistical Approach

Based on the assumption that the relationship of each pair of parameters (CO vs. NOx) is linear, simple linear regression models were selected to express the relationship of NOx to CO. The models are of the form:

$$Y = a + bX$$

Where

Y is the unknown concentration of NOx estimated as a function of X

X is the known concentration of CO. The constant "a" is the intercept of the regression line and "b" is the slope which is the rate at which Y changes with unit change of X.

The degree and direction of the relationship between the two variables were estimated using Pearson's correlation coefficient. A correlation coefficient of 0 indicates no correlation, while a correlation coefficient of 1 indicates perfect correlation between two variables. Correlation coefficients above 0.5 indicate that there is correlation between the variables in a tested pair, with stronger correlation for pairs with coefficients closer to 1.

Analyzed Data Sets

A total of five data sets were analyzed for 1997, 1998 and 2004; one for each of the quarterly monitoring periods and one for the four periods combined. To increase the confidence of results, each data set includes measurements for all four ventilation zones for each pollutant (including uphill and downhill data).

Each of the 2004 data set includes between 1,250 to 2,100 hours of measurements for each quarter and approximately 6,000 hours for the year. For the 1997/98 data sets, each includes approximately 1,300 hours of measurements for the quarter and approximately 5,200 hours for the full year. The 1997/98 data represents the Early Opening Phase fleet and vehicle classification, which contains a higher percentage of trucks. An additional set for all summer and winter periods combined was created to compare CO/NOx relationship during these time periods.

Correlation Coefficients and Linear Regression Models

The scatter plots of all the data sets analyzed indicate that the assumption of linearity is valid, since the majority of the pairs of X and Y values are concentrated around the regression line. The results of the correlation analysis of all data sets indicates moderate to strong correlation between CO and NOx. Pearson correlation coefficients for each monitoring period are above 0.8 for 2004 and between 0.5 and 0.82 for 1997/98 data sets.

Figures 2 through 6 present the scatter plots for the winter and summer data for 2004, 1998, and 1997, respectively. These six data sets have correlation coefficients above 0.8 for 2004 and 1998, and above 0.63 for 1997. Table 3 presents the linear regression models for the prediction of NOx as a function of CO for all data sets, and the CO/NOx ratios determined by these regression models at a CO level of 10 ppm.

Figure 2: CO/NOx Relationship Based on Monitored Levels in Ted Williams Tunnel January 2004

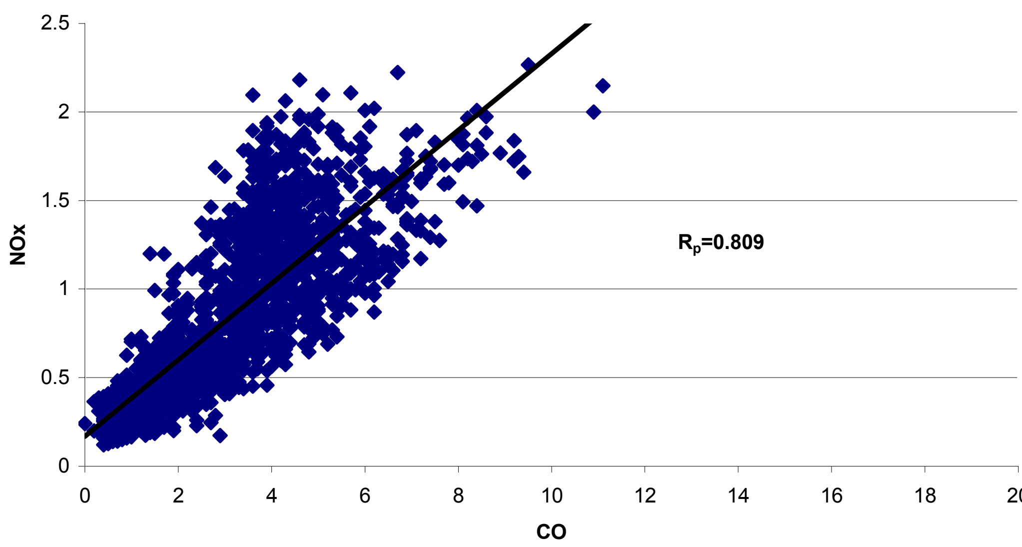


Figure 3: CO/NOx Relationship Based on Monitored Levels in Ted Williams Tunnel August 2004

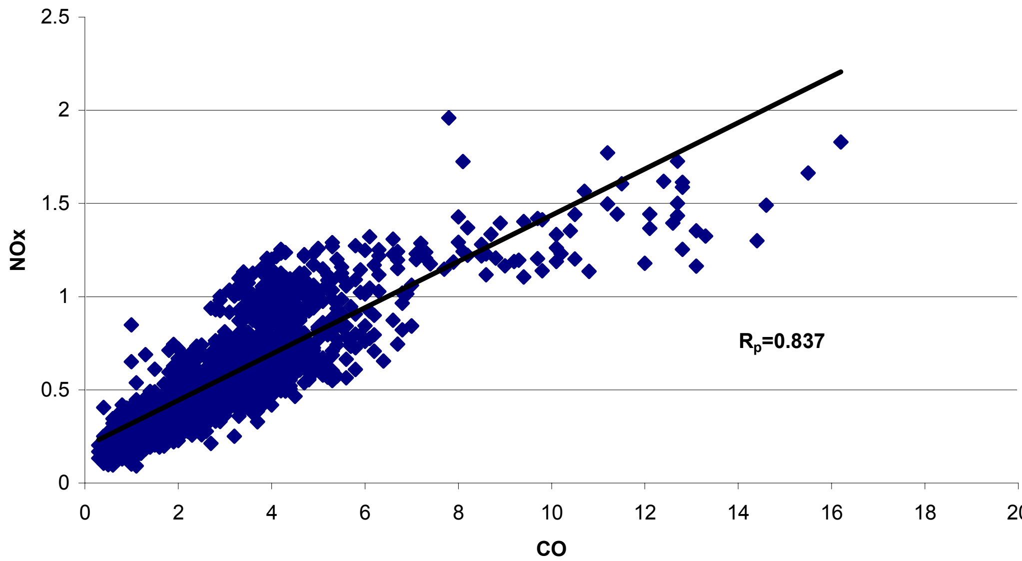


Figure 4: CO/NOx Relationship Based on Monitored Levels in Ted Williams Tunnel December 1998

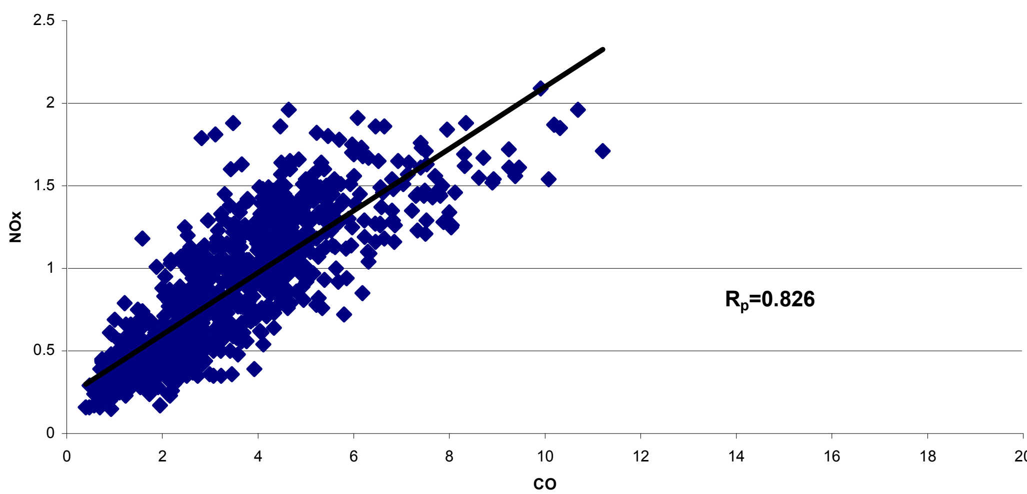


Figure 5: CO/NOx Relationship Based on Monitored Levels in Ted Williams Tunnel
July 1998

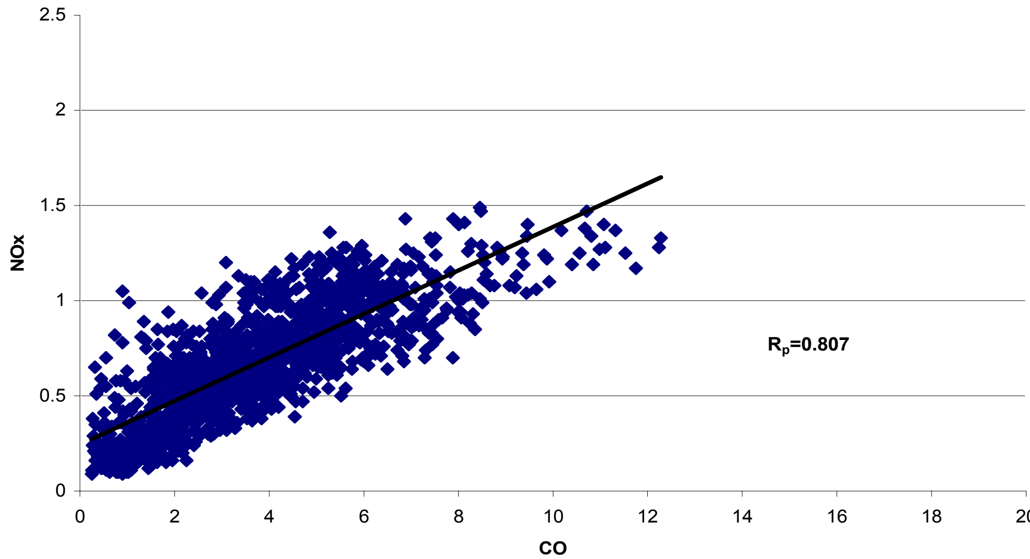


Figure 6: CO/NOx Relationship Based on Monitored Levels in Ted Williams Tunnel
March 1997

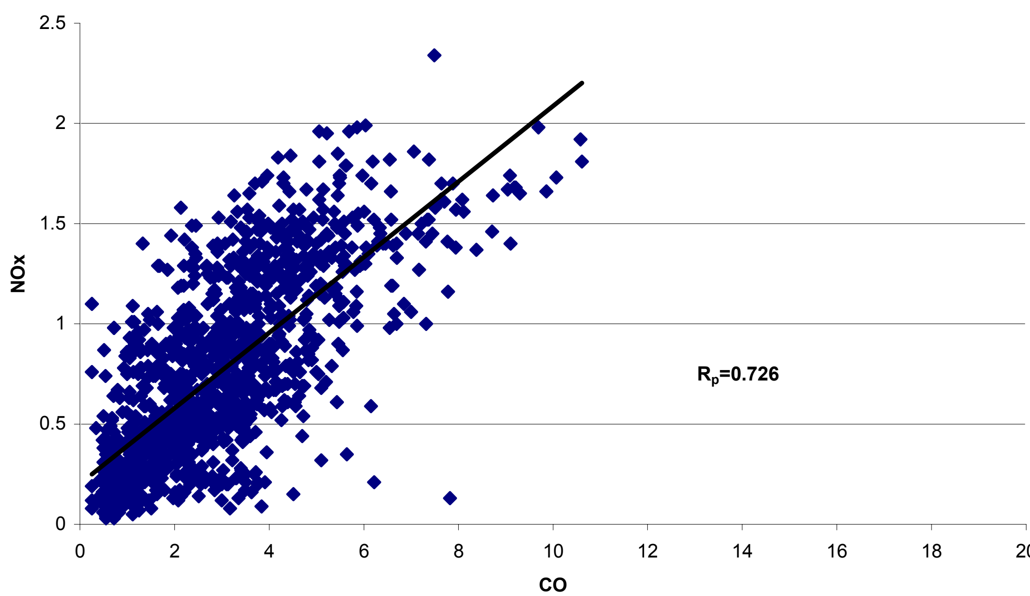
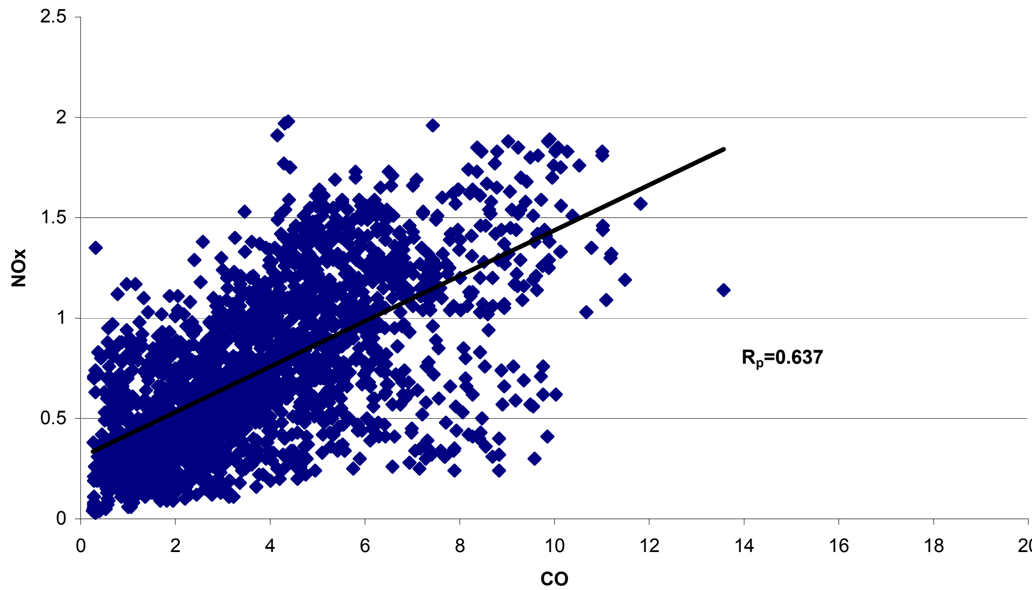


Figure 7: CO/NOx Relationship Based on Monitored Levels in Ted Williams Tunnel
Summer 1997



As it can be observed from these figures and table, the 2004 data sets indicate that the highest CO/NOx ratios occur during the summer period (August) and the lowest during the winter period (January). This is a direct result of higher measured NOx levels in winter as compared to summer, and small variation in measured CO levels between summer and winter. Both the 1997 -1998 data sets indicate a similar seasonal trend, where the highest CO/NOx ratios occur during the summer-fall period (July-September) and the lowest during the winter period (December-March).

A comparison of the CO/NOx ratios predicted by the summer and winter data sets for each of the three years is presented in table 4. The results of these three individual years of data are very similar despite the seven year difference in the fleet, and the higher percentage of heavy duty vehicles during 1997/98. In all cases the summer ratios are one third higher than the winter ratios, reflecting the higher measured NOx levels during the winter periods for all three years.

Table 3: Linear Regression Models and correlation Coefficients

Year	Month	Regression Models	Pearson Correlation Coefficient	CO/NOx Ratio @ 10 ppm
2004	January	NO_x = 0.167 + 0.212 x CO	0.809	4.30
	April	NO_x = 0.116 + 0.186 x CO	0.828	5.12
	August	NO_x = 0.191 + 0.125 x CO	0.837	6.96
	October	NO_x = 0.114 + 0.134 x CO	0.813	6.89
	All Data	NO_x = 0.163 + 0.157 x CO	0.755	5.77
1998	April	NO_x = 0.259 + 0.119 x CO	0.750	6.88
	July	NO_x = 0.246 + 0.114 x CO	0.807	7.21
	October	NO_x = 0.276 + 0.086 x CO	0.510	8.91
	December	NO_x = 0.223 + 0.188 x CO	0.826	4.76
	All Data	NO_x = 0.296 + 0.108 x CO	0.654	7.26
1997	March	NO_x = 0.203 + 0.188 x CO	0.726	4.79
	June	NO_x = 0.190 + 0.101 x CO	0.669	8.35
	September	NO_x = 0.364 + 0.148 x CO	0.797	5.43
	December	NO_x = 0.322 + 0.097 x CO	0.632	7.63
	All Data	NO_x = 0.333 + 0.109 x CO	0.627	6.99

Table 4: CO/NOx Ratios at 10 ppm Based on Linear Regression Models

Monitoring Year	1997	1998	2004	All Years
Summer	6.96	7.21	6.96	6.99
Winter	4.79	4.76	4.30	4.55

COMPARISON TO MOBILE 6.2 PREDICTIONS

CO and NOx emission factors were estimated using the U.S.EPA MOBILE 6.2.03 Emission Factor Model released in May 2004. This version reflects the effects of the new vehicle standards and vehicle turnover. An effort was made to use as much site specific input data as possible in order to reflect the fleet, driving modes, and ambient conditions that could occur within the tunnel for each monitoring period.

A review of the studies regarding the sensitivity of MOBILE 6.2, performed by EPA and the Federal Highway Administration, indicated that the most significant parameters that could produce large changes in predicted emissions for 2005 are: Reid Vapor Pressure (RVP), and temperature. The variation of these two parameters could change CO emissions by 60-80%, and NOx by 5-20% between summer and winter. Other parameters such as registration data, air conditioning and sulfur content appear to have lesser differences for both pollutants.

Considering the importance of these parameters, emission factors for the fleet using the tunnel were estimated for the four months (i.e., January, April, August, and October) corresponding to the periods when monitoring data was collected during 2004.

The following inputs and assumptions were used for each scenario:

- Massachusetts DEP input files including the I/M, anti-tampering, LEV programs, vehicle registration data, and local area parameters as of 2004;
- Only running emissions for light duty vehicles were considered (i.e., start emissions were excluded) in order to replicate interstate highway travel;
- Reid Vapor Pressure (RVP) of 6.8 psi was used for August and 13.5 psi for January, April and October;
- Average monthly minimum and maximum ambient temperatures measured at Logan International airport during each monitoring period were used for each data set;
- Specific local values for gasoline and diesel sulfur contents for each monitoring month;
- Average daily vehicle classification data was based on traffic survey data collected on I-90 EB and WB for autos, light-duty trucks and heavy-duty trucks.
- Light duty gasoline trucks were divided into four groups (LDGT 1, 2, 3, and 4) and heavy duty trucks were split between heavy-duty gasoline vehicles (HDGV) and heavy-duty diesel vehicles (HDDV) based on Mass DEP registration data for 2004.

The emission factors for CO and NOx were estimated using these inputs for a speed range from 15 to 40 miles per hour (mph) at 5 mph intervals. It should be noted that very little variation in the CO/NOx ratios occur for the different speeds within this speed range.

As it can be observed in table 5, the MOBILE 6.2 January CO emission factors are approximately 75% higher than the August emission factors, while the January NOx emission factors are approximately 30% higher than the August ones.

Table 5: 2004 Mobile 6.2 Emission Factors at 40 MPH

Pollutant	January	April	August	October
CO (gm/mile)	11.84	10.16	6.81	9.83
NO_x (g/mile)	1.34	1.14	1.02	1.17

The resulting MOBILE 6.2 CO/NOx ratios for each quarter (for the full speed range) are presented in table 6. As it can be observed, the lowest CO/NOx ratio occurred in summer; the winter ratio was almost 30% higher. This is opposite to the results of the monitoring program.

Table 6: 2004 Average CO/NOx Ratios Based on Mobile 6.2 Emission Factors

Month	January	April	August	October
Ratio	8.72	8.76	6.32	7.87

CONCLUSIONS

One of the principal objectives of the TWT monitoring program was to develop a statistical method using monitored CO levels as a predictor for estimating NOx levels for compliance demonstration with the Massachusetts 1-hour NO_2 Policy Guideline.

The statistical analysis produced a good correlation between the CO and NOx data with correlation coefficients above 0.8 for the 2004 data, and between 0.5 and 0.82 for 1997/98 data sets. This proved that the linear regression models could be used to predict NOx as a function of CO, eliminating the need of continuous NOx monitoring.

The results of the 6,000 hours of data collected during 2004 indicated that average hourly CO levels were lower than anticipated (2 to 5 ppm), with a maximum CO concentration of 16.2 ppm. The average hourly NOx levels ranged from 0.2 to 1.2 ppm, with a maximum NOx concentration of 2.26 ppm. The evaluation of the seasonal variation in average pollutant levels indicated that NOx was approximately 30% higher in winter than summer, as anticipated. The variation of CO levels between summer and winter was within 4%, which was not expected; CO emissions are known to peak during the winter months.

The 2004 CO/NOx ratios varied between 4.3 and 7.0. The highest CO/NOx ratios occurred in August during the summer period, while the lowest occurred during January. This is attributed to the higher NOx levels measured in winter, in conjunction with minimal seasonal variation of the measured CO levels. A comparison to the 1997/98 data sets indicated a similar pattern with slightly higher CO/NOx ratios, most likely due to the higher percentage of heavy duty vehicles during 1997/98. The highest 1997/98 CO/NOx ratios also occurred during the summer period.

The seasonal variation of the MOBILE 6.2 predicted ratios was opposite to those ratios obtained from the monitored data. MOBILE 6.2 predicted CO emission factors were 75% higher in winter than in summer, while the monitoring data indicated a minimal 4% variation between summer and winter measurements. As for NOx emission factors, both the MOBILE 6.2 predictions and the monitored data exhibit a similar increase (i.e., 30%) during winter months. As a result, the CO/NOx summer ratios from the 2004 measured data followed the MOBILE 6.2 estimates closely (6.9 versus 6.3 MOBILE); while the CO/NOx winter ratios were very different (4.3 versus 8.7 MOBILE).

Despite our efforts to simulate site specific conditions in MOBILE 6.2, the causes for the monitored data not reflecting the CO increases during the winter months as predicted by MOBILE 6.2 need further investigations. It is possible that other input parameters will have to be evaluated, or that the Boston fleet is cleaner than anticipated by MOBILE. Continued discussions with DEP and EPA Region I in this subject matter are expected.

Based on the fact that measured data reflects the most current vehicular emissions within the Boston CA/T Project area; and because the summer season is the period when the highest O_3 and NO_2 background levels occur (NOx is the critical pollutant for emission limit determination), the use of the regression formula based on the 2004 summer data would be more appropriate for use in the compliance demonstration in support of the Project's Operating Certification.

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KEY WORDS

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