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Modeling of Ambient Black Carbon Concentration Using Traffic, Temporal and Meteorology Data in Connecticut

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Abstract

Black carbon is a component of fine particle pollution that exerts adverse effects on both global climate change and human health. It is produced through incomplete combustion of fossil fuels and biofuels. Therefore, some of its major emission sources are diesel engines, residential heating and industry. Due to its strong ability to absorb solar energy, black carbon is one of the major contributors to global warming. In addition, black carbon and other fine particle pollutants can be inhaled into the lower respiratory track, causing and exacerbating health conditions such as asthma, chronic obstructive pulmonary disease, low birth weight, cardiovascular diseases and lung cancer. Current black carbon monitoring sites are located in close proximity to roads with heavy traffic volume. The dispersion of ambient black carbon is subjected to many influencing factors. Therefore, the concentration of ambient black carbon in residential areas is much lower than that in heavy traffic areas. Environmental health studies using these data are likely to overestimate the concentration of ambient black carbon. As a result, the true threshold for adverse health effects may be lower than what have been reported in these studies. This paper aims to use existing data on ambient black carbon, traffic volume, daily temperature, daily wind speed and daily precipitation level in Connecticut to construct a linear regression model which can be used to reliably predict the level of ambient black carbon in places where black carbon monitors are not available. Data from five black carbon monitor stations, geographically matched traffic count stations and meteorology stations were collected and analyzed. Results showed that black carbon was significantly influenced by seasonal cycle, days of the week, daily temperature and daily average wind speed. In contrast, traffic volume did not have statistically significant influence on ambient black carbon concentration. This study suggests that ambient black carbon is strongly affected by seasonal cycle, daily temperature and inversely affected by daily wind speed, but not by traffic volume, especially as the point of interest moves further away from traffic source. However, given that this study did not account for other sources of emission, such as residential heating and industry emission, the relationship between ambient black carbon and various emission sources could be further explored.

Acknowledgement

I would like to express my deepest appreciation to my two thesis readers, Professor Theodore Holford and Professor Brian Leaderer, for their patient and resourceful guidance. Their utmost brilliance and passion for public health research is an inspiration not only for this thesis, but also for my study and future career as a public health professional.

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Background

Black carbon (BC) is a component of atmospheric aerosols that absorbs visible radiation. It is comprised of elemental carbon and several organic carbon species. BC is produced by incomplete combustion of fossil fuels, biofuels, and biomass. Thus, some of its major emission sources include diesel engines, forest fires, residential heating and industry[i]. In 2005, it is estimated that the United States emitted 0.64 million tons of BC, putting the United States the 7th leading emitter globally[ii]. Globally, it was estimated that 8.4 million tons of BC was emitted in 2000. Asia, Africa and Latin America are the other regions that emit large amounts of BC. However, the sources of emission in these countries vary drastically from the United States, with open biomass burning, residential cooking and heating being the most significant sources.

Environmentally, BC absorbs solar energy most strongly compare to other particulate matters (PM). Per unit mass, BC can absorb a million times more light energy than carbon dioxide. Due to its strong absorbing and poor reflecting ability, BC is believed to be a major contributor to global climate change[iii]. When BC is deposited on snow and ice, it accelerates the melting process by absorbing light and increasing temperature[iv]. In contrast to carbon dioxide, which has an atmospheric lifetime of over 100 years, the atmospheric lifetime for BC spreads from days to weeks. The short lifetime of BC makes it an excellent target for global warming effort because reducing BC production is likely to result in significant climate change in the short-term.

From a public health perspective, the health consequences of BC are less well studied but generally believed to be in similar to that of PM2.5. PM2.5 particles are small enough to be inhaled into the lower respiratory track, causing and exacerbating conditions such as asthma, chronic obstructive pulmonary disease, low birth weights, heart attack and lung cancer[v]. The exact health effects of BC are still being debated because other simultaneously released PM2.5 particles such as polyaromatic hydrocarbons can condense on the surface of BC. In early animal models, BC has been demonstrated to be associated with rat lung tumors. This association prompted International Agency for Research on Cancer (IARC) to move BC from category 3 to 2B, a possible human carcinogen[vi]. In human occupational studies, the results are mixed. While two Europe studies showed excess risk of lung cancer among workers who work in carbon black production facilities, occupational cohort studies in the U.S failed to demonstrate any significant association after adjusting for exposure and lifestyle habits[vii]. Due to difficulties in follow-up and measurement, most occupational studies were subjected to loss to follow-up or confounding limitations, such as smoking[viii]. The main non-occupational exposure sources to BC are traffic and residential heating. Whether BC itself is harmful or serves as a surrogate for other PM2.5 particles is unclear, but BC has been associated with asthma and decreased lung function in both women and children[ix][x]. Therefore, BC is an important air pollutant to be monitored for both global warming and human health purposes.

Currently, U.S. Environmental Protection Agency (EPA) BC monitoring stations are located in close proximity to major traffic routes. Many air pollution health studies use these measurements to estimate the effect of BC on adverse health outcomes such as asthma[xi][xii]. One disadvantage of this approach is that the concentration of BC in residential areas may drastically differ from that in traffic areas, because atmospheric BC concentration can be affected by many factors including precipitation and wind during the course of dispersion. Hence, using BC measurements in places with high traffic volume may cause an over estimation of BC concentration in residential areas, suggesting the actual level of BC that can cause an adverse outcome is lower than what we observe in the studies. Therefore, this paper aims to statistically describe and model the concentration of BC, using historical BC, season, traffic, temperature, precipitation, snow and wind data. The goal is to produce a reliable regression model that can be used in the future to estimate BC level in areas further away from EPA monitoring stations.

Method

As a component of PM2.5, BC is monitored by the PM2.5 urban and rural speciation monitoring networks. The urban Chemical Speciation Network (CSN) measures urban BC in particular, with approximately 200 monitors located in major urban areas. Measurements are taken once every three days. PM2.5 filters were obtained from EPA and BC concentration were measured by light absorption/optical technique. A specific wavelength laser beam was passed through the sample and the amount of light absorption by particles is measured. Laser beam of different wavelengths can be used to tell different types of carbon present, such as black and brown carbon [xiii]. Five EPA BC sites were selected in the state of Connecticut to capture geographical, traffic and meteorology variations. They were Danbury, East Hartford, Norwalk, Waterbury and Westport (for a map of the selected EPA sites, refer to Appendix). BC concentration and its log-transformation were first examined for distribution pattern and missing values. Both non-parametric and parametric models were explored. One temporal and two seasonal explanatory variables were then created to test for temporal and seasonal effects, according to the following formula:

$\mathrm{TRIG} = (\mathrm{DATE} - \mathrm{Jan}/01/2002)/365 * 2\pi$

$\mathrm{SINTRIG} = \mathrm{SIN}(\mathrm{TRIG})$

$\mathrm{COSTRIG} = \mathrm{COS}(\mathrm{TRIG})$

TRIG was created by transforming the date of measurement into a trigonometry unit similar to radians. In this way, one calendar year would correspond to a sinusoidal cycle. The parameter estimate of TRIG would reflect the overall trend of BC concentration across time. The parameter estimates of SINTRIG and COSTRIG reflect the amplitude of the sinusoidal cycle and hence the presence of any seasonal effect. By including sine and cosine terms, the regression allows for a flexible starting point of the sinusoidal cycle, and the starting point of the sinusoidal cycle can be calculated by $\tan^{-1}[\beta_{\mathrm{Cos(TRIG)}} / \beta_{\mathrm{Sin(TRIG)}}]$.

Continuous traffic data count of 2002-2012 was obtained from Connecticut Department of Transportation (DOT). Continuous traffic monitors were set up around major highways and local routes at forty locations in Connecticut (for the list and map of routes monitored and location, refer to Appendix). Number of cars passed by per direction, per hour was recorded for 24 hours per day, seven days a week. Total number of cars that passed by a monitoring station per direction, per day, was calculated by adding up hourly counts. The continuous traffic counts was then further trimmed to accurately reflect the traffic volume around each black carbon monitoring station site from 2002-2006. Eleven traffic monitoring stations were picked and matched by dates to EPA BC monitoring station based on their geographical proximity. Prior to merging traffic data to BC data, the temporal trend of traffic data was analyzed, using methods similar to that of BC concentration trend. Seven independent variables were created to test the effects of daily total traffic volume and days-of-the-week (six dummy variables Monday to Saturday).

Meteorology data from 2002 to 2006, including daily temperature, precipitation, snowfall and average wind speed were obtained from the National Oceanic and Atmospheric Administration online database. Four meteorology monitoring sites were selected to match the geographical location of EPA BC monitoring stations (for a map of meteorology stations, refer to Appendix). Meteorology data was then evaluated for missing values and matched by date by geographical location to each EPA BC monitoring site. Norwalk and Westport EPA BC sites shared meteorology data from Bridgeport due to their close geographical proximity. Four explanatory variables were created to test the influence of daily temperature, precipitation, snowfall and average wind speed on BC concentration. Precipitation and snowfall were further divided to two categories (two dummy variables) to test the effect of any precipitation/snowfall in contrast to no precipitation/snowfall at all.

Table 1. Summary of the match between EPA BC monitoring stations and identified meteorology and traffic monitoring sites

EPA BC Station	Meteorology Monitoring Site	Traffic Monitoring Site	Route Monitored
Danbury	Danbury	Newtown	I-84
East Hartford	Hartford	Manchester	I-84
		Wethersfield	I-91

		Berlin	15
		West Hartford	I-84
Norwalk	Bridgeport	New Canaan	124
		Norwalk	I-95
Waterbury	Woodbury	Watertown	8
		Cheshire	I-691
		Middlebury	I-84
Westport	Bridgeport	Westport	1
		Norwalk	I-95

Table 1

With independent variables assembled, the following linear regression model was fitted for each EPA site to explain BC concentration using time, traffic, days-of-the-week and meteorology observations:

Log(BC concentration) = α+β_1(Daily Total Traffic Volume)+ β_2[Sin(TRIG)] + β_3[Cos(TRIG)] + β_4 (TRIG)+ β_5(Monday) + β_6(Tuesday) + β_7(Wednesday) + β_8(Thursday) + β_9(Friday) + β_{10}(Saturday) + β_{11}(Daily Average Wind Speed) + β_{12}(Daily Maximum Temperature)+ β_{13}(Any Precipitation)+ β_{14}(Any Snowfall)+ε

Backwards elimination for traffic sites and joint tests were further performed for each regression model to obtain the best fitted model and the parameter estimates were interpreted.

Results

Black Carbon Concentration

Overall there were 1535 available observations from 2002 to 2006. The mean BC concentration was 0.9421 microgram per cubic meter (ug/m^3), with a standard deviation of 0.5842. Basic statistical analysis showed that BC concentration is subjected to large variation with extreme outliers. Outliers exert high leverage on regression analysis and hence distort parameter estimates. Therefore, raw concentrations were log-transformed by the formula:

Logconc = Log (concentration + 10)

Table 2. Summary of the log-transformed BC concentration at each EPA site

Location	No. of Observation	Mean (ug/m^3)	Standard Deviation
Danbury	268	2.3889	0.0559
East Hartford	261	2.3748	0.0421
Norwalk	458	2.3891	0.0507
Waterbury	497	2.4040	0.0517
Westport	51	2.3836	0.0471

Table 2

Figure 1. LOESS fitted lines for raw and log-transformed BC concentration for each EPA site (For aggregate BC observation plots, refer to Appendix)

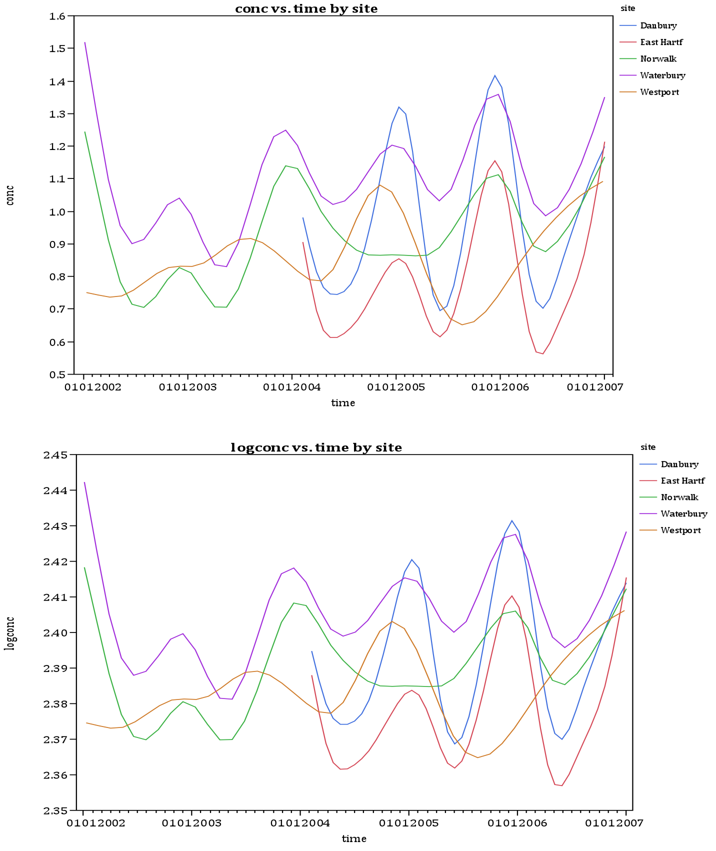


Figure 1

Both aggregate and site-specific analyses showed strong cyclical trend, with BC peaks occur during winter seasons and valleys in summer seasons. To statistically test for the temporal trend, log-transformed BC concentration was first explained by independent variable TRIG, SINTRIG and COSTRIG.

Table 3. Summary of seasonal and temporal effects each EPA site

Site	Danbury***	East Hartford***	Norwalk***	Waterbury***	Westport***
Adjusted R	0.1377	0.2184	0.0926	0.1136	0.2776
	Parameter Estimate	Parameter Estimate	Parameter Estimate	Parameter Estimate	Parameter Estimate
Intercept	2.3997**	2.3829**	2.3819**	2.3988**	2.2159**
TRIG	-0.0002	-0.0002	0.0005*	0.0003	0.1586*
SINTRIG	-0.0108*	-0.0129*	-0.0074*	-0.0114**	-0.0786*
COSTRIG	0.0301**	0.0282**	0.0120**	0.0224**	0.2187*

* Parameter estimate statistically significant at α=0.05 level

** Parameter estimate statistically significant at α=0.0001 level

*** Overall F-test < 0.0001

Table 3

In general, the BC concentration around Danbury, East Hartford and Waterbury EPA monitoring sites showed no obvious overall trend, while Norwalk, Waterbury and Westport showed significant upward trend from 2002 to 2006. All five sites showed significant seasonal variation, suggesting that the BC concentration followed a yearly sinusoidal pattern from 2002 to 2006. To further confirm the significance of the yearly sinusoidal pattern, a joint-test was performed for SINTRIG and COSTRIG.

Table 4. Summary of F-Test for seasonal pattern in BC concentration

EPA Sites	Season Effect			
	F-Value	DF1	DF2	Pr>F
Danbury	38.71	2	490	<0.0001
East Hartford	33.08	2	238	<0.0001
Norwalk	38.61	2	837	<0.0001
Waterbury	54.28	2	839	<0.0001
Westport	3.80	2	98	0.0258

Table 4

F-statistics further confirmed that the yearly sinusoidal pattern was significant at all EPA sites. The starting point of sinusoidal cycle was then calculated for each EPA sites, using the formula $\tan^{-1}[\beta_{Cos(TRIG)} / \beta_{Sin(TRIG)}]$.

Table 5. Summary of the starting point of each sinusoidal cycle

EPA Site	Starting Point in Trigonometry Unit	Starting Point in Date
Danbury	-1.2263	12-Mar
East Hartford	-1.14177	7-Mar
Norwalk	-1.01821	28-Feb
Waterbury	-1.10003	4-Mar
Westport	-1.22578	12-Mar

Table 5

Traffic Volume

Overall, 275988 observations were collected from all forty DOT sites, with 3047 missing values (1.10%). On average, 19586 cars passed by a monitoring station per direction per day, with a standard deviation of 19560.1454. After restraining observations to the eleven matched sites, there were 31652 observations available from 2002-2006, with 547 missing values (1.73%). Since all eleven routes are major highways/turnpikes/state routes, it is very unlikely that any of these routes would have a zero daily total traffic count. Hence, zero values (4068 observations, 12.85%) were treated as missing values and were dropped out from the analysis.

Figure 2. Overall and site-specific traffic trend around the eleven DOT sites from 2002 to 2006

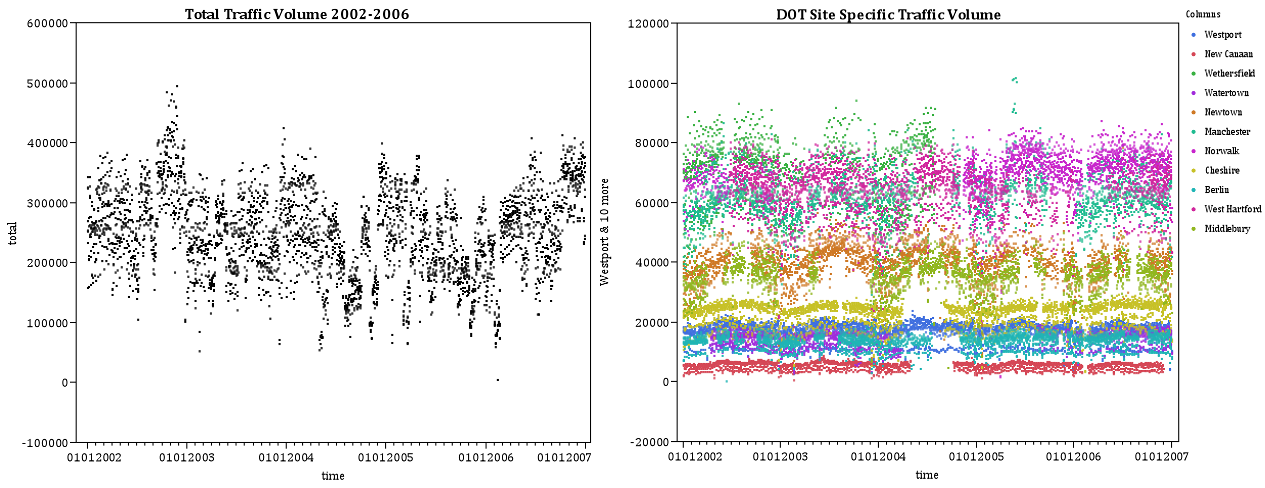


Figure 2

On average, 33368 cars passed by a monitoring station per direction per day, with a standard deviation of 23118.2553.

Table 6. Summary of traffic volume and number of available observations after matching by dates

EPA BC Site	Traffic Monitoring Site	Route Monitored	No. of Available Observations	Mean Traffic Volume / No. of cars	Standard Deviation
Danbury	Newtown	I-84	368	40624	5305
East Hartford	Manchester	I-84	342	62425	8184
	Wethersfield	I-91	96	65843	13620
	Berlin	15	361	13390	2503
	West Hartford	I-84	293	62596	8108
Norwalk	New Canaan	124	790	5263	1184
	Norwalk	I-95	368	71864	6335
Waterbury	Watertown	8	492	14147	2541
	Cheshire	I-691	851	22311	3979
	Middlebury	I-84	615	35102	5205
Westport	Westport	1	100	16694	3526
	Norwalk	I-95	368	71864	6335

Table 6

DOT traffic data was further analyzed in several ways. First, correlation between DOT sites within each EPA BC site is analyzed. Correlation is a major concern in this analysis because traffic routes are connected. A regression model with multiple highly correlated independent variables will distort the parameter estimates due to multicollinearity.

Table 7. Summary of Person Correlation Coefficient between DOT sites within each EPA BC site

East Hartford EPA BC Site

DOT Site	Berlin	Manchester	West Hartford	Wethersfield
Berlin	1.0000	0.7340	0.7921	0.7157
		<.0001	<.0001	<.0001
Manchester	0.7640	1.0000	0.7807	0.8053
	<.0001		<.0001	<.0001
West Hartford	0.7921	0.7807	1.0000	0.8483
	<.0001	<.0001		<.0001
Wethersfield	0.7157	0.8053	0.8483	1.0000
	<.0001	<.0001	<.0001	

Norwalk EPA BC Site

DOT Site	New Canaan	Norwalk
New Canaan	1.0000	0.4114
		<.0001
Norwalk	0.4114	1.0000
	<.0001	

Waterbury EPA BC Site

DOT Site	Waterbury	Cheshire	Middlebury
Watertown	1.0000	0.8809	0.7169
		<.0001	<.0001
Cheshire	0.8809	1.0000	0.7790
	<.0001		<.0001
Middlebury	0.7169	0.7790	1.0000
	<.0001	<.0001	

Westport EPA BC Site

DOT Site	Westport	Norwalk
Westport	1.0000	0.4966
		<.0001
Norwalk	0.4966	1.0000
	<.0001	

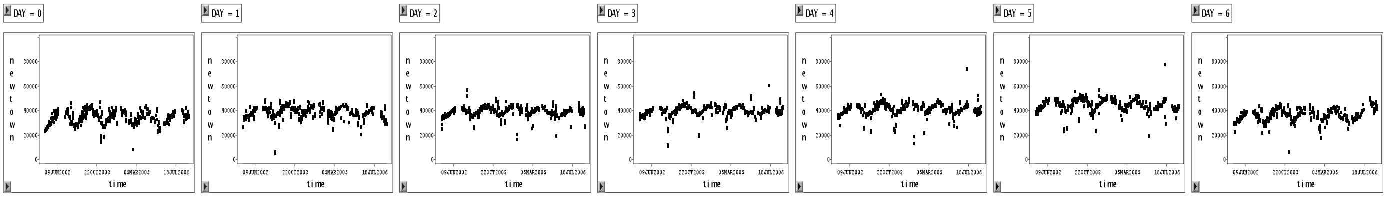
Table 7

Correlation analysis showed that daily traffic volumes were highly correlated within each EPA site. Therefore, one DOT traffic site for each EPA BC site was selected to avoid multicollinearity. Based on Table 3, traffic data from Wethersfield was dropped because low number of observation will reduce the power of the study. In addition, traffic data from Norwalk, West Hartford, and Watertown were dropped too due to large chunks of missing observations.

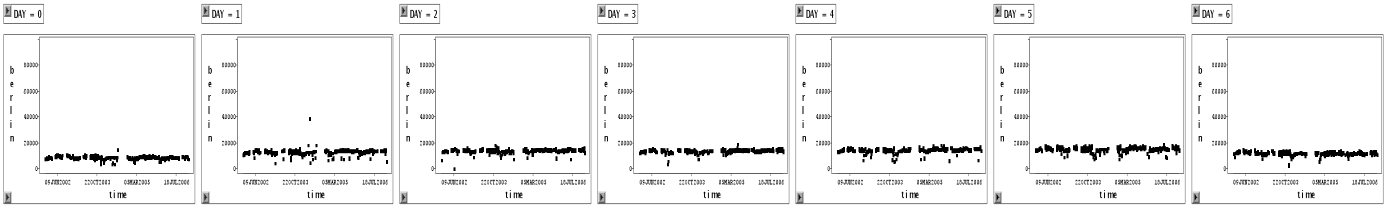
Figure 3. Traffic volume by day of the week for each DOT site

Sunday-Saturday

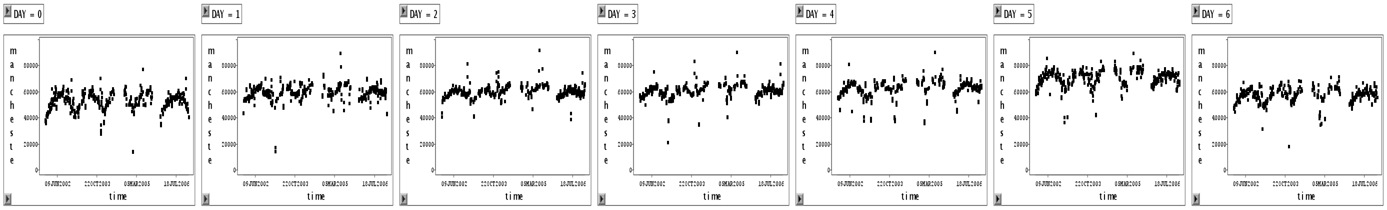
Newtown



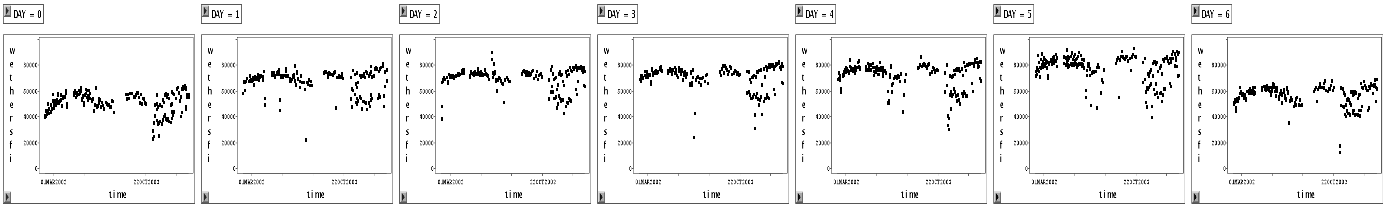
Berlin



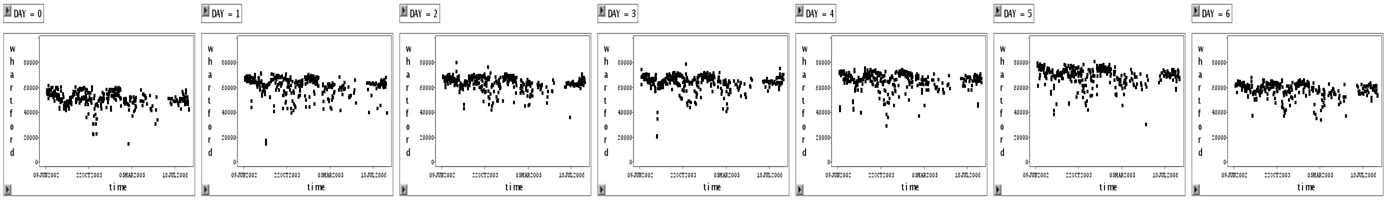
Manchester



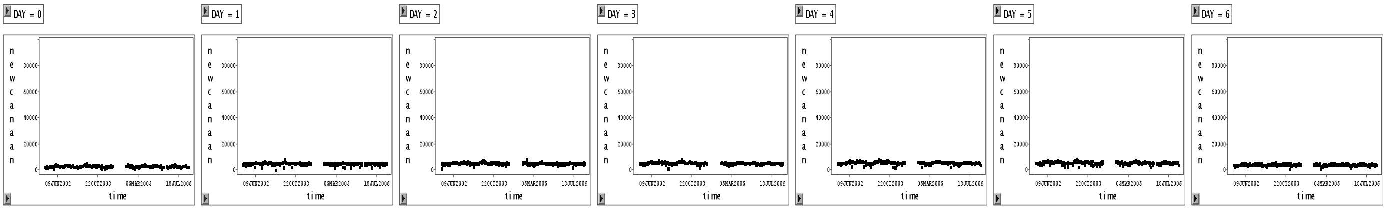
Wethersfield



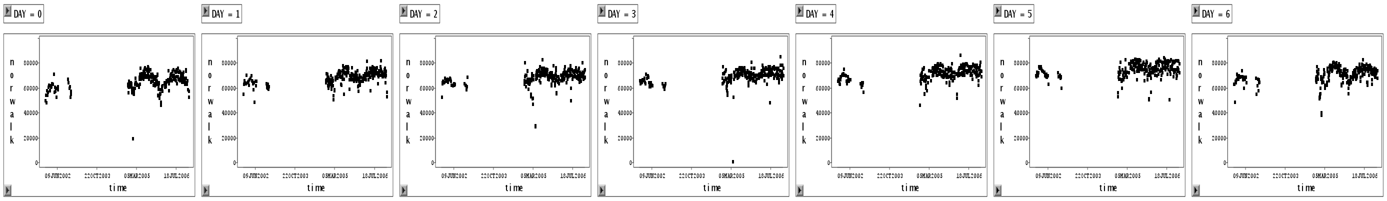
W Hartford



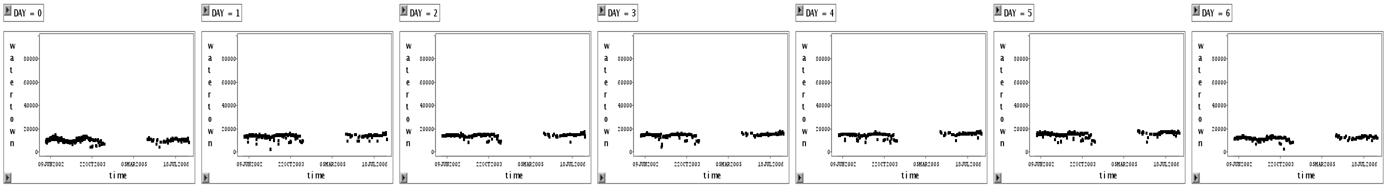
New Canaan



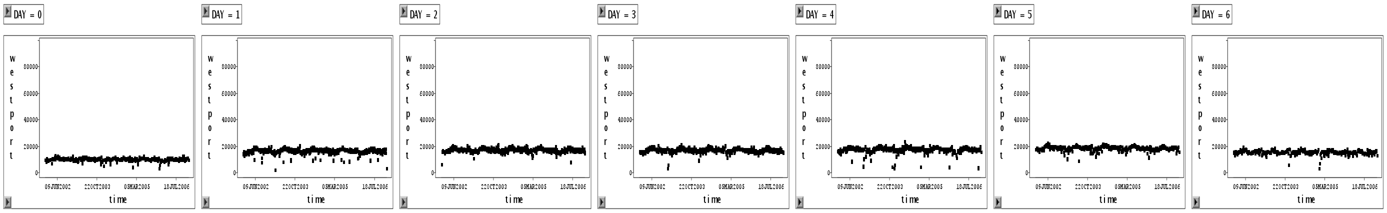
Norwalk



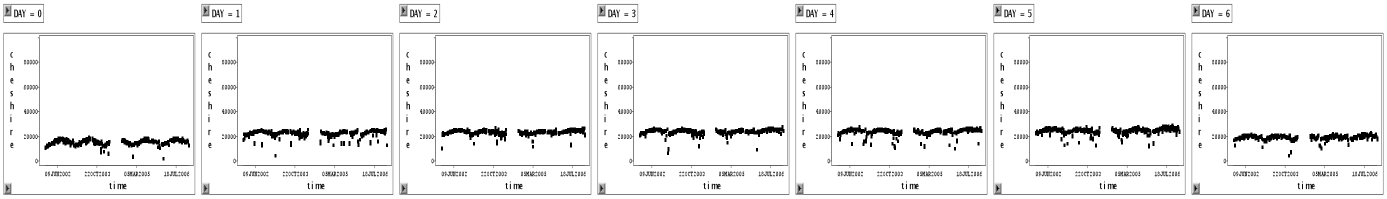
Watertown



Westport



Cheshire



Middlebury

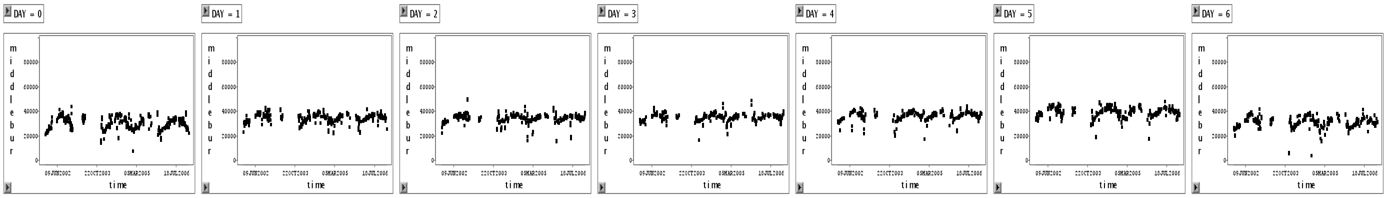


Figure 3

Second, days-of-the-week effect was analyzed because traffic volume often varies with the day of the week, with fewer cars commuting during the weekend.

Table 8. Summary of days-of-the-week effect on traffic volume, compare with Sunday

DOT Site	Newtown***	Berlin***	Manchester***	New Canaan***	Cheshire***	Middlebury***	Westport***
Adjusted R	0.3082	0.6620	0.3558	0.5807	0.5571	0.2697	0.5293
	Parameter Estimate	Parameter Estimate	Parameter Estimate	Parameter Estimate	Parameter Estimate	Parameter Estimate	Parameter Estimate
Intercept	35514**	9256.7895**	54565**	3379.8362**	16123**	31240**	10489**
Mon	3582.9517**	3677.2570**	7227.8816**	2091.2768**	6441.2040**	4212.8419**	4767.8214**
Tue	4932.4917**	4988.3836**	7184.3991**	2458.6592**	7598.8658**	3445.6720**	7487.3929**
Wed	6841.0535**	5484.3657**	8570.9053**	2452.5249**	8019.5966**	4597.3123**	6793.0500**
Thu	6850.2364**	5881.3067**	11762**	2556.6855**	8537.3193**	6082.6277**	8372.8125**
Fri	10171**	6030.1897**	16664**	2524.8073**	8847.0374**	8268.9197**	9213.4500**
Sat	3524.2952**	3166.4262**	4594.9430**	1159.7799**	3616.0282**	416.2727	6212.5357**

*   Parameter estimate statistically significant at α=0.05 level

** Parameter estimate statistically significant at α=0.0001 level

*** Overall F-test < 0.0001

Table 8

Based on the analysis above, days-of-the-week had significant effects on daily traffic volume at all DOT sites. Compare with Sundays, traffic volume significant increased during weekdays and Saturdays, with magnitudes ranging from a thousand to more than ten thousand cars per day.

Third, temporal and seasonal trends were analyzed for traffic data in similar ways as BC concentration. From Figure 2, it was obvious that site-specific traffic volume followed some kind of cyclical pattern with valleys occurring during the winter seasons. One possible explanation for this pattern might be people commute less frequently by car during holiday seasons.

Table 9. Summary of temporal and seasonal trends of traffic volume at relevant DOT sites

DOT Site	Newtown***	Berlin	Manchester***	New Canaan***	Cheshire***	Middlebury***	Westport***
Adjusted R	0.2484	0.0086	0.1445	0.0896	0.1157	0.2588	0.1345
	Parameter Estimate	Parameter Estimate	Parameter Estimate	Parameter Estimate	Parameter Estimate	Parameter Estimate	Parameter Estimate
Intercept	41374**	13215**	69606**	5450.5460**	22275**	35786**	18047**
TRIG	-31.3041	7.9135	-295.4162*	-14.8080*	9.4414	-20.3089	-110.1187*

SINTRIG	-1709.0883**	-348.0403	-1908.0481*	-186.5187*	-808.4982**	-1577.7698**	-449.6757
COSTRIG	-3759.5294**	-314.4527	-3914.9644**	-489.4427**	-1743.5225**	-3479.1030**	-1725.8703*

* Parameter estimate statistically significant at α=0.05 level

** Parameter estimate statistically significant at α=0.0001 level

*** Overall F-test < 0.0001

Table 9

Temporal and seasonal effects of traffic volume are less consistent across DOT sites. New Canaan and Westport showed significant decrease of traffic volume overtime, while the rest showed no significant trend over time. All DOT sites with the exception of Berlin showed significant seasonal variations. The starting point of each sinusoidal cycle was then calculated for each DOT site, using the formula $\tan^{-1}[\beta_{\mathrm{Cos(TRIG)}} / \beta_{\mathrm{Sin(TRIG)}}]$

Table 10. Summary of the starting point of each sinusoidal cycle

DOT Site	Starting Point in Trigonometry Unit	Starting Point in Date
Newtown	1.144122	7-Mar
Berlin	0.734743	11-Feb
Manchester	1.117301	5-Mar
New Canaan	1.206703	11-Mar
Cheshire	1.136595	7-Mar
Middlebury	1.145036	8-Mar
Westport	1.315913	17-Mar

Table 10

Comparing Table 5 and Table 9, the starting points of the seasonal sinusoidal cycles for both BC and traffic lied close to each other, suggesting that their seasonal cycles were approximately in phase. This supported the idea that traffic volume is explanatory to ambient BC concentration.

Daily Meteorology Data

Daily maximum and minimum temperatures, precipitation, and average wind speed measurements from 2002 to 2006 were obtained from the National Oceanic and Atmospheric Administration. Across the five-year period, the average daily maximum temperature was 16.1478°C with a standard deviation of 10.3421°C. Daily minimum temperature was 6.3113°C with a standard deviation of 9.6237°C. Daily maximum temperatures and minimum temperatures perfectly correlate with each other.

Figure 4. Trend of daily maximum and minimum temperatures

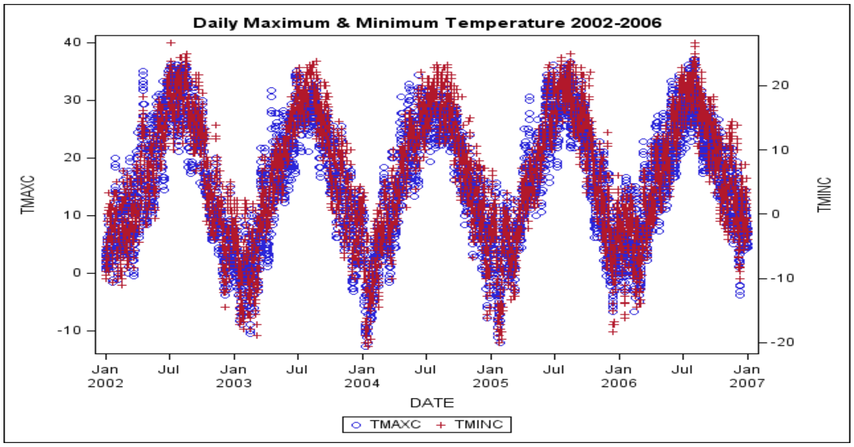


Figure 4

Data on daily average wind speed was missing for all meteorology sites except for Hartford and Bridgeport. Therefore, the effect of wind speed on BC concentration could only be analyzed for East Hartford, Westport and Norwalk EPA BC sites. Around Hartford, the average daily wind speed from 2002 to 2006 was

2.9283m/s with a standard deviation of 1.3226m/s. Around Bridgeport, the daily average wind speed from 2002 to 2006 was 4.0419m/s with a standard deviation of 1.7261m/s. Seasonal patterns could be observed in daily average wind speed data, with peaks occurring during winter and spring seasons.

Figure 5. Trend of daily average wind speed across the five years around Harford and Bridgeport areas

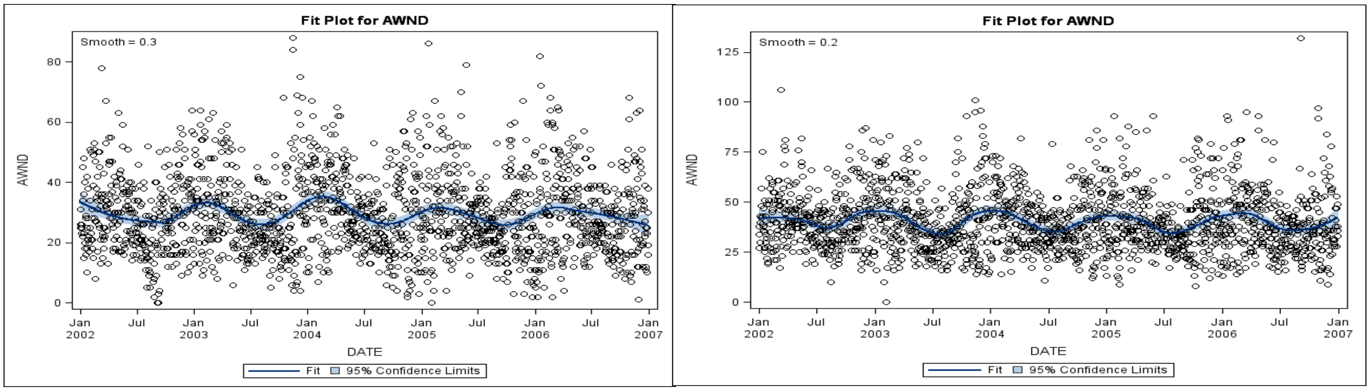


Figure 5

In addition, data on daily precipitation and snowfall around four meteorology sites was analyzed. The mean amount of daily precipitation between 2002 and 2006 was 0.3581 inch, with a standard deviation of 0.9604 inch. The mean amount of snowfall was 0.3728 inch with a standard deviation of 2.4019 inch. The distribution of daily precipitation and snowfall were highly skewed. (For the frequency distribution of daily precipitation and snow, refer to Appendix) Since precipitation and snowfall have wash-off effects on ambient BC, daily precipitation and snowfall data were divided into two categories, no precipitation/snowfall and any precipitation/snowfall.

Regression Analysis

Traffic volume was first added to the model to observe the unadjusted effects of traffic on ambient BC concentration. Backwards eliminations were performed for EPA BC sites East Hartford and Waterbury to select the best explanatory DOT traffic site (for the backward elimination intermediate steps, refer to Appendix). The traffic volume around Manchester explained little about the BC concentration around East Hartford, as the parameter estimate was not statistically significant. Hence, Manchester was dropped out of the analysis. Both Cheshire and Middlebury were not statistically significant at α=0.05 level. However, the P value for Cheshire was much lower than that of Middlebury and close to 0.05. Therefore, Middlebury was dropped out of the analysis. Both adjusted R-square values and p-values improved after dropping the two independent variables.

Table 11. Summary of Traffic effect on BC concentration

Site	Danbury	East Hartford	Norwalk	Waterbury***	Westport
Adjusted R	0.0020	-0.0465	0.0149	0.0442	-0.0048
	Parameter Estimate	Parameter Estimate	Parameter Estimate	Parameter Estimate	Parameter Estimate
Intercept	2.4230**	2.3750**	2.3585**	2.3404**	2.3285**
Traffic Parameter Estimates	-0.0080	0.00002	0.0557*	0.0283**	-0.0114
Traffic Sites	Newtown	Berlin	New Canaan	Cheshire	Westport

* Parameter estimate statistically significant at α=0.05 level

** Parameter estimate statistically significant at α=0.0001 level

*** Overall F-test < 0.0001

Table 11

Based on the initial analyses, daily total traffic counts around Norwalk and Waterbury EPA BC sites had significant effects on BC concentration, whereas the traffic counts around Danbury, East Hartford and

Westport had no significant effect on BC concentration. Using Norwalk as an example, ambient BC concentration is estimated to increase by 5.37% (e^$^{0.0557}$-1) for every 10,000 increase in car count.

Table 12. Summary of linear regression model populated with temporal, seasonal and days-of-the-week variables

Site	Danbury***	East Hartford***	Norwalk***	Waterbury***	Westport***
Adjusted R	0.1640	0.2842	0.1413	0.2402	0.2719
	Parameter Estimate	Parameter Estimate	Parameter Estimate	Parameter Estimate	Parameter Estimate
Intercept	2.3758**	2.4211**	2.3479**	2.3363**	2.3285**
TRIG	-0.0005	-0.0001	0.0006*	0.0001	0.0007
SINTRIG	-0.0091*	-0.0144*	-0.0074*	-0.0051	-0.0244*
COSTRIG	0.0369**	0.0262**	0.0224**	0.0354**	0.0113
Monday	0.0102	0.0326*	0.0145	0.0208*	0.0329
Tuesday	0.0322*	0.0577**	0.0270*	0.0306*	0.0427
Wednesday	0.0337*	0.0335*	0.0099	0.0100	0.0125
Thursday	0.0217	0.0484*	0.0255*	0.0115	0.0530*
Friday	0.0199	0.0521*	0.0167	-0.0004	0.0151
Saturday	0.0183	0.0149	0.0022	-0.0013	0.0198
Traffic Parameter Estimates	0.0020	-0.0549*	0.0378	0.0242*	0.0152
Traffic Sites	Newtown	Berlin	New Canaan	Chesire	Westport

* Parameter estimate statistically significant at α=0.05 level

** Parameter estimate statistically significant at α=0.0001 level

*** Overall F-test < 0.0001

Table 12

With temporal, seasonal and days-of-the-week variables added, total daily traffic count around Waterbury remained to be significant, while traffic counts near Norwalk became insignificant. Counter-intuitively, the daily total traffic count near East Hartford seems to decrease ambient BC concentration. For every 10,000 increase in traffic count, the model predicts that the BC concentration around East Hartford will decrease by 5.34% (e^$^{-0.0549}$-1), holding all other variables constant.

Finally, all explanatory variables, including temperature, precipitation, snowfall and average wind speed were added to the regression model.

Table 13. Summary the overall regression model for each EPA BC site

Site	Danbury***	East Hartford***	Norwalk***	Waterbury***	Westport***
Adjusted R	0.2561	0.5323	0.5450	0.3015	0.6461
	Parameter Estimate	Parameter Estimate	Parameter Estimate	Parameter Estimate	Parameter Estimate
Intercept	2.3147**	2.4012**	2.3830**	2.3778**	2.2723**
TRIG	-0.0005	0.0002	0.0006**	0.0010	0.1433*
SINTRIG	0.0112*	0.0018	0.0125**	0.0031	-0.0602*
COSTRIG	0.0904**	0.0426**	0.0645**	0.0530**	0.2027*
Monday	0.0075	0.0256*	0.0237**	0.0451**	0.0373*
Tuesday	0.0210	0.0445**	0.0341**	0.0485**	0.0594**
Wednesday	0.0273*	0.0310*	0.0239*	0.0378*	0.0558**

Thursday	0.0060	0.0352*	0.0288**	0.0459*	0.0703**
Friday	0.0061	0.0363*	0.0293**	0.0419*	0.0494*
Saturday	0.0131	0.0119	0.0127*	0.0226*	0.0200
Temperature	0.0044**	0.0016*	0.0032**	0.0035**	0.0004
No Precipitation	-0.0029	-0.0047	-0.0102*	0.0144*	-0.0161
No Snowfall	-0.0253*	-†	-0.0029	-0.0365*	0.0278
Wind Speed	-††	-0.0014**	-0.0018**	-††	-0.0026**
Traffic Parameter Estimates	0.0069	-0.0197*	0.0199	-0.0142	-0.0044
Traffic Sites	Newtown	Berlin	New Canaan	Chesire	Westport

* Parameter estimate statistically significant at α=0.05 level

** Parameter estimate statistically significant at α=0.0001 level

*** Overall F-test < 0.0001

† No snowfall data available for East Hartford

†† No wind speed data available for Danbury and Waterbury

Table 13

With all explanatory variables added to the model, the adjusted R square value for all EPA BC sites improved significantly. Traffic volume for all EPA BC sites except East Hartford had no significant effect on BC concentration. The parameter estimates for traffic volume around East Hartford remained negative, suggesting that for every 10,000 increase in daily car count, the ambient BC concentration around the area would drop by 1.95%, holding all other variables constant. It is also noteworthy that all EPA BC sites were subjected to seasonal and days-of-the-week effects, suggesting that comparing with Sundays, weekdays almost always led to a higher ambient BC concentration. For example, the ambient BC concentration around Waterbury area on a Monday would be 1.05 times of that on a Sunday, holding all others constant. In addition, daily average wind speed had significant negative effect on ambient BC concentration. For every 1m/s increase in wind speed, ambient BC concentration would drop by 0.14%-0.26%. Daily maximum temperature, precipitation and snowfall are three interesting explanatory variables because the parameter estimates for precipitation and snowfall oscillated between positive and negative across the five EPA BC sites. One possible explanation for this observation is that BC concentration affects the probability of precipitation and snowfall by heating up the air and changing air convection[xiv]. Hence, there might be the problem of reverse causation with these three explanatory variables.

Both seasonal and days-of-the-week effects were highly significant for all EPA BC sites. Since traffic volume were subjected to similar seasonal and weekly cycles, it was important to analyze how much of the seasonal and days-of-the-week effects observed in ambient BC concentration was due to the cyclic pattern in traffic. Therefore, joint tests were performed for seasonal and days-of-the-week separately, controlling for meteorology effects.

Table 14. Summary of F-test statistics

	Season Effect				Days-of-the-week Effect			
	F-Value	DF1	DF2	Pr>F	F-Value	DF1	DF2	Pr>F
Danbury	48.1982	2	344	<0.0001	2.0878	6	344	0.1365
East Hartford	33.0400	2	228	<0.0001	4.0464	6	228	0.0012
Norwalk	149.2582	2	775	<0.0001	10.0633	6	775	<0.0001
Waterbury	31.4604	2	250	<0.0001	4.4762	6	250	0.0030
Westport	4.5278	2	85	0.0135	4.7179	6	85	<0.0001

Table 14

Joint tests for seasonal effects were significant for all EPA sites, suggesting that the seasonal effect observed in BC concentration cannot be fully explained by the seasonal pattern observed in traffic volume. In addition, joint tests for days-of-the-week effect were significant for all sites except Danbury, suggesting that the days-of-the-week effect of BC concentration cannot be fully explained by the days-of-the-week pattern in traffic volume too.

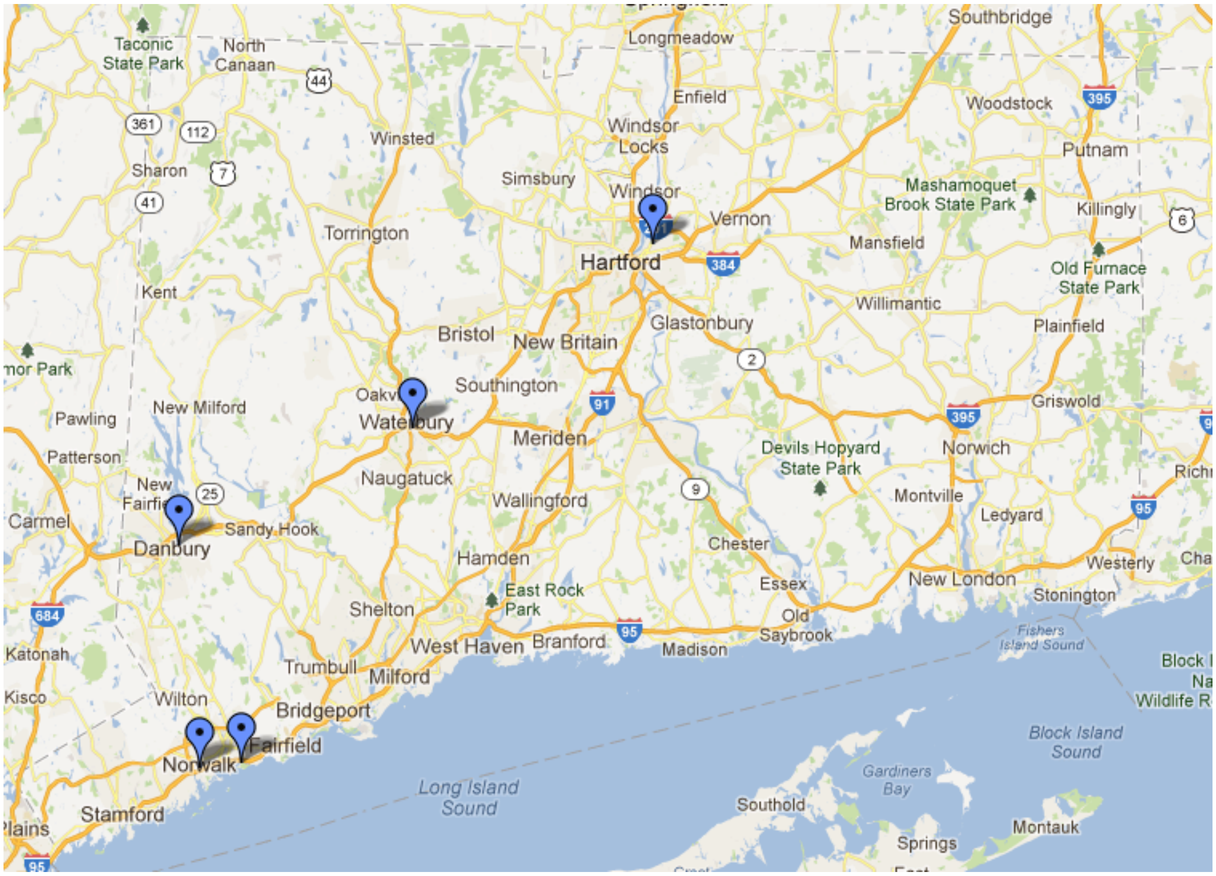
Discussion

Based on the five linear regression models for five Connecticut EPA BC monitoring stations, it can be concluded that seasonal fluctuation, days-of-the-week and daily average wind speed had significant effects on ambient BC concentration. This suggests that the distribution of ambient BC concentration follows a seasonal pattern, increases during weekdays and decreases when wind gets stronger. However, the linear regression models failed to demonstrate any significant relationship between traffic and ambient BC concentration with the exception for East Hartford, which yielded a counter-intuitive negative impact on ambient BC concentration. This could be due to poor choice of traffic monitoring site. The traffic sites chose for this study may not represent the traffic volume around the EPA BC monitoring stations. BC dispersion pattern is highly influenced by wind and wind direction. The chosen traffic sites might have been located in a downstream position where the BC concentration cannot be captured by the EPA BC monitoring sites. In addition, traffic is not the only source of ambient BC. Residential heating and industry are some of the other sources, which the study failed to include due to data limitation. Temperature, precipitation and snow are three variables that are subjected to reverse causation. On one hand, precipitation and snow should have wash-down effect on ambient BC concentration. On the other hand, ambient BC concentration changes aerosol composition and temperature, and hence influences the probability of precipitation and snow. It has been suggested that BC might have be responsible for the droughts and floods we see in China and India in recent years[xv].

BC remains to be an important air pollutant in most countries around the world. It has been associated with multiple adverse health outcomes ranging from respiratory to cardiovascular diseases. In addition, BC has perhaps one of the strongest impacts on global warming among all air pollutants. Despite what has been demonstrated by the study, this study can be further improved on the choice of matching traffic sites. In addition, future study can explore ways to look at the wash-down effect of precipitation and snow without the reverse causation problem. One possible way would be to look at surrogate variables that are correlated with precipitation but are not influenced by BC concentration.

APPENDIX

Map of EPA sites

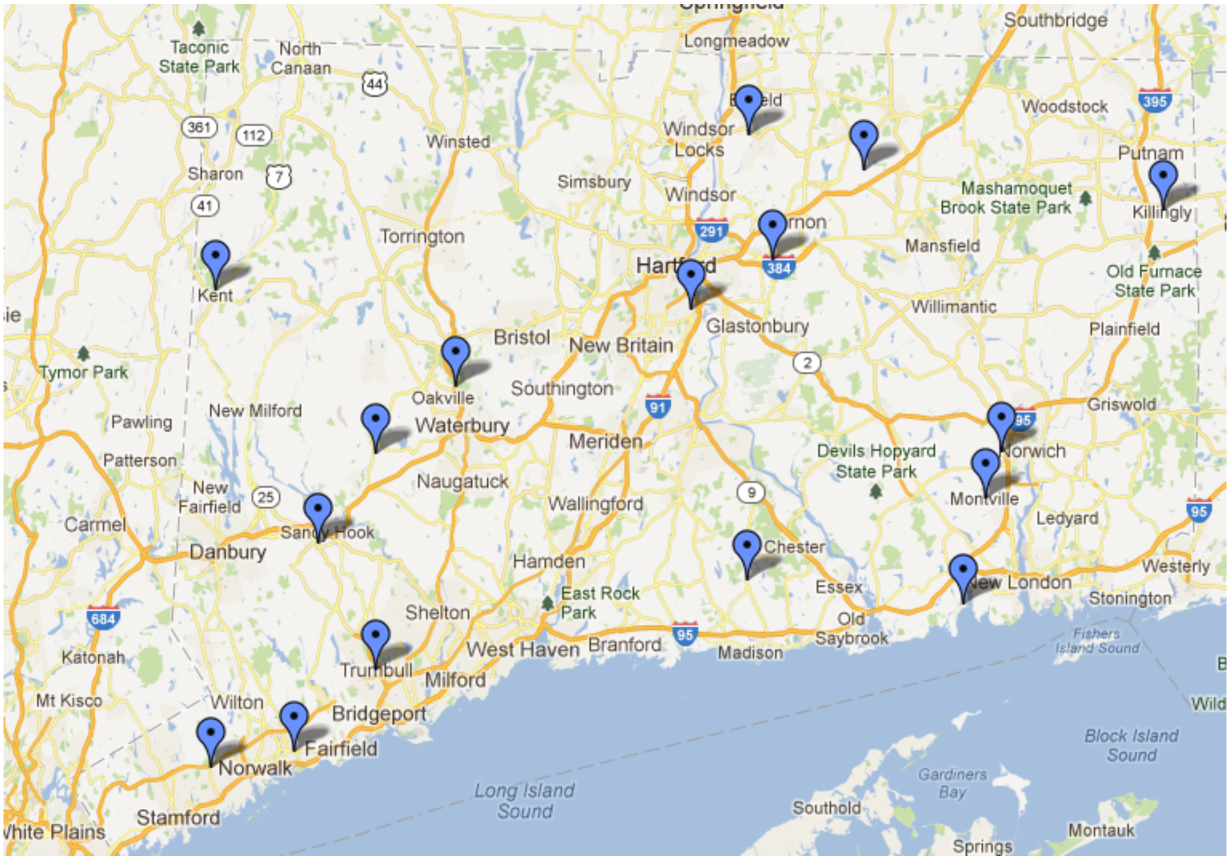


All highways / routes monitored by Connecticut Department of Transportation

Highways/Routes monitored	Location
I-84	Newtown, Manchester, Union, West Hartford & Middlebury
I-91	Wethersfield, Enfield & Wallingford
I-95	Norwalk, Branford, East Lyme & Groton
I-395	Norwich & Killingly
I-691	Cheshire
1	East Lyme & Westport
2	Colchester & North Stonington
5	East Windsor
6	Woodbury
7	Kent
8	Waterbury, Colebrook & Bridgeport
9	Haddam
10	Simsbury
12	Killingly
15	Trumbull, Hamden & Berlin
30	Tolland
32	Montville
34	Orange
66	Hebron

81	Clinton
124	New Canaan
217	Middletown

Map of DOT sites



Backwards elimination intermediate step to choose the best DOT site for each EPA BC site

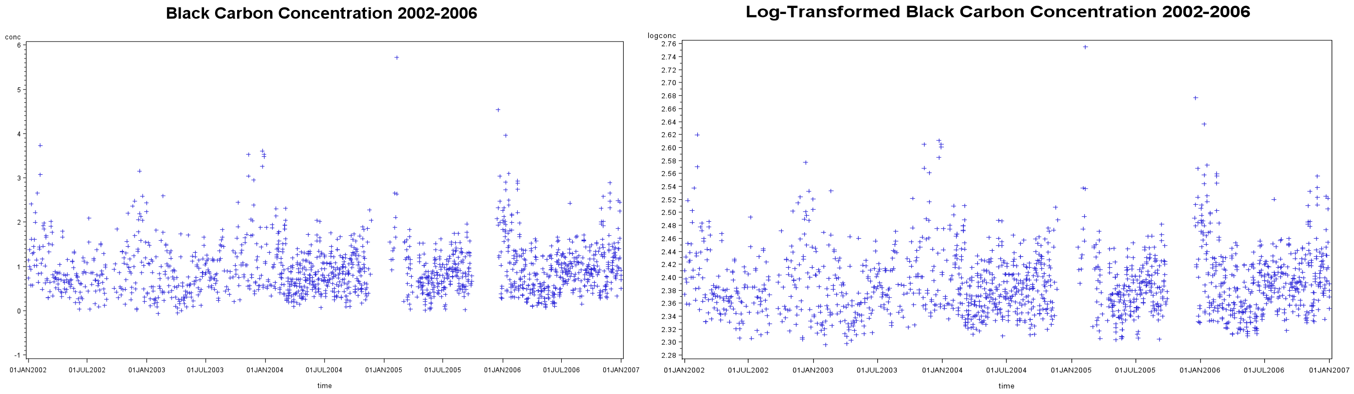
Site	Danbury	East Hartford	Norwalk	Waterbury	Westport
Adjusted R	0.1640	0.2811	0.1413	0.2386	0.2719
	Parameter Estimate	Parameter Estimate	Parameter Estimate	Parameter Estimate	Parameter Estimate
Intercept	2.3758**	2.4204**	2.3479**	2.3369**	2.3285**
TRIG	-0.0005	-0.00007	0.0006*	0.0001	0.0007
SINTRIG	-0.0091*	-0.0144*	-0.0074*	-0.0051	-0.0244*
COSTRIG	0.0369**	0.0262**	0.0224**	0.0354**	0.0113
Monday	0.0102	0.0326*	0.0145	0.0207	0.0329
Tuesday	0.0322*	0.0577**	0.0270*	0.0304*	0.0427
Wednesday	0.0337*	0.0336*	0.0099	0.0098	0.0125
Thursday	0.0217	0.0484*	0.0255*	0.0113	0.0530*
Friday	0.0199	0.0521*	0.0167	-0.0004	0.0151
Saturday	0.0183	0.0149	0.0022	-0.0015	0.0198
Newtown	0.0020	-	-	-	-
Manchester	-	0.0017	-	-	-
Berlin	-	-0.0553*	-	-	-

New Canaan	-	-	0.0378	-	-
Cheshire	-	-	-	0.0247	-
Middlebury	-	-	-	-0.0004	-
Westport	-	-	-	-	0.0152

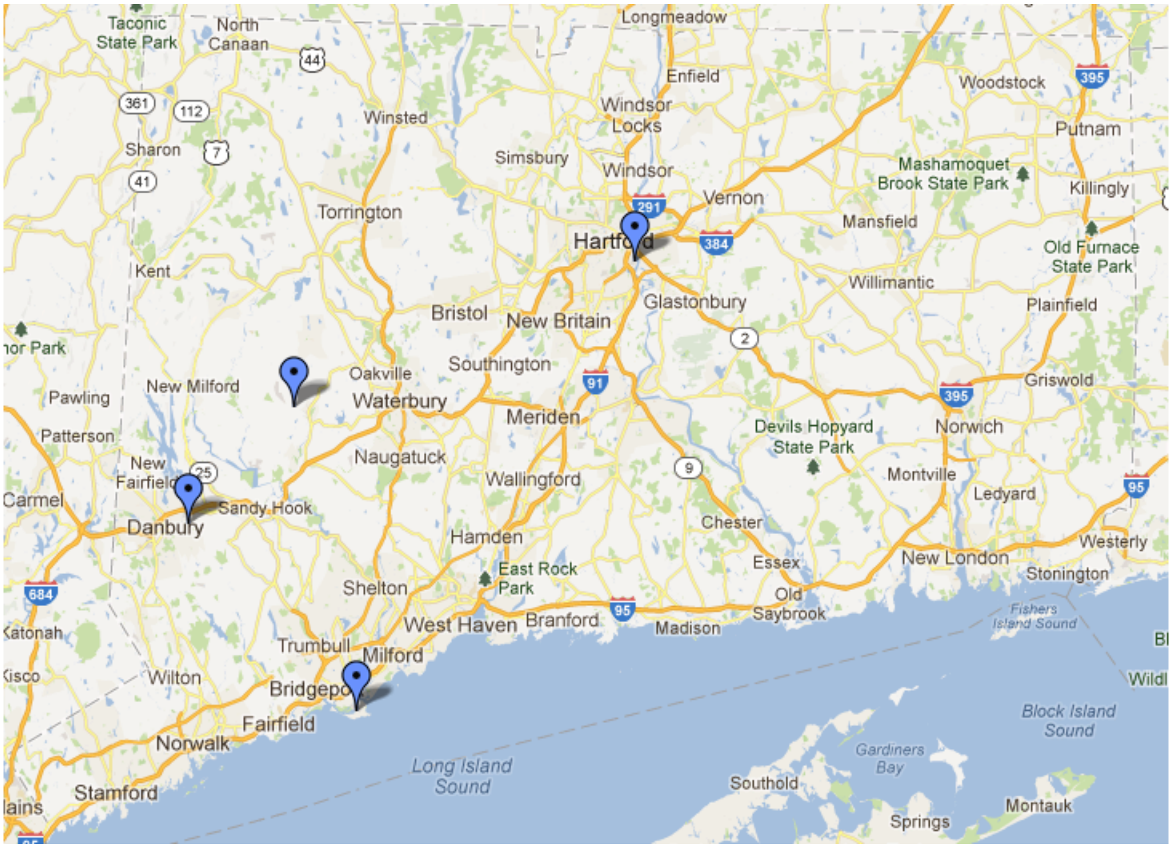
* Parameter estimate statistically significant at α=0.05 level

** Parameter estimate statistically significant at α=0.0001 level

Raw and log-transformed BC concentration measurements from 2002-2006

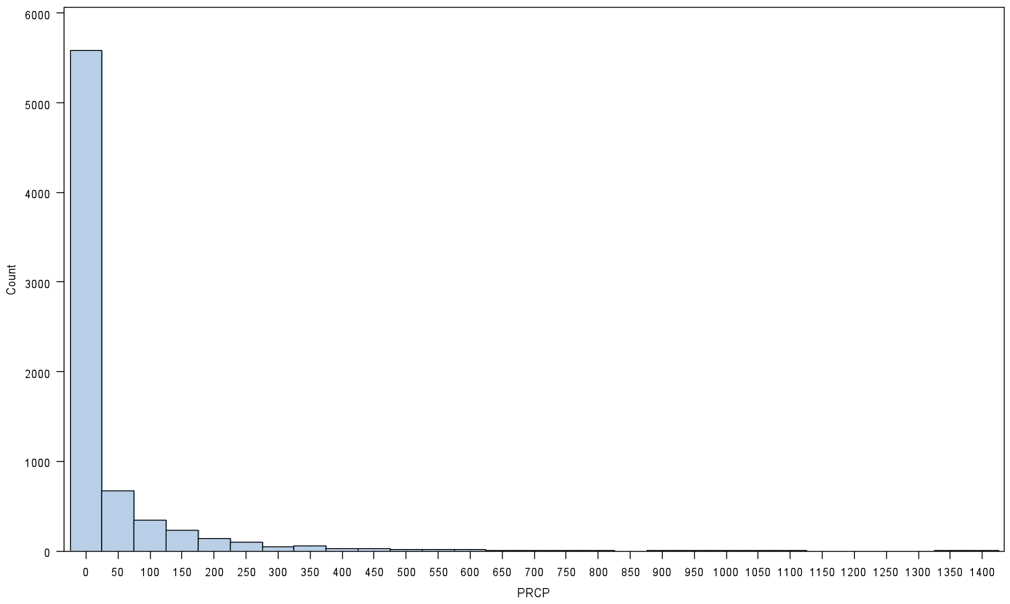


Map of meteorology stations in CT

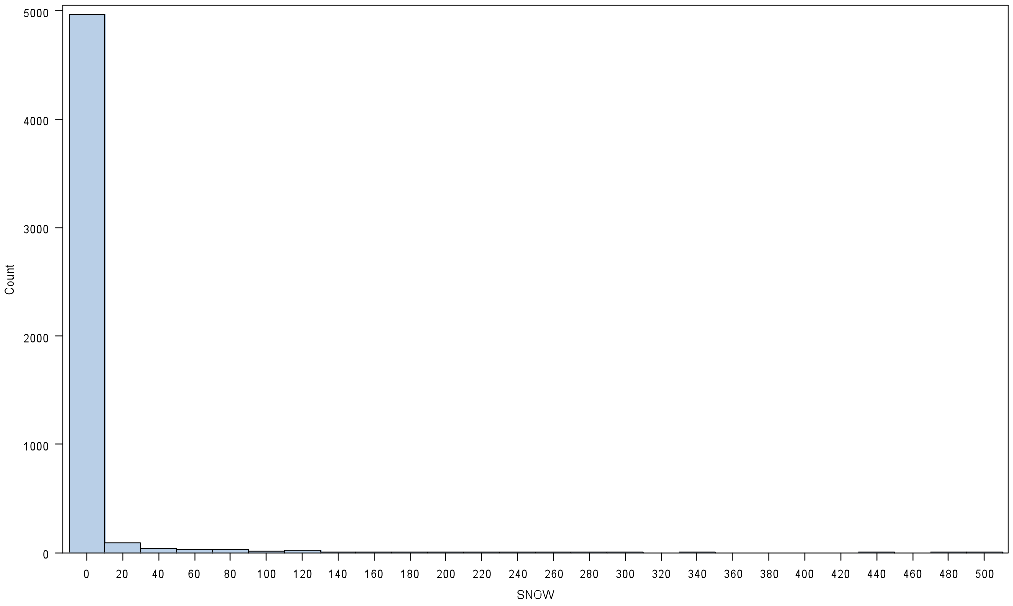


Frequency distribution of daily precipitation 2002-2006

frequency distribution of daily precipitation



frequency distribution of daily snowfall



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[x] Gauderman et al., The effect of air pollution on lung development from 10 to 18 years of age. N Engl J Med. 2004; 351(11):1057-1067.

[xi] Suglia et al. Association between traffic-related black carbon exposure and lung function among urban women. Environ Health Perspect 2008 October; 116(10):1333-1337

[xii] Gauderman et al., The effect of air pollution on lung development from 10 to 18 years of age. N Engl J Med. 2004; 351(11):1057-1067.

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