Field-Level Examination of Air Quality in a Financially Challenged and Demographically Diverse region of Virginia (USA)

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***Abstract*— Concentrations of ambient NO_x and $PM_{2.5}$ were measured in an urban area of Virginia using a mobile emissions measurement lab. Concentrations were correlated with demographic and socioeconomic information using GIS to detect instances of adverse air pollution exposure by disadvantaged populations. Race comparison results showed that both minority and mixed populations experienced NO_x and $PM_{2.5}$ concentration levels as high as 89 ppb and 19 µg/m^3, respectively. However, in all cases of adverse air quality exposure, income level was a factor. For example, low income populations, regardless of race, were exposed to average NO_x concentrations ranging from 54 to 89 ppb with 30 minute average concentrations as high as 130 to 137 ppb. For $PM_{2.5}$, mixed race, low income populations experienced average concentrations of 19 µg/m^3 with 30 minute sustained concentrations as high as 42 µg/m^3, 23 – 95% higher than the NAAQS limit. On the contrary, high-income neighborhoods with median household incomes (MHIs) ranging from $42,600 – $59,800 experienced much lower NO_x concentrations between 22 – 26 ppb, 70 – 109% lower than high minority, low income sites. Comparative studies reveal that low income, minority populations tended to experience cancer risks 3-12 times higher than high-income populations. A DPM risk analysis was also conducted. Low-income populations in the Norfolk area, regardless of race, were experiencing DPM concentration ranging between 0.2-3.2 µg/m^3. Using EPA DPM risk analysis methods, results showed an increase of 183-1029 extra cancers per one million people at various low income sample locations, which is 9-53 times higher than the high-income populations in the same urban area.**

Keywords—Environmental justice, air pollution, ambient air quality, NO_x emissions, $PM_{2.5}$ emissions, socioeconomic air quality factors, adverse air quality exposure

1. INTRODUCTION

1.1 Air Quality and Environmental Justice

Environmental justice issues involve the adverse health and economic effects of environmental hazards when disproportionately suffered by minority and low-income communities. It is well known that air pollution adversely affects the health of disadvantaged populations [1-5]. These populations often live in urban settings, have low socioeconomic status and more often than not include a large number of ethnic minorities [5]. Many studies have been conducted that link adverse health effects with the demographic characteristics of particular urban areas. One study conducted on British air quality concluded that there were positive relationships between poverty and known respiratory diseases (i.e. – asthma) in the London area [6]. Another similar study conducted in Leeds, United Kingdom determined that there were strong positive correlations between social deprivation and respiratory health [7]. In 2001, a workshop report published by the American Lung Association confirmed that higher air pollution levels have been directly linked to the prevalence of asthma in children and adults, and in the United States, most deaths from asthma occur in the urban areas [5]. The report also determined that the asthma mortality rates among African Americans was 2.5 times higher than among Caucasians, and that analysis of those deaths showed further correlation with high poverty rates and air pollution. Similar studies conducted in New York City have shown that asthma mortality rates associated with urban air pollution were four times the citywide rate in the predominantly African American neighborhood of East Harlem [5]. A 2007 study from Canada reported higher mortality rates and increased cardiovascular disease factors associated with poor environmental conditions such as air pollution [2]. More interestingly, the study looked at environmental inequalities from a neighborhood perspective, better defining the necessity for scientists to further study the adverse effects of poor air quality on a micro level.

Correlations between urban industrial air pollution and disadvantaged areas have been recognized by researchers as well. A study conducted in Hamilton, Ontario, Canada linked mortality and cardio-respiratory issues with exposure of minority and lower income neighborhoods to $PM_{2.5}$ generated from the manufacturing of steel [8]. In 1999, researchers examined the sociodemographic characteristics of people living near industrial sources of air pollution in Kanawha Valley, West Virginia, Baton Rouge, Louisiana and Baltimore, Maryland. Results of the study determined that higher instances of diminished health quality existed in lower socioeconomic status areas and areas consisting of high minority concentrations. Adverse health effects associated with vehicle related air pollution are also of concern. A study of southern California vehicle related air pollution exposure found that minority and high poverty neighborhoods bear more than two times the level of traffic density than the rest of southern California. Furthermore, research showed increased exposure to vehicle related air pollutants in those areas [9]. Another study conducted in Boston, Massachusetts estimated the exposures of 413 children within a disadvantaged neighborhood to traffic related pollution. The study found an association between air pollution and asthma, and went even further by determining that children exposed to violence are more susceptible to air pollution and asthma[10]. A recent study, also in Massachusetts, found that disadvantaged neighborhoods were disproportionately exposed to diesel vehicle particulate matter emissions which were linked to increased incidences of lung cancer and asthma in those neighborhoods [11]. In New Zealand, researchers revealed that there are approximately 400 cases of premature mortality per year due to exposure to particulates emitted from vehicles; most adverse health outcomes related to poor air quality are increasingly associated with areas of low socioeconomic status and higher social deprivation [12, 13].

1.2 GIS and Air Pollution in Disadvantaged Areas

Geographical Information Systems (GIS) has been used extensively with reported air quality information to draw conclusions about air emissions and their effects on disadvantaged populations; however, very few GIS based studies use actual measured neighborhood scale emissions to determine exposure. Many studies locate populations by geocoding (assigning mapping coordinates) addresses and then using proximity analysis of a contaminant source as a surrogate for exposure. Environmental monitoring data is then integrated into the analysis to predict scenario based health outcomes[14]. Studies have shown that this method has bias and errors associated with it. One study in Orange County, Florida, compared four different geocoding methods with proximity analysis to determine the effect of positional error associated with these techniques on the analysis of exposure to traffic related air pollution of children at various school locations. Results of this study determined that the 95% root mean square error, statistical magnitude of various quantities, was greater than 300 meters in some cases, which could indicate positional inaccuracies on the data sources[15]. Other studies have used GIS to graphically provide information on the demographic characteristics of neighborhoods and correlate these results with industrial pollutant releases from emissions inventories such as the Toxic Release Inventory (TRI) maintained by the EPA[16, 17]. GIS has the ability to provide a graphical database capable of providing health officials with the information necessary to properly direct programs for environmental clean-up and disease prevention. GIS can also be used as an environmental justice indicator by relating air quality risks with various sociodemographic characteristics[18]. This research uses the exploration capabilities of GIS with actual measured neighborhood scale emissions to provide an exposure analysis of various disadvantaged neighborhoods within the Norfolk, Virginia area to harmful air pollutant concentrations. By using GIS capabilities with actual measurements, achieving a more accurate exposure footprint is possible and thereby can provide public health officials with more comprehensive information on where to target remediation programs.

1.3 Direct Emissions Measurements in Disadvantaged Areas

Much research has been conducted using proximity analysis and EPA reported air quality data (i.e. - NATA reports, Air Emissions Inventories, etc.) to provide information about the exposure of disadvantaged populations to polluted air emissions; however, very little work has been done that provides actual neighborhood scale air pollutant concentration estimates within disadvantaged neighborhoods and how those measured concentrations adversely affect the residents of that neighborhood. This research focuses on nitrogen oxide (NO_x) and fine particulate matter ($PM_{2.5}$) concentrations in the Norfolk, Virginia and surrounding areas measured during the summer of 2008. A comparative study is used to analyze the adverse effects of NO_x and $PM_{2.5}$ versus other published data and a diesel particulate matter (DPM) risk analysis is conducted on all sites. The potential harmful effects of these pollutant concentrations on varying demographic and socioeconomic population characteristics are explored. The objective of the research is to compare perceived risks associated with each location and identify instances of possible environmental inequity. GIS and local health information are used in conjunction with recorded demographic characteristics of the measured areas to determine their relationship. Areas of both low and high socioeconomic status and ethnic diversity are located within the measurement footprints. Measurements are obtained using the Flux Lab for the Atmospheric Measurement of Emissions (FLAME). The FLAME is a uniquely mobile air quality measurement system capable of taking pollutant concentration measurements at any location and has been extensively described in previous publications[19]. The analyses use the concentration measurements to estimate risk within particular neighborhoods. Measurements were taken at 16 locations (SL 1-16) within a 12 square kilometer area and include parts of Norfolk, Chesapeake, Portsmouth and Virginia Beach, Virginia (Figure 1). Due to instrument malfunction at SL 9, SL 11 and SL 12, concentration measurements at those locations are not included in this analysis.

2. METHODS

2.1 Site

A 12 square kilometer area within the city of Norfolk, Virginia and its surrounding areas (Chesapeake, Portsmouth and Virginia Beach) was the focal point for this measurement campaign. Norfolk is located within the Greater Tidewater area of Virginia and has a population of approximately 250,000. Norfolk is home to a significant amount of industries to include coal processing, rail yard activities, shipping industry, power generation and much more. The minority (i.e. - African American, Asian, American Indian/Pacific Islander, etc.) population in Norfolk makes up approximately 48% of the residents. According to 2000 census data, the median household income in the Norfolk area was $32,000. Approximately 20% of the population of Norfolk lives below the poverty level and about 45% of those residents are single mother households[20]. Norfolk and its surrounding areas are designated as one and eight hour ozone non-attainment areas, and based on EPA records, during the hot summer months, often experiences high levels of particulate matter. In 2006, the Virginia Department of Environmental Quality reported annual point source emissions of 3,600 tons in the City of Norfolk alone. Figure 1 shows the 12 representative sample locations chosen for measurement in the Norfolk area. Locations were chosen based on their proximity to various sources of anthropogenic area emissions sources as well as their varied demographic characteristics. Most locations are within close proximity to neighborhoods of varying economic status. Air quality in each location was sampled during normal weekly operations for 10 hours beginning at 7:00 AM and ending at 5:00 PM.

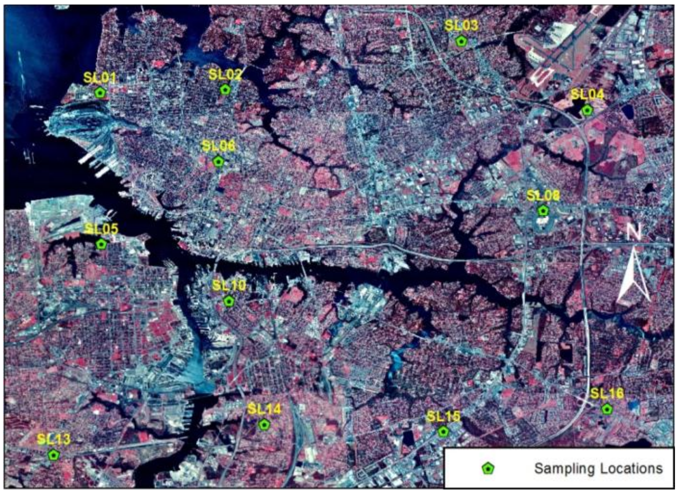

Figure 1. Sample locations within Norfolk, Virginia and surrounding areas

2.2 Equipment

The FLAME is a customized television news van with an extendable mast that rises to 15.5 m. A sonic anemometer (Applied Technologies SATI-3K) and sample tubing are mounted on a rotating platform on top of the mast. A pump draws air at 20 L min^{-1} through 0.5-inch PTFE conductive tubing (TELEFLEX T1618-08) down to ground level, and gas and particle analyzers subsample the air through a custom designed Teflon manifold. Analyzers inside the van measure NO_x (Eco Physics CLD 88Y, 1-s response time) and $PM_{2.5}$ (DustTrak 8520, 1-s response time) concentrations. A data logger (National Instruments Compact FieldPoint 2110) records the measurements at 10 Hz. The equipment is powered using a 4500 W gasoline generator (Onan GENSET 4500 Series).

2.3 Quality Control and Post Processing of Data

Quality assurance and control measures included calibration of the NO_x analyzer before and during the field campaign and testing for sampling line losses. Losses of NO_x were 0.57%, and water vapor losses were eclipsed by humidity variations in the atmosphere during the test periods. A slight loss in $PM_{2.5}$ (8% ± 5%) was also noted. Gravimetric filter samples of $PM_{2.5}$ were collected during the field campaign for calibration of the DustTrak, an aerosol photometer whose response is dependent on particles' optical properties. The DustTrak's average concentrations were 14 ± 0.3% higher than the filter-based ones, and because filters may also be subject to sampling artifacts, we have elected to report the factory-calibrated DustTrak $PM_{2.5}$ values rather than correct them to match the filters. Standard post-processing of the measurements included hard spike removal, soft spike removal and application of a low pass filter to ensure valid concentration measurements.[21-23]

2.4 GIS Methods

GIS was used to analyze and validate demographic comparisons of various neighborhood populations and their exposure to harmful levels of NO_x and $PM_{2.5}$. Using GIS, we combined information regarding demographics with socioeconomic data retrieved from the 2000 census compiled by the US Census Bureau. Combining the statistical information obtained from GIS with measured NO_x and $PM_{2.5}$ concentrations from the FLAME, we were able to identify instances of disproportional air pollutant exposure by various demographic and socioeconomic groups within Norfolk and the surrounding areas. 13 site locations within the 12 square kilometer Norfolk sample area were chosen for analysis. Sample location statistics within the reference areas were compiled using GIS based files from the US Census Bureau, US Geological Survey (USGS), and the Earth Resources Observation and Science (EROS). Using the compiled data, we were able to discern population demographic and financial information. The census data identifies population characteristics such as minority populations, income levels, age and gender. The research focuses on the demographic disproportion of ambient air quality as it relates to various demographic and socioeconomic characteristics within each sampling area.

3. RESULTS AND DISCUSSION

Figures 2 and 3 show the median household incomes and demographic composition at each of the 13 measurement locations as determined by 2000 census data. As shown in the figure, inner city areas, where higher levels of industrial activity were noted, contain higher percentages of minorities. The figure also shows that a high percentage of the predominantly minority inner city sites are also financially challenged and living below the U.S. Department of Health and Human Services (HSS) Poverty Line of $22,000 for the average 4 person family. Sites were located within a varied range of socioeconomic and demographic characteristics.

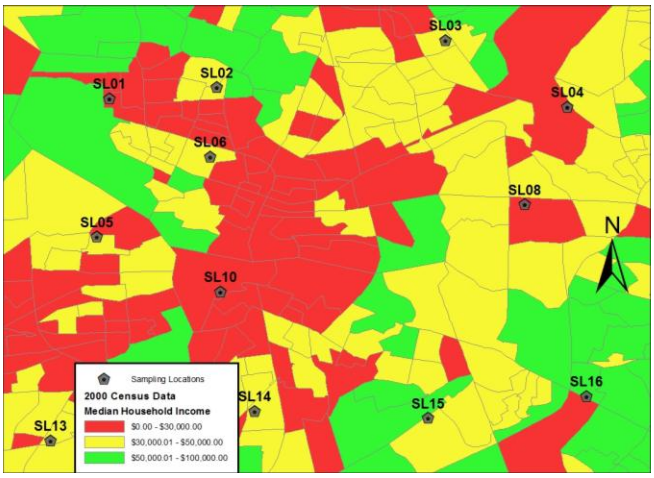

Figure 2. Median household income of 13 sample locations in Norfolk and surrounding area

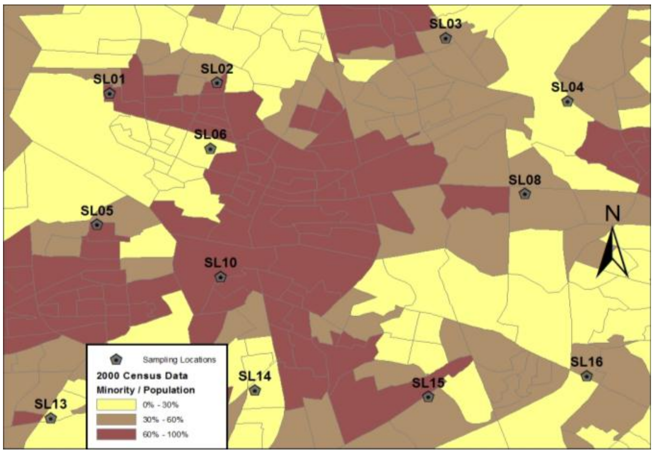

Figure 3. Demographic characteristics at 13 sample locations in Norfolk and surrounding area

Minority populations surrounding the sample locations ranged from 9% to 98%. Median household incomes (MHI) ranged from \$20,268 to \$59,779. Table 1 shows NO_x and $PM_{2.5}$ concentrations at each site compared with sample location demographic and financial characteristics. SL 10 maintained the highest average daily NO_x concentration at 89 ppb (170 $\mu g/m^3$) with SL 4 reporting the highest average $PM_{2.5}$ concentrations at 19 $\mu g/m^3$. Population characteristics at SL 10 show that the area is 98% minority with a MHI just below the HHS poverty line at \$21,131. SL 1, which also had high minority percentages at 85.9%, experienced high NO_x concentrations at 54 ppb with high average $PM_{2.5}$ concentrations of 9.6 $\mu g/m^3$. The MHI at SL 1 was \$20,268, 8.2% below the HHS poverty line. SL 14 and SL 16, which had the smallest minority populations, experienced the lowest NO_x concentrations at 22 ppb. $PM_{2.5}$ concentrations at SL 14 and SL 16 were 6.9 $\mu g/m^3$ and 1.7 $\mu g/m^3$ respectively. MHIs at SL 14 and SL16 were \$42,563 and \$59,779 respectively, which are 64% and 92% higher than the HHS poverty line.

Other demographic characteristics such as age and predominant gender are also shown in Table 1 for each site location. Gender comparisons of each site show that most sites contained a female majority, however, on average, the male and female percentages were very close to 50% at all sites. Average age at the sample locations ranged from 20 to 48 years with SL 2 having the oldest population range and SL 4 having the youngest. SL 14 and SL 16 had some of the oldest residents at 42 and 43 years respectively. The oldest residents were in SL 2 and 6 at 48 and 47 years respectively. MHIs at SL 2 and SL 6 were in the mid-range at \$35,833 and \$34,583 respectively, approximately 47% higher than the HHS poverty line.

A further review of the available GIS data revealed that SL 2 had the highest percentages of elderly (above 65 years old) at 34.9% and some of the lowest levels of NO_x but highest $PM_{2.5}$ concentrations measured during the campaign. SL 1, which had a relatively high NO_x concentration of 54 ppb, had the lowest median age at 24 years and approximately 30% of the population at SL 1 was under the age of 17. Elderly populations at SL 1 were 8.6%, which is lower than the average percentages of elderly at all sites of 15.4%. SL 4, which had the lowest median age at 20 years old, experienced the highest $PM_{2.5}$ concentrations at 19 $\mu g/m^3$. SL 4 also had the lowest percentages of the elderly in the areas. High $PM_{2.5}$ concentrations at SL 4 can likely be attributed to ongoing construction in the area. For SL 10, which experienced the highest NO_x concentration, both the underage and elderly percentages were higher than most sites at 26.8% and 17.4% respectively.

Table 1. NO_x and $PM_{2.5}$ concentrations at 12 sample locations with demographic and financial characteristics

Date	Site	NO_x(ppb)	$PM_{2.5}$($\mu g/m^3$)	Financial Characteristics	Demographic Characteristics				
					Race (%)		Gender (%)		Median Age
				Median Household Income($)	Caucasian	Minority	Male	Female	(years)
06/02/08	SL 1	54±75	9.6±1.8	20,268	14	86	50	50	24
06/03/08	SL 2	24±23	8.6±4.9	35,833	29	71	46	54	48
06/04/08	SL 3	26±64	1.1±0.4	41,346	55	45	50	50	37
06/05/08	SL 4	24±18	19±23	24,091	71	29	49	51	20
06/09/08	SL 5	31±60	1.0±0.3	38,846	20	80	48	52	31
06/10/08	SL 6	36±48	1.0±0.5	34,583	79	21	45	55	47
06/12/08	SL 8	34±33	16±15	22,829	38	62	48	52	35
06/17/08	SL 10	89±48[a,b]	3.3±0.3[b]	21,131	2	98	46	54	38
06/23/08	SL 13	46±17	6.4±3.8	35,223	81	19	50	50	35
06/24/08	SL 14	22±14	6.9±1.1	42,563	91	9	48	52	42
06/25/08	SL 15	26±24	2.3±2.7	46,250	49	51	52	48	33
06/26/08	SL 16	22±7	1.7±0.6	59,779	64	36	47	53	43

[a] Lower bound since concentrations exceeded the analyzer's maximum range of 5000 ppb for ~40 s in 8.5 hours.

[b] Excludes the first 90 min of measurements, when concentrations exceeded analyzers' upper limits.

3.1 Effects of NO_x and $PM_{2.5}$ Concentrations (Comparative Study)

As shown in Table 2, significant research has been conducted providing relationships between NO_x and $PM_{2.5}$ exposure and increased incidences of asthma, asthma related symptoms, and mortality due to lung cancer, respiratory issues and poor cardiovascular health [10, 24-34]. For example, a study conducted in 31 cities around China determined that NOx as a single pollutant corresponded to a 1.5%, 2.3%, 2.6%, and 2.7% increase of total mortality, cardiovascular, respiratory mortality, and lung cancer respectively for every 10 $\mu g/m^3$ increase in concentration [24]. The average concentration measured in the China study was approximately 50 $\mu g/m^3$. When compared with the Norfolk data, concentrations at six of the 12 sample locations were higher than the average NO_x concentrations measured in China, which based on the study would significantly increase the probability of adverse health effects associated with NO_x exposure. For example, at SL10, NOx concentrations were 89 ppb (170 $\mu g/m^3$) corresponding to risk increases of 25.5%, 39.1%, 44.2%, and 45.9% for total mortality, cardiovascular, respiratory mortality, and lung cancer respectively. On average, the population surrounding SL10 is experiencing a risk of mortality that is 17 times higher than the 31 cities studied in China. A further review of the GIS census data reveals that at SL 10, these adverse conditions are being experienced by a low income, high minority population. Another similar study conducted in Denmark found that NO_x concentrations between 17.2 and 30 $\mu g/m^3$ could be associated with an average 9% increase in cancer risk with a 30% increase in cancer risk for every 10 $\mu g/m^3$ increase in concentration above 30 $\mu g/m^3$[32]. With this logic, the residents at SL 1, 8 and 10 would experience a 215%, 101% and 413% increase in cancer risk respectively, which is approximately 3.7, 1.2 and 8.2 times higher than the other sample locations. Also, when compared with GIS census data, SL 1, 8 and 10 are all high minority, low income neighborhoods being adversely subjected to higher levels of NO_x pollution. On the contrary, SL 2, 3, 14, 15 and 16 are all high income, low minority or mixed neighborhoods that are subjected to much lower levels of NO_x pollution indicating possible exposure inequities. For example, at SL 14 and 16, residents are subjected to NO_x concentrations of approximately 22 ppb (41 $\mu g/m^3$). Based on the China study, this equates to a 34% increase in cancer risk, versus the 100 – 400% increase experienced by residents around SL 1, 8, and 10.

From Table 2, adverse health effects attributable to $PM_{2.5}$ exposure were noted at concentrations ranging between 17.7 and 94 $\mu g/m^3$. For example, one report conducted in six US cities found that premature death can be associated with $PM_{2.5}$ concentrations as low as 2 $\mu g/m^3$ [35]. SL 1, 2, 4, 8, 13 and 14 experienced concentrations that were between 25% and 117% higher than those measured in the study indicating a greater risk of premature death at these sites. Another study conducted using data obtained through the American Cancer Society (ACS) found that every 10 $\mu g/m^3$ increase in $PM_{2.5}$ concentration above 17 $\mu g/m^3$ corresponded to 6 and 8% increases in the risk of cardiovascular and respiratory mortality respectively [31]. According to this study, all of the sample locations experienced no increase in risk due to $PM_{2.5}$ exposure except SL 4. Based on an average $PM_{2.5}$ concentration of 19 $\mu g/m^3$, SL 4 experienced increased cardiovascular and respiratory mortality risks of 6.78 and 9.04% respectively. This increase was likely due to noted instances of increased construction activity in the area, contributing to a temporary increase in $PM_{2.5}$ emissions. At SL 10, $PM_{2.5}$ data was excluded from the measurements during the hours of 7:30 to 10:30 due to a sustained exceedance of the analyzers' upper measurement range of 0.1 mg/m^3. Many studies provided similar results but with varying average concentrations. For example, a study conducted in 27 communities around the US reported a 1.2%, 1.0%, and 1.8% increase in total, cardiovascular, and respiratory mortality for every 10 $\mu g/m^3$ increase in $PM_{2.5}$ concentration above 15.7 $\mu g/m^3$[26]. In this instance, the population at SL 4 would be experiencing a 1.6%, 1.3%, and 2.4% increase in the risk of total, cardiovascular, and respiratory mortality respectively.

Table 2. Comparative NO_x and $PM_{2.5}$ Studies

Authors	Pollutants				Health Effects	
	NOx concentration ($\mu g/m^3$)	Increment ($\mu g/m^3$)	$PM_{2.5}$ concentration ($\mu g/m^3$)	Increment ($\mu g/m^3$)	NO_x	$PM_{2.5}$
Nielsen et. al.[32]	17.2 – 29.7	10	---	---	Increased risk of lung cancer	---
Cao et al[24]	50	10	94	10	Increased risk of mortality from cardiovascular or respiratory complications and lung cancer	Increased risk of mortality from cardiovascular or respiratory complications and lung cancer
Pope et al (ACS)[31]	---	---	17.7	10	---	Increased risk of mortality from cardiovascular or respiratory complications and lung cancer
Franklin et al[26]	---	---	15.7	10	---	Increased risk of mortality from cardiovascular or respiratory complications and lung cancer

3.2 *Correlation of NO_x and $PM_{2.5}$ Concentrations to Characteristics and the NAAQS*

The EPA regulates six criteria pollutants for the protection of public health and the environment. Among these pollutants are NO_2 and $PM_{2.5}$. Knowing that NO_x consists of NO_2 and NO, and using the EPA recommended ambient ratio method (ARM) of 0.75 NO_2 to NO_x, we can determine the theoretical amount of NO_2 at each sample location (Table 2). Of the 12 sites, only SL 10 exceeds the NAAQS for NO_2; however, based on previous studies, concentrations as low as 7 ppb have caused adverse respiratory and cardiopulmonary reactions in children and elderly adults. For example, a study conducted in Perth, Australia [36], concluded that children experienced adverse health effects from average NO_2 concentrations of 7 ppb, with a range of 0 – 24 ppb, which in the upper range is between 8% and 115% lower than concentrations experienced at eight of the 12 sample locations.

From Table 3, demographics at the sample locations varied with median age ranges of 24 years up to 48 years. Some sites consisted of high percentages of children under the age of 17 and elderly populations over the age of 65. For example, SL 5 consisted of 32.4% of the population being under the age of 17 and SL 2 had an elderly population of 34.9%. Based on many epidemiological studies and Integrated Science Assessments (ISA), child and elderly populations face much higher risks of developing long term respiratory symptoms and infections such as asthma from poor air quality and NO_2 concentrations ranging from 3 – 50 ppb. Also, a number of studies reported an increase of between 1% and 13% for children and elderly adults (<65 years) exposed to adverse air quality [37].

When conducting a race and financial based comparison, some striking correlations are noted. For example, the populations at SL 1, 8 and 10 were mostly minority at 86%, 62% and 98% respectively. These sites also had some of the highest concentrations of NO_2 at 41, 26 and 67 ppb respectively. Populations at SL 14 and 16 were low minority areas and had much lower concentrations of NO_2 at 17 ppb for both sites. Of all characteristics however, financial characteristics proved to have the highest degree of correlation when compared with concentration data. In all cases, higher concentrations of NO_x and $PM_{2.5}$ were associated with populations living just above, at or below the HHS poverty line of $22,000. For example, at SL 8 NO_x concentrations were very high in the morning hours between 07:30-0830. During this time, the 1-hour NO_x concentration was measured at 112 ppb. 62.3% of the population surrounding this site is minority with a MHI of $22,829, which is 33% lower than the overall MHI of the Norfolk area. At SL 10, average NO_x concentrations were approximately 89 ppb, which is 68% higher than NAAQS NO_2 standards and 23% higher using the EPA ARM method. Populations surrounding SL 10 experienced high NO_x concentrations at most times during the day; especially, during the rush hour, when the 1-hour average NO_x concentrations were between 130-150 ppb. 98% of the population at SL 10 is minority with a median household income of $21,131, 41% lower than the Norfolk average. SL 10 was located close to major highways (I-264, I-464, Highway 460, and Highway 337) and surrounding the residential area at SL 10 was an industrial ship painting facility, ship repairing industries, on-going construction, a port authority shipping operation, and fuel storage facilities. Also adjacent to SL 10 (< 1 km) were three industries required to report emissions releases to the EPA toxic release inventory (TRI). On the contrary, at SL 14 and 16, residents only experienced NO_x concentrations of 22 ppb and NO_2 concentrations of 17 ppb, 68% lower than the EPA NAAQS. The majority of the population at SL 14 and 16 was Caucasian with MHIs of $42,563 and $59,779 respectively, which is 33% and 87% higher than the average Norfolk area MHI.

Table 3. Sample location concentration comparisons to EPA NAAQS

Date	Site	NO_x(ppb)	EPA ARM Method	$PM_{2.5}$(μg/m^3)	NAAQS	
			NO_2(ppb)		NO_2	$PM_{2.5}$
06/02/08	SL 1	54±75	41	9.6±1.8		
06/03/08	SL 2	24±23	18	8.6±4.9		
06/04/08	SL 3	26±64	20	1.1±0.4		
06/05/08	SL 4	24±18	18	19±23		
06/09/08	SL 5	31±60	23	1.0±0.3		
06/10/08	SL 6	36±48	27	1.0±0.5	53 ppb (Annual)	15 μg/m^3 (Annual)
06/12/08	SL 8	34±33	26	16±15	100 ppb (1 hr)	35 μg/m^3 (24 hr)
06/17/08	SL 10	89±48[a,b]	67	3.3±0.3[b]		
06/23/08	SL 13	46±17	35	6.4±3.8		
06/24/08	SL 14	22±14	17	6.9±1.1		
06/25/08	SL 15	26±24	20	2.3±2.7		
06/26/08	SL 16	22±7	17	1.7±0.6		

[a] Lower bound since concentrations exceeded the analyzer's maximum range of 5000 ppb for ~40 s in 8.5 hours.

[b] Excludes the first 90 min of measurements, when concentrations exceeded analyzers' upper limits.

3.3 *Correlation of NO_x and $PM_{2.5}$ Concentrations to Characteristics and the NAAQS*

According to the California EPA Air Resources Board (ARB), diesel particulate matter (DPM) emissions make up approximately 6% to 17% of all rural and urban particulate emissions respectively. DPM emissions cause health effects from both short term or acute exposures and also long term chronic exposures. Acute exposure to DPM may cause irritation to the eyes, nose, throat and lungs as well as some neurological effects such as lightheadedness. There is also considerable evidence that DPM is a likely carcinogen [38]. As a final comparison to this analysis and to further study the possible harmful effects of the ambient $PM_{2.5}$ emissions experienced at the 12 sites, an EPA based risk analysis was conducted utilizing EPA based methodology [39]. A risk analysis helps to identify probabilities of adverse health effects to populations at the various sample locations and how the risk is proportioned based on demographic characteristics at each location. Utilizing the $PM_{2.5}$ concentrations reported in Table 1 above and correcting for DPM percentages of 6 and 17%, a range of DPM exposures can be calculated using Equation 1.

$$Exp = \frac{C_a \times BR \times EF \times ED \times CF}{AT} \qquad (1)$$

C_a is the concentration of DPM in the air (mg/m^3), BR is the breathing rate (302 L/kg-day), EF is the exposure frequency (350 days/year), ED is the exposure duration (70 years), CF is the conversion factor (1000 L/m^3), and AT is the averaging time (25,550 days). Using the calculated DPM exposure values and an EPA derived DPM cancer slope factor (CSF) of 1.1 mg/kg-d, the cancer risk of DPM at each sample location can be calculated using Equation 2.

$$Risk = Exp \times CSF \qquad (2)$$

DPM cancer risk assessments are calculated in Table 4 for the 12 sample locations using ARB derived nationwide and urban estimates of 6% and 17% respectively. Based on the California ARB study, DPM corresponds to more than 70% of all adverse health risks with an estimated 540 cancers per one million people nationwide. From Table 4, SL 1 and 8, which were high minority sites with MHIs at or below the poverty line, experience cancer risks consistent with ARB estimates with SL 8 being 60% higher than ARB estimates in the upper range. $PM_{2.5}$ data from SL 10, which recorded the highest NO_x concentrations during the campaign, was excluded from this analysis due to $PM_{2.5}$ concentrations exceeding the analyzer's maximum range of 100 μg/m^3 during the first 90 minutes of measurements. Contrary to SL 1 and 8, SL4 had the highest range of DPM related cancer risk at 363 – 1,029 cancers per one million people, 91% higher than the ARB estimates. SL 4 consisted of a low minority, low income population. Residents of SL 1, 4, 8, and 10 experienced significantly higher risks than the other eight sample locations, which had MHI ranges between 57% and 171% above the poverty line and experienced 13% to 96% lower risk than the ARB estimate. Results indicate that adverse health effects are not race specific but rather income specific suggesting that residents of poorer neighborhoods in Norfolk, regardless of race, are subjected to cancer risks that are 9 – 53 times higher than residents within the high-income sample locations.

Table 4. Risk Assessment for DPM within the 12 sample locations using 6% and 17% of ambient $PM_{2.5}$ as DPM

Date	Site	DPM (mg/m^3)	Exposure (mg/kg-d)	Risk	One per million	Minority (%)	Income ($)
06/02/08	SL 1	5.8-16.3E-04	1.7-4.7E-04	1.8-5.2E-04	183-520	86	20,268
06/03/08	SL 2	5.2-14.6E-04	1.5-4.2E-04	1.64-4.6E-04	164-466	71	35,833
06/04/08	SL 3	6.6-18.7E-05	1.9-5.4E-05	2.1-5.9E-05	21-60	45	41,346
06/05/08	SL 4	1.1-3.2E-03	3.3-9.3E-04	3.6-10.3E-04	363-1029	29	24,091
06/09/08	SL 5	6.0-17.0E-05	1.7-4.9E-05	1.9-5.4E-05	19-54	80	38,846
06/10/08	SL 6	6.0-17.0E-05	1.7-4.9E-05	1.9-5.4E-05	19-54	21	34,583
06/12/08	SL 8	9.6-27.2E-04	2.8-7.8E-04	3.1-8.6E-04	306-866	62	22,829
06/17/08	SL 10	2.0-5.6E-04	5.7-16.2E-05	6.3-1.7E-05	63-179	98	21,131
06/23/08	SL 13	3.8-10.9E-04	1.1-3.1E-04	1.2-3.4E-04	122-347	19	35,223
06/24/08	SL 14	4.1-11.7E-04	1.2-3.4E-04	1.3-3.4E-04	132-374	9	42,563
06/25/08	SL 15	1.4-3.9E-04	4.0-11.3E-05	4.4-12.5E-05	44-125	51	46,250
06/26/08	SL 16	1.0-2.8E-04	3.0-8.3E-05	3.2-9.2E-05	32-92	36	59,779

[a] Not included in correlation since construction activities occurring during sampling campaign

4. CONCLUSION

Ambient NO_x and $PM_{2.5}$ concentrations measured in the Norfolk area clearly indicate a relationship between demographics and exposure to harmful levels of air pollution. Results revealed that both high minority and mixed neighborhoods were experiencing NO_x and $PM_{2.5}$ concentration levels as high as 89 ppb and 19 μg/m^3, respectively. The strongest relationship existed between socioeconomic characteristics and pollution exposure levels. For example, high minority (86 – 98%), low income (MHI: $20,200 – $21,200) populations at SL 1 and 10 were exposed to average NO_x concentrations ranging from 54 to 89 ppb with 30 minute sustained concentrations in those areas as high as 130 and 137 ppb, respectively which clearly exceed the NAAQS NO_2 limit of 53 ppb. SL 8, a low minority (38%), low income (MHI: $22,300) neighborhood experienced average NO_x concentrations of 34 ppb with 30 minute sustained concentrations as high as 67 ppb. For $PM_{2.5}$, SL 4, a low minority (29%) low income (MHI: $24,000) neighborhood experienced an average concentration of 19 μg/m^3 with 30 minute sustained concentrations as high as 42 μg/m^3, 23 – 95% higher than the NAAQS limit of 15 μg/m^3. On the contrary, high income neighborhoods such as those at SL 14, 15 and 16 (MHI: $42,600 - $59,800) experienced much lower NO_x concentrations between 22 – 26 ppb, 70 – 109% lower than concentrations experienced at SL 1 and 10. A comparative literature analysis on the adverse health effects of NO_x and $PM_{2.5}$ indicates that minority and low income populations in the Norfolk area may be experiencing cancer risks that are 3 – 12 times higher than the high income populations within the same urban area. Results of $PM_{2.5}$ DPM risk comparisons clearly demonstrated that, regardless of race, low income populations in the Norfolk area were exposed to higher DPM concentrations ranging between 0.2 – 3.2 μg/m^3, which according to EPA DPM risk analysis procedures likely results in 183 – 1029 extra cancers per one million people per year at these locations which is 9 – 53 times higher than risks associated with the high income population areas.

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