Investigating Air Quality at the University of North Carolina at Chapel Hill

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This study aims to measure the concentration of PM\textsubscript{2.5} on campus at the University of North Carolina at Chapel Hill and determine policies that the University can implement to improve public health. Particulate matter, or PM, is the term for a mixture of solid particles and liquid droplets found in the air. Examples of PM include dust, smoke, and dirt. PM is emitted from both anthropogenic and natural sources that can be primary (emitted directly) or secondary (formed in the atmosphere) sources. Although PM exists at nearly all sizes, it is most often measured in two major groups: coarse particles between 2.5 and 10 micrometers (PM\textsubscript{10}) and fine particles smaller than 2.5 micrometers (PM\textsubscript{2.5}) (“Airborne Particulate Matter”). PM\textsubscript{2.5} exposure has significant impacts on human health, even when ambient PM pollution is below the National Ambient Air Quality Standards set by the EPA. While everyone can be negatively affected by air pollution, those that belong to a sensitive population, including children, the elderly, and those with predisposed respiratory and cardiovascular diseases, are most at risk to suffer negative health impacts from PM\textsubscript{2.5} inhalation. Sustained exposure to PM\textsubscript{2.5} is 90-100% certain to cause premature mortality in humans (Thornburg).

The research team used AirBeam mobile air sensors and PurpleAir stationary air sensors to measure PM\textsubscript{2.5} concentrations on campus. The mobile AirBeam sensors were carried around campus during morning, afternoon, evening, and off-peak data collection on both weekdays and weekends. This data was used to determine the air quality on campus. The data was also used to find “hotspot” areas on campus that experienced higher concentrations of PM\textsubscript{2.5} when compared to the rest of campus. The PurpleAir sensors were used to collect comparative data to validate the AirBeam findings. A web-based dispersion modeling software called C-PORT was also used to model the concentration of PM\textsubscript{2.5} on campus caused by the UNC Cogeneration Facility and cars on campus roads. While the AirBeam and PurpleAir sensors measure total PM\textsubscript{2.5}, the C-PORT model only accounted for pollution emitted from the UNC Cogeneration Facility and cars on campus roads. This allowed the team to determine whether the cogeneration plant and cars were the main polluters of PM\textsubscript{2.5} on campus. C-PORT was also used to model the impact of potential policies on air quality. However, the model only allows for policies that affect one of the model inputs including traffic volume, traffic speeds, fleet mix, and the UNC Cogeneration Facility details.
Overall, the air quality on campus was found to be good. However, the data also revealed a number of “hotspot” areas around campus at both near and away from major roads. Furthermore, when comparing the observed total concentration of PM$_{2.5}$ to the modeled concentration from the cogeneration plant and cars, it was concluded that secondary sources not captured by the model were the main contributors of PM$_{2.5}$ on campus. These findings should help shape further study into the air quality on campus.

The team modeled policies such as decreasing the exhaust velocity at the cogeneration plant, closing roads, and electrifying portions of the fleet mix. While these policy changes would improve air quality and decrease the annual mortality rate, the University may be able to have a greater impact on public health by using funds elsewhere, such as building more exercise facilities or providing healthier food. At present, the University does not have an urgent need to reduce PM$_{2.5}$ concentrations on campus. However, the University should not take this finding as a perpetual bill of good health for the air quality on campus. Rather, the University should continue to be vigilant in monitoring air quality through funding further studies and continue to follow best practices for reducing PM$_{2.5}$ pollution on campus.
What is air pollution? What is PM2.5?

Air pollution can be defined as the presence of toxic chemicals and/or compounds in the air which are not usually present, at levels that pose health risks. Air pollution is one of the most serious environmental problems the world faces today, and it is largely a man-made problem, stemming from many different sources (“What is Air Pollution?”). These sources can be classified as stationary, mobile, or natural. Stationary sources include power plants, factories, and dry cleaners. Mobile sources include cars, buses and planes, and natural sources include windblown dust and volcanic eruptions. The EPA classifies the air pollutants from sources like these into six principal pollutants: nitrogen dioxide, ozone, sulfur dioxide, carbon monoxide, lead, and particulate matter (“Air Quality Planning and Standards”).

Particulate matter, or PM, is the term for a mixture of solid particles and liquid droplets found in the air. Examples of PM include dust, smoke, and dirt. PM is emitted from both anthropogenic and natural sources that can be primary (emitted directly) and secondary (formed in the atmosphere). Although PM exists at nearly all sizes, it is most often measured in two major groups: coarse particles between 2.5 and 10 micrometers (PM\textsubscript{10}) and fine particles smaller than 2.5 micrometers (PM\textsubscript{2.5}) (“Airborne Particulate Matter”). While PM\textsubscript{2.5} is invisible to the naked eye, and since it is so small and light, these fine particles can cause decreased visibility in the air, creating a fog-like haze.

Figure 1: Figure 1 provides a visual representation of how small PM\textsubscript{2.5} particles are.
Air quality is a crucial indicator of the cleanliness of ambient air and serves to alert officials and citizens to potential public health and safety issues. Particulate matter is one of the many pollutants that is monitored as a component of air quality. PM$_{2.5}$ concentrations are reported by an Air Quality Index (AQI) that gives guidance on the cleanliness of ambient air and whether or not it may cause public health issues. In December of 2012, the EPA updated the National Ambient Air Quality Standard (NAAQS) for PM$_{2.5}$. The annual standard was reduced from 15 µg/m$^3$ to 12 µg/m$^3$, meaning that the average air quality for the year should fall in the “good” category. The daily PM$_{2.5}$ standard was retained at 35 µg/m$^3$, meaning to be considered healthy air quality on a given day, the level should not exceed the “moderate” category (“NAAQS Table”). See the Air Quality Index (AQI) table below.

Table 1:

<table>
<thead>
<tr>
<th>AQI Category</th>
<th>Index Values</th>
<th>µg/m$^3$</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>0 to 50</td>
<td>0 to 12</td>
<td>Air quality is considered satisfactory, and air pollution poses little to no risk.</td>
</tr>
<tr>
<td>Moderate</td>
<td>51 to 100</td>
<td>12.1 to 35.4</td>
<td>Air quality is acceptable; however, unusually sensitive individuals may experience respiratory symptoms.</td>
</tr>
<tr>
<td>Unhealthy for Sensitive Groups</td>
<td>100 to 150</td>
<td>35.5 to 55.4</td>
<td>Increasing likelihood of respiratory symptoms in sensitive individuals, aggravation of heart or lung disease and premature mortality in persons with cardiopulmonary disease and the elderly.</td>
</tr>
<tr>
<td>Unhealthy</td>
<td>151 to 200</td>
<td>55.5 to 150.4</td>
<td>Increased aggravation of heart or lung disease and premature mortality in persons with cardiopulmonary disease and the elderly; increased respiratory effects in general population.</td>
</tr>
<tr>
<td>Very Unhealthy</td>
<td>201 to 300</td>
<td>150.5 to 250.4</td>
<td>Significant aggravation of heart or lung disease and premature mortality in persons with cardiopulmonary disease and the elderly; significant increase in respiratory effects in general population.</td>
</tr>
<tr>
<td>Hazardous</td>
<td>301 to 500</td>
<td>250.5 to 500</td>
<td>Serious aggravation of heart or lung disease and premature mortality in persons with cardiopulmonary disease and the elderly; serious risk of respiratory effects in general population.</td>
</tr>
</tbody>
</table>

Table 1 lists the National Ambient Air Quality Standards (NAAQS) and guidelines as set by the EPA.
Health Effects:

PM$_{2.5}$ exposure has significant impacts on human health, even when ambient PM pollution is below the NAAQS. While everyone can be negatively affected by air pollution, those that belong to a sensitive population, including children, the elderly, and those with predisposed respiratory and cardiovascular diseases, are most affected. Sustained inhalation of PM$_{2.5}$ is 90-100% certain to cause premature mortality in humans (Thornburg).

Effects on the respiratory system

After twenty years of studies, scientists have revealed a strong correlation between PM exposure and respiratory morbidity and mortality. This suggests that deposition of PM on epithelial cells, caused by inhalation, can prompt systemic inflammation, which undermines lung function. Studies done in the European Union have reported that PM$_{2.5}$ exposure decreased the average lifespan by 8.6 months. Those more significantly impacted by this pollution are those that already suffer from respiratory diseases like asthma and bronchitis. This is because the inflammatory response aggravates the asthmatic response to inhaled allergens and also diminishes the effectiveness of the immune system, making sensitive populations more prone to infections (Grunig et al.). This evidence shows there is a relationship between PM$_{2.5}$ levels and increased incidence of respiratory illnesses such as asthma, chronic bronchitis, chronic obstructive pulmonary disease (COPD), and pneumonia (Thornburg).

Effects on the cardiovascular system

Through the blood and lymph, chemicals in PM$_{2.5}$ are transferred to cells to cause systemic inflammation. Subsequently, this PM inhalation activates autonomic neuronal reflexes, causing vasoconstriction. The affected blood vessels can become less responsive to drugs designed to increase blood flow. Systemic inflammation can also cause changes in vascular activity, limiting the ability for blood to reach the heart and brain. The functionality of cardiac muscle is also altered, leading to illnesses such as ischemic heart disease, along with structural abnormalities such as atherosclerosis. Additionally, PM$_{2.5}$ decreases platelet function. When platelet function is diminished, it can create blood clots, which can lead to heart attacks and strokes (Grunig et al.).

Background of air quality in NC

Clean Smokestacks Act of 2002

In 2002, North Carolina passed the Clean Smokestacks Act, which set caps on the total annual emissions of nitrogen oxides (NOx) and sulfur dioxide (SO2) by the two major energy providers, Duke Energy and Progress Energy. These caps required them to permanently reduce their year-round emissions of NO$_x$ 77% by 2009 and SO$_2$ 73% by 2013. With these steep caps, North Carolina effectively forced Duke Energy and Progress Energy to retire all forty-five coal-fired electric generating plants within the state (Andrews).
There were no benefits to the company to exceed the new limits, because if the companies over complied, they were forced to surrender the excess emissions to the state. This process is contrary to what many states do with their cap-and-trade systems, where if you exceed the expectations you can sell the excess to other companies so that they can pollute more. Maintaining strict policy, the Clean Smokestacks Act required both companies to report their processes for reducing these harmful gases in addition to reporting on their steps for reducing mercury and CO₂ (Andrews). Because of this policy, North Carolina was able to make advances in air quality (see Figure 2).

In March 2004, North Carolina petitioned the EPA under the Clean Air Act, which was later denied, saying that the power plants in five upwind states contributed to its noncompliance with the PM₂.₅ standard. The petition was denied in part because they had generated a new federal implementation plan for the new Clean Air Interstate Rule (CAIR) that would resolve the issues claimed. This new CAIR would require substantial reductions of NOₓ and SO₂ across all 28 eastern states using a cap and trade system. This, however, would not assure cleaner air for North Carolina; instead allowances could be bought from over-compliance from other states in the region. With this petition, North Carolina became the first state to challenge the EPA’s proposed CAIR, which ultimately led to the creation of a stricter Cross-State Air Pollution Rule (CSAPR) (Andrews).

Figure 2:

Figure 2 shows evidence that North Carolina’s actions with the Clean Smokestacks Act have led to lower levels of PM2.5 in the Piedmont region.
In January of 2006, North Carolina initially sued the Tennessee Valley Authority (TVA) claiming a public nuisance, asserting that TVA’s power plants were unreasonably affecting North Carolina and its citizens. Specifically, the state claimed that airborne particles, or PM, from TVA’s electricity generating power plants were “threatening the health of millions of residents, the financial viability of the entire region, and the beauty and purity of a vast natural ecosystem” (Hornstein). In addition to these claims, North Carolina alleged that this air pollution cost the state government and its citizens billions of dollars each year due to increased health care expenses, sick days, and lost revenues from tourists to NC’s mountain region (see Figure 3), which doesn’t consider the loss in biodiversity that the region is facing as a result of the pollution (Hornstein). The TVA denied all of the allegations against it, and instead claimed that since they were in compliance with state and federal regulations, they could not be considered a public nuisance. The state noted that they were making strides towards better air quality with the CSA but that the TVA was impeding their progress. Initially, the courts decided in favor of North Carolina, ordering the TVA to install enhanced pollution controls on their plants at an estimated cost of $1 billion.

Unhappy with this decision, the TVA appealed and the case went back to trial in 2009. The Fourth Circuit rejected North Carolina’s public nuisance claim against activities that were expressly regulated by the Clean Air Act. North Carolina, dissatisfied with the NAAQS authorized by Congress, requested that the federal courts rule to impose more strict standards. This attempt proved fruitless since it would take years of research to scientifically come up with new requirements. In the meantime, the NAAQS would have to have been replaced with localized and unjustified requirements that would leave whole states and industries exposed to the uncertainty of conflicting court orders across the nation. After the court refused North Carolina’s request and sided with the TVA, North Carolina appealed to the Supreme Court (Hornstein).

After years of legal battles, the TVA settled in a consent decree with North Carolina to reduce its overall capacity to generate coal-fired electricity. They promised to phase out 18 of their coal-burning generators by 2017. In addition, the TVA spent $3 billion to $5 billion on pollution controls for the remaining plants that used coal (Hornstein). With these changes, health and tourism in North Carolina were positively impacted.

Figure 3:

Figure 3 shows the view from Purchase Knob, Great Smoky Mountains National Park. The air quality and clarity is clearly diminished in 2005, around the time of the lawsuit.
Local Air Quality - Orange County

North Carolina’s air quality has improved since the settlement of the TVA case and the Clean Smokestacks Act of 2002. These emissions reductions have had positive impacts on local air quality as well.

The American Lung Association grades counties across the US on an A to F scale in terms of air pollution. While Orange County, the county Chapel Hill is located in, was not a county that was monitored, many neighboring counties, including Durham and Caswell Counties, were monitored. The ratings have drastically improved for these counties in the last couple years, increasing from D’s in 2016 to A’s and B’s. Caswell and Durham Counties’ grades were B and A, respectively ("How Healthy is the Air We Breathe?").

Currently outdoor air pollution on campus is being monitored by two PurpleAir stationary monitors, one located outside Whitehead Hall and one outside UNC Environmental Sciences and Engineering. In addition, another monitor is located on the Chapel Hill Public Library for more coverage throughout the city. These measurements can be viewed by the public.

Research Purpose

Chapel Hill is home to sixty thousand people and the University of North Carolina at Chapel Hill, a college known for its academics, research, and sports teams. This historic college town is consistently shaped by a steady stream of young, driven students attending the University, hosting an undergraduate enrollment of around 19,000 at any given time. Many students participate in outdoor sports, whether it be recreationally or collegiately. This presents a problem for those that have respiratory illnesses such as asthma because these activities require more oxygen to supply the body—oxygen they get from polluted air. Because of the University’s acclaim, many also visit the campus for tours and sporting events, meaning there is often an influx of people on the 729-acre campus, adding to the concern for having clean, healthy air in Chapel Hill.

In addition to the large number of visitors, Carolina also has an impressive hospital system that hosts hundreds of thousands of patients and loved ones each year. UNC’s Medical Center is made up of N.C. Memorial Hospital, N.C. Children’s Hospital, N.C. Neurosciences Hospital and N.C. Women’s Hospital. Carolina’s campus is also home to the NC Cancer Hospital and the UNC Lineberger Comprehensive Cancer Center (“UNC Health Care”). With these institutions hosting many ill patients, it is important to consider how these sensitive populations, which include children, the elderly, and those with predisposed respiratory and cardiovascular diseases, are affected by air pollution. Knowing this, a team of UNC students set out to take an inventory on the state of UNC’s air quality, by monitoring PM$_{2.5}$ levels, in order to determine the magnitude of the threat of air pollution to the campus and the surrounding community.
Sensors

*AirBeam*

The development of low cost, portable air quality sensors enables the general public to analyze and explore their environment in ways previously unattainable and in addition to regulated monitoring that organizations such as the EPA complete. Although portable sensors are not regulated by the EPA or tested to meet the requirements of higher-grade air quality monitors used by the EPA, they are valuable for research, personal exposure monitoring, education, and pollutant source identification. The EPA identifies five important steps in gathering useful data when using portable sensors: ask a question; develop an approach; determine sensor location; collect measurements; and analyze, interpret, and communicate results (Williams *et al*.). These five steps were used as the foundation of this air quality research. Developing a clearly defined research question is vital to the success and direction of the project. When developing the approach, factors taken into account were the domain of interest, the methodology of data collection such as who, when, where, and how data would be collected, and the number of sensors used. Sensor location was determined based on the research domain and for full coverage of the campus. Measurements were collected based on the time slots of the web-based model that was used.

![Figure 4](image)

Figure 4 shows an Airbeam and the Aircasting system.
Data were obtained using the AirBeam 1 wearable monitors. The AirBeam 1 is a mobile device that is capable of measuring sound, particulate matter, temperature, and relative humidity. It uses a light scattering technique to measure particulate matter. Air is drawn in through a sensing chamber where light from a laser within the device scatters off of particulate matter in the airstream. The light scatter that occurs is registered by a detector and converted to a measurement that estimates the number of PM$_{2.5}$ particles in the air (Aircasting). The open sourced platform, Aircasting, was used in tandem with the AirBeam 1 devices to map the PM$_{2.5}$ data and to obtain downloadable CSV files. Aircasting is an application that can be downloaded to Android mobile devices and used to record and display data from the AirBeam 1 devices. While the Airbeam is in use, the Aircasting mobile application updates measurements every second and uses the measurements to map and graph the data in real time on the device. After the session is completed, the data can then be uploaded to the Aircasting website where the map of the session is shown and a downloadable CSV can be exported (Aircasting).

Figure 5:

Figure 5 shows the Aircasting platform after a run. The color of the line depicts the air quality in µg/m$^3$ in that location.

PurpleAir

PurpleAir air quality sensors were also used to collect data. PurpleAir sensors are fixed sensors that use a similar technique to the AirBeam’s to assess air quality. A fan is used to draw air past a laser, causing the laser to reflect off of particles in the air. The reflections are used to estimate the amount of particulate matter in the air (PurpleAir). Three PurpleAir monitors are installed on UNC’s campus. The first is installed indoors in Phillips Hall, the second and third are outdoor monitors installed outside Whitehead Residence Hall and outside UNC Environmental Sciences and Engineering. The two outdoor sensors were used in data analysis as outdoor air quality in Chapel Hill was the topic of interest for this research.
C-Tools

Community Air Quality Tools, or C-TOOLS, are a group of easy to use, web-based air quality models developed by the UNC Institute for the Environment in collaboration with the EPA to model air quality on a local scale. There are two models that are included in the C-TOOLS web based platform right now, C-LINE and C-PORT. C-LINE was developed to model pollutant emission sources from roadways, while C-PORT was developed to model port-related sources and other point sources in addition to pollutants from roadways. The model chosen for this research was C-PORT as it allows the user to input point sources such as power plants and other point sources. C-PORT models the concentration of a variety of pollutants including NOx, SO2, CO, PM10, and PM2.5 in addition to other toxins such as benzene, formaldehyde, and acetaldehyde (UNC Institute for the Environment).

C-PORT uses a variety of different meteorological conditions in combination with pollutant data to predict how the pollutants will disperse and overlays this dispersion onto a map. The meteorological conditions that can be altered in C-PORT are atmospheric stability, season, and wind direction. Atmospheric stability within C-PORT can range from stable to convective. Stable meteorological conditions indicate a stable atmosphere with a relatively low dispersion rate and will result in greater ground level pollutant concentrations near the emission source, while convective conditions indicate a turbulent atmosphere that disperses pollutants more quickly resulting in lower ground level concentrations but a wider plume from point sources such as power plants. Wind directions can also be modeled within C-PORT by using the seasonal average or by choosing one of sixteen different wind directions within C-PORT.

Four time periods can be chosen within C-PORT for model runs. The time periods include AM peak, midday, PM peak, and off peak. AM peak is from 7:00am to 8:59am, midday is from 9:00am to 3:59pm, PM Peak is from 4:00pm to 6:59pm, and off peak is from 7pm to 6:59am. The user can also choose to model a scenario on a weekday or a weekend within C-PORT. Altering these parameters within C-PORT will change the volume of traffic and the types of vehicles on the road.

The default road network included with C-PORT is the 2013 Highway Performance Monitoring System (HPMS). However, other road networks such as HPMS 2016 or OpenStreetMap can be uploaded into C-PORT and used to model scenarios. Each road within C-PORT has a corresponding road name, road type, average annual daily traffic, average speed, and a fleet mix profile. There are four possible road types in C-PORT; rural restricted access, rural unrestricted access, urban restricted access, and urban unrestricted access. Average annual daily traffic is the number of vehicles on an average day for a given road. The fleet mix of a road contains two components; vehicle mix and fuel mix. Vehicle mix is the percentage of the total fleet a particular vehicle type makes up. The total fleet is divided into six categories; passenger vehicles, small commercial trucks, school buses, transit buses, large commercial trucks, and other large trucks. The fuel mix is the percentage of vehicles that are gasoline, diesel, or compressed natural gas for each of the six vehicle types. The road name, road type, average annual daily traffic, average
speed, and fleet mix profile can all be changed to analyze different modelling scenarios.

After input parameters are chosen, the C-PORT model is run, and it produces a dispersion pattern that is overlaid on a map of the area of interest. Darker shades of blue on the output map indicate a greater concentration of pollutants. An inspection feature can also be used to click on a particular point on the map. When a point is selected, the pollutant concentration is shown for that specific point and the percentage of the total concentration that is due to area sources, point sources, railways, roads, and ships in transit is displayed.

**Figure 6:**

![Figure 6](image)

Figure 6 contains an image of an example output that the C-PORT model produced. This particular image was the result of the weekday AM Peak model run with the cogeneration plant point source and the observed AADT values from traffic counts. The orange dot is the location of the cogeneration plant. The darker the shade of blue on the map, the higher the concentration of PM$_{2.5}$.

**GIS**

A geographic information system, or GIS, is a tool for gathering, managing, and analyzing data. It analyzes spatial location and organizes layers of information to visualize data. GIS, commonly used via the platforms ArcMap and QGIS, both used in this study, reveals insights into data such as patterns, trends, and relationships. The tool was used in this study to further analyze data from the AirBeam and C-TOOLS runs.

Using the CSV file outputs from each C-TOOLS run, a set of maps was created using the GIS mapping software QGIS. By summing the PM$_{2.5}$ measurements at each individual point in the C-TOOLS output, which contained contributions from roads as well as the UNC Cogeneration Facility point source, the mean PM$_{2.5}$ value of every point could be calculated. Using this value,
the departure from mean and percent departure from mean values were calculated for each point. After inputting this modified CSV file into QGIS, a series of heat maps were created based on the percent departure from mean values that highlight various PM$_{2.5}$ hot spots around campus. A hot spot analysis was created for each time period in alignment with the AirBeam runs for comparison purposes. There is a map for AM peak, midday peak, PM peak, and off peak time periods on both the weekday and weekend, for a total of 8 C-TOOLS hot spot analysis maps.

Figure 7:
Methods

Air Quality Data Collection

Collecting air quality data on campus was necessary in order to compare C-PORT model results with actual field data and also to quantify the total PM2.5 in the area. To do so each team member was assigned a walkable section and were required to walk that section during different intervals of the day, collecting PM$_{2.5}$ data using Airbeam sensors. The team chose to collect PM$_{2.5}$ data on the University's campus as well as areas south of campus that contain other UNC facilities. The UNC Hospitals Emergency Room, the UNC Children’s Hospital, and the UNC Cancer Hospital were all included because many individuals walking through these areas belong to the PM$_{2.5}$ sensitive population group. The domain that was chosen is outlined in Figure 8 and includes the area from Franklin Street to Mason Farm Road, the southernmost road. The domain was divided into 7 walkable sections to facilitate data collection by team members.

Figure 8:

Figure 8 shows the domain chosen to collect PM2.5 data on the campus of UNC and UNC hospitals. The circled numbers indicate section labels.
Each team member walked an assigned section during four time intervals on the weekend and weekdays. The time intervals included AM peak: 7:00am to 8:59am, midday: 9:00am to 3:59pm, PM Peak: 4:00pm to 6:59pm, and off peak: 7pm to 6:59am. These intervals are the same intervals the C-PORT model uses to model the fluctuation of PM$_{2.5}$ during different times of the day. Each team member collected a total of eight Airbeam runs, four during the week and four during the weekend. The primary limitation of this data collection was the lack of continuity between the dates and times that team members conducted their walks. It was nearly impossible for all 7 members to walk their sections at the same times on the same days.

The precision of the Airbeam data was tested by placing all seven sensors outside for 30 minutes (Figure 9). The collected Airbeam data was compared to PurpleAir, C-TOOLS, and the Amory, Millbrook, and Triple Oak monitors. Figure 9 shows that the Airbeams were precise, all monitors except the monitor in zone three showed the same patterns and magnitudes of PM$_{2.5}$ changes. The Airbeam tracking PM$_{2.5}$ in zone 3 was the only monitor that displayed significantly higher PM$_{2.5}$ levels. This error was corrected by utilizing statistics that accounted for the offset.

**Traffic Count Data Collection**

The default road network built in to C-TOOLS did not effectively represent smaller roads around campus such as McCauley Street. However, C-TOOLS allows the user to upload a customized road network. In order to have an up-to-date road network, OpenStreetMap, a road network, was used with the generated fleet mixes and traffic counts. The traffic count was conducted to manually find and calculate Average Annual Daily Traffic, or AADT, values, which is a measure of traffic volume. After taking traffic counts and recording fleet mixes, the OpenStreetMap values were substituted with the values for some of the C-TOOLS runs the team conducted. Given the initial assumption that road sources would be a major contributor to PM2.5 concentrations at UNC, it was important to conduct C-TOOLS runs with recent fleet mixes and AADT values.

Team members took traffic counts at four locations that, taken together, were determined to be representative of all the roads on and near campus. These locations can be seen in the following image:
The locations on Manning Road and Columbia Street were used as a representation for the main thoroughfares of Chapel Hill. Additionally, they were used to benchmark the results of this study against the North Carolina Department of Transportation (NCDOT) AADT values which conducts traffic counts on both of these roads. East Cameron Avenue was chosen because it is a smaller road that is not measured by the DOT, but is a commonly used road on campus for both cars and pedestrians. The final location was McCauley Street which was used to model roads in the neighborhoods surrounding campus. These roads allowed for a proper model of the entire domain with custom AADT values and fleet mixes.

The methodology to determine fleet mix and traffic counts uses a manual counting method described in a report by the Center for Transportation Research and Education of Iowa State University (Iowa State University, 2018). Fleet mixes were based on the fleet mix categories used in C-TOOLS to make the data substitution process easier. Those categories counted are passenger vehicles, small commercial trucks, school buses, transit buses, large commercial trucks, and other large trucks. To prepare, the recorder noted the time of day, location, and weather conditions and positioned themselves away from the edge of the road and intersections. The observer took count for a 15-minute period. Observations were made once during each of the time periods of 7:00am to 8:59am, 9:00am to 3:59pm, 4:00pm to 6:59pm, and 7pm to 6:59am on two separate days, once during the week and once on the weekend. To determine

Figure 10 shows a map of UNC’s campus with the traffic count locations marked by red dots.
the AADT values, the 15 minutes samples were converted to hourly counts, which were assumed to be representative of each hour during the time period collected. The hourly counts are then used to calculate a daily traffic count for weekdays and weekends. These daily counts are then weighted (5x for weekday and 2x for weekend) to formulate a weekly traffic count. The weekly counts are then seasonally adjusted, aggregated for 52 weeks, and then divided by 365 to arrive at an AADT count for each road segment.
Statistics

Ambient air quality can be assessed through testing various pollution contributors that have the ability to alter particulate matter concentrations. For the purpose of this research project, PM$_{2.5}$ was observed on UNC’s campus through a thorough analysis of meteorological, geographical, and computational model alterations to determine where on campus PM$_{2.5}$ was set to affect the most people. Changes in elevation were also seen as a potential factor, where the assumption was made that increasing distance from sea level would positively correlate to an increase in PM$_{2.5}$ concentrations observed for that particular area. In order to do fully assess primary and secondary pollution contributors, C-TOOLS was used as a reference of expectant values of PM$_{2.5}$ concentrations, where only pollutants from primary sources such as vehicles and the plume of emissions from the cogeneration plant were modeled. Secondary sources were not captured by the model, but impacted the raw values collected from the AirBeam sensors. Given this information, it was expected that C-TOOLS would report much smaller PM$_{2.5}$ concentrations than the AirBeam sensors would.

Running statistical tests on each of these variables discussed allowed for a thorough examination at which, if any, primary and secondary contributors resulted in a significant impact of particulate matter concentrations in the ambient air on campus. To conduct these tests on the large data sets, a numerical computing software called Matlab was used alongside Excel. In Matlab, there was a 95% confidence level and an 0.05 alpha ($\alpha$) value pre-programmed for every test run in the program. The useful relationship between C-TOOLS model and the AirBeam sensors allowed for the identification of areas where unexpected concentrations of PM$_{2.5}$ occurred. These hotspots were ones that did not lie near the road closest to the location of the value measured, or in the same vicinity as the cogeneration emissions plume, and did not follow the wind direction for a given day.
**Meteorology and Elevation**

Meteorology is a known factor for changing particulate matter concentrations, where natural influencers such as precipitation, temperature, relative humidity, wind direction and speed often contribute to fluctuations in PM concentrations in ambient air. These factors can also contribute to increasing the variability of PM$_{2.5}$ concentrations, as meteorology changes on a day-to-day basis. Whether influenced by anthropogenic occurrences, natural disasters, or influxes in the local climate, changes in weather parameters effects the values of PM$_{2.5}$ in a given area, causing a deviation from the pattern of which particulate matter can accumulate. Wind direction and speed proved to result in strong correlations where high PM$_{2.5}$ measurements would be concentrated around, given emissions from the cogeneration power plant and cars.

There were times when hotspots of PM$_{2.5}$ concentrations appeared that couldn’t be explained by wind direction or speed. One example observed was through precipitation rates, where after a rain event the PM$_{2.5}$ concentrations would be inherently lower than when measurements were taken during dry conditions. In zone 4 during a midday peak time slot (measurement taken between 9AM and 3PM), after a rain the average concentration of PM$_{2.5}$ was 3.06 µg/m$^3$ where during the same time slot in the same zone, on a day with no rain, the readings would report an average of 20.17 µg/m$^3$ concentration. Tests were run to compare the correlation between the effects of relative humidity on the particulate matter concentrations, where anticipated results were inclined to show that an increase in relative humidity would also correlate with a rise in PM$_{2.5}$ concentrations. These results were not seen as consistently as expected, giving r-squared correlation coefficient (R$^2$) values as low as 0.02 and p-values that ranged from 0.007 - 0.001 for all analysis.

A similar observation was also seen with elevation (Figure 11), where the p-value was extremely significant at 1.34 x 10-15, but had an R$^2$value of 0.006 to show inconsistency among variables. Given that the p-values proved to be significant enough to reject the null hypothesis that existed between relative humidity, elevation, and PM$_{2.5}$ concentrations, it was expected to see R$^2$values that were much closer to 1, indicating that there existed a strong correlation between the two variables. Since this finding was not the case, it was concluded that the variation is occurring through bias and error where there was a lack of repeated measurements that could have improved the validity of the correlations.
Departure from Mean and Distance from Roads

Due to the variability of the data collected from the AirBeams (where measurements were completed within the same time period, but at different dates and times for different zones), the team looked at the departure from the mean of the AirBeam data, specifically focusing on the percent of PM$_{2.5}$ concentration readings that deviated from the mean of that zone recording. The team pulled data from PurpleAir and the AQS sites to compare to the results from AirBeam, in order to obtain more confidence in the accuracy of the sensors that were used to collect the data. This methodology was utilized in order to normalize the data, as a means of generating values that could be analyzed through normal distribution. Data was then compared to the distance a PM$_{2.5}$ value was taken at from the closest road in meters, creating the ability to draw the hopeful conclusion that higher concentration values would lie relatively close to to the road. C-TOOLS modeled this by showing expectant primary sources of pollution such as emissions from cars and the cogeneration plant to have high PM$_{2.5}$ concentrations around the roads and in areas where the plume of the plant settled over. There was a correlation between departure from the mean and the distance to the closest road, but after generating maps of the collected PM$_{2.5}$ values, there were hotspots of high concentrations of PM$_{2.5}$ over 12 µg/m$^3$ and µg/m$^3$ that could not be explained by the C-TOOLS model. These areas of high concentrations were then called hotspots, observed during different time slots on different days. After this finding was made, T-tests were run on the time slots that the hotspots were
occurring in order to assess the anomalies that were occurring. One particular hotspot located around the Rams Head Dining Hall during the weekend and weekday off peak time slots (7pm-6am) was investigated, where the correlation between the distance to the closest road (m) and particulate matter concentration was tested through an F-stat and T-test (Figure 12). Both data sets had an identical significant p-value of 1.1x10-16 and R2 value of 0.006, which follows the pattern that the null hypothesis of there not being a dependent relationship between the two variables exists, but having a correlation coefficient that small suggests otherwise.

Figure 12:

Figure 12 shows Weekend and Weekday Off-Peak PM$_{2.5}$ concentrations ($\mu$g/m$^3$) plotted against the distance from the closest road (meters) to where the value was measured. Observations indicating a high concentration of PM$_{2.5}$ ranging from 1 to 18 $\mu$g/m$^3$ can be found to be anywhere from 0 to 50 meters from the road closest to where the value was taken. A hotspot can be seen on the graph existed around 45 meters from the road, having a PM$_{2.5}$ values of 60 to 72 $\mu$g/m$^3$.

In efforts to further assess these hotspots, data was downloaded from the C-TOOLS model and compared with the AirBeam data to see if hotspots were occurring similarly in and around the intersections near these were occurring. Data in C-TOOLS was exported through a point system that had a locator number to match up with every point measured in AirBeam with a latitude and longitude coordinate. Through this arrangement, correlation tests were run that showed how C-TOOLS and how AirBeam varied at the same geographical locations on campus. Figure 13 shows the residuals associated with AirBeam values in comparison to C-TOOLS, where the model always simulated extremely low values of PM$_{2.5}$ unlike the raw values recorded by the AirBeams. The number of residuals represents the difference between the observed PM$_{2.5}$ concentrations against the model concentrations, where only primary sources are shown and secondary sources are omitted. For the the same time slot as discussed before, where the Rams Head Dining Hall hotspot is located (Weekday Off-Peak) the number of residuals were approximately 201.4, indicating a large difference between the output C-TOOLS was showing against the raw data values collected on campus. Findings like these were similar for the all the time frames of the hotspots found: C-TOOLS reporting low PM$_{2.5}$ values that typically never exceeded 4 $\mu$g/m$^3$, and AirBeam with varying high concentration values and high residual values.
This finding contributed to conclusions that hotspots were attributed to lurking variables or unknown causes besides the primary sources of car and power plant emissions.

Figure 13:

![Weekday Off-Peak CTOOLS and Airbeam Comparison](image)

Figure 13 shows residuals during Weekday Off-Peak for the comparison of raw values recorded from the AirBeams, against the C-TOOLS values at the same geographic location on campus. The high number of residuals represents the significant difference between the observed AirBeam values and the expected C-TOOLS model outputs for particulate matter concentrations.

**AirBeam Disparities**

After running tests that proved to exhibit high variation and inconsistent findings regarding the main causes of elevated levels of PM$_{2.5}$ concentrations on campus, the possibility that the AirBeams themselves were uncalibrated became a plausible feasibility. In order to better assess the precision and accuracy of their performance, a calibration test was run between all seven of the AirBeams, at the exact same place outside and during the exact same time. Figure 14 shows the results of this test, how there exists a temporal trend between them, but that overall disparities between the sensors were also prevalent. Considering the AirBeam sensors were operating at the exact time and place, it was expected that the correlation coefficient of the sensors would be close to one, but that was not the case. This finding revealed that there could possibly be a calibration glitch with the AirBeams that possibly resulted in the high amounts of variation of the PM$_{2.5}$ data collected throughout the study. During the calibration tests, the sensor used to measure zone 4 displayed PM$_{2.5}$ values higher than rest of the other outputs, which was
not a typical trend for this sensor. The sensor that emitted the lowest PM$_{2.5}$ concentrations during the calibration test did typically report reduced values during runs. Patterns that appeared during the calibration test showed that they could explain findings from the AirBeam runs. Sensors that typically produced low PM$_{2.5}$ concentrations in zone 7 consistently, reported low values in the test, whereas sensors that normally recorded higher PM$_{2.5}$ values were reported from sensors that did not consistently reflect higher concentrations. The variation that occurred between the data collected from the AirBeams could also have resulted from a number of events. For example, the fact that data was not collected throughout all the zones during the exact same time (not just within the same time frame) could have resulted in more accurate correlations made between the zones.

Figure 14:

![Graph showing calibration run data](image)

Figure 14: The calibration test conducted between all seven of the AirBeams on October 23rd, 2018. Temporal trends exist, but poor correlation coefficient values suggest that the AirBeams are not completely calibrated correctly.
GIS

GIS was used to visualize the AirBeam and C-TOOLS data to find any patterns or correlations between AirBeam runs, hot spot locations, or other general trends that might have emerged. In terms of the AirBeam data, four different sets of hot-spot analysis maps were produced: each time period’s AirBeam run’s percent departure from the mean PM$_{2.5}$, all observed values over 35 µg/m$^3$ in each period, all observed values over 12 µg/m$^3$ in each period, and runs only taken on the same day and time period. The data was uploaded into QGIS and overlaid on an OpenStreetMap road network. Before continuing the explanation and significance of some of the maps, it is important to understand QGIS’s heat map analysis tool as it was used for each set of maps. Heat mapping is a method of showing the geographic clustering of a set of values to define areas of high occurrence versus areas of low occurrence. It allows data to be geographically visualized so that patterns of higher density or clusters of activity emerge. It uses a color gradient to denote areas of increasingly higher density.

The AirBeam maps created a narrative that were often unexplainable with hot spots occurring both where they were expected, locations such as busy intersections, and in places they were not expected like areas very far from roads and not located in the cogeneration plume. The map that displays this most clearly is all the observed values over 35 µg/m$^3$.

Figure 15:

Figure 15 shows a heat map of all AirBeam values over 35 µg/m$^3$ with each concentration labeled by the time period they were recorded in.
Figure 15 shows hot spots that were expected to occur in areas of high traffic such as those at the intersection of Cameron Avenue and Columbia Street and the intersection of Franklin Street and Columbia Street. However, it also showed high concentrations of values over 35 µg/m³ in spots that were not expected. Most notable are the values for the Weekday AM, Weekend AM, and Weekday Off Peak runs. These concentrations were found on relatively calm streets, such as the Weekday AM hot spot on Cameron Avenue and the Weekend AM hot spots on Raleigh Street, or not found on a street at all, such as the Weekday Off Peak run that was found in Ram’s Head Plaza. Some of these concentrations can be explained in terms of location and traffic, but it was found later through the C-TOOLS analysis that road sources may not be a significant contributor to the overall PM$_{2.5}$, even in these locations, indicating that background or secondary PM$_{2.5}$ are significant sources.

Furthermore, unusual concentrations of PM$_{2.5}$ were continually observed along areas not associated with heavy traffic, the cogeneration plume, or located along roads at all when the percent departure from the mean values in each run were modeled. The following two maps illustrate this point. Note the hotspots located away from road segments.

Figure 16:
C-PORT was used as a method of attempting to validate the mobile sensor data, to quantify and compare contributions from the cogeneration plant to road sources, and to model potential policy recommendations to improve air quality in Chapel Hill. First, the HPMS 2013 road network was removed and the HPMS 2016 network was uploaded into C-PORT to ensure that AADT values and roads were updated. The cogeneration plant was added to the model and the model was run for all time periods for both weekdays and weekends. However, many of the smaller residential and back roads were not included in the HPMS 2016 road network, so a new network was created using OpenStreetMap. The model was again run for all time periods on both weekdays and weekends with the updated OpenStreetMap road network. After traffic counts were completed and AADT values were calculated for the roads where counts were conducted, the road network was again modified and the new AADT values calculated from the traffic counts were added to the model.

The C-PORT results showed that concentrations due to roads were highest at intersections and roads with the highest AADT values. As the distance from the road increased, the PM$_{2.5}$ contribution from the road source decreased. The plume from the cogeneration plant followed the wind direction. The seasonal average for Chapel Hill was from the northwest to the southeast so the plume followed this direction for all of the runs using the average wind direction. To
attempt to validate the AirBeam data using C-PORT, the model was altered so that the wind direction and the time period parameters in the model were consistent with the AirBeam walk. When the model output was compared to the mobile sensor data, there were cases where the C-PORT output predicted high concentrations of PM$_{2.5}$ that were consistent with the locations of high concentrations on campus from the AirBeam mobile sensors. However, for the majority of the walks that were made on campus, the C-PORT model results did not match with the AirBeam data well. The raw values for PM$_{2.5}$ concentrations in the C-PORT output were compared with the values that the AirBeam mobile sensors measured. C-PORT consistently resulted in values that were significantly lower than that of the AirBeam sensors. C-PORT outputs for typical conditions predicted maximum concentrations on campus within the domain of 1.1-1.2 µg/m$^3$. The AirBeam walks resulted in mean concentrations ranging from 5.8 µg/m$^3$ for the midday time slot to 16.8 µg/m$^3$ for the off-peak time slot. AirBeam walks also saw instances of concentrations greater than 35 µg/m$^3$ for some of the mobile sensor walks. The C-PORT model does not consider background PM and only modeled the emissions from the cogeneration facility and the roads. The discrepancy between the AirBeam mobile sensors and the C-PORT outputs suggest that the primary sources of PM$_{2.5}$ that C-PORT models may not be as significant of a contributor to the overall PM$_{2.5}$ when compared to secondary and background sources.

Figure 18:

![Figure 18: An AirBeam map displaying values over 12 ug/m$^3$ on runs from October 4th, compared to a C-TOOLS run modeling this day. Notice the wind direction and how the plume lines up with some of the observed AirBeam hot spot location.]

Figure 19:

![Figure 19: AirBeam values over 12 ug/m$^3$ on runs from October 7th compared to a C-TOOLS model of this day. The plume and road sources are not a factor in the AirBeam recordings. This comparison is illustrative of most of the comparisons in this study.]


Additional C-PORT model simulations were run to determine what the worst-case scenario conditions would be for Chapel Hill. The worst-case scenario was determined to be PM peak weekday with stable atmospheric conditions. Changes were made to this worst-case scenario to attempt to model the effects that policy changes would have on the PM$_{2.5}$ concentrations. The policy changes modelled in C-PORT were decreasing the velocity of the cogeneration stack, the closure of the Columbia Street and Cameron Avenue intersection, the closure of Cameron Avenue and South Road, and the electrification of a portion of the vehicle fleet. Decreasing the velocity from the cogeneration plant stack resulted in a maximum decrease in PM$_{2.5}$ of 0.004 ug/m$^3$, a minimal impact on the PM$_{2.5}$ concentrations (Table 2). The closure of Cameron Avenue and South Road resulted in a maximum decrease of 4.8 ug/m$^3$ (Table 2). The electrification of a portion of the vehicle fleet was achieved by determining how much of the AADT was passenger gasoline vehicles. Then, to simulate electrifying a percentage of the fleet, that percentage of passenger gasoline vehicles were removed from the fleet and the new AADT was used in the model. For example, 10% electrification corresponded to a 10% reduction in passenger gasoline vehicles from the fleet while a 50% electrification was simulated by reducing passenger gasoline vehicles by 50%. Electrifying the fleet by 10% resulted in a maximum PM$_{2.5}$ concentration decrease of 1.3 ug/m$^3$, a 30% electrification resulted in a 3.0 ug/m$^3$ decrease, and a 50% electrification of the fleet resulted in a 4.9 ug/m$^3$ decrease in PM$_{2.5}$ (Table 2).

Table 2:

<table>
<thead>
<tr>
<th>Policy Recommendation</th>
<th>Relative Difference Max (%)</th>
<th>Raw Difference Max (ug/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25% Decrease in Velocity from Co Gen</td>
<td>0.17</td>
<td>0.004</td>
</tr>
<tr>
<td>Cameron Road Closure</td>
<td>47</td>
<td>1.7</td>
</tr>
<tr>
<td>South Road Closure</td>
<td>73</td>
<td>4.8</td>
</tr>
<tr>
<td>Cameron and South Road Closures</td>
<td>73</td>
<td>4.8</td>
</tr>
<tr>
<td>10% Electrification on Manning, Columbia, Cameron</td>
<td>13</td>
<td>1.3</td>
</tr>
<tr>
<td>30% Electrification on Manning, Columbia, Cameron</td>
<td>23</td>
<td>3.0</td>
</tr>
<tr>
<td>50% Electrification on Manning, Columbia, Cameron</td>
<td>39</td>
<td>4.9</td>
</tr>
</tbody>
</table>

Table 2 shows the potential policy recommendations that were modeled using C-PORT. The resulting maximum changes in relative difference and raw difference for each of the policy changes are shown. Relative difference max is the maximum percent decrease in PM$_{2.5}$ from a policy change. The maximum raw difference is the maximum decrease in concentration of PM$_{2.5}$ as a result of the policy change.
These policy recommendations modeled in C-PORT only address primary sources of pollution (i.e. the cogeneration facility and cars). However, secondary sources of PM$_{2.5}$ are not modeled in C-PORT. The C-PORT model found the highest concentration of PM$_{2.5}$ to be around 2 µg/m$^3$ whereas Air Beams frequently measured concentrations over 12 µg/m$^3$. C-PORT only models for primary sources of pollution while the Air Beams measure total concentration. It can thus be concluded that secondary sources of PM$_{2.5}$ can be the larger contributor to pollution. These sources were anecdotally observed to be cooking exhaust, construction, and lawn care.

**Lives saved**

In order to quantify the health benefits of reducing PM$_{2.5}$, an analysis was conducted to quantify how PM$_{2.5}$ impacts the county level mortality rate of Orange County, NC. By introducing foreign particles into the lungs, various respiratory conditions may arise and cause premature death. A 2009 study aimed to understand how the quality of ambient air impacts human health. The study provides the following function in order to assess how a reduction in PM impacts a reduction in premature mortality (Krewski et al.).

$$y = \Delta y (1 - \frac{1}{e^{\beta x}})$$

The function requires the baseline incidence rate, $\Delta y$, which is the current incidence rate for the population. The baseline incidence rate for Orange County was found within the WONDER database created by the Centers for Disease Control (CDC Wonder). The mortality rate included all ages and deaths that were caused by diseases of the respiratory system including: acute upper respiratory infections, influenza, pneumonia, acute lower respiratory infections, diseases of upper respiratory tract, chronic lower respiratory diseases, and lung disease. The $\Delta x$ represents the change in PM$_{2.5}$ as a result of an action, like road closures or an increase in vehicle electrification. The change in PM$_{2.5}$ is found by subtracting the C-PORT predictions of PM$_{2.5}$ levels after different policies are implemented from the current PM$_{2.5}$ levels. The $\beta$ coefficient in the equation is 0.00582 which was found by Krewski et al. by conducting a regression model that tells how much time it will take for one variable to affect the other. In this model $\beta$ represents how much the new mortality rate will change with a change in PM$_{2.5}$. 


The current population of the county is 144,946 according to the U.S. Census Bureau. The mortality rate for respiratory disease in Orange County is 51.4 deaths per 100,000 people. The baseline deaths due to respiratory disease in Orange County residents is 72 deaths per year. Using the policy change model outputs from C-TOOLS the change in mortality rate and amount of lives saved from implementing the policy can be predicted. The scenarios that saved the most lives were closing South Road, 30% and 50% electrification of vehicles traveling on Manning, Columbia, and Cameron. Closing South Road will save 1.98 lives per year, a 30% electrification of vehicles on Manning, Columbia, and Cameron will save 1.25 lives every year, and a 50% electrification of vehicles on these roads will save 2.02 lives yearly. From these results the best policy recommendation would be to increase the electrification of vehicles driving on Manning, Columbia, and Cameron. This could be done through incentives that encourage drivers to switch from gas to electric. However, further research including a cost benefit analysis must be conducted in order to assess the feasibility of this policy suggestion.

**CoGen’s new permit and its implications**

*Changes to the Permit/what does the new permit allow*

In March of 2018, the UNC Cogeneration Facility applied for a new permit (Application No. 6800043.18A) that would approve the installation of several dry sorbent injection systems to further assist in hydrogen chloride (HCl) absorption. These new systems are expected to increase PM_{2.5} emissions, but due to the presence of baghouses, these PM emissions will be filtered and the increase will amount to 3.709 tons/year. This amount was calculated by the North Carolina Division of Air Quality, who further stated that this calculation was done assuming a worst-case scenario boilers firing 100% coal at maximum firing rate), and while the calculated
increased emissions are already low, the actual emissions increase will be insignificant due to the nature of the baghouse filtering process (North Carolina Division of Air Quality).

Impact on UNC’s campus

The new permit and its implications on particulate matter in Chapel Hill were modeled using C-PORT to analyze its possible effects. The permit was modeled by altering the total annual PM$_{2.5}$ emissions from the cogeneration point source within C-PORT. It was estimated that the change in PM due to the new permit could be up to 0.847 lbs/hour, corresponding to an increase of 3.709 tons/year (North Carolina Division of Air Quality). The possible increase of 3.709 tons/year was modeled in C-PORT and resulted in a maximum increase in PM$_{2.5}$ of 0.31 µg/m$^3$, an increase of 25.5% when compared with the current emissions of the cogeneration plant. The effects were most significant within the plume of the cogeneration plant and dissipated quickly as the distance from the plume increase.
At the outset of this project, the goal was to find policies that would improve air quality on campus and benefit public health as a result. The team modeled policies such as decreasing the exhaust velocity at the cogeneration plant, closing roads, and electrifying portions of the fleet mix. While these policy changes would improve air quality and decrease the annual mortality rate, the University may be able to have a greater impact on public health by using funds elsewhere, such as building more exercise facilities or providing healthier food. The air quality on campus was overall found to be good and there does not seem to be an urgent need to reduce the concentration of PM$_{2.5}$. However, University should continue to monitor air quality on campus to determine if policy changes are needed in the future and follow existing best practices to reduce PM$_{2.5}$ pollution.

The research team recommends that the University monitors air quality on campus by installing more stationary sensors and funding further research. The University should install PurpleAir monitors on buildings near hotspots on campus, such as on Peabody Hall next to the intersection of N. Columbia and Cameron Ave. The University should also install these sensors near Rams Head Plaza, Davis Library, and Kenan Stadium as well as at high pedestrian traffic locations on campus that were not found to be hotspots, such as the Pit.

Further research is needed to not only monitor air quality, but to find main secondary sources of pollution and assess the health impacts on students and faculty. This research should focus on secondary sources of PM$_{2.5}$ to determine if there are viable opportunities to reduce pollution from these sources. Research should also be conducted on the health impacts of long term and four year exposure to PM$_{2.5}$ to assess the health risk posed to faculty and students. Furthermore, the University should audit regulations concerning secondary sources of PM$_{2.5}$ on campus, including construction activities, food services, and landscaping activities, to ensure that best practices to reduce PM$_{2.5}$ are implemented. The team recommends that the University conducts an audit of this kind every four years.

At present, the University does not have an urgent need to reduce PM$_{2.5}$ concentrations on campus. However, the school administration should not take this finding as a perpetual bill of
good health for the air quality on campus. Rather, the University should continue to be vigilant in monitoring air quality and continue to follow best practices for reducing PM$_{2.5}$ pollution on campus.
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