ABSTRACT

Title of Document: PLACEMENT OF SMALL VERTICAL AXIS WIND TURBINE TO MAXIMIZE POWER GENERATION INFLUENCED BY ARCHITECTURAL AND GEOGRAPHIC INTERFACES IN URBAN AREAS

Jason Burtnick, Ralph Fairbanks, Francis Gross, Edward Lin, Bethany McCrone, John Osmond

Directed by: Mr. Bryan Quinn
Department of Electrical and Computer Engineering and Institute for Research in Electronics & Applied Physics

Current methods for large-scale wind collection are unviable in urban areas. In order to investigate the feasibility of generating power from winds in these environments, we sought to optimize placements of small vertical-axis wind turbines in areas of artificially-generated winds. We explored both vehicular transportation and architecture as sources of artificial wind, using a combination of anemometer arrays, global positioning system (GPS), and weather report data. We determined that transportation-generated winds were not significant enough for turbine implementation. In addition, safety and administrative concerns restricted the implementation of said wind turbines along roadways for transportation-generated wind collection. Wind measurements from our architecture collection were applied in models that can help predict other similar areas with artificial wind, as well as the optimal placement of a wind turbine in those areas.

PLACEMENT OF SMALL VERTICAL AXIS WIND TURBINE TO MAXIMIZE POWER GENERATION DUE TO ARCHITECTURAL AND GEOGRAPHIC INTERFACES IN URBAN AREAS

BY

TEAM AWE
(Artificial Wind Energy)

Jason Burtnick
Ralph Fairbanks
Francis Gross
Edward Lin
Bethany McCrone
John Osmond

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Advisory Committee:
Mr. Bryan Quinn, Chair
Dr. Cinzia Cirillo
Dr. David J. Lovell

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INTRODUCTION

The global energy sector is at a critical crossroad. An increasing demand for energy coupled with dwindling supplies creates a challenging issue for energy companies and governments around the world: How can populations meet the ever increasing energy demand once traditional, non-renewable fuel sources are depleted? This problem can be addressed in part by increasing the proportion of the world's energy generated from renewable energy sources. Aside from improving the prospects of tackling current and future energy needs, the use of many types of renewable energy sources has a secondary, but substantial, benefit of producing less pollution relative to their fossil fuel counterparts. This is the main justification behind a push for natural renewable energy; however, this push does not come without struggle. Although omnipresent sources of energy such as solar energy, wind power, and geothermal power occur naturally, they tend to be inconsistent, making them difficult to predict and relatively unreliable when compared with current applications of fossil fuels. Additionally, the current methods for capturing these natural, universal energy sources typically require a large initial capital investment. With these considerations in mind, our research sought to reap the benefits of the renewable resource of wind by designing a novel approach that makes wind energy modeling more affordable and attractive for both public and private investment.

Our team's project explored the use of small-scale wind generation as an alternative to both fossil fuels and standard methods of generating wind energy. Currently, the majority of wind energy is produced by large, multi-million dollar turbines placed on offshore areas or on rural wind farms. The practice of using these enormous turbines in isolated environments effectively bars this type of wind energy generation in populated urban areas, where electricity is needed most. Though cities and suburban areas are clearly not ideal placement sites for larger turbines due to limited space, safety concerns, and aesthetic reasons, this is not to say these environments are unfit for any type of wind energy generation at all. In addition to natural wind, these areas also exhibit significant amounts of "artificial wind," or wind that is created from the wake of a human-made moving or stationary body, including cars, airplanes, trains, tunnels, and architecture. Overall, the question that governed our research was: Through qualitative analysis and field research, how can we develop a predictive model for optimally placing a small-scale, vertical axis wind power generator for cost effective energy generation in varying artificial wind environments? We conjecture that architectural and geographic interfaces in urban areas will influence wind patterns in such a way that positions of maximal wind speed can be predictable across locations based on corresponding environmental characteristics. With the results of this study, we contribute to a new and growing sector within the renewable energy market.

LITERATURE REVIEW

Prior to and throughout the development of a research plan, our team investigated the current state of existing wind energy generation methods, their economic and environmental benefits relative to nonrenewable sources, and the practicality of utilizing artificial wind as an energy source. In this review of literature, we examine the ways through which the current literature justifies an investigation into this avenue of renewable energy and gives us a basis off of which to develop new potential applications and contributions.

Energy Demands and Consumption

Energy usage is so interlaced with modern society, it is nearly impossible to imagine the world without it. People depend on energy for nearly everything, from daily commutes to construction of new buildings to the manufacturing of household goods. The World Bank estimates that the average worldwide per capita energy use in a year is approximately 1,852.45 kg of oil equivalent, and that number only continues to grow (2014). World energy consumption is projected to increase at an average rate of 1.1% a year, seen in Figure 1.1, leading to an overall increase from 524 quadrillion British thermal units (Btu) in 2010 to an expected 820 quadrillion Btu in 2040 (EIA, 2013).

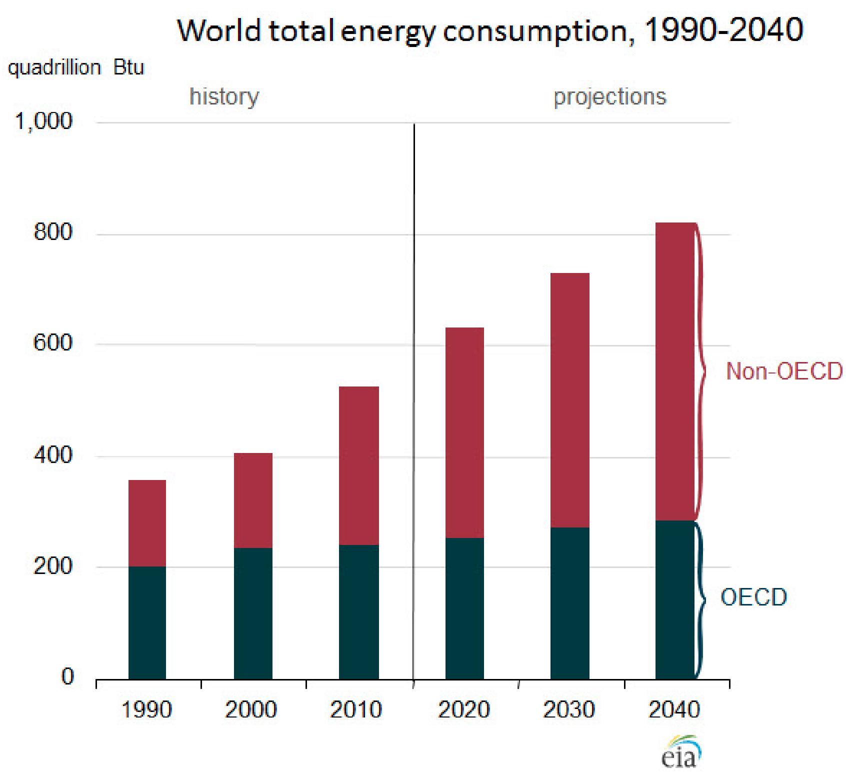

Figure 1.1: Historical energy consumption and expected consumption (EIA, 2013).

Figure 1.1 compares historical energy consumption to expected consumption in the next few decades. The data shows a steady upward trend in energy usage in the projections section, which is consistent with the historical data. Energy consumers are split into OECD (Organization for Economic Cooperation and Development) and Non-OECD, with Non-OECD nations being the main contributor to the increase in total energy consumption. Since most countries belonging to the OECD are more mature developed nations with slower anticipated economic growth, their growth in energy demands are not as high as developing nations experiencing booms to their economies and populations.

<u>Comparison of Renewable and Nonrenewable Energy Sources</u>

Though conservative energy practices are admirable and certainly helpful in the effort to fulfill energy needs and reduce pollution, the actual use of electricity and energy is not the major source of our global sustainability problem; the manner in which we produce electricity is. Producing the same exact amount of energy can have drastically different impacts on the environment depending on what type of generation method is used.

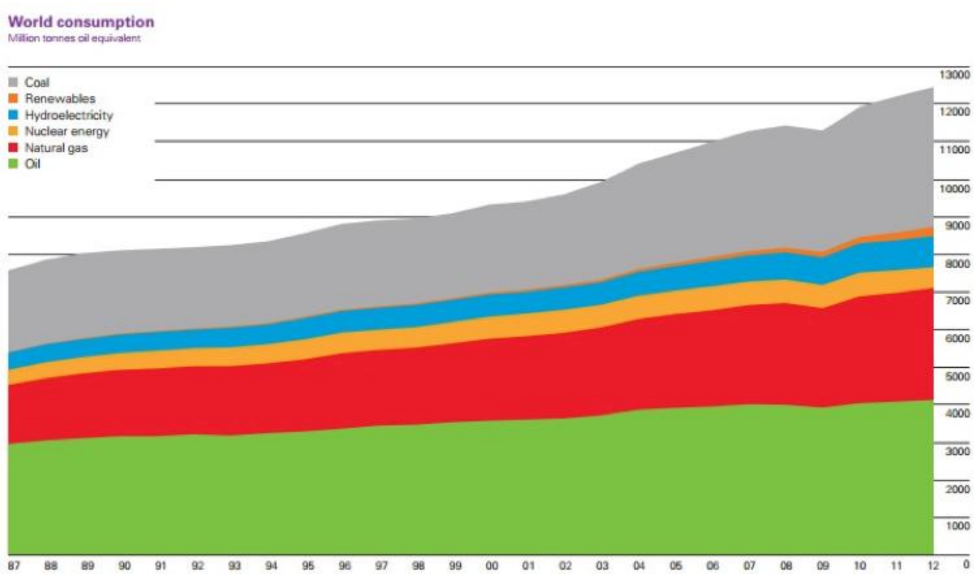

Figure 1.2: World consumption of energy from various energy sources (Dudley, 2013).

The graph above illustrates the amount of consumed energy generated from coal, renewables, hydroelectricity, nuclear energy, natural gas and oil from 1987-2013 (Dudley, 2013). This data reveals two concerns relating to energy production. Not only has energy consumption steadily increased over this time period, but consumption is overwhelmingly dependent on natural gas, oil and coal, all of which are nonrenewable energy sources. The renewables section (marked dark orange on graph) is barely visible prior to the year 2000, and still remains a mere fraction (1.9%) of the total energy consumed. “ The world's energy market, worth around 1.5 trillion dollars, is still dominated by fossil fuels” (Shafiee, 2009).

Wind Energy: Effects of Natural and Artificial Formations

Wind is formed by the large scale movement of air in the atmosphere from areas of higher pressure to areas of lower pressure. Areas with steep changes in altitude, or areas geographically close to such areas, are more prone to higher wind speeds. As shown in this map from the National Renewable Energy Laboratory, wind speeds are highest in the central US (Figure 1.3).

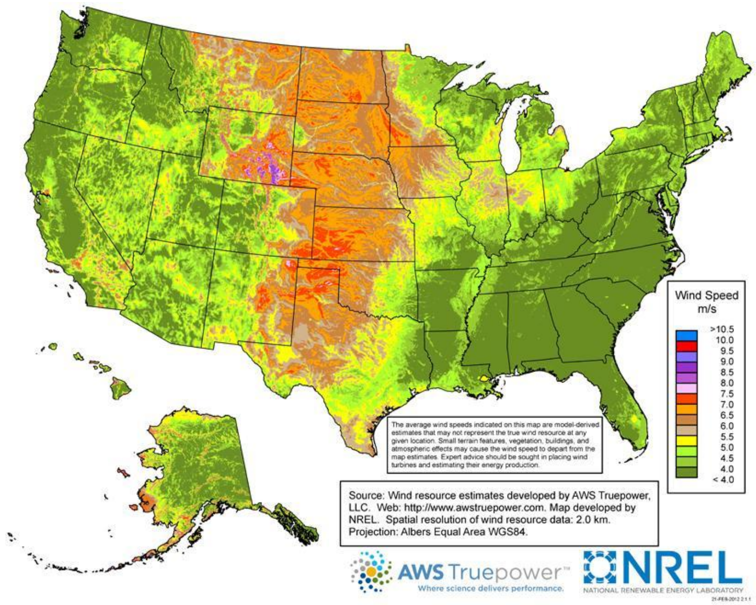

Figure 1.3: Wind speeds in the United States (National Renewable Energy Laboratory)

Elevation variance is a major contributor to this national pattern of wind speeds (Figure 1.4). The Rocky Mountains and areas to the west have relatively high elevation but generally low wind speeds, reflected in the light green to yellow shaded regions on the NREL map. To the east however, the mountains slope down and elevation begins to drop into the Great Plains, where the highest wind speeds in the continental US occur (shown in orange to red area). The effects of higher elevation can also be seen to some degree in the northeastern US, where the Appalachian Mountains produce a similar effect but on a much smaller scale, due to the range’s smaller size relative to the Rockies.

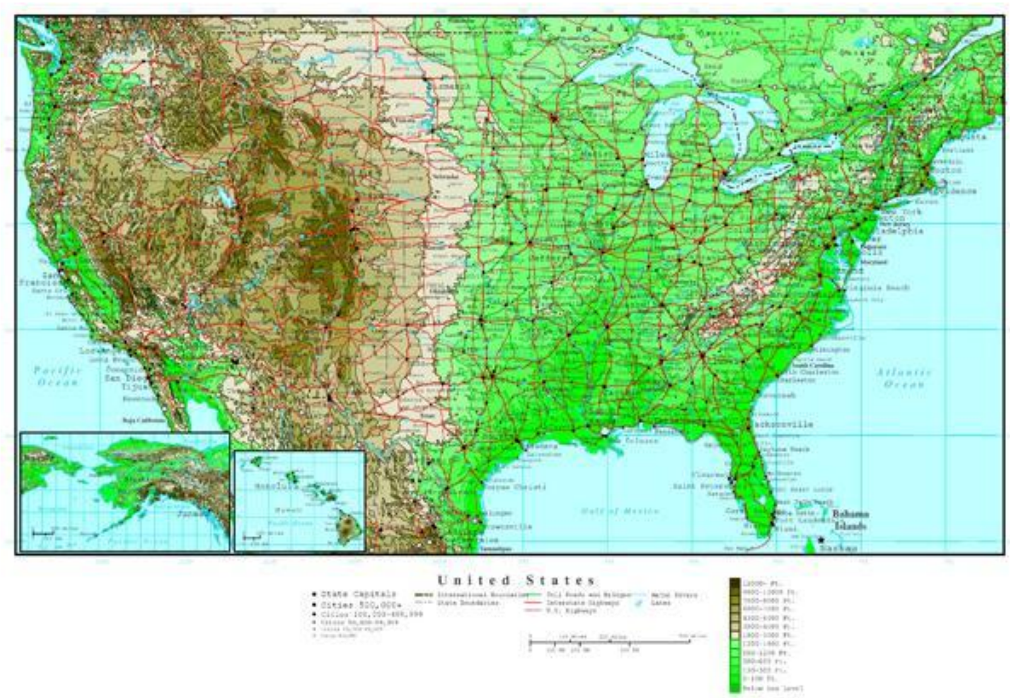

Figure 1.4: Elevation variance with regards to winds in the United States (National Renewable Energy Laboratory)

Heating along slopes in areas of steep elevation change influence these patterns of higher wind speeds. Air closest to the ground is heated first, causing it to rise. In flatter areas, the air simply flows vertically. However in areas where a slope is present, the air tends to move up the slope as it offers a path of less resistance. This horizontal component generates these national patterns of wind documented in the map above. An opposite cooling effect takes place during the night, but this phenomenon also contributes to areas of high wind speeds (Figure 1.5). As the air cools it sinks, flowing down the slope and generating wind (Yang et al., 2009).

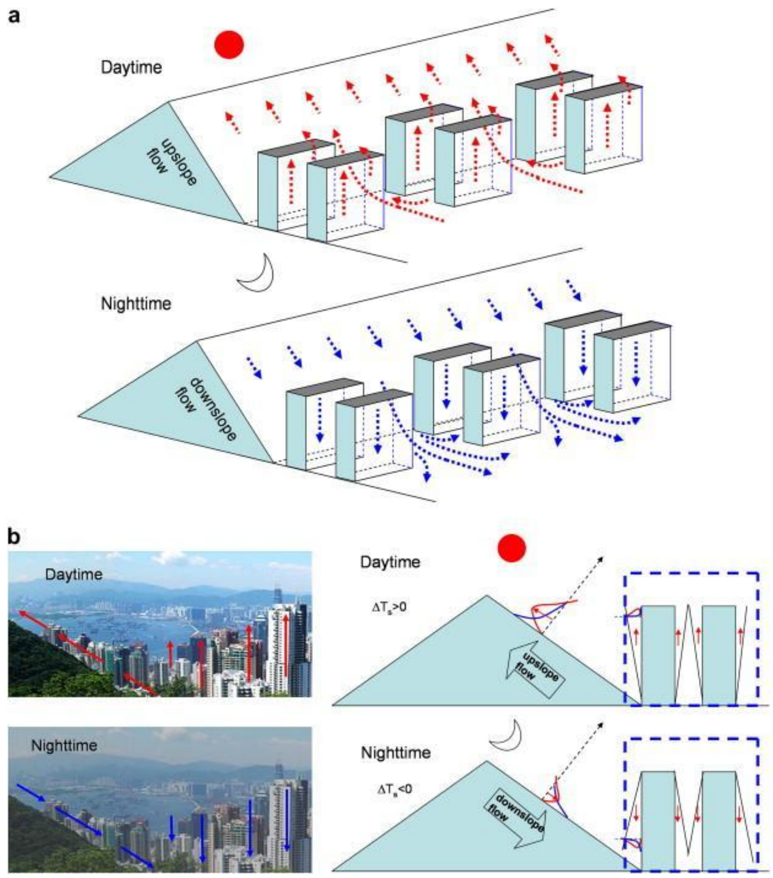

Figure 1.5: Representation of day and nighttime flow on slopes (Yang et al., 2009).

An understanding of the basis of natural wind formation is relevant to research on artificial wind as both are influenced by the distribution of geographical features. The above information related to national wind patterns is also applicable on a local scale. Flat areas adjacent to a hilly area are potentially advantageous places for our wind turbines to be placed. This would potentially be useful for areas near roads in remote places, where such geographical features are more likely to be found.

Buildings also affect wind flow, in much the same way as hills. Buildings tend to heat from the bottom up, drawing movements of wind along them (Yang et al., 2009). This causes an upward flow of air during the day and a downward flow during the night as the building cools (Figure 1.5). This information will be useful in understanding appropriate placement near buildings. The flow in the vertical directions, both positive and negative, will affect the horizontal flow of air, causing the horizontal winds to slow down. As such, we will need to be cognizant that our turbines and anemometers are placed far enough away from buildings to avoid these boundary layer effects.

Economic Analysis of Wind Energy

The Energy Payback Ratio (EPR) is a straightforward and popular performance indicator for energy generating systems. The ratio analyzes the total energy produced by the system during its normal lifetime and compares this value to the input of energy needed to construct, operate, fuel, maintain and decommission or dispose of that same system (White 2007). EPR is calculated using the following equation:

$$EPR = \frac{E_{n,L}}{(E_{mat,L} + E_{con,L} + E_{op,L} + E_{dec,L})}$$

where

$E_{n,L}$ = the net electrical energy produced over a given plant lifetime, L.

$E_{mat,L}$ = total energy invested in materials used over a plant lifetime L.

$E_{con,L}$ = total energy invested in construction for a plant with lifetime L.

$E_{op,L}$ = total energy invested in operating the plant over the lifetime L.

$E_{dec,L}$ = total energy invested in decommissioning a plant after it has operated for a lifetime L.

Intuitively, a system producing more energy relative to its energy investment will make for a stronger incentive to use this system, both from an economic and environmental standpoint. This relationship is quantitatively expressed in the Energy Payback Ratio, as the greater the benefit, the higher the EPR. Systems with an EPR of less than 1.0 are considered outright energy losses as they fail to produce even the same amount of energy as the inputs needed to run them. Systems with an EPR or projected EPR between 1.0 and 1.5 are still not recommended for development, as they consume nearly as much energy as they produce (Gagnon, 2005). Projects with very low EPRs (even if they are greater than 1.0) are likely to be financial failures and/or environmental burdens, as the ratio does not include factors such as atypical conditions, unforeseeable setbacks, R&D expenses and pollution costs.

The most commonly used form of wind turbines are the large, horizontal-axis wind turbines (HAWTs) frequently found offshore and on commercial wind farms. The large majority of the total investment in these systems can be attributed to the costs associated with the initial purchase and installation of the turbine. The cost of maintenance is minor relative to its installation, as the total operation and maintenance (O&M) expense is only 10-15% of the initial capital investment over its entire 20-30 year lifetime (European Wind Energy Association 2009). Additionally, when considering wind is the free and natural fuel source that powers these turbines, the levelized cost (net cost to install and operate/expected life-time energy output) of a wind farm at 8.2 cents per KWh is less than that of an advanced clean-coal plant or nuclear plant at about 11 cents per kWh (US Energy Information Administration 2012). Because the placement of these wind turbines is virtually permanent and the amount of wind passing through the blade determines their power generating capacity, the most effective improvements in wind power yields in recent years can be linked to computer models that optimize turbine placement (Foley et al. 2012). Wind farms ultimately rely on moderately unpredictable natural wind patterns for successful operation, which require extensive analysis prior to placement. These models have contributed to an increase in wind power production efficiency (Sahin 2004). However, most of the current research on wind modeling and placement is specialized for these high risk, large-scale wind turbines on rural wind farms. Because these turbines require huge initial costs for construction and placement before their investment can be recouped via energy generation, the concentration of applied research in this area favors HAWTs over VAWTs. With that observation noted, and the fact that there is a limited number of ideal locations with high enough volumes of natural wind to warrant the use of these specialized models, other effective methods for capturing wind are crucial for the future of wind power (Busel et al. 2006).

In existing studies on the economics of small-scale vertical axis wind turbines (VAWTs), researchers have typically concluded that small turbines, despite having low maintenance costs and reliability at “90-100%” (Bellarmine et al. 1996), are not viable with low wind speeds. The availability of an energy generating system typically defined as the percentage of time that the system is physically capable of producing electricity (not the percentage of time that it is actually producing electricity). High availability systems, therefore, are those that have very little downtime due to scheduled maintenance or equipment malfunctions. One study in Ireland focused on these independent systems where the researchers used micro wind turbines to power household electronics. The conclusion, based on data from power output and in consideration of average household electricity usage, costs, regulations, and return on the investment, was that such systems are not viable with wind speeds under 5 mph, but could have a payback period of less than twenty years in areas with wind speeds greater than 6 mph (Li et al. 2012). With regard to the economic viability of small horizontal wind turbines (HAWTs) in certain arrangements, a group of researchers in Barbados concluded that the HAWTs are expensive and complicated to install and connect to a large electric-grid system (Bishop et al. 2008). However, producing an independent system that stores the energy in a battery without the connection to the grid eliminates that particular financial burden and simplifies potential technical complications.

In terms of efficiency rates (the ratio of the amount of wind input to the output in energy in kilowatt-hours), researchers have found that VAWTs are able to compete with HAWTs in the right environmental conditions, based on data and reviews of those turbines (Bhutta et al. 2012). Additionally, other researchers investigated the viability of harvesting the artificial wind created between buildings in an urban environment using VAWTs (Muller et al. 2012). The results showed the turbines had fairly high efficiency rates in scale-testing and that VAWTs on buildings could potentially be a viable option for wind energy generation.

Furthermore, researchers have analyzed the potential natural wind energy in Malaysia and come to the conclusion that large-scale wind turbines did not seem viable in this region, but that small-scale turbines could be viable based on their lower overall cost (Tiang et al. 2012). Therefore, not only are small-scale wind turbines the better alternative for placing next to a buildings and roadways from a physical requirement, they are a much more cost effective option for research on artificial wind collection.

Small-scale vertical axis wind turbines

Utilizing small-scale turbines to collect wind energy is not a novel approach as there have been a number of studies that utilize them in their research. These studies typically look into implementing small-scale turbines in rural communities where power grids are less accessible or nonexistent. One such experiment installed small-scale wind turbines in rural Thailand and compared the cost to that of diesel energy and purchasing energy off of the Thai grid. The study divided wind into different classes based on speed, with all but the lowest class outperforming diesel engines in terms of levelized cost of electricity (LCOE). The study also found that the small-scale wind power could not compare to the selling cost of the Thai grid except in areas with the highest wind speeds (7.0 – 9.4 m/s) (Glassbrook et al., 2010).

		Annual energy output for various wind classes (assumed 20% efficiency) (kWh)									
Turbine	Swept area (m^2)	1.1	1.2	1.3	1.4	2	3	4	5	6	7
20 kW	70.9	427	4730	7890	11,100	15,500	21,400	27,500	33,200	41,800	76,800
5 kW	31.9	180	2000	3350	4720	6610	9170	11,800	14,300	18,000	33,100
2.5 kW	19.6	48.5	688	1320	1770	2540	3620	4590	5580	7010	12,700
400 W	1.08	2.22	32.3	62.3	84.1	122	174	222	271	341	626

Figure 1.6: Annual energy output from swept area. Note the larger increase from wind class 1.1 to 1.2 and the much larger values in wind class 7 (Glassbrook et al., 2010).

Even though the small-scale wind energy does not have the competitive LCOE of energy bought from the Thai grid, there are still environmental benefits to using renewable energy. This creates a reason for government subsidies that may levelize the economic benefits of using wind energy. The installation of small-scale wind turbines in rural communities will reduce Thailand’s greenhouse gas burden and reduce the rate of climate change’s negative consequences. In order to avoid 1 ton of CO_2 using conventional means, it would cost 1840 to 3930 THB (approximately 57.13 – 122.01 USD). Preliminary calculations of the cost of installing small-scale wind turbines leads to values in this range, meaning that there is a high incentive to subsidize them. These preliminary values do not account for the fossil fuels needed to make the turbine, but any increase in turbine efficiency in the future will only increase these expected environmental benefits (Glassbrook et al., 2010).

Another study mentioned in the previous section was performed in Barbados, which is a country 99% dependent on using imported fossil fuels to meet its energy requirements. This study determined that the cut-in wind speed for VAWTs is roughly 2m/s, and that in only 2.93% of cases there will be no output from the VAWTs. Additionally, VAWTs do not have cut-out speeds, meaning that while HAWTs will shut down at higher wind speeds, VAWTs will continue to collect energy under these extreme wind conditions. Much like the study performed in Thailand, this study determined that from a purely economic standpoint that using small-scale VAWTs is not comparably advantageous to obtaining energy from large-scale wind generation. Still, the studies mentions additional benefits to using VAWTs such as lower RPMs making them less conspicuous, and lower collision rates with animals (Bishop et al., 2008).

While these two studies conclude that small-scale wind energy is not viable from a solely economic standpoint, the difference between their experimental setup and ours is that both placed the turbines in open spaces in rural areas that included unpredictable wind speeds. While generally unsuccessful, the Thailand study did show that small-scale wind energy was economically feasible in areas with the largest amounts of natural wind. Therefore, if artificial wind can create a more predictable source of larger wind speeds, small-scale wind energy will likely be viable in these locations.

The use of the airflow associated with buildings has been used as a ventilation technique for centuries, with modern buildings featuring new designs for ventilation. An example of ventilation is buildings contain courtyards. The courtyards serve as transitional zones by providing a relatively enclosed space, causing airflow to be channeled and directed in and around a building (Khan et al., 2008). While this increase in wind speeds serves as a way to ventilate the building, the wind that is created can also be repurposed for energy collection through small-scale turbines.

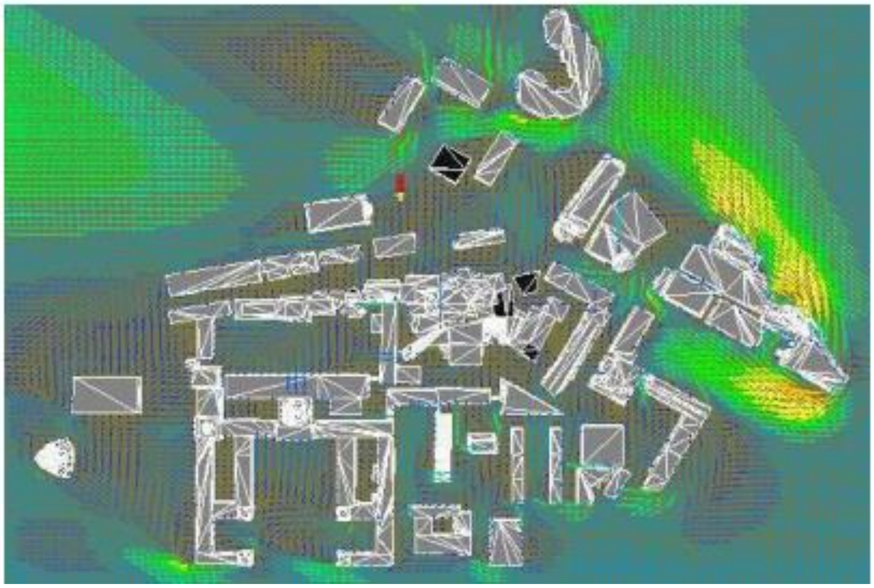

Figure 1.7: Wind distribution around the Stata Center in Massachusetts (yellow: high wind speed, green: moderate wind speed, and blue: low wind speed) (Chen, 2009).

While the wind that surrounds buildings serves as a good method of natural ventilation, there have also been studies showing that the wind surrounding buildings causes discomfort to pedestrians. For this reason, architects and engineers are looking for ways to reduce wind speeds surrounding buildings while maintaining a system of natural ventilation. This may seem counterintuitive to our desire to capture artificial wind caused by architecture, but the study has concluded that creating a system of natural ventilation while lowering wind speeds outside the building is a very difficult task due to the amount and complexity of the wind profiles (Chen, 2009). What the study does show us is that current architecture produces significant and observable wind that could be collected, meaning that small-scale wind energy can be implemented in these areas.

Another instance of ventilation applicable to small-scale wind energy is evident on the tops of buildings. A current technology uses small-scale VAWTs on the tops of buildings for ventilation. Instead of producing and storing energy, these turbines connect to a ventilation system inside the building. When the turbine spins, negative pressure is produced inside which forces air to leave the building (Khan et al., 2008). These turbines are successful at ventilating buildings because large wind speeds are produced on top of buildings due to their elevation and architecture. When wind hits the face of a building, positive pressure develops on the side being hit and negative pressure develops on the opposite side. This causes air to move above the building at speeds much faster than the natural wind speeds on ground level.

In recent years, the production of wind energy in urban environments has become a larger focus of research as more people are living in cities and power requirements are at an all-time high. Currently, around 75% of the world's power is consumed in cities and global energy requirements in 2040 are projected to increase by around 30% from 2010 values (Ishugah et al., 2014). With growing issues such as the depletion of fossil fuels and environmental deterioration, it is paramount to find effective alternative energy sources.

One major positive aspect about utilizing wind that forms in cities as a means of producing energy is that losses due to transmission will be reduced. While 75% of the world's power is currently consumed in cities, much less is actually produced in those cities and losses are accumulated from the distance traveled to transport this energy (Ishugah et al., 2014). In addition, the necessity to create the infrastructure to transport the energy into the cities will no longer exist if the energy is generated alongside the places where it will be used.

In theory, placing wind turbines inside of cities is an excellent way to harvest energy within a city's boundaries, but research into the subject did not begin to catch steam until recent years due to technological limitations and a lack of full understanding of the urban wind profile. Additionally, there are other issues regarding the implementation of wind turbines in populated setting, such as potential aesthetic and noise concerns. These issues and previous technological limitations are currently being rectified with technological advancements in wind turbine technology. Over the past few decades, turbines have increased their energy output by 5% while halving their weight and noise emissions (Ishugah et al., 2014).

For the purposes of collecting wind energy in an urban setting, VAWTs are the ideal choice for a number of reasons. One such reason is that HAWTs have essentially plateaued in terms of efficiency due to their historical wide-scale use and development, while VAWTs have room to improve with further research. Advancements could include greater energy generation and a reduction in space requirements. Another reason for VAWTs over HAWTs is that the use of small scale wind energy mitigates the possible pedestrian concerns. While the VAWTs may not be aesthetically pleasing to some citizens and some noise is to be expected, these issues will not be nearly as impactful as installing HAWTs would be.

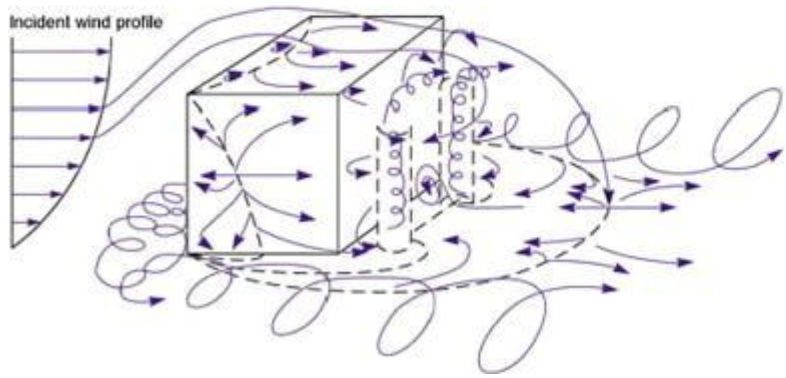

Figure 1.8: Visualization of the complex turbulent wind profile around a building

The main reason for selecting VAWTs over HAWTs for our research is because of the turbulent wind profile evident in urban environments. While limited research on urban wind speeds with respect to turbine applications has been conducted, we have a general idea of wind profiles when they hit surfaces such as those of buildings. When wind hits buildings, a complex turbulent flow forms with the turbulent wind flowing in essentially all directions. This leads to VAWTs as being the best type of turbine to use for the purposes of this project since their ability to capture wind in all directions leads to more effective energy collection in turbulent wind profiles. HAWTs would not be usable since they can only collect wind from one direction, meaning they will miss the majority of energy available in this turbulent environment.

Another aspect of the turbulent wind profile is that wind speed increases with height as the turbulence decreases and the air goes around the buildings. For this reason, our experiment involves a height component alongside the ground position since both factors can greatly influence the wind speed near architecture compared to the open-environment wind speed. Future research should also be conducted which will weigh the benefits of trying to obtain higher speed winds at higher heights with drawbacks such as higher costs and increased structural concerns.

Artificial Wind

Artificial wind is defined in this context as wind created from the wake of a human-made moving or stationary body. This phenomenon can be purported by anyone who has ever stood along a roadway with passing vehicles, walked through an especially drafty alley or doorway, or felt the current from a ceiling fan. Artificial wind, though not perfectly predictable, does have some advantage over natural wind with respect to its consistency and foreseeability in certain urban environments (Nadis, 1994). Inserting an element of increased predictability has promising potential to address the previously stated issue of uncertainty in turbine placement and the creation of a suitable model. Many highways can consistently generate 10-12 miles per hour wind for about eighteen hours per day (Nadis, 1994). However, there is limited published research on the viability of artificial wind as a source of renewable energy. Through our research, we intended to replace simple speculation of artificial wind usefulness with formal scientific exploration of the viability of capturing wind affected by various human-made structures.

Wind forecasts, as well as estimates for the production of artificial wind, are beneficial research elements that we utilized throughout the project (Foley et al., 2012). In a number of studies, researchers have had success in modeling and accurately predicting the performance of the fluid dynamics and wakes in wind turbines similar to those that used (Modi et al., 1993). However, some of these studies highlight issues with torque decay with increasing tip speed with experimental data (McTavish et al., 2012) and difficulties in choosing appropriate input parameters in "complicated terrains" (Vermeer et al., 2003). Based on the analysis of these model layouts with acknowledgement to these concerns, we sought to determine the proper positioning for wind turbines to maximize the receiving wind velocity, thereby producing the most energy (Elliott et al., 1990).

Limited research involving wind turbine applications and wind speeds has been conducted in in urban environments (Ishugah et al., 2014). In cities, buildings and obstacles can form complex turbulent air waves. As a result, it is challenging to collect wind energy with the turbulent air flow, as depicted in Figure 1.12.

Small-scale VAWTS are especially valuable in these cases of turbulent wind, due to their ability to respond immediately to changes in wind direction. Wind speed assessment in Masdar city showed promising results for small wind turbine implementation in cities (Ishugah et al., 2014). An average of 4.5 m/s was observed in the study of wind velocities throughout one year, as depicted in Figure 1.9.

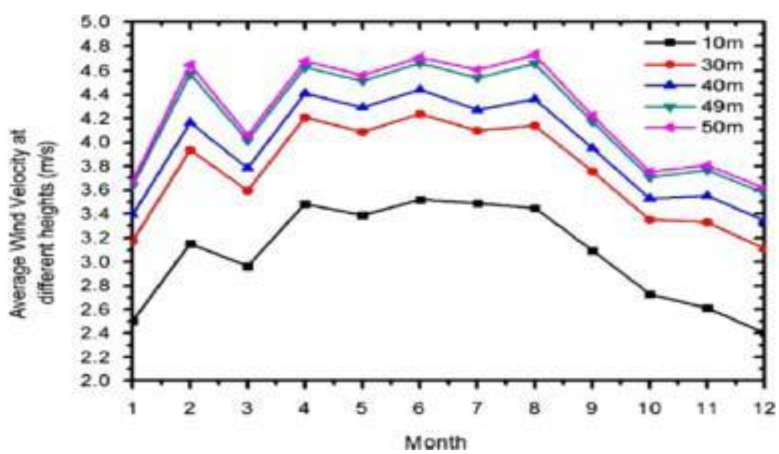

Figure 1.9: Monthly average wind speed in 2010 (m/s) (Janajreh et al., 2013)

Despite the lack of extensive research for wind turbine applications in urban environments, there are some instances in which turbines have been integrated into those environments. One such method is integrating wind turbines along roadways in order to collect the energy expended by vehicles moving at high speeds. A horizontal axis approach was proposed by an Arizona State University student, shown in Figure 1.10 (Ishugah et al., 2014).

Figure 1.10: Concept design of horizontal axis wind turbines installed on highway

As previously mentioned, the challenge with this proposed installation is accurately accounting for turbulent airflow generated by the moving traffic (Ishugah et al., 2014). Another difficulty is the lack of characterization of the wind in these areas, though some studies have been conducted to characterize resources in order to create devices dedicated to collecting wind on roadways (Morbiato et al., 2014).

Other methods for implementing wind turbines in urban areas include integrating the turbines into the architectural form or retrofitting the turbines onto existing buildings. Micro-wind turbines (Bahaj et al., 2007) are commercially available integration of wind energy collection onto existing buildings. These turbines' performances would vary depending on roof positions, building size, and roughness of upwind area (Ishugah et al., 2014).

METHODS & TECHNICAL APPROACH

Overview

Our team's research study focused on addressing previously stated opportunities in renewable energy with a specific focus on wind energy. Currently, the majority of wind collection systems is large-scale; research indicates that large scale wind energy is cumbersome and ultimately has its disadvantages – especially the large initial investment for installation (Blanco 2009). Our research focuses on small-scale wind energy collection as an alternative to large-scale wind energy collection, taking into consideration the small-scale, vertical axis wind turbines that can collect artificial wind. Our researched was aimed to look into the placement of small turbines to maximize the collection of artificial wind energy produced on roadways in the wake of moving vehicles and through architectural set ups. Through the study of artificial winds along roadways and buildings, we hoped to analyze the optimal placement of a small-scale, vertical axis wind turbine that would be implemented in urban environments. Specifically, we are hoping to develop a predictive model and method based on topology that can be used to determine the ideal placement of a VAWT in urban environments.

Experimental Procedures

To examine the effects of placement and location on a turbine's energy collection abilities, field data were collected and analyzed. Collection was done in two phases: a transportation testing phase and an architecture testing phase. Wind measurements were made using anemometer arrays (Appendix E) and compared to real-time weather data obtained from the College Park Airport in order to isolate the artificial winds. Measurements were compared in regards to location of the arrays and the area surrounding the arrays. These arrays were compared to each other in each run of each location.

<u>Phase I: Transportation Testing [Original Approach]</u>

Our first approach attempted to study wind patterns created in the wake of moving vehicles. However, this phase was ultimately abandoned after preliminary testing. The following details what tests were to be done, should this phase had occurred, as well as why this phase was not conducted to its full extent.

Initial tests were to be done adjacent to roads of varying traffic density near the University of Maryland, College Park. These roadways included I-495, Kenilworth Avenue, Baltimore Avenue, and the "M" circle located near the front entrance to the university campus. Arrays would collect wind measurements along open sections of the roadways, away from any traffic lights or stop signs. In addition to isolating artificial winds by using real-time weather data, a second anemometer array would be placed away from the roadway as a control measurement. This control would only measure natural wind, allowing the separation of artificial winds in the first anemometer array readings. In order to correlate any artificial winds with traffic volume, a pressure cable would be laid across roadways, counting sets of tires that would drive across. Wind speeds and traffic patterns, including volume, type, and speed, would be incorporated into a model allowing predictions on optimal wind collection at a certain location relative to the roadway.

Preliminary testing involved an anemometer array being passed by one vehicle at a time. The performance of the anemometers along with different vehicles and vehicle speeds was measured. This procedure is outlined in Appendix F. It was concluded that one vehicle driving by an array did not provide any significant artificial winds.

In conjunction with preliminary tests, communication was set up between the team and the Maryland State Highway Administration (SHA), as well as the University of Maryland Department of Transportation Services (DOTS). The team was able to procure permission from DOTS for preliminary tests in the parking lot (Appendix F). However, the Maryland SHA communication failed after several months of attempted emails and calls. Without permission from the Maryland SHA, testing was not able to be conducted along major roadways. With insignificant artificial winds obtained from preliminary tests, and without the means to test multiple vehicles, artificial winds made through modes of transportation were not able to be analyzed.

Had the transportation testing been possible and finished, this data would have been imported and verified with computational models in order to predictive wind behavior along the aforementioned roadways. In these computations, scaled models of several types of vehicles such as SUVs, compact cars, pickup trucks, and tractor-trailers would be placed into simulations in order to determine wake patterns generated by these vehicles at the speeds at which they were traveling along the roadways. This would allow for prediction of the optimal placement of a turbine to collect the artificially generated winds.

Phase II: Architectural Testing [Updated Approach]

Overview:

After abandoning the transportation tests, we shifted our focus to architectural testing. The tests were done at various locations within the University of Maryland campus. Each location was chosen based on their different topographical features, and are shown in Figure 2.1. The locations include the side of the Xfinity Center close to the softball fields (Location 1), on Technology Dr. along the Manufacturing Building (Location 2), between the Chemical and Nuclear Engineering Building and the Jeong H. Kim Engineering Building (Location 3), behind McKeldin Library (Location 5), and on Fieldhouse Dr. between the Plant Science and Regents Parking Garage (Location 4).

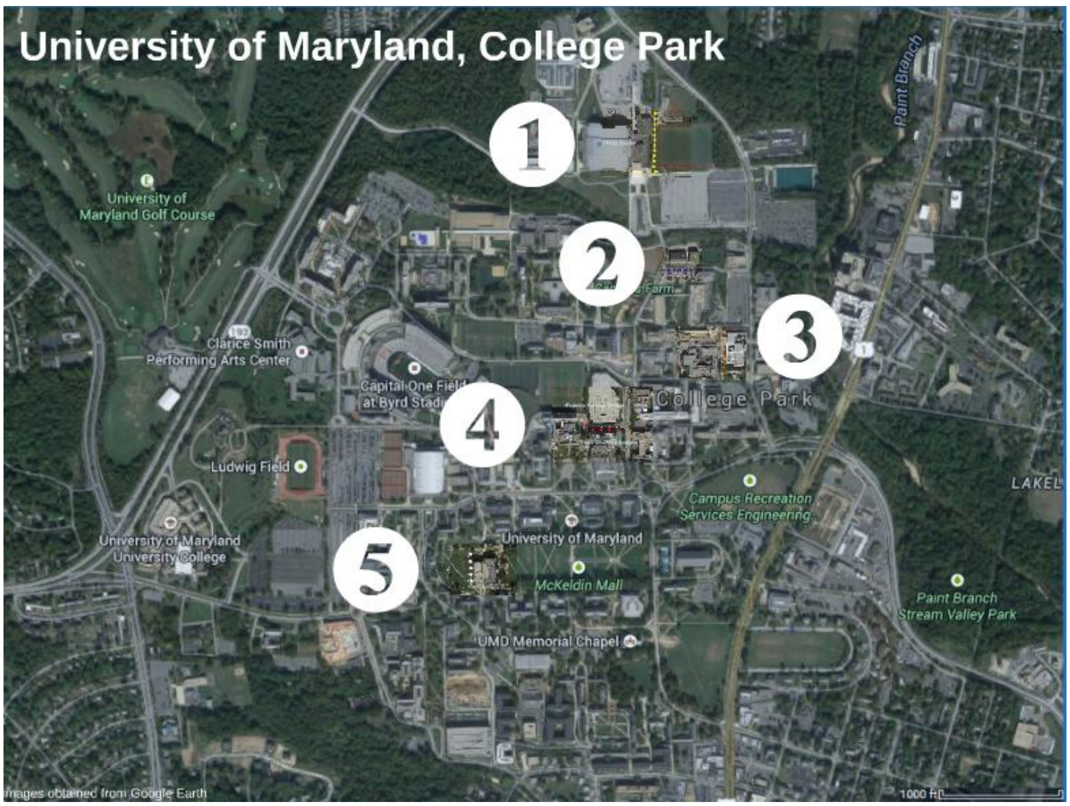

Figure 2.1: University of Maryland campus map with testing locations marked

The anemometer arrays were placed at specific GPS coordinates within these locations to collect wind speed data with relation to a predetermined control point. Pictures of the locations and their points are identified in our methods.

Within an area, the control point remained constant. It was attempted to put the control points in areas that were as open as possible but still close to their corresponding data points. The data points were always placed within the vicinity of architecture and in a straight line for the sake of consistency. An anemometer array was placed at the control point and stayed there for the remainder of the data collection process in that area. One or two more anemometer arrays were placed at different data points or were moved to other points before the start of each test. Each test lasted about five or ten minutes per data point. Each array had three anemometers at different heights; three feet, six feet, and nine feet. The anemometers would measure the average wind speed over the course of three seconds every five seconds. The step by step procedure is outlined in appendix G.

The wind speeds at each point were recorded and observed in relation to the architecture, topography, and the wind speed at the control point. Using the data gathered at each point and comparing it to the other data and control points, a predictive model was developed to determine the optimal placement of small scale wind turbines.

Materials:

The three anemometer arrays used in the previous transportation testing were reused for our new methodology. Arduino UNOs were used instead of NI I/O Bricks as a form of collecting data. Each anemometer array also required a computer in order to save the data recorded by the Arduino UNO's. A fifty foot string was used to mark out the data points and a GPS was used to find the GPS coordinates of each point.

Preparation:

The computers used for data collection needed to have the up to date Arduino drivers installed. In addition, if the computer is a PC, PuTTY, or any program capable of logging R5-232 text, was needed in order to read the Arduino data from the serial port.

The wired connections of each anemometer was checked and if needed repaired before each test.

Procedure:

All required materials were brought to the day's test location. Each of the three anemometer arrays were assembled and connected to an Arduino UNO. The anemometers were connected to the Arduino in accordance to their height. One array was placed at the location's defined control point. The other two arrays were placed on hand trucks and moved to the location's first two data points. Computers were connected to the Arduino UNO at each array in order to save the recorded wind speeds. The Arduino program was then run simultaneously for all anemometer arrays for about five minutes. After five minutes, the Arduino programs were stopped and the arrays are moved to the location's next set of data points. The program ran for five minutes at each data point until wind speeds at all data points were recorded. See appendix G for an in depth step by step procedure.

RESULTS, ANALYSIS, AND DISCUSSION

Overview

The data we collected was imported into Microsoft Excel, which allowed us to analyze wind speeds at particular positions at each location. In particular, we were looking for locations where the wind speed was consistently higher (relative to our control point) than other locations. First, plots of average wind speed (for the anemometer at 10 feet above the ground) at each of the test positions for both the control and moving arrays were observed. We chose to analyze the data from the highest anemometer because it read the most consistently and was nearly always the fastest. We were able to show that the lowest anemometer read significantly slower than the highest anemometer at a confidence level over 99.9% (using a t-test for paired sample means). This is due to boundary conditions imposed by the ground, causing wind speeds near ground level to be slower than wind speeds slightly higher.

We analyzed the data from each campus location individually first, and then looked to find similarities in the topography of the locations that could account for any patterns evident in the data. We looked to see at what particular points within each location wind speeds varied significantly from other points at the same location, and then cross referenced these points with other "significantly" different points at the other locations to see what similarities existed between the two locations which could account for these wind patterns.

Results:

Location 1: Xfinity Center

The team conducted four separate runs of data collection at the Xfinity Center Location over the span of a month. A map of the data collection area with an overlay of position numbers is shown in Figure 3.1. Plots of average wind speed at each position number for both the control and moving array are shown below in Figures 3.2, 3.3, 3.4, and 3.5. The "moving" array was the one which moved to a new position every 5-10 minutes, while the "control" array stayed at position number 1 for the duration of the collection period. For example, in the figures below the "Control" wind speed at Position Number 8 is the wind speed at Position Number 1 when the "Moving" array was at Position Number 8.

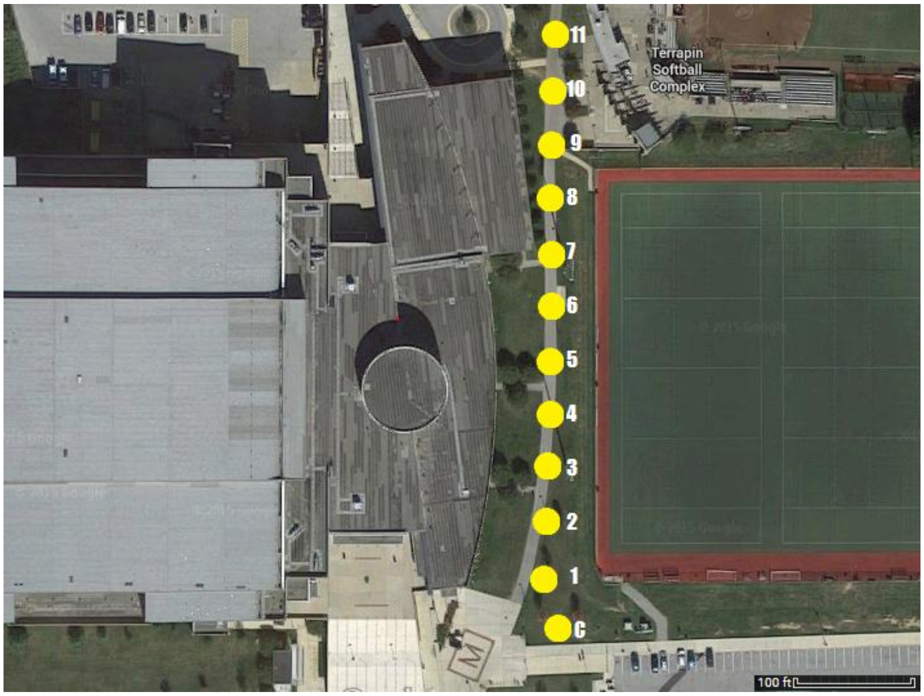

Figure 3.1: Xfinity Center testing location

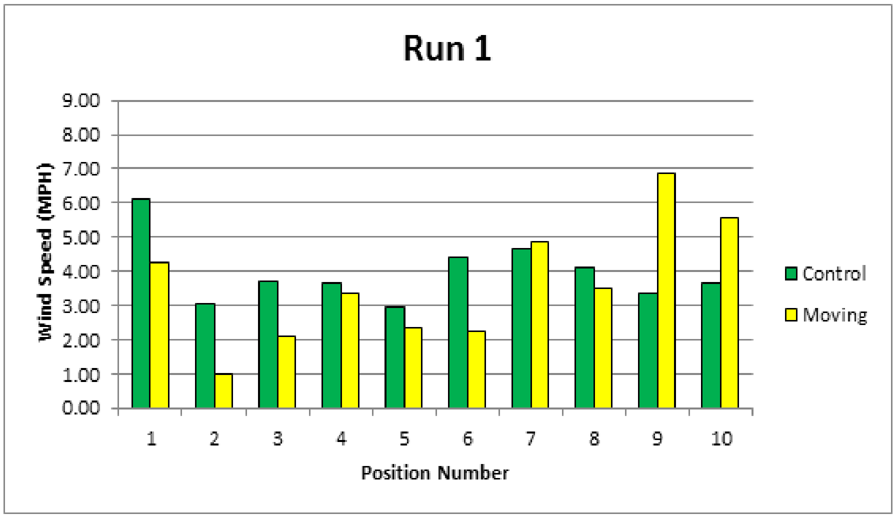

Figure 3.2: Average wind speed, Xfinity run 1

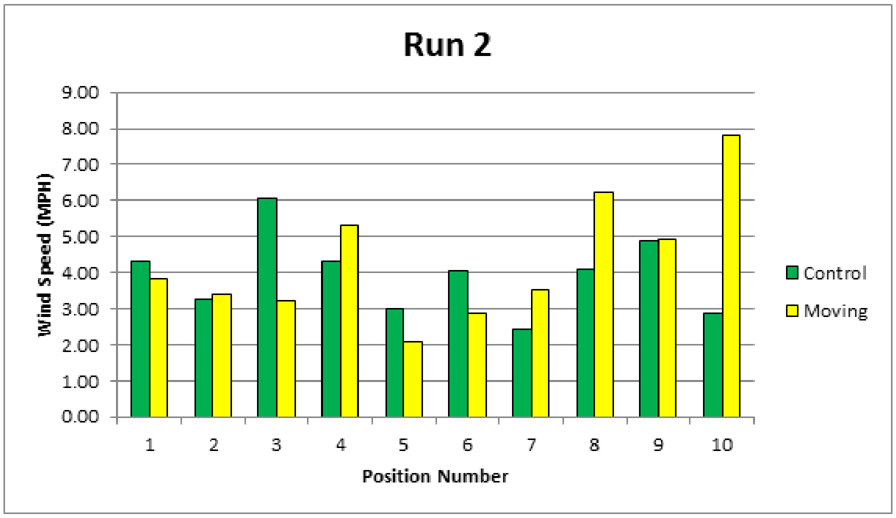

Figure 3.3 Average wind speed, Xfinity run 2

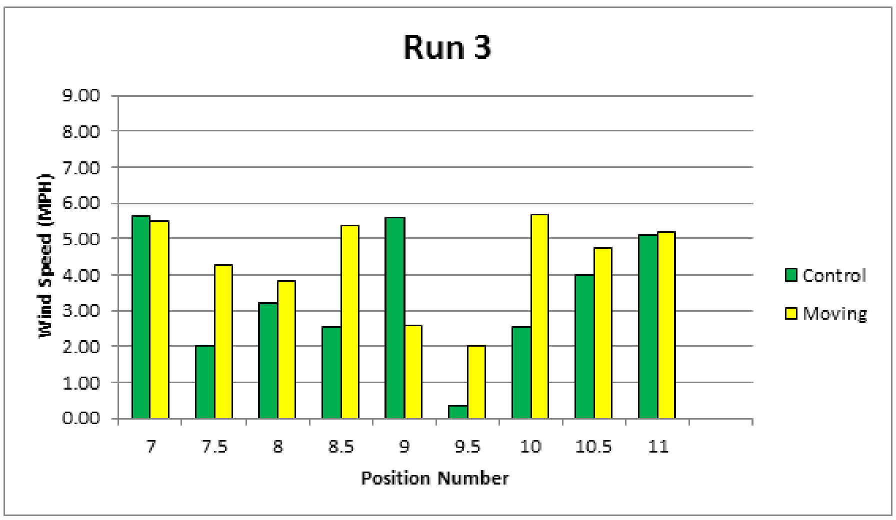

Figure 3.4: Average wind speed, Xfinity run 3

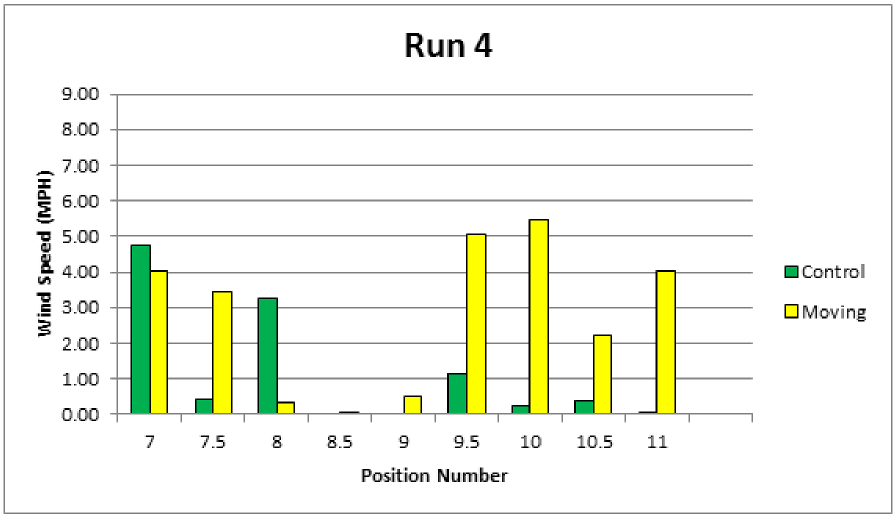

Figure 3.5: Average wind speed, Xfinity run 4

We looked qualitatively at the above plots to see if there were any positions which were significantly faster or slower than the control point for every set of data. We can see that between positions 9 and 11 the moving array was nearly always significantly faster than the control array. In order to quantify this difference statistically, we used a t-test for paired sample means. We put together all four runs at positions 9 and 10 and ran a t-test on this combined data set. For positions 9.5, 10.5, and 11 there were only two data sets each. Finally, we ran a t-test on a combined data set with all of the runs at every point between 9 and 11. An example of a t-test table generated by excel is given in Table 1.1. The remainder of the t-test tables can be found in Appendix J. A summary of the key results of the t-tests is given in Table 1.2.

Table 1.1: Xfinity Position 9 t-test paired two sample for means

t-Test: Paired Two Sample for Means Position 9 Xfinity		
	Moving	*Control*
Mean	5.35	3.15
Variance	20.32	13.30
Observations	248	248
Pearson Correlation	0.34	
Hypothesized Mean Difference	1.70	
df	247	
t Stat	1.66	
P(T<=t) one-tail	0.05	
t Critical one-tail	1.65	
P(T<=t) two-tail	0.10	
t Critical two-tail	1.97	

In Table 1.2, we see that with a “Hypothesized Mean Difference” of 1.70 we get a one-tail P-value of 0.05. What this means is that we can say with 95% confidence that the difference in means between the two sets of data is at least 1.70 mph. Or alternatively, that we are 95% confident that the wind speed at Position 9 was 1.70 mph faster than the wind speed at the control point. This is a very significant difference in speed between the control point and position 9, and we feel highly confident in our data since it was taken on four separate days over the course of an entire month. We have summarized the hypothesized mean difference at the 95% significance level for each t-test performed below in Table 1.2.

Table 1.2: T-test hypothesized mean difference

Position Number	t-test Hypothesized Mean Difference at 95% significance
9	1.70 mph
9.5	1.70 mph
10	3.20 mph
10.5	0.05 mph
11	1.20 mph
9-11	2.20 mph

We can see from the above table that every position between 9 and 11 was significantly faster than the control point. Additionally, when we look at all the data in that region of the Xfinity location as a whole we notice that the region is 2.2 mph faster than the control point at the 95% confidence level. This may not seem like a huge difference in wind speed, but keep in mind that the averages we saw for the control array were between 1 and 6 mph, so a difference of 2.2 mph is very substantial. In a later section, we will discuss what the possible causes of this significant difference and how they relate to the other locations tested.

Location 2: Plant Sciences and Regents Parking Garage

The team conducted three separate runs of data collection at the Plant Sciences and Regents Parking Garage Location over the span of one day. A map of the data collection area with an overlay of position numbers is shown in Figure 4.1. Once again, the average wind speeds at each position were plotted and we looked for positions which were significantly faster or slower than the control. Plots of average wind speed at each position number for both the control and moving array are shown below in Figures 4.2, 4.3, and 4.4.

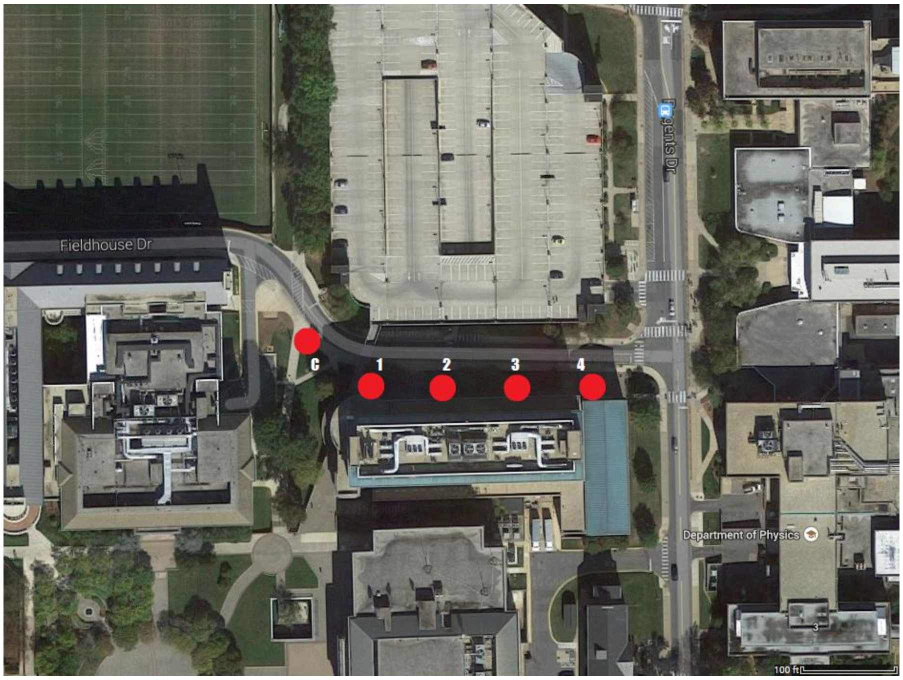

Figure 4.1: Plant Sciences Building testing location

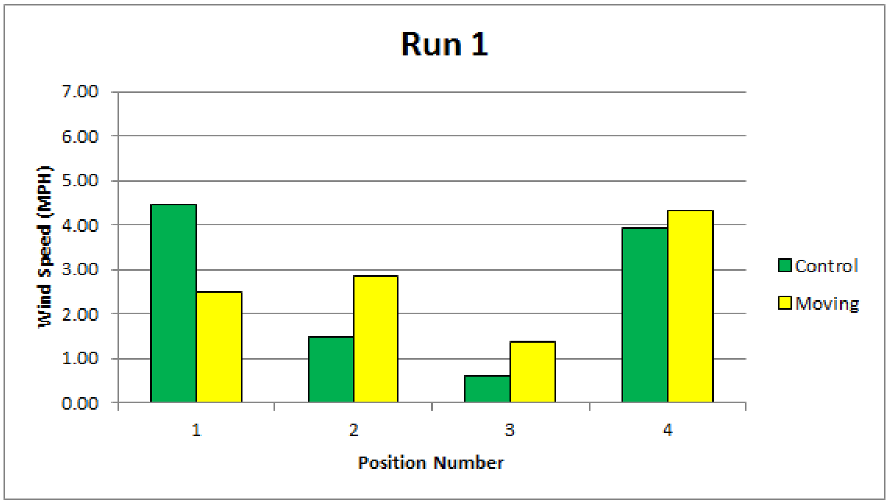

Figure 4.2: Average wind speed, PLS run 1

Figure 4.3: Average wind speed, PLS run 2

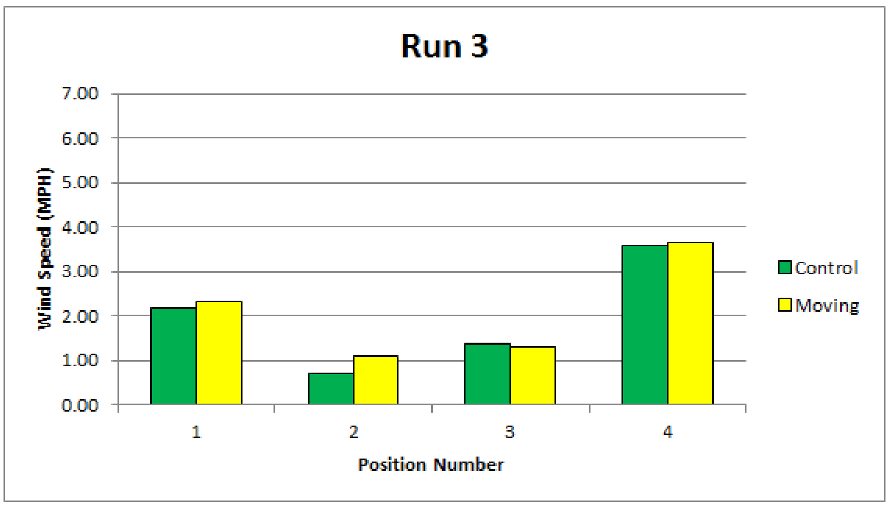

Figure 4.4: Average wind speed, PLS run 3

Using similar analysis techniques to those used above for the Xfinity set of data we can see that Position Number 1 is significantly slower than the control point over the course of the three runs. We again employed a t-test to quantify this difference, a summary table of which is shown below in Table 2.1

Table 2.1: T-test summary for Plant Sciences

t-Test: Paired Two Sample for Means Position 1 Plant Sciences		
	Control	*Moving*
Mean	3.55	1.84
Variance	13.29	8.63
Observations	229	229
Pearson Correlation	0.12	
Hypothesized Mean Difference	1.20	
df	228	
t Stat	1.74	
P(T<=t) one-tail	0.04	
t Critical one-tail	1.65	
P(T<=t) two-tail	0.08	
t Critical two-tail	1.97	

We can see from the above table that the control is at least 1.20 mph faster than the moving array at position one with 96% confidence. The differences in speed between the other positions and the control were not statistically significant. In a following section, we discuss the significance of position 1 being significantly slower than the other positions in the context of our entire project.

Location 3: Manufacturing

The team conducted three separate runs of data collection at the Manufacturing Building over the span of two months. A map of the data collection area with an overlay of position numbers is shown in Figure 5.1. Once again, the average wind speeds at each position were plotted and we looked for positions which were significantly faster or slower than the control. Plots of average wind speed at each position number for both the control and moving array are shown below in Figures 5.2, 5.3, and 5.4.

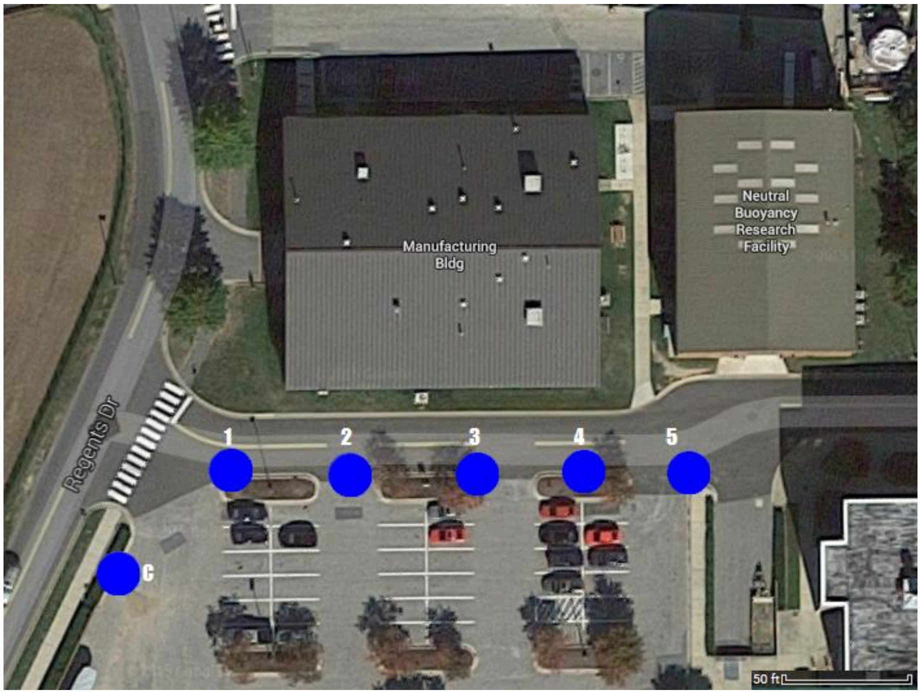

Figure 5.1: Manufacturing Building testing location

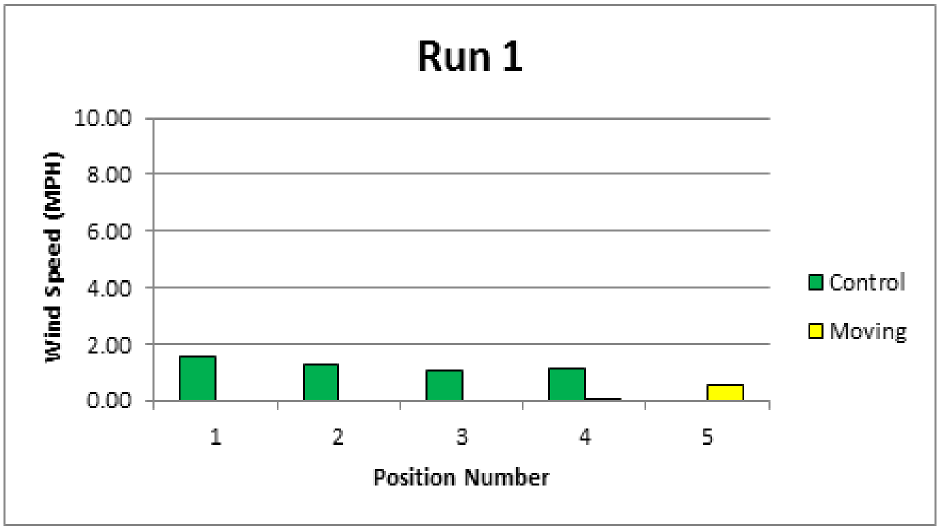

Figure 6.2: Average wind speed, Manufacturing run 1

Figure 5.3: Average wind speed, Manufacturing run 2

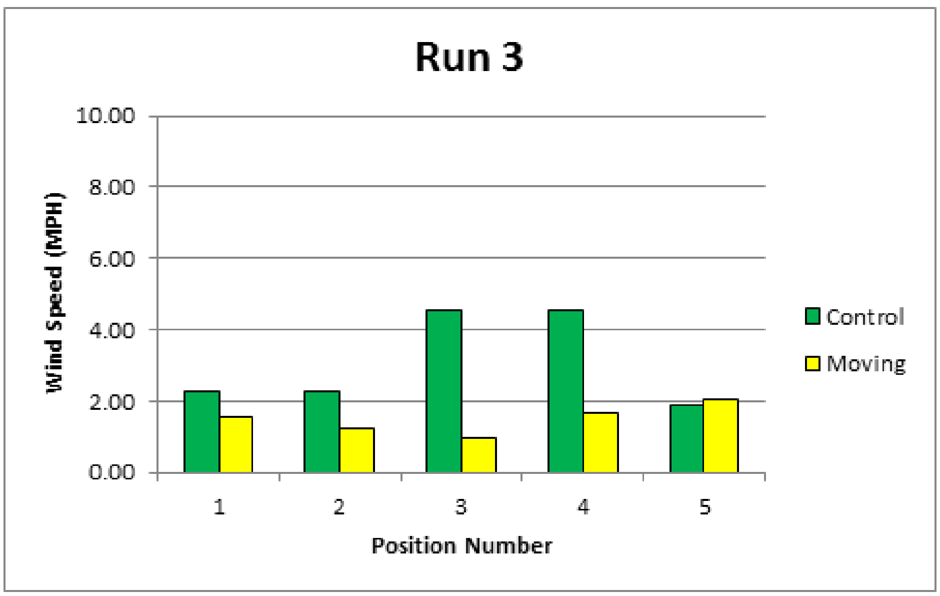

Figure 5.4: Average wind speed, Manufacturing run 3

We can see in Figure 5.2 that the wind speed was extremely low both for the control and the moving arrays. This was due to very still conditions on October 31. We threw this set of data out when performing the t-tests for this reason. However, in the other two data sets we can see that positions 2 and 3 look slower on average than the control point. To quantify this difference statistically we again performed t-tests for paired sample means, the summary table of this analysis is given below in Table 3.1 and the detailed t-test tables are given in Appendix J.

Table 3.1: T-test hypothesized mean difference for Manufacturing Building

Position Number	t-test Hypothesized Mean Difference at 95% significance
2	1.75 mph
3	1.50 mph
2-3	1.87 mph

Table 3.1 shows us that the region containing points 2 and 3 was at least 1.87 mph slower than the control point at the 95% significance level. We believe that the main cause of this was that the wind on each day we tested was blowing predominantly to the South (toward the bottom of Figure 5.1). This caused positions 2 and 3 to be shielded from the wind by the Manufacturing building, while the control point received no shielding from the building. This is a demonstration of a very elementary, but nonetheless critical, fact about wind in urban areas; buildings can block the wind. It is therefore important to consider the locations of these "dead zones" when selecting a location for an urban wind turbine. This will be discussed further in a later section.

Location 4: Kim Engineering Building/Chemical and Nuclear Engineering

The team conducted three separate runs of data collection at the Kim Engineering and Chemical and Nuclear Engineering buildings over the span of two months. A map of the data collection area with an overlay of position numbers is shown in Figure 6.1. Once again, the average wind speeds at each position were plotted and we looked for positions which were significantly faster or slower than the control. Plots of average wind speed at each position number for both the control and moving array are shown below in Figures 6.2, 6.3, and 6.4.

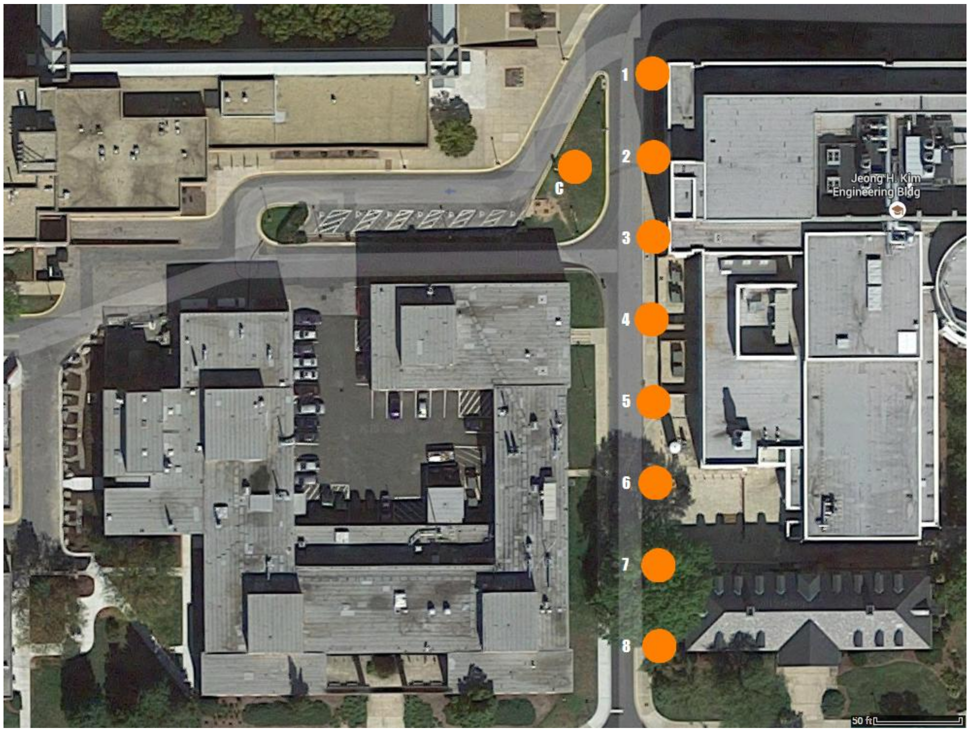

Figure 6.1: Chemical & Nuclear Engineering Building testing location

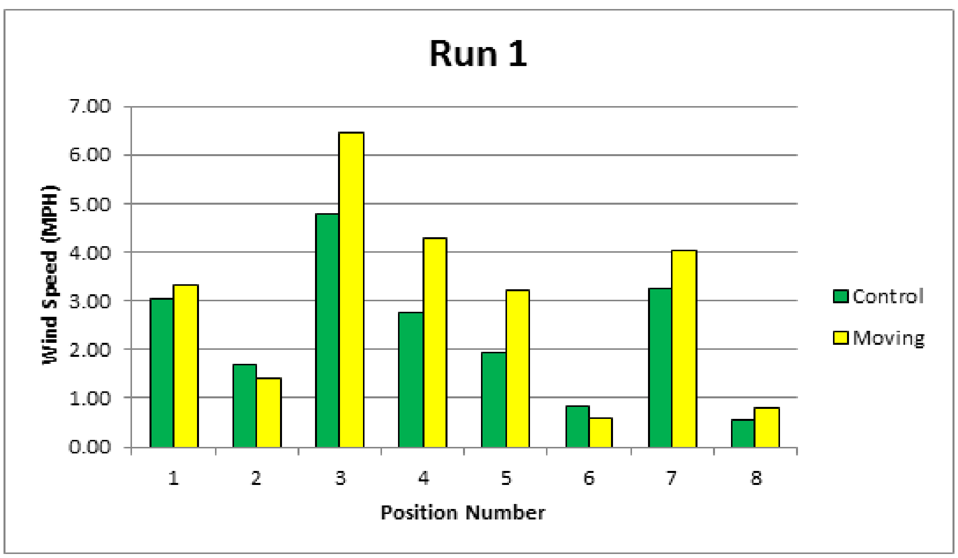

Figure 6.2: Average wind speed, CHE run 1

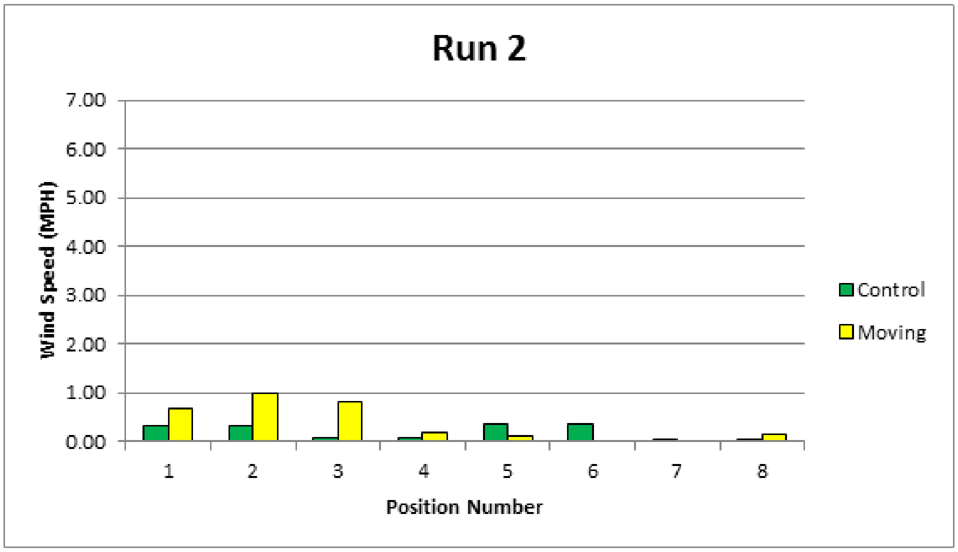

Figure 6.3: Average wind speed, CHE run 2

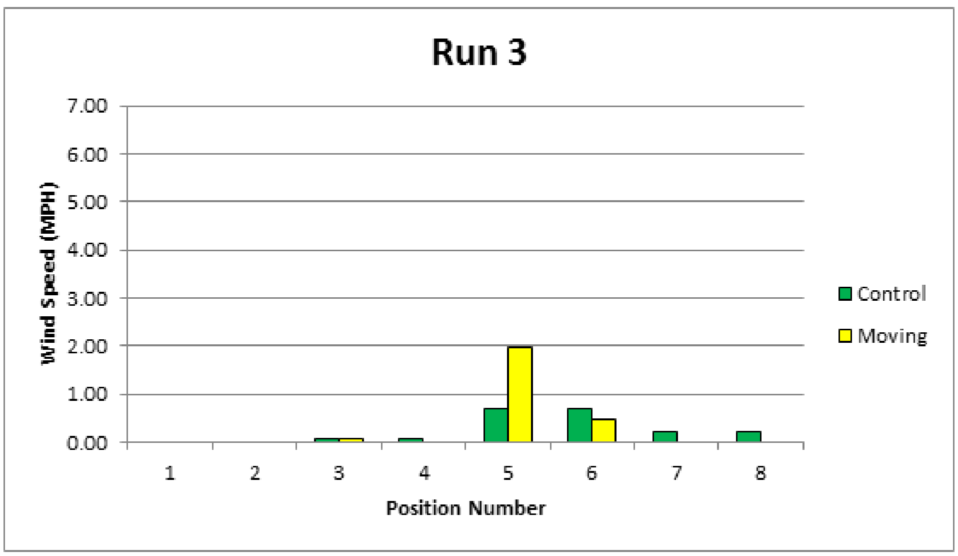

Figure 6.4: Average wind speed, CHE run 3

After analyzing the data gathered at the Kim Engineering and Chemical and Nuclear Engineering Buildings we were unable to say that any positions were significantly different than the control at the 95% confidence level. All the t-tests resulted in P-values greater than 0.05 for a Hypothesized Mean Difference of 0. The fact that all positions were similar at this location is useful to us in determining what types of topological conditions affect wind in urban areas. We can say that the conditions at this location do not materially affect wind speeds, based on our limited testing.

Location 5: McKeldin Library

The team conducted two separate runs of data collection at McKeldin Library over the span of one day. A map of the data collection area with an overlay of position numbers is shown in Figure 7.1. Once again, the average wind speeds at each position were plotted and we looked for positions which were significantly faster or slower than the control. Plots of average wind speed at each position number for both the control and moving array are shown below in Figures 7.2 and 7.3.

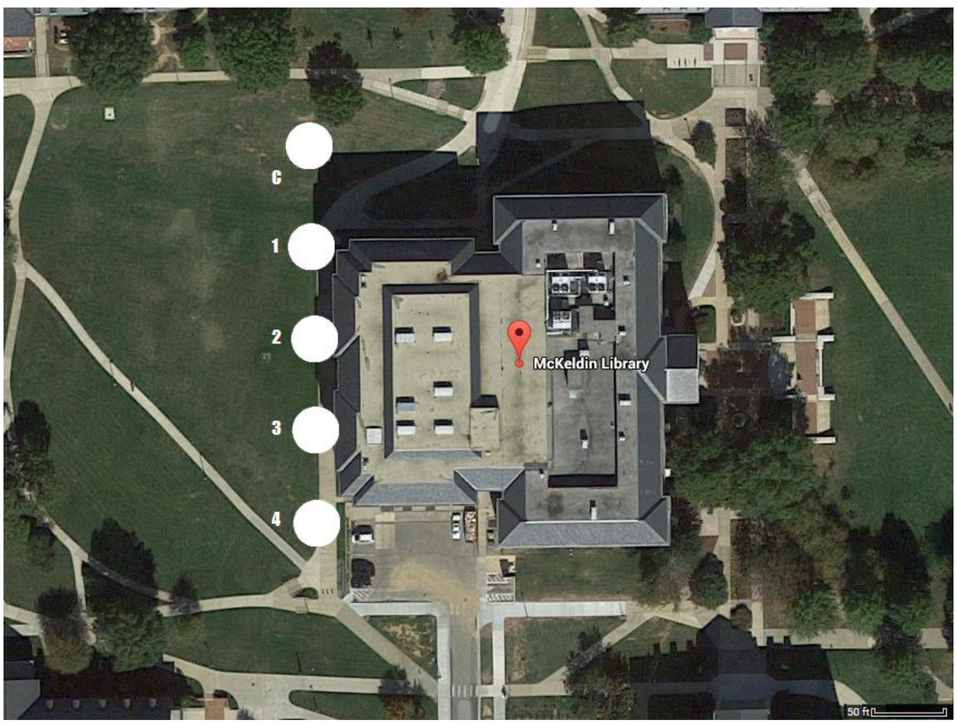

Figure 7.1: McKeldin Library testing location

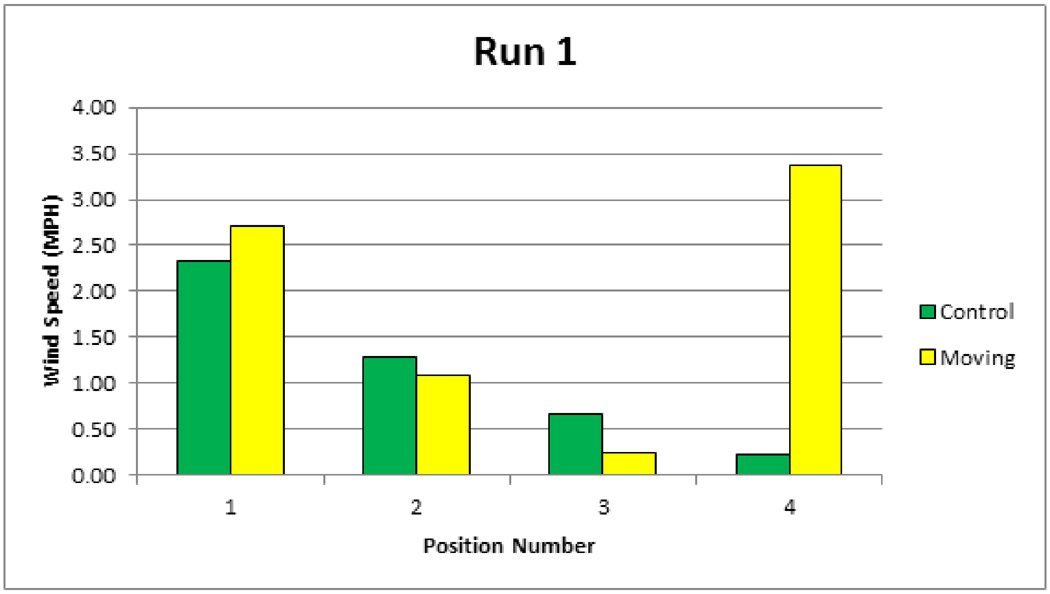

Figure 7.2: Average wind speed, McKeldin run 1

Figure 7.3: Average wind speed, McKeldin run 2

In Figures 7.2 and 7.3, it is important to note that when this data was collected it was done in a "back and forth" pattern. So position 4 on both of these graphs has the same data. After analyzing this data, we could not say confidently whether any of the positions were significantly different from the control.

Analysis & Discussion

With the analysis completed for the individual locations it is now possible to compare between the locations to determine if there are any common features that are causing higher/lower wind speeds to occur. This understanding of how certain topological features affect wind speeds is the first step in developing a predictive model for determining optimal placement of a VAWT in an urban environment. We first looked at positions which had significantly higher wind speeds than other positions in the same location and see if there are any common features to these positions.

We know that at Location 1 (Xfinity Center), positions 9-11 were much faster than the control point. We also notice that these positions lie in between the Xfinity Center and the entrance to the softball stadium. On the map it is clear that this is a "pinch point," a point where the two buildings are closer together than at any other point. A map with statistically significant positions can be found in Appendix I. At position 9, there exists a pinch point with a distance of 90 feet, and at position 10, there is a pinch point of 70 feet. We see much higher wind speeds here, which is an indication that the Venturi effect is speeding up the air flow through this particular point. This confirms our earlier prediction that pinch points would be good locations to place a VAWT.

One key variable we were unable to control for during our testing and subsequent analysis was wind direction. The direction of the wind clearly has a large impact on how the architecture and landscape will affect wind speeds measured by our equipment. For example, with gathering wind data near the wall of a building, there is a large difference between wind speeds recorded if the wind is blowing parallel to the wall versus perpendicular to it. When the wind is blowing perpendicular to and away from the wall then there will be no wind measured by the test equipment, since the building is effectively shielding the arrays from the wind. If the wind direction changes from parallel to perpendicular between one test point and another, we might conclude from our data that one point was significantly faster than another because of the topological features present at that point when in fact a simple change in wind direction was responsible.

The team opted not to measure wind direction during our test for the simple reason that in our test locations wind direction was too unpredictable and independent. The anemometer arrays measured wind speeds at low heights where wind speed and direction is incredible variable. Wind tends to swirl close to the ground in a manner which we would be unable to predict. Additionally, we observed that wind direction could change second to second, and that these changes were not consistent from location to location. For this reason, instantaneous wind direction data would not have been much use to our data analysis. However, general wind direction data could potentially be used in a later, more extensive project as an added variable to consider.

With our team’s limited time and budget, we felt we would be unable to devote resources in order to account for this extra variable, which was not the primary focus of the project. We tried to account for any variability in our data due to this unknown quantity by collecting data over several hours on each test day, and spreading the test days out over several weeks. The team focused solely on how certain topological features affected gross wind speed rather than how the combination of topological features and wind speed affected it.

Limitations

One of the major concerns of this research was obtaining the necessary permits to place the anemometer arrays and turbines along our proposed roadways. Without permits on the desired range of roadways, we would be unable to collect sufficient data and would not be able to complete a predictive computational model. In addition, the model generation phase brings up issues such as the prediction of traffic versus the actual diversity and dynamic nature of real world traffic. The long-term data would have been an undoubtedly useful baseline for providing estimations for traffic patterns, but the predictive strength of those estimates will not be truly and absolutely accurate. Another threat to the viability of the project is the potential for rubbernecking near the turbine or anemometer arrays on roadways – any interference with the flow of traffic could affect the data collected. This is also a very large safety concern, and thus will require the permission of the local government. Because we were unable to procure the permits, we were unable to conduct the first phase of our research.

Another constraint that limited the scope of our project was time. Both our projected and actual timelines are shown in Appendix B. As shown in Figure 8.1, attempts at obtaining permits from the Maryland SHA took approximately 7 months before correspondence ceased. Preliminary transportation testing was delayed as a result of the lack of permission from the Maryland SHA. By the time we were able to conduct our first preliminary transportation test, we had approximately one and one half years left for the project timeline. Architectural testing was also constrained by time, due to various poor weather conditions and lack of availability of team members. Seen in Figure 8.1, we stayed at our first testing site at the Xfinity Center for approximately 6 months in order to perfect collection methods. Should the SHA correspondence have succeeded, or did not delay the project, further investigations into our current locations as well as other locations would have been conducted.

Future Work

Due to the limitations encountered during the course of our research, there is quite a bit of work that can be done in the future to expand on our experiments. The first step for any future researchers is simply to continue to collect more data, both in the locations we tested, different locations with similar properties, and different locations with a variety of different architectural and environmental characteristics. Realistically, we were not able to collect enough data to draw any concrete conclusions or causal relationships. Instead, our results are closer to preliminary qualitative evidence. While they are not substantial enough to determine the causal relationships that drive business and economic investments, they do offer the groundwork and meticulous methodology for continued research into the effect of physical and architectural characteristics on the generation of artificial wind patterns.

An increase in the amount of data collected in a diverse range of areas and over a sufficiently long period of time will yield data that can support conclusions on causal relationships. Ideally, this data will confirm and solidify the qualitative observations we were able to establish in our experiments. These relationships can then be used to definitively identify areas that would lead to increased wind speeds simply based on their physical characteristics. The degree to which natural wind speeds are increased by surrounding structures can then inform decisions on whether or not these areas can be reasonably selected to support small scale turbines for wind power collection.

A major element and initial goal of our research study was to develop a model for cost-effective optimal turbine placement. While there are potential environmental benefits of utilizing a wind energy power generation system as an alternative to nonrenewable sources, we would not recommend further exploration of this topic if the system did not have a net economic gain. In general, when designing any energy generation system one must be cognizant of the total energy produced by the system during its normal lifetime and be able to compare this value to the input of energy needed to construct, operate, fuel, maintain and decommission or dispose of that same system, as illustrated by the Energy Payback Ratio (EPR) model. Ideally, given enough time we would have collected enough data so we could get a fair estimate of absolute average wind speed in a location rather than just a relative comparison between locations. Since power increases with the cube of wind speed, being able to identify in absolute terms the speed at a specific coordinate is necessary to make a fair economic analysis. In the future, we would need to perform tests for longer periods of time on many different dates to create accurate and more complete wind profiles of our testing locations.

Aside from wind speed, we would also need to collect data on power generation of specific VAWTs as power generation is also a function of rotor diameter, which varies depending on the model, as well as project power outputs as VAWTs become more efficient in the future. Additionally, costs of maintenance, turbine manufacturing and batteries, security, and environmental impacts would also need to be considered in order to fully analyze cost effective optimal placement. Since we were unable to complete this task due to the limitations of our research, we cannot yet comment on whether this line of research is worth continuing from a financial perspective.

If further data collection and research can be used to establish a firm and replicable pattern between architectural structures and artificial wind generation, then it can be utilized in exciting ways. An example application is a program that could automatically identify areas that could be used for wind collection. This program would examine areas using existing geographic information systems (GIS) data to identify locations that fit the parameters for artificial wind generation. Implementation of this program would allow for topographical analysis along with architectural analysis, to provide the optimal locations after at the effects of elevation, building design, building placement, etc. The wind speeds resulting from the architecture in question can then be evaluated through the lense of economic viability. It is difficult to say whether or not there would be any areas whose artificial wind creation would justify the deployment of vertical axis wind turbines, but a tool to effectively and efficiently analyze this would be a truly exciting prospect for alternative energy.

The overall purpose of this project was inspired by the fact that renewable energy sources are currently mostly used in rural areas and, more specifically, wind energy is only used in rural areas. The energy sector is reaching a point where renewable energy must become more prominent as fossil fuels continue to deplete. While VAWTs and the collection of wind energy in urban centers will not solve the looming energy issue by itself, it will help contribute to the issue and can be used alongside additional renewable sources in order to potentially create self-sustaining cities from an energy perspective. The idea of renewable energy in urban settings is still in its infancy, and building on projects such as this one are the first steps to develop the field in the future.

CONCLUSION

Initial transportation testing did not show promising results and we were unable to procure permission from the Maryland SHA to conduct more extensive experimentation. Because of these setbacks, we were not able to procure enough data to develop a model of artificial wind generated by modes of transportation. We have provided the basis for a consistent wind measurement method in an urban area that provides information for the optimal placement of a small vertical axis wind turbine. The data collection method can be applied to other locations on or around campus, such as between North Campus residence halls, South Campus residence halls, and by South Campus Commons. Enhancements of the anemometer arrays may be required in order to protect them in these locations due to the high density of human traffic from the student population.

We are able to provide, through magnitude mapping, information for the future development of a model for optimal placement for a small-scale, vertical axis wind turbines on the University of Maryland, College Park campus. The amount of data that we collected is not enough to confidently create a predictive model beyond qualitative observations, but additional data can augment our existing data to create a more in-depth model.

Other information that can be incorporated into the model in the future would include GPS, GIS, and economic analysis to provide a topographical analysis and improve the optimization of turbine placement. In further studies, we hope to fully develop a predictive model that will pinpoint the location for maximum wind, artificial or natural, collection in a tight, urban environment. This model should then be able to not only determine the best location for turbine placement, but also its economic viability.

APPENDIX A: BUDGET

Table 4.1: Projected budget for original approach

Item	**Cost**
Four Anemometers	$360
Materials for Array	$150
MATLAB/LabVIEW Software	Provided by UMD Institution
Access to Wind Tunnel	$200
Small-Scale Models of Various Cars	$20
Local Traffic Data	Provided by CATT Lab
One Wind Turbine (Mentor Paid for Two Already)	$5000
Gas Expense	$100
Car Rental Expense (2 weeks)	$550
Three Road Permits	$150
Turbine Repair	$100
Turbine Maintenance	$200
Pressure Cable	$200
I/O Brick	$800
Conferences/Events/Other	$1000
Total	**$8830**

Table 4.2: Final approximate costs of research study

Item	**Cost**
Nine Anemometers	$720
Materials for Three Arrays	$60
MATLAB/LabVIEW Software	Provided by UMD Institution
Access to Wind Tunnel	Provided by UMD Institution
Breadboard, Circuits and Wires	$50
Three Arduino Unos	$75
Gasoline and Vehicles for Testing	Provided by Teammates
Two Furniture Dollys	Provided by Mentor
Three Laptops	Provided by Teammates
Logging Software	Available for Free Download
Handheld GPS Device	Provided by Mentor
Conference to Amsterdam	Provided by UMD Institution
Total	**$905**

APPENDIX B: TIMELINES

Table 5.1: Projected timeline for original approach's milestones

	2013				2014				2015	
	Wint	Spr	Summ	Fall	Wint	Spr	Summ	Fall	Wint	Spr
Refine Literature Review	■	■	■	■	■	■	■	■	■	■
Apply for Necessary Permits	■	■	■	■						
Obtain Traffic Data	■	■								
Collect Data from Roadways					■	■				
Revise Proposal	■									
Collect Data from Vehicles				■						
Test Vehicle Wakes in Wind Tunnel				■						
Begin Computer Modeling	■	■	■	■						
Input Anemometer Data into Computer Model					■	■				
Refine Model					■	■				
Find Expert(s)/Possible Discussants	■	■	■	■	■	■	■	■		
Create Thesis Outline				■						
Analyze Data					■	■	■	■		
Draft Thesis					■	■				
Edit Thesis Draft							■	■		
Complete Final Thesis									■	■
Defend Thesis										■

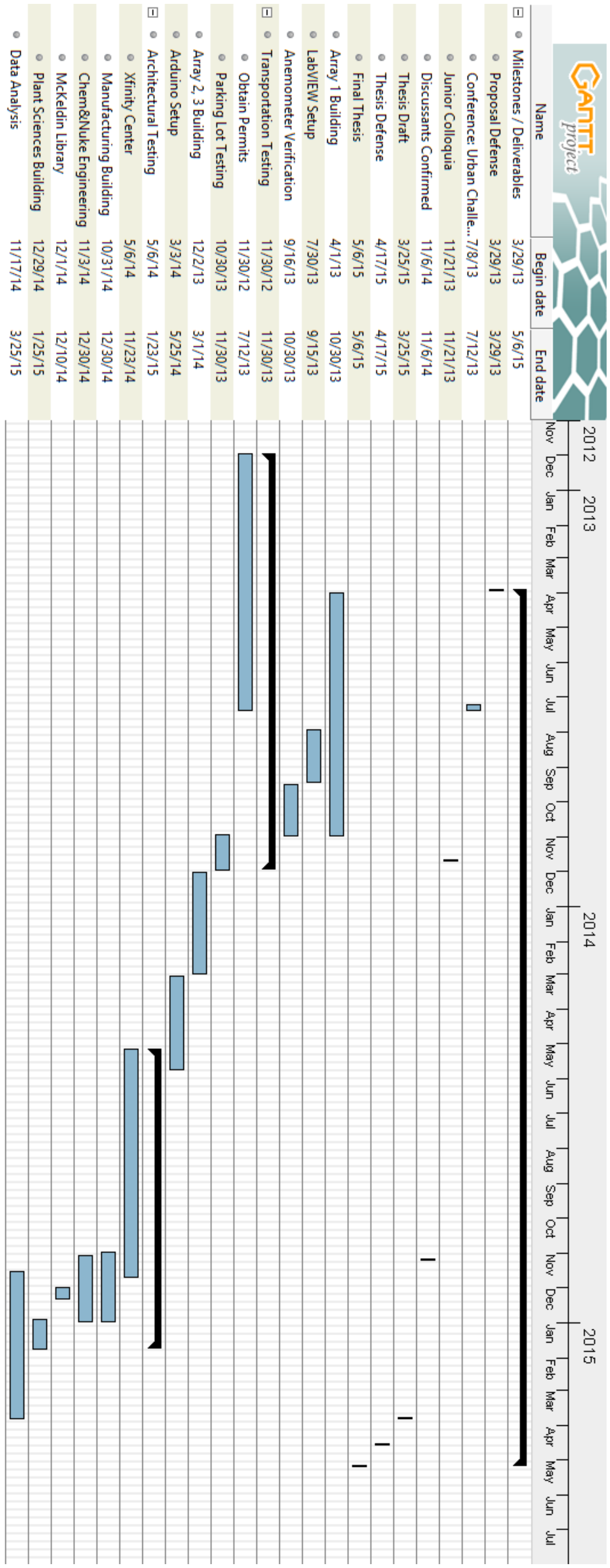

Figure 8.1: Timeline for updated approach, including milestones and deliverables

APPENDIX C: VERTICAL AXIS V. HORIZATONAL AXIS TURBINE

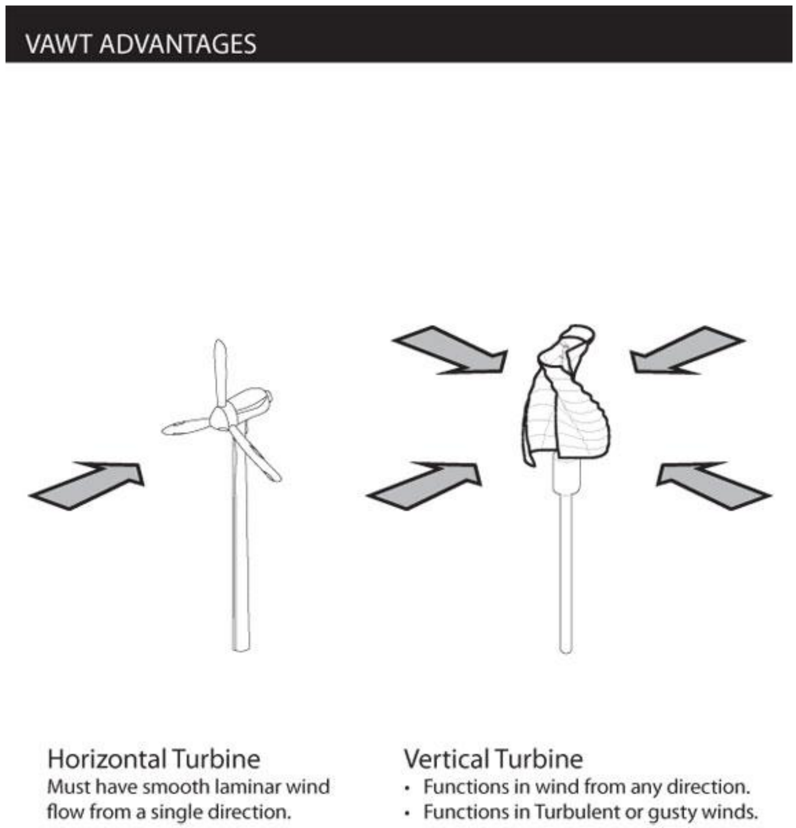

Figure 9.1: Key difference between a VAWT and a HAWT - the direction of axis rotation (Source: helixwind.com).

While there are several design variations of the VAWT, the axis remains consistent.

APPENDIX D: PERMIT ACQUISITION PROCESS

A key obstacle for implementing the real-world testing of the turbines along the proposed roadways was gaining permission to place turbines along government-owned roads. To that end, the team contacted the Federal Highway Administration and/or the local College Park government in order to obtain necessary permits. In regards to the "M" circle at the University of Maryland, the sub-team would have also contact the university administration for details on acquiring the proper permits for any on-campus testing. We would have needed to modify the methodology accordingly in order to prove the legitimacy of the overall research study to the governing bodies. Should the permits have proven impossible to obtain, we would not test along highways and instead, gather data in a more controlled setting using personally-owned vehicles on smaller, local roads in addition to placing the turbines along various roads on the University of Maryland's campus. This alternative would have been limiting, but would still generate valuable data over a period of hours for roads of that size.

Our communication with the Maryland State Highway Administration failed to proceed after July 12, 2013. We were able to obtain permission from the University of Maryland Department of Transportation for the Parking Lot Procedure outlined in Appendix F. In the results discussed in Appendix F, the shift away from the transportation phase of our methods is described; hence the aforementioned local road testing was also abandoned.

APPENDIX E: ANEMOMETER ARRAY

Figure 10.1: General form of the anemometer array.

The center body piece is pole made from aluminum; prototypes were initially made using polyvinyl chloride (PVC) pipes. The pole is balanced using three screws attached to the base in order to keep the pole perpendicular to the surface of the ground. The foundation is a bucket filled with cement in order stabilize the structure.

APPENDIX F: PARKING LOT TESTING PROCEDURE

Overview

The purpose of this test was to experimentally determine whether or not there is a measurable wind effect created by a moving vehicle. This experiment involved driving a vehicle at increasing increments of speed past a movable anemometer array and determining the relative speed of the wind flowing past the array, both visually and through measurement software. We set up our experiment in the parking lot outside the University of Maryland's Xfinity Center on a Sunday morning in order to have a controlled, open area to test in. We worked in conjunction with the University's Department of Transportation to obtain exclusivity for a section of the parking lot during the duration of our testing. This data, once matched with the wind speeds calibrated at the wind tunnel, provided valuable data contributing to our overall research project in determining if wind from moving vehicles is able to generate enough energy for substantial economic returns

Goals

The general goal of the experiment was to start an initial exploration into the potential relationship between cars and wind generation. Specifically, we wanted to determine the wind speeds produced by a car driving at increasing increments of speed. We hoped to correlate the increasing speeds of the car with increasing wind speed measurements. If this relationship held, this experiment would be an essential jumping off point for examining in greater detail whether or not using the wind generated by moving cars was a potentially viable alternative energy source. The experiment also sought to address very basic questions about the relationship between wind speeds and location relative to the passing vehicle. Locations varying in both the X and the Z planes were taken at every car speed for exactly this purpose. Obviously, another goal of the experiment was simply to gather this data safely and within the limitations stipulated from our correspondence with DOTS.

Materials and Supplies

The following is a list of materials and supplies used in the experiment. This list can be used as a reference when going through the detailed methodology that follows.

Technical

- anemometer array
- bread board
- charged battery
- electrical connecting wire
- inverter
- computer and LabVIEW software

Nontechnical

- traffic cones
- tape
- chalk
- tape measure
- stopwatch
- camera

Pre-Experimental Preparation/Protocol

Before we conducted the experiment, we set up the anemometer array and circuit for data acquisition outside of the lab. To do this, we need to extended the wiring on the anemometer array in order to attach the anemometer terminals to the circuit breadboard from a safe distance. Also, the battery and inverter were set up in order to run the power supply, which is necessary to provide DC power to the op-amps on the circuit. We also needed to compile the VI into an executable that could be run portably. This is essential as the executable can be deployed and run on any computer with a LABVIEW runtime environment installed. This is far easier than launching the program from the development environment, which requires a license to use. For the implementation of the experiment, we needed to make sure that the parking lot was adequately empty on the Sunday in question. Finally, before we drove by the anemometers and began to take data, we needed to set up hash marks using chalk to judge the horizontal distance from the car to the anemometer array as well as a chalk line (or cone) designating when the driver should begin to apply the brakes.

Experimental Methods/Protocol

The following is a detailed list of the steps followed for this experiment. This list is meant to provide guidance to anyone hoping to recreate the experiment as well as details on the procedure followed.

1. Set up experimental site. Make sure there are no other vehicles parked in the testing area. Connect the inverter to the battery and bread board. Run the electrical wiring from the bread board to the anemometer array. Test anemometer

array for reading accuracy. Put down any traffic cones available to block off testing area from the public.

2. Position anemometer array approximately halfway down the driving track. Tape down markings at 5 feet, 10 feet and 15 feet parallel from the driving track. Place anemometer at 5 foot marking. Set anemometer at 3 feet.
3. Have driver position vehicle at the beginning of the track. Have passenger in front seat to watch speedometer and tell the driver when to brake as the driver is focusing on keeping in line with the track.
4. Drive vehicle as straight as possible down the track at 25 mph. A spotter standing near the anemometer array will determine approximately how far away the vehicle was from the anemometer based on the tape markings. Passenger should record speed of vehicle once it is in line with the array and tell the driver to begin braking 10-20 feet after passing the array.
5. Check to see if software is registering data from the anemometer. Adjust as needed.
6. Repeat trials increasing speed in 10 mph increments to 45 mph.
7. Repeat trials with varying speeds and with the anemometer array set at 10 feet, then 15 feet in horizontal distance from the track. Repeat trials again with anemometer array set at 6 feet and 9 feet vertical distance.
8. Repeat with different sized vehicles if available and as needed.
9. There should be 3 different speeds, 3 different horizontal distances and 3 different vertical distances. This would make 27 different combinations of trials per vehicle. If at any point one of the changed parameters is found to have little

impact on wind speed (such as a particular horizontal or vertical distance) those trials can be forgone.

10. After testing is completed and data is collected, break down site and remove tape and any traffic cones from testing area. Unhook wire, the battery and inverter from the breadboard and pack up all supplies.

Method of Data Collection

The wind speed data was collected using the data collection VI. This software simply takes voltage readings from the anemometers and converts that data into a wind speed value in mph. The program was run from the moment the car began moving until the moment that it stopped (for each trial run). The intention was to isolate a jump in wind speed measurements when the car passed the array. In addition to the wind speed measurements, we collected data on the speed of the car and the distance from the car to the array as it passed by. Two separate spotters were used to take these readings. For every pass of the vehicle, we saved the wind speed data with both the corresponding distance and speed readings for further analysis after the experiment.

Controls and Variables for Experiment

Controls

- route location
- no ambient traffic
- spotter that determines x-distance
- anemometer array
- car passenger that determines mph

Independent Variables

- horizontal distance from car to anemometer (5, 10, and 15 ft)
- vertical distance from ground to anemometer (3, 6, and 9 ft)
- speed of car (25, 35, and 45 mph)
- type of vehicle
- truck
- sedan

Dependent Variable

- amount of wind collected

Safety Concerns and Safety Protocol

Driving vehicles at the noted speeds is potentially dangerous without the proper precautions. Both driver and passenger wore seatbelts. In order for the driver of the vehicle to keep his or her attention on the road, a passenger monitored the speed instead. Also, the anemometer array was set up at the halfway point of the course, allowing for ample room for the driver to decelerate.

The testing was done on a Sunday morning in a low traffic area to minimize the amount of ambient pedestrian and vehicular traffic. In case there was any, safety cones were set up to avoid other vehicles and pedestrians from driving onto the course . Two team members, one on each end, served as a backup to prevent any interference. Before, during, and after testing, the team members not in the car kept a safe distance (no less than 10 feet) from the moving vehicle.

Results

The results of the experiment were discouraging in regards to our attempt to establish a correlation between a moving vehicle and wind speeds generated nearby. Even at our fastest runs, we could not see an increase in measured wind due to the passing of the vehicle. This data lead us to conclude that moving vehicle on a mid speed roadway (under 50 mph) would not be adequate as a source of energy generation.

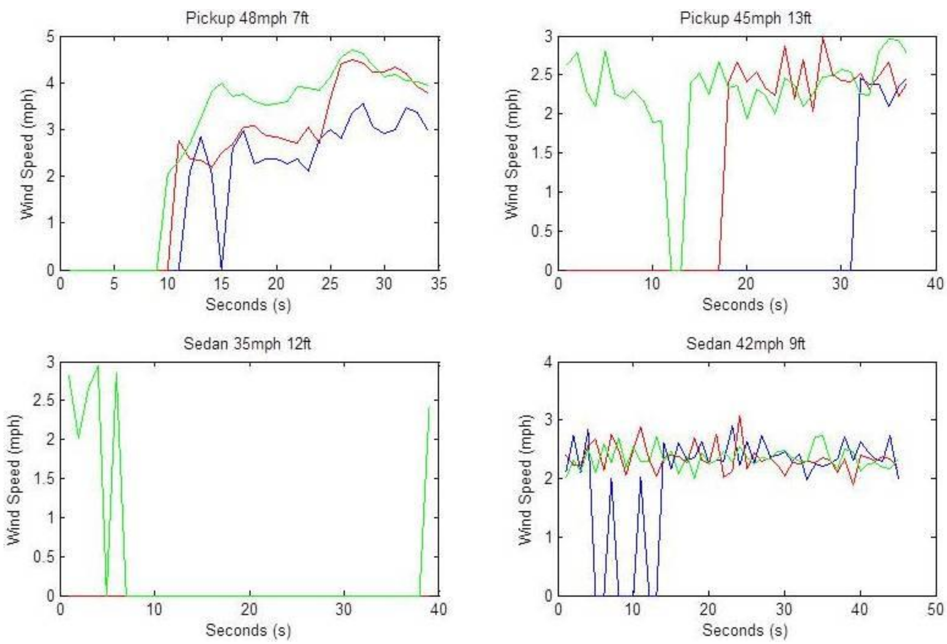

Figure 11.1: Data obtained from transportation testing

The graphs depict the wind speed in response to passing vehicles over the time of the test conducted. The desire was to use these graphs to be able to consistently pinpoint a spike in measured wind speed. This spike would represent the moment when the vehicle passed the anemometer array. In theory, these spikes would grow in amplitude as the speed of the vehicle increased. The graphs above make it apparent that this behavior was not verified through our experiment. There was no way to specifically discern when the vehicle passed the array with any consistency and leads to the conclusion that passing vehicles at the measured moving speeds are not adequate for artificial wind generation.

Visuals

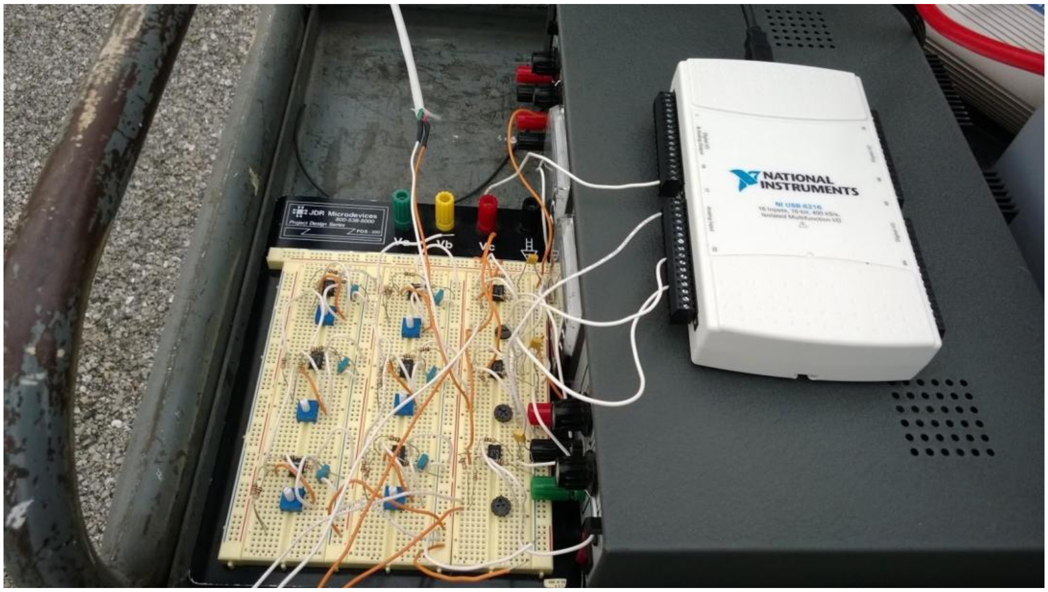

Figure 11.2: Breadboard and I/O brick

Figure 11.3: Anemometer array with connections to breadboard

APPENDIX G: COLLECTION PROCEDURE FOR ARCHITECTURE ANALYSIS

<u>Set up</u>

1. Assemble anemometer arrays
    a. Each aluminum pole is marked 3 times at 3ft intervals
        i. One arm is pressure screwed into place at each of the marks
    b. Each of the three anemometers on each array is color coded
        i. Color marks are made on anemometer and other end of wire
        ii. Colors are arbitrary, only to confirm anemometer connections
        iii. Anemometers are placed on each arm
        iv. Anemometers are plugged into Arduino Uno unit
            1. Bottom at Analog 1
            2. Middle at Analog 2
            3. Top at Analog 3
            4. Ground wires are bound together and set to ground
    c. Aluminum pole is set in cement foundation
    d. Secure array to two-wheel dolly, if applicable
2. Connect Arduino Uno unit to computer
    a. Open Arduino software and confirm port number
    b. Open “putty”
        i. Putty settings
            1. Session
                a. Connection type: Serial

        b. Serial line: COM_ (port number for Arduino)
        c. Speed: 115200
    2. Logging
        a. Session logging: All session output
        b. Check “Flush log file frequently”
  c. Ensure filename is different per session
  d. Click “Open” to start session
      i. Close window to end session
3. Sessions run for 5 minutes
4. Wheel applicable arrays 50 feet along pre-determined testing line

APPENDIX H: TECHNOLOGY OVERVIEW

The main goal of the technology used in this project was to accurately and reliably collect wind speed data. This data was essential to our project and was used to experimentally examine potential sources for artificial wind collection. The wind measurement devices used were anemometers. These were assembled into arrays that were made of PVC material and had three anemometers each. The anemometers were placed three feet apart in order to take measurements at different points in the z-plane. The rest of the technology was used to extract and record data from these anemometer arrays.There were two major iterations of the technology used in this manner. The first was using NI LabVIEW software to write a program capable of reading data from an NI I/O brick. The second iteration of the data collection technology improved on this system through the use of Arduino Uno Microcontrollers and C code.

Anemometer Array

This was simply a device for mounting three anemometers for wind speed measurement each placed three feet apart. The array itself was made of PVC and the stand was a bucket filled with cement in order to ensure stability.

LabVIEW System

The LabVIEW system used a LabVIEW language program to take and record data inputs (written to a local text file) from the anemometer array via a NI I/O brick. In order to make this program portable it was compiled into an executable that could be run without a LabVIEW license on any computer that had installed a free runtime environment from NI.

LabVIEW Drawbacks

This system had two glaring drawbacks. The first was a technical issue. The I/O brick often experienced "ghosting," meaning the inputs on one of the I/O ports were mistakenly read from all of them, causing faulty identical readings. The work-around for this problem was complicated, needed an additional circuit to take the inputs from the anemometers and then feed the separated signals to the I/O brick after passing through a circuit implemented on a breadboard.

This system was very inconvenient and not at all portable. It was difficult to implement and often unreliable, as the entire system could be rendered useless by the failing of a single exposed circuit component on the breadboard. In addition to the difficulty of implementing it and the poor nature of its performance, the LabVIEW System was too expensive to scale up when the direction of the project demanded to read from three separated arrays simultaneously. The I/O brick itself was $600, a prohibitive cost.

Arduino Setup

The Arduino setup used an Arduino UNO board that recorded the average wind speed over a span of three seconds every five seconds. The setup required a laptop, an anemometer array, and the Arduino UNO board. The Arduino UNO would read from each anemometer in the array simultaneously and write the values to a blank text document on the laptop.

The Arduino setup made the data collection process require minimal effort. The small Arduino UNO board allowed for easy transport along with the anemometers and made setup fast and simple.

<u>Visual References</u>

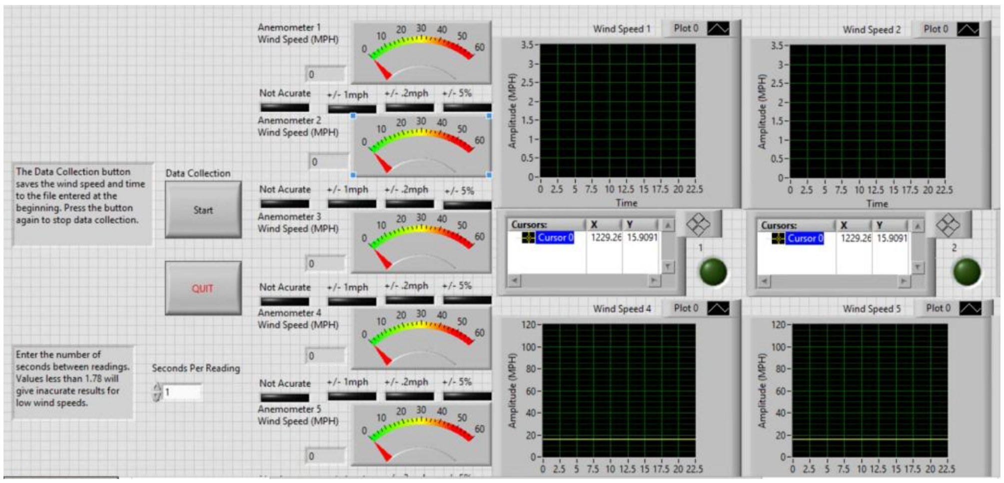

Figure 12.1: Partial View of LabVIEW User Interface

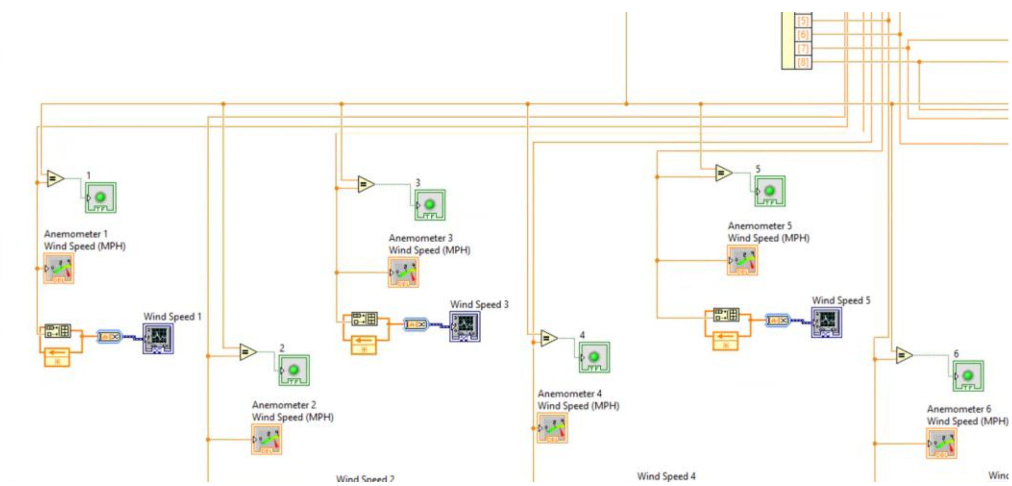

Figure 12.2: Partial View Of LabVIEW Code (Block Definition Diagram)

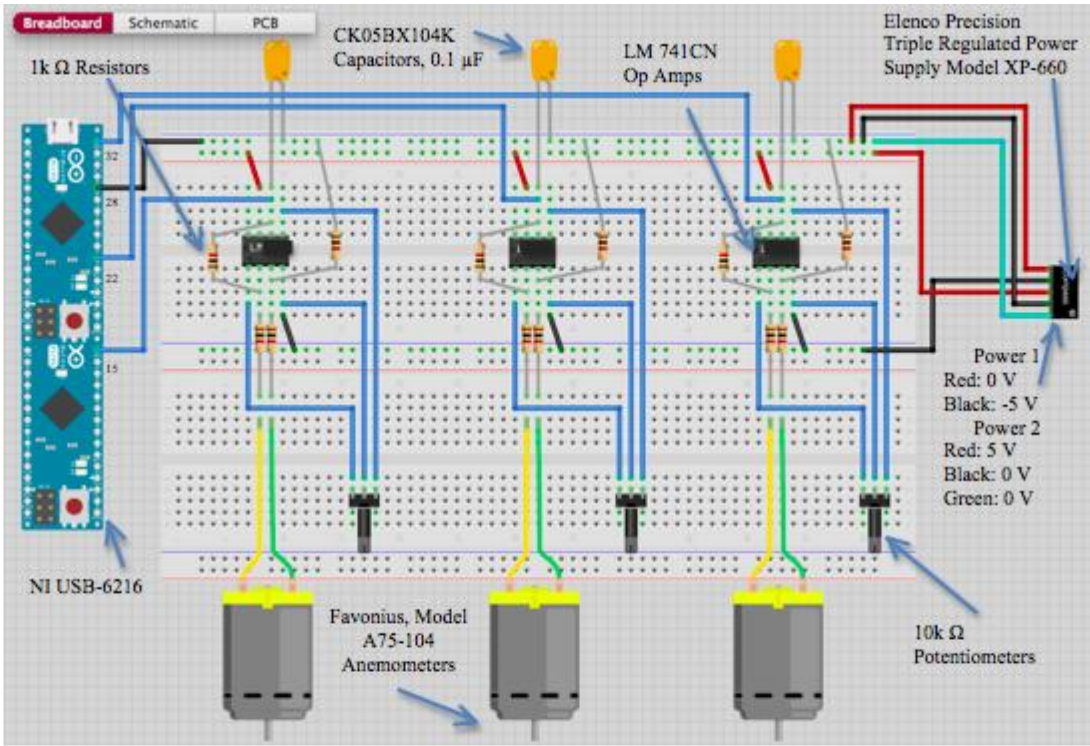

Figure 12.3: Anti-Ghosting Circuit

Arduino Code

```
# define threshhold 23
# define transferf 1.7
unsigned int currval1 = 0;
unsigned int currval2 = 0;
unsigned int currval3 = 0;
unsigned int change1 = 0;
unsigned int change2 = 0;
unsigned int change3 = 0;
float velread1 = 0;
float velread2 = 0;
float velread3 = 0;
unsigned long period = 3000; //sample length (sfreq's)
unsigned int delaytime = 1000; //time between samples (milliseconds)
unsigned int sfreq = 1000; //sample frequency (microseconds)
uint32_t starttime = 0;
uint32_t stoptime = 0;

void setup(){
 Serial.begin(115200);
}
```

```
void loop(){
 if(analogRead(A1) > threshhold)
   currval1 = 1;
 if(analogRead(A2) > threshhold)
   currval2 = 1;
 if(analogRead(A3) > threshhold)
   currval3 = 1;
 change1 = 0;
 change2 = 0;
 change3 = 0;
 starttime = micros();
 for (unsigned long i = 0; i < period; i++){
   frequencyCounter();
 }
 stoptime = micros();
 transferFunction();
 printvals();
 delay(delaytime);
}

void frequencyCounter(){
 if(analogRead(A1) > threshhold) {
   if(currval1 == 0){
     currval1 = 1;
     change1++;
   }
 }else{
   if(currval1 == 1){
     currval1 = 0;
     change1++;
   }
 }
 if(analogRead(A2) > threshhold) {
   if(currval2 == 0){
     currval2 = 1;
     change2++;
   }
 }else{
   if(currval2 == 1){
     currval2 = 0;
     change2++;
   }
 }
 if(analogRead(A3) > threshhold) {
   if(currval3 == 0){
```

```
     currval3 = 1;
     change3++;
   }
  }else{
   if(currval3 == 1){
     currval3 = 0;
     change3++;
   }
  }
  delayMicroseconds(sfreq);
}

void transferFunction(){
 velread1 = ((change1/2)*transferf*1e6) / (stoptime-starttime);
 velread2 = ((change2/2)*transferf*1e6) / (stoptime-starttime);
 velread3 = ((change3/2)*transferf*1e6) / (stoptime-starttime);
}

void printvals(){
 Serial.print(velread1);
 Serial.print(", ");
 Serial.print(velread2);
 Serial.print(", ");
 Serial.println(velread3);
}
```

APPENDIX I: MAGNITUDES OF SIGNIFICANT POSITIONS

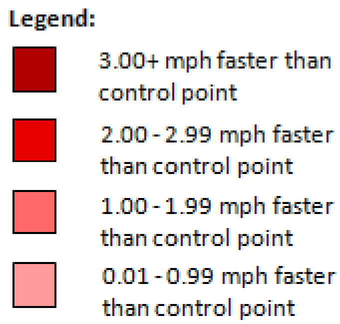

Figure 13.1: Legend of significantly faster magnitudes

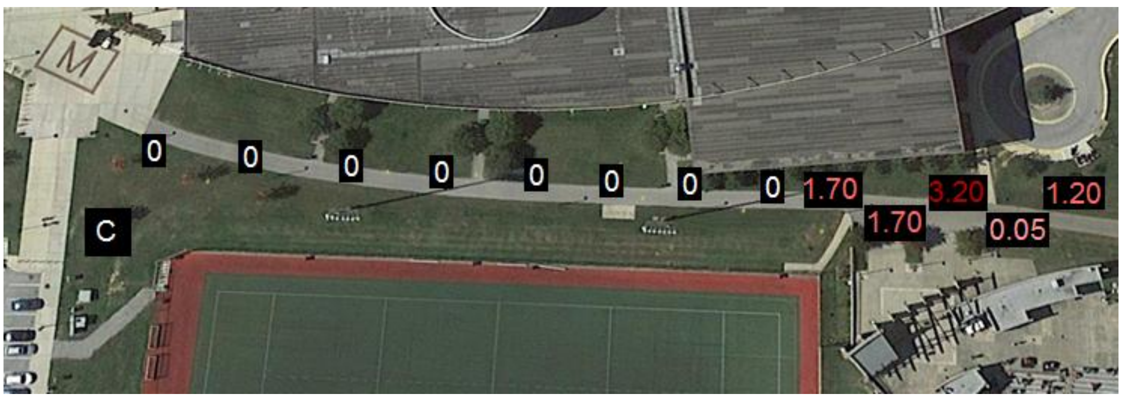

Figure 13.2: Significantly faster positions and magnitudes – Xfinity Center

Figure 13.3: Significantly slower positions and magnitudes – Manufacturing

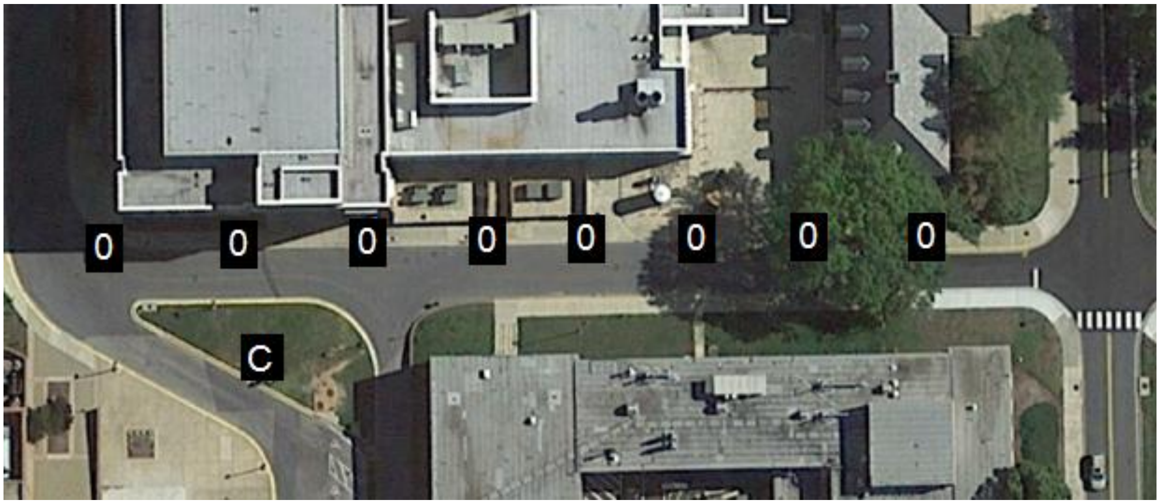

Figure 13.4: No positions of significance – Chemical & Nuclear Engineering

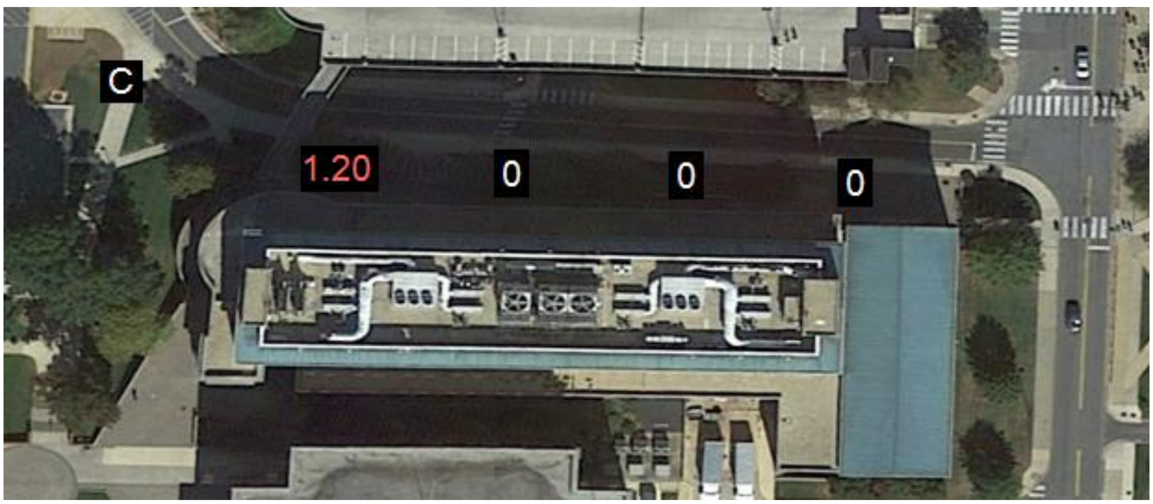

Figure 13.5:Significantly faster positions and magnitudes – Plant Sciences

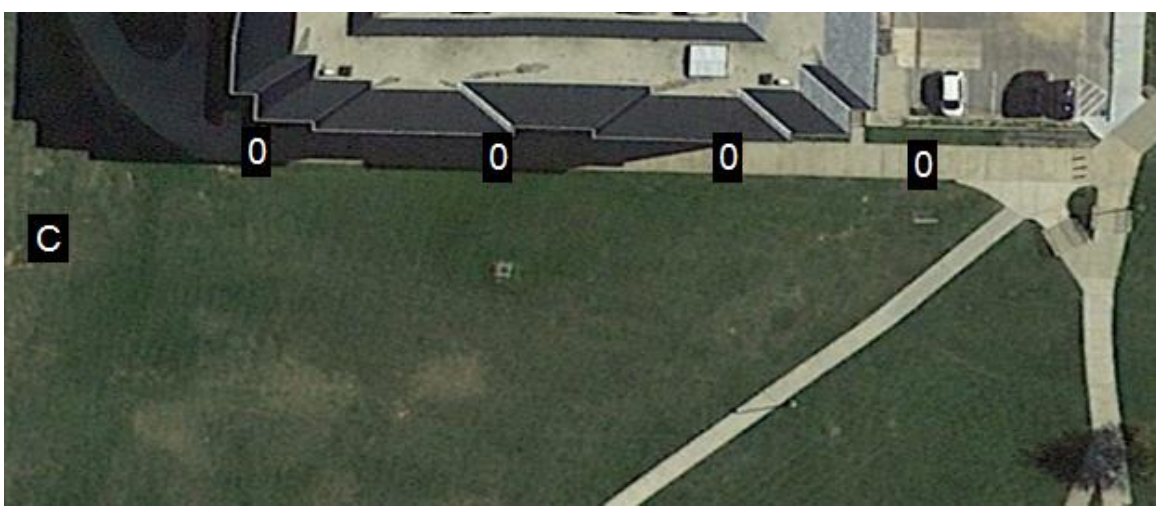

Figure 13.6: No positions of significance – McKeldin Library

APPENDIX J: T-TEST SUMMARY TABLES

Table 6.1: T-test Xfinity Site 9

t-Test: Paired Two Sample for Means Position 9 Xfinity		
	Moving	*Control*
Mean	5.35	3.15
Variance	20.32	13.30
Observations	248	248
Pearson Correlation	0.34	
Hypothesized Mean Difference	1.70	
df	247	
t Stat	1.66	
P(T<=t) one-tail	0.05	
t Critical one-tail	1.65	
P(T<=t) two-tail	0.10	
t Critical two-tail	1.97	

Table 6.2: T-Test Xfinity Site 9.5

t-Test: Paired Two Sample for Means Position 9.5 Xfinity		
	Moving	*Control*
Mean	3.76	1.25
Variance	8.16	15.23
Observations	112	112
Pearson Correlation	-0.13	
Hypothesized Mean Difference	1.70	
df	111	
t Stat	1.67	
P(T<=t) one-tail	0.05	
t Critical one-tail	1.66	
P(T<=t) two-tail	0.10	
t Critical two-tail	1.98	

Table 6.3: T-test Xfinity Site 10

t-Test: Paired Two Sample for Means Position 10 Xfinity		
	Moving	*Control*
Mean	6.32	2.61
Variance	5.72	16.83
Observations	248	248
Pearson Correlation	0.08	
Hypothesized Mean Difference	3.20	
df	247	
t Stat	1.77	
P(T<=t) one-tail	0.04	
t Critical one-tail	1.65	
P(T<=t) two-tail	0.08	
t Critical two-tail	1.97	

Table 6.4: T-test Xfinity Site 10.5

t-Test: Paired Two Sample for Means Position 10.5 Xfinity		
	Moving	*Control*
Mean	4.02	3.30
Variance	9.87	24.64
Observations	117	117
Pearson Correlation	0.40	
Hypothesized Mean Difference	0.05	
df	116	
t Stat	1.66	
P(T<=t) one-tail	0.05	
t Critical one-tail	1.66	
P(T<=t) two-tail	0.10	
t Critical two-tail	1.98	

Table 6.5: T-test Xfinity Site 11

t-Test: Paired Two Sample for Means Position 11		
	Moving	*Control*
Mean	5.08	2.85
Variance	14.22	19.64
Observations	112	112
Pearson Correlation	0.20	
Hypothesized Mean Difference	1.40	
df	111	
t Stat	1.70	
P(T<=t) one-tail	0.05	
t Critical one-tail	1.66	
P(T<=t) two-tail	0.09	
t Critical two-tail	1.98	

Table 6.6: T-test Xfinity Sites 9 to 11

t-Test: Paired Two Sample for Means Positions 9-11 Xfinity		
	Moving	*Control*
Mean	5.20	2.72
Variance	12.89	17.35
Observations	837	837
Pearson Correlation	0.21	
Hypothesized Mean Difference	2.20	
df	836	
t Stat	1.70	
P(T<=t) one-tail	0.04	
t Critical one-tail	1.65	
P(T<=t) two-tail	0.09	
t Critical two-tail	1.96	

Table 6.7: T-test Plant Sciences Site 1

t-Test: Paired Two Sample for Means Position 1 Plant Sciences		
	Control	*Moving*
Mean	3.55	1.84
Variance	13.29	8.63
Observations	229	229
Pearson Correlation	0.12	
Hypothesized Mean Difference	1.20	
df	228	
t Stat	1.74	
P(T<=t) one-tail	0.04	
t Critical one-tail	1.65	
P(T<=t) two-tail	0.08	
t Critical two-tail	1.97	

Table 6.8: T-test Manufacturing Site 2

t-Test: Paired Two Sample for Means Position 2 Manufacturing		
	Control	*Moving*
Mean	4.72	2.18
Variance	18.74	13.40
Observations	119	119
Pearson Correlation	0.18	
Hypothesized Mean Difference	1.75	
df	118	
t Stat	1.67	
P(T<=t) one-tail	0.05	
t Critical one-tail	1.66	
P(T<=t) two-tail	0.10	
t Critical two-tail	1.98	

Table 6.9: T-test Manufacturing Site 3

t-Test: Paired Two Sample for Means Position 3 Manufacturing		
	Control	*Moving*
Mean	5.84	3.50
Variance	26.49	19.68
Observations	109	109
Pearson Correlation	0.42	
Hypothesized Mean Difference	1.50	
df	108	
t Stat	1.69	
P(T<=t) one-tail	0.05	
t Critical one-tail	1.66	
P(T<=t) two-tail	0.09	
t Critical two-tail	1.98	

Table 6.10: T-test Manufacturing Sites 2 to 3

t-Test: Paired Two Sample for Means Position 2-3 Manufacturing		
	Control	*Moving*
Mean	5.25	2.81
Variance	22.66	16.76
Observations	228	228
Pearson Correlation	0.33	
Hypothesized Mean Difference	1.87	
df	227	
t Stat	1.68	
P(T<=t) one-tail	0.05	
t Critical one-tail	1.65	
P(T<=t) two-tail	0.09	
t Critical two-tail	1.97	

GLOSSARY

Anemometer – a common instrument used at weather stations, designed to measure wind speed

Artificial wind energy – wind that is created from the wake of a human-made moving or stationary body, including but not limited to cars, airplanes, trains, tunnels, buildings

Efficiency – optimization of energy and voltage generation while maintaining low levels of resource expenditures in the form of materials or time

Electrostatic load – a loss in the electrostatic charge due to the transfer of energy, will be used in our project to simulate transferring our generated energy to a street lamp or other device requiring electricity

Fluid dynamics – the flow of fluids (specifically air in this project) and its interaction with moving bodies, such as vehicles and turbine blades

Horizontal axis wind turbines (HAWTs) – a wind turbine where the main rotor shaft is at the top of the tower and pointed directly into the wind, more common as a large-scale design and generally considered the more efficient design

LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) – system design platform that operates under the graphical language "G" and used for data acquisition and instrument control

Large-scale wind energy– a wind farm operation that generally uses very tall, horizontal wind axis turbines and used to generate large amounts of commercial energy

Levelized cost – net cost to install a renewable energy system divided by expected life-time energy output

MATLAB (Matrix Laboratory) – numerical computing environment that allows for creation of user interfaces, function and data plotting, implementation of algorithms and matrix manipulation; will be used to simulate various wakes created by moving objects

Natural wind – wind that is naturally created by the movement of air from high to low pressure areas due to the earth's natural rotation; this is the force that needs to be factored out when studying artificial wind energy

"Normal" traffic patterns – traffic in which the vehicles are moving at or above speed limit; the vehicles are not hindered by accidents or construction

Renewable energy – energy sources that are either omnipresent (solar and wind) or can be restored in a reasonable amount of time (trees); this is contrasted with nonrenewable energy (fossil fuels and mineral deposits); this project focuses on wind as the renewable energy

Self-sustaining – a system that creates virtually all of the energy it needs to operate i.e. a solar calculator

Small-scale – a wind operation, typically a single turbine, that does not aim to commercially generate and distribute large amounts of power; this project utilizes a small-scale approach to wind energy

Traffic – the movement of vehicles on roadways that is characterized by high concentration and high speed movement

Vertical axis wind turbines (VAWTs) – wind turbine design where the main rotor shaft is arranged vertically, generally considered less efficient than HAWTs because of lower rotational speed, but does not need to be pointed directly into the source of wind

Viability – in terms of this research project, the level of economic return a system would create that dictates whether or not the system is worth implementing. Example: a viable system would have a short return-of-investment period, where funds used for the turbine, maintenance, installation, generator, etc. would be made back within five to ten years.

Wake – a region of recirculating air that flows immediately after a moving or stationary body, that can be explained through fluid dynamics

Wind farms – multiple large-scale wind turbines that are used in commercial energy production, generally subsidized by the government due to its zero-emission energy generation; comparable to a coal or nuclear power plant but for wind

Wind turbine – a device that converts the kinetic energy of wind into mechanical energy

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