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Assessing the Structural, Driver and Economic Impacts of Traffic Pole Mounted Wind Power Generator and Solar Panel Hybrid System

Anuj Sharma Ph.D.

University of Nebraska at Lincoln, asharma3@unl.edu

Justice Appiah Ph.D.

University of Nebraska–Lincoln

Scott K. Rosenbaugh

University of Nebraska–Lincoln, srosenbaugh2@unl.edu

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Anuj Sharma, Ph.D.

Assistant Professor
Department of Civil Engineering
University of Nebraska-Lincoln

Justice Appiah, Ph.D.

Postdoctoral Research Associate

Scott Rosenbaugh

Research Engineer



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MATC

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Anuj Sharma, Ph.D.
Assistant Professor
Department of Civil Engineering
University of Nebraska-Lincoln

Scott Rosenbaugh
Research Engineer
Department of Civil Engineering
University of Nebraska-Lincoln

Justice Appiah, Ph.D.
Postdoctoral Research Associate
Department of Civil Engineering
University of Nebraska-Lincoln

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Abstract

This project evaluates the physical and economic feasibility of using existing traffic infrastructure to mount wind power generators. Some possible places to mount a light weight wind generator and solar panel hybrid system are: i) Traffic signal pole and ii) Street Light pole. Traffic signal poles can themselves have multiple designs depending on type of mount (mast arm vs. span wire) and the width of the intersection (load carried) etc. The close proximity of street light poles and traffic signal poles to the traffic cabinets, which can be used for storing the battery banks, make them good candidates to mount the hybrid system. This project assesses the structural impacts of the hybrid system on different poles listed above. Lincoln standard plans will be used for identifying the pole and foundation design. Structural analysis involves a first principal for wind load analysis and an explicit finite element analysis using LS-Dyna for evaluating fatigue. Methodologies to conduct economic analysis are developed. Economic impacts of the proposed wind power system were evaluated by a before and after study at a test intersection in Lincoln, Nebraska. A cost and benefit analysis was performed to identify the economic efficiency at the test site.

Executive Summary

The transportation sector consumes about 28% of the total energy consumed by all sectors in the United States. The economic crisis the United States has witnessed over the past decade, coupled with an increased concern for the future of the environment, has created a push towards the production of renewable energy systems. Renewable electric power production in the public right-of-way will cut the overall power needed to operate and maintain highway systems and, therefore, will reduce highway agency operating costs.

Wind power generators are innovative designs that harness the earth's natural energy. Large scale designs of these structures have been efficiently implemented throughout the country, producing high levels of energy and ultimately substantial monetary savings. This project investigated dynamic effects of mounting smaller wind power generators on existing transportation infrastructures, and evaluated the economic feasibility.

This project assesses the structural impacts of the hybrid system on different traffic signal poles. Local wind data was analyzed to produce equivalent gust forces for the applied loading to the structures. Three separate loading scenarios were examined: i) alternative vortex shedding on a traffic signal, ii) alternative vortex shedding on a luminaire pole, and iii) direct drag on a traffic signal. Both analytical and numerical methods were used to obtain solutions for peak displacements and corresponding overturning moments associated with these loading conditions.

Methodologies were developed to analyze the economic efficiency of the wind generator system. A cost and benefit analysis was performed to identify the economic efficiency at the test site.

Chapter 1 Introduction

The transportation sector consumes about 28% of the total energy consumed by all sectors in the United States, according to the Energy Information Administration's 2010 statistics (EIA, 2010). The economic crisis that the United States has witnessed over the past decade, coupled with an increased concern for the future environment, has created a push towards the production of renewable energy systems. Renewable electric power generation within the public right-of-way will cut the energy needed to operate and maintain the highway systems, and therefore, will reduce highway agency operating costs. The excess power generated by renewable energy systems will generate additional revenue for highway agencies. The use of renewable electric power will also promote the development of green roadways.

In this project, the feasibility of mounting a wind power generator and solar panel hybrid system on an existing traffic signal pole and street light poles will be evaluated. Figure 1.1 presents a hypothetical sketch for the traffic pole mounted wind power generator. The electric power generated can be used to supply power to the roadway/traffic signal light and the excess power generated can be supplied to the main grid. The deployment of the proposed wind power generators on existing infrastructure can dramatically change the role of the public right-of-way from an energy consumer to an energy producer.

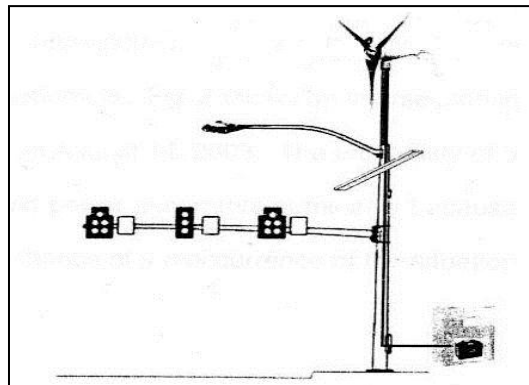


Figure 1.1 Hypothetical Sketch of a Traffic Pole Mounted Wind Generator

The distributed renewable power generation will significantly increase the security, reliability, efficiency, quality, flexibility, and sustainability of the electric power supply. Before a large scale deployment of wind power generators, decision makers need a detailed analysis of these devices on the economics, sustainability, and safety of the transportation system. Both structural impact and economic efficiency impact have been analyzed in this study. We identified the costs associated with structural changes necessitated by the proposed renewable wind power system (RWPS). The economic impact analysis in this study would facilitate informed decision making for wide scale deployment of wind generators and solar panels on traffic signal poles.

Chapter 2 Current State of Practice

Sustainable transportation systems will benefit by using the existing transportation infrastructure as a backbone to generate renewable energy. Most of the current research in sustainable transportation deals with renewable fuels but few literatures exist about the renewable energy projects on roadway infrastructures. Current projects with different renewable applications in transportation infrastructures in the United States are as summarized in Appendix A.

2.1 Wind Energy projects on Transportation Infrastructure

Wind is a clean energy source and has been used in many industries. The typical site for small wind systems is in rural areas, because the best wind resource for generating electricity is strong wind blowing over a flat landscape. Urban and suburban areas have many buildings, trees, signs and other obstacles which disrupt available wind resources. There have been some wind energy projects in transportation infrastructures in several states.

Maryland State Highway Administration (MD SHA) installed a small vertical wind turbine to light an LED overhead sign in Western Maryland in 2007(American Public Power Association, 2007). The project cost \$10,000. The wind turbine is designed to be used for over 20 years and cut 80% of the electricity cost of the LED sign.

In June 2009, MD SHA installed a wind turbine pilot renewable energy project (The Bay Net, 2005). Based on wind assessments conducted by the Maryland Energy Administration, MD SHA installed a small, 60-foot tall wind turbine at the back parking lot of the Westminster Maintenance Facility in Carroll County. This project is aimed to determine the feasibility and the effectiveness of using wind energy to help power SHA facilities. The wind turbine was chosen in this project because of the ease of installation, cost and maintenance compared to other

technologies. The project costs \$25,000 and produces an average of 700 kilowatt-hours per month, reducing more than 1,400 lbs of CO₂ that would otherwise be produced by fossil fuels every month. The designed life of the turbine is 20 to 25 years and it can reduce greenhouse gas emissions equal to driving 15 to 18 automobiles 150,000 miles each. The turbine operation doesn't cause any noise or visually intrusive problem.

The Massachusetts transportation and environmental officials plan to install a 400-foot-tall wind turbine of a rated 1,500 kilowatts capacity at a 68-acre, state-owned site adjacent to the Massachusetts Turnpike's Blindfold Rest Area (Shoemaker, 2010). This site was chosen based on the size of the land, its proximity to the electrical grid and high elevation. The expected wind energy production is 3,000 megawatt-hours every year, enough to provide electricity to approximately 400 households. The production will be sold to Western Massachusetts Electric Company or another utility provider. Solaya Energy will design, construct and finance the wind turbine system. It will lease the land and pay rent equal to 3.5% of annual power sales, or approximately \$16,600 for the first year of operations. Turnpike Authority is guaranteed a minimum rent of \$15,000 each year over the 20-year lease period.

2.2 Wind and Solar Hybrid Systems

Wind resources vary by time of day and season. A sufficient wind resource is critical to make wind energy economical. Wind and solar can compensate each other by integrating wind and solar generation in one system.

Many parking facilities have been designed to use both wind and solar energy. The Canopy Airport Parking in Denver, Colorado, opened in November 2010, is said to be the greenest parking facility in the world (Canopy Airport, 2010). The parking lot is built with 16,900 watts solar arrays (fig 2.1), a 9,600 watts wind turbine farm and geothermal energy

generation. The renewable energy technologies help the building save 70% compared to a similar building without the energy savings additions, and provide free charging to electric and hybrid vehicles at the parking lots.



Figure 2.1 Solar Panels Installed at Canopy Airport Parking (source: Car Stations)

Researchers from the University of Minnesota developed the solar/wind hybrid powered street light to study the benefit of renewable energy in supplying rural Intelligent Transportation System (ITS) applications (Kwon, Weidemann & Cinnamon, 2008). The system was installed in the Minnesota Department of Transportation's District-1 parking lot, consisting of a 130 watts solar panel and a 400 watts small wind turbine, as shown in figure 2.2. A two-year field test found that wind can provide supplementary energy when solar energy is not sufficient to power the lighting applications. In many rainy and snowy days when solar radiation is deficient, wind is strong and can provide alternative energy resources. This study also suggests that a solar/wind powered system is cheaper than a grid –tied system for most remote ITS applications. Solar/wind

generators, along with sufficient battery storage, can provide a reliable power source for remote ITS applications.



Figure 2.2 Solar/Wind Hybrid Powered Street Light Installed in Minnesota

2.3 Solar Energy projects on Transportation Infrastructure

In recent years, the use of photovoltaic (PV) solar energy technology for electric power generation and distribution has been incorporated within the highway right-of-way in several European countries, as discussed in next section. In the United States, the first solar highway project was conducted by the Oregon Department of Transportation (Oregon Office of Innovative Partnerships and Alternative Funding, 2008). Ground-mounted PV array was installed at the interchange of I-5 and I-205 and connected to the power grid for clean electricity

generation and distribution. The project finished in December 2008 and cost \$1,280,000 with an annual electricity production of 112,000 kilowatt-hours. It provides 28% of the power for the interchange.



Figure 2.3 Oregon Solar Highway (source: Oregon Live.com)

The Hawaii Department of Transportation plans to install a solar photovoltaic power system at Lihue Airport (Cooler Planet, 2009). The systems are expected to produce 1,200,000 kilowatt-hours of energy each year. Over the system's 20 year lifetime, the arrays will offset up to 26,000,000 lbs of CO₂ emissions, the equivalent of removing more than 1,400 cars from the road.



Figure 2.4 Solar Power Systems at Lihue Airport in Hawaii (source: Hawaii DOT)

The airport operations officials in El Paso, Texas, installed solar-powered lighting in the facility's long-term, overflow parking lot (Hawaii DOT, 2009.). The project, completed in March 2010, costs \$330,000, which is about 60% less than a standard lighting installation. The solar lighting project for the 2,200 space parking lot was funded through the airport capital improvement budget. The solar lighting is estimated to save the city \$40,000 per year in electricity costs.



Figure 2.5 Solar-powered Lighting at El Paso Airport, TX (source: www.elpasotexas.gov)

A 1-megawatt solar cell parking lot of the Manheim NJ Auto Dealers Exchange in Bordentown, New Jersey was constructed in 2010 (Sandru, 2010). More than 5,000 photovoltaic panels were installed within a total area of 104,000 feet². The panels were tied in to one single meter via 11 separate inverters. The system is connected to the grid, and will generate more than 1,000 megawatts per year, which is roughly the amount required to power 114 households. The 1,900,000 lbs of reduced CO₂ is equivalent to annual emissions from 158 cars.



Figure 2.6 Solar Cell Parking Lot in Bordentown, NJ (Source: The Green Optimistic)

Many “green rest areas” or “Eco-Friendly Rest Areas” along the national highways are designed as energy saving buildings, like the I-89’s Green Rest Stop in Sharon, Vermont and the rest areas on U.S. Highway 287 west of Chillicothe, Texas. Some of the green rest areas also have renewable energy production facilities. The North Carolina Department of Transportation opened the Northwest North Carolina Visitor Center on Oct. 1 2009, which is located on the

northbound side of U.S. 421 in North Wilkesboro (NCDOT, 2009). The 10,030-square-foot green rest area cost \$12,000,000 to build. It has roof-mounted solar panels to preheat water for restrooms. The 14 photovoltaic panels installed atop the building are expected to produce nearly 4,400 kilowatt hours per year.

2.4 Summary

Renewable energy has great potential in the transportation sector. However, there is still a lack of standard policies and tools to measure effectiveness for using existing transportation infrastructure to generate renewable energy. Most of the current deployments are individual efforts by state or local agencies to test a new technology. There is a strong need of documenting these scattered efforts and provide some guiding business models that can be followed for such implementation. There is also a need for developing guidelines for assessing economic, social and environmental impacts.

Chapter 3 Physical Feasibility Check

The first step to conduct an RWPS project is to investigate the physical feasibility at a desired site. The criteria of a feasible site for an RWPS include the requirements on traffic pole structure, zoning laws and site topography. Wind turbines make noise and may cause aesthetics and ecological problems. Noise can be during the construction and operation of the system. The ecological impact can be the increased number of bird kills near the site of the wind turbine. The wind turbines used in this project are small turbines which make less noise, shadow and visual impact. Potential negative impacts should also be considered prior to the project implementation. In this chapter, we discuss the zoning-related issue and the requirements on surrounding and topography. The structural analysis will be discussed in next chapter and the negative impact will be evaluated in Chapter 5.

3.1 Zoning Laws

Zoning ordinances dealing with small wind turbine installation need to be determined prior to installation of an RWPS. Zoning ordinances vary at different levels of government. Federal zoning laws have some restrictions to protect air traffic, which affects turbine towers higher than 200 feet and turbines installed within 10 miles of air strips. State and local zoning laws should also be checked. The zoning laws can be obtained from the local planning department. Usually, the state energy office has references for the placement of small wind systems.

The City of Lincoln Planning Department provided the zoning-related regulations for our case study. There was no statewide law in Nebraska that specifically affects wind turbine tower construction. The Lincoln Planning Department is able to grant a special permit to allow wind energy systems to exceed the height provisions of any zoning district, except the agriculture and

agricultural residential zones. The zoning districts are shown in figure 3.1. Most zoning ordinances have a height limit of 35 feet. As the RWPS would be installed at the height of the signal pole, no action was needed. The local traffic operation agency confirmed the legality to mount the RWPS on traffic poles.

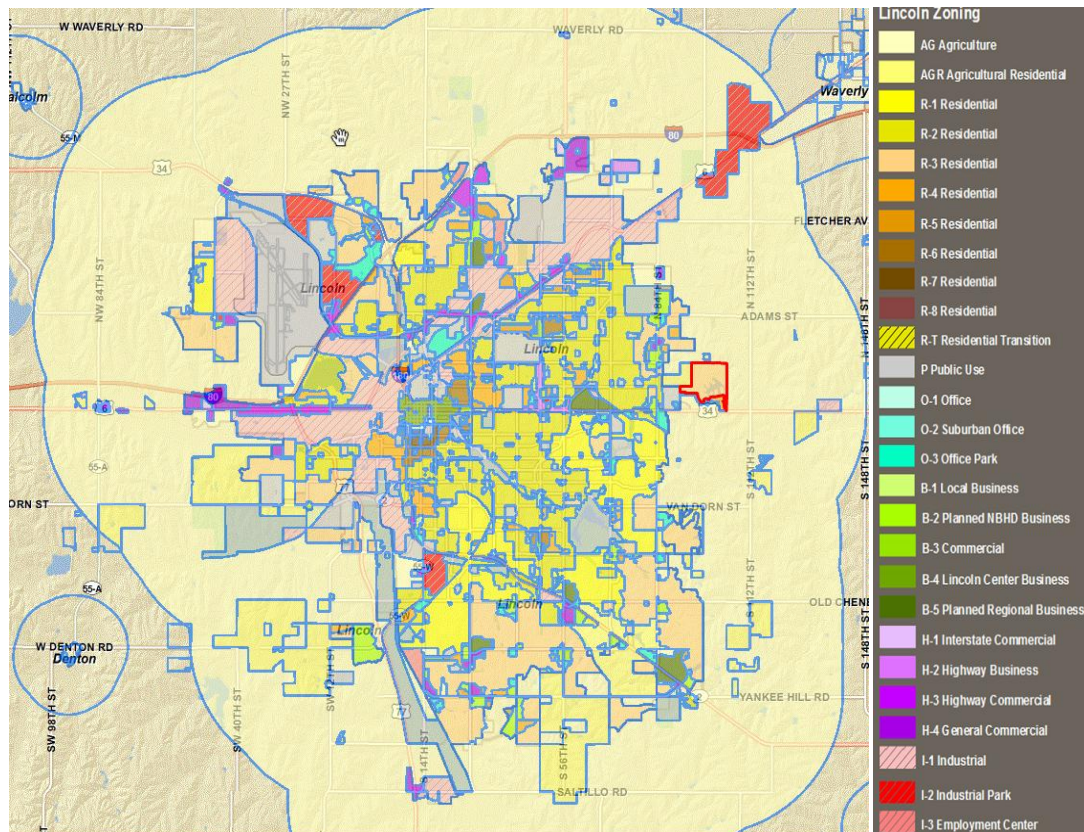


Figure 3.1 Lincoln Zoning Districts (source: City of Lincoln Planning Department)

3.2 Surrounding and Topography

The height of the turbine tower, nearby buildings and the topography of the site all affect the wind energy production. Because of zoning restrictions and fixed heights of existing traffic poles, it's impossible to increase the energy production by increasing turbine mounted height. To maximize production, turbines should be sited upwind of any obstacles to harness the

strongest wind. Buildings, trees, signs and other obstacles can disrupt wind flow and cause turbulence. Turbulence reduces the power output and causes additional stress on the wind turbine and signal pole. The efficiency of the wind turbine is also decreased if wind direction is not horizontal due to the obstruction created by any obstacles. Especially in urban areas, the built up environments have a significant impact on the incoming wind and therefore make it difficult to find a suitable site for a turbine (Sinisa, Campbell & Harries, 2009). The obstacles to wind in the urban and suburban areas raise the effective ground level for wind to the height of the surrounding structures (Sharman, 2010). Gipe (2009) found that the effect of any obstacle of height H creating turbulence is not significant at a distance of $20 H$ or greater from the obstacle, as illustrated in figure 3.2. The topography of the site also affects the potential performance of the wind turbine, as shown in figure 3.3 (Hamlen & Meadows, 2010). A field study is necessary to check the surroundings and terrain at the subject site. In case an obstruction is present, it becomes critical to have a site-specific evaluation.

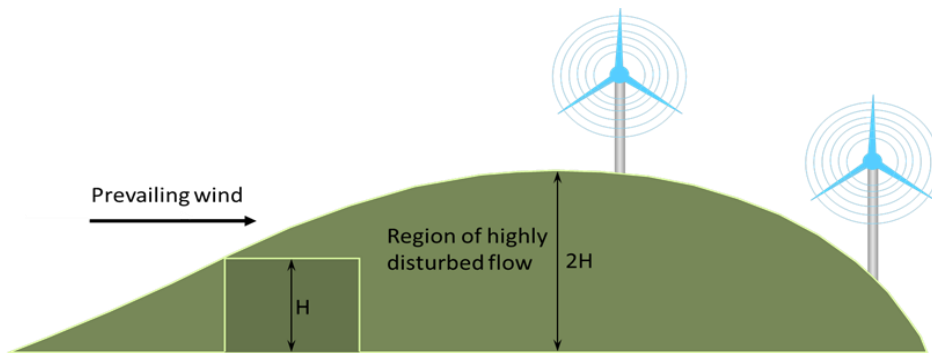


Figure 3.2 Obstruction of the Wind by an Obstacle of Height H

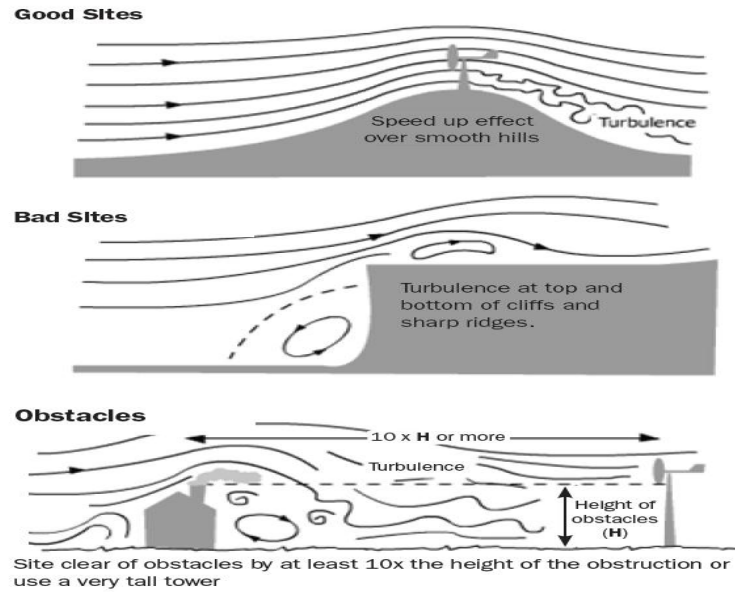


Figure 3.3 wind turbulence and obstruction varies by site

The intersection studied in Lincoln is far away from residential areas. It is close to a shopping center, but no obstacle exists within 250 feet around it. There is also no obstacle higher than 25 feet within 500 feet from the intersection.

Chapter 4 Structural Analysis

4.1 Background

Wind power generators are innovative designs that harness the earth's natural energy. Large scale designs of these structures have been efficiently implemented throughout the country, producing high levels of energy and ultimately substantial monetary savings. Structural impact is important for an RWPS project because the structural stability of poles is a critical limit for the design and selection of wind turbine generators. The pole specifications can be found at the local traffic operation agency. Wind data at the subject site is also needed for conducting the structural analysis. This project conducted a study to investigate the dynamic effects of mounting a wind power generator onto existing luminaire structures. Local wind data was analyzed to produce equivalent gust forces for the applied loading to these structures. Three separate loading scenarios were examined: i) alternative vortex shedding on a traffic signal, ii) alternative vortex shedding on a luminaire pole, and iii) direct drag on a traffic signal. Both analytical and numerical methods were used to obtain solutions for peak displacements and corresponding overturning moments associated with these loading conditions. The total calculated stresses in each anchor bolt and two out of the three poles from these moments were deemed to be acceptable according to suggested AASHTO limits. Lincoln Public Works and Utilities Department provided us with the signal pole specifications and wind data.

4.2 Structures

4.2.1 Traffic Signal Poles

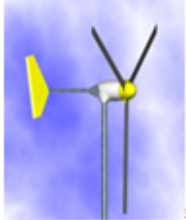
The city of Lincoln standard plans for signal mast arms and luminaire poles were used as a basis for consideration. Minimum design heights, maximum mast arm distances, and corresponding sectional properties were chosen from these documents for analysis. The selection

of the mast arm provided a worst case loading scenario, whereas the design height provided a baseline limit case. Therefore, if the combination design was deemed infeasible for this scenario than any other existing design standard would also be infeasible.

4.2.2 Wind Generator and Solar Panels

The wind turbine selected for this analysis was the BWC XL.1 manufactured by Bergey Windpower Co., Inc. This turbine weighs 75 lb, is designed for installation heights greater than 30 ft and requires 44 in. of blade clearance. Although no specific dynamic loading characteristics could be obtained on the BWC XL.1 wind turbine, the manufacturer specifies a maximum thrust load of 200 lb. for wind speeds up to 120 mph. Details of the wind generator used in the analysis are shown in table 4.1.

Table 4.1 Wind Generator Details

Windmill	Rated Power	Weight	Rotor Diameter	Cut-in Wind Speed	VAWT/HAWT	Price	
Bergey XL.1	1-kW	75-lbs	2.5-m	2.5-m/s	hwt	2790	

For this analysis, the solar panels were given an area of 15 ft² and up to two panels could be installed on a single traffic signal structure. Although the orientation angle at which a solar panel is installed depends on the specific site location, all solar panels were conservatively

assumed to be mounted at a 45-degree angle from vertical. Additionally, the solar panels were assumed to face the same lateral direction as the traffic signals.

4.3 Critical Design Configurations

The critical attachment locations for each of the energy generating devices were selected to maximize the stresses to the existing system. The only restriction to the attachment locations was that the devices would not be located on the mast arm. Thus, the loads and stresses imparted to the pole would be maximized if the wind turbine and solar panels were mounted at the highest possible locations. As a result, the wind turbine was always mounted to the top of the traffic pole (above the luminaire). To ensure the turbine blades had adequate clearance, the turbine was mounted at a height of 5 ft greater than the nominal mounting height of the luminaire. For example, if the nominal height of the existing luminaire system was 40 ft, the pole was extended such that the wind turbine was centered at a height of 45 ft.

Although a wind turbine was to be included in all design configurations, the number of solar panels could vary up to two per system. Therefore, three critical design configurations were identified: i) a wind turbine and two solar panels; ii) a wind turbine and a single solar panel; and iii) a wind turbine only. These design configurations are illustrated in figure 4.1. Higher mounting locations would result in increased loads and stresses applied to the existing structure. Thus, when two solar panels were to be used, the first was mounted at the top of the existing pole (outside the required blade clearance) while the second was located near the mast arm attachment point. When only a single solar panel was to be used, it was mounted at the mast arm attachment point.

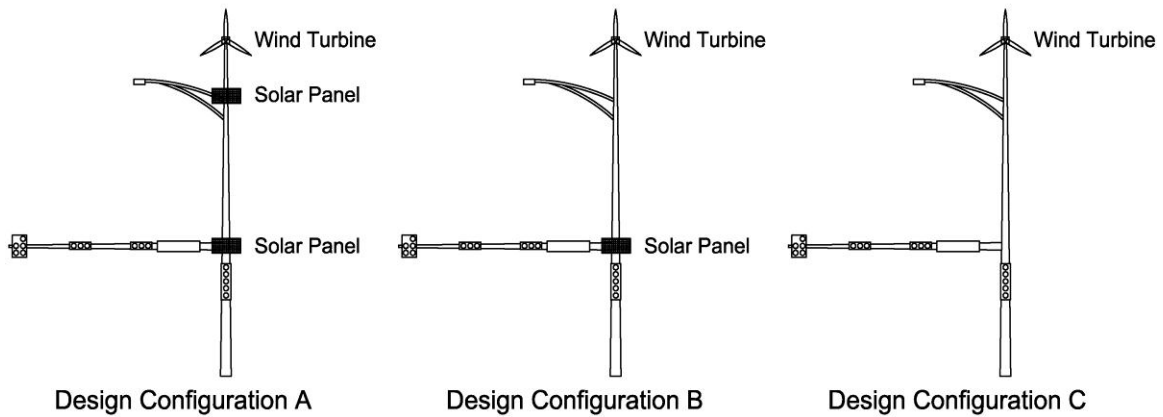


Figure 4.1 Design Configurations for Energy Generating Devices

4.4 Analysis Procedure and Methodology

Ideally, the dynamic effects that wind loading has on the proposed design configurations would be evaluated through physical testing. However, results of such testing were not available at the time this analysis was conducted. Additionally, attempting to evaluate the systems under variable, dynamic loads would be extremely difficult as wind magnitude and frequency combinations are endless and each can cause drastically different stresses. Therefore, the traffic signal pole systems were evaluated utilizing the static, allowable stress analysis outlined in the 2009 AASHTO Standard Specification for Structural Supports for Highway Signs, Luminaires, and Traffic Signals (AASHTO, 2009). Details of the AASHTO recommended evaluation procedure are described in the following sections. A sample calculation for a traffic signal pole used in Lincoln is shown in Appendix B.

4.4.1 Design Load Cases

According to table 3-1 of the AASHTO document referred above, four load combinations were necessary to evaluate each system's design configurations. However, load case I consisted of only the dead load of the structure. Since the addition of the wind turbine and solar panels

would add minimal weight to the traffic pole structure, this load case was ignored. Therefore, only load combinations II, III, and IV were utilized in the analysis and are shown in table 4.2.

Table 4.2 Load Combinations

Load Combination	Applied Loads	Design Category
II	(Dead Load) + (Wind Load)	Strength
III	(Dead Load) + (Ice Load) + $\frac{1}{2}$ (Wind Load)	Strength
IV	(Natural Wind Gust Load)	Fatigue

Load combinations II and III were formulated to evaluate the ultimate strength of the structure as they combine to the system's self-weight (dead load), wind load applied to the structure, and the weight of ice coating the surface of the structure. Since these peak loads are rarely observed, AASHTO allows for a 33% increase in allowable stress. Therefore, the calculated allowable stresses were multiplied by an allowable stress increase factor (ASIF) of 1.33.

Load combination IV was designed to evaluate fatigue in the structure caused by three different dynamic loads: i) galloping-induced cyclic loads of the mast arm; ii) natural wind gusts, and iii) truck-induced wind gusts. However, the fatigue design loads for the galloping-induced cyclic load and the truck-induced wind gusts acted in a different plane than the loads of the additional wind turbine and solar panels. Therefore, only the natural wind gust load case was evaluated for fatigue as the applied loads would be magnified by the addition of the energy generating devices.

Each pole was tapered so the mass of the pole could not be simply halved at each node. The middle node carried two-thirds of the weight of the pole, to account for the heavier section on the bottom. For the traffic signal, the mass of the mast arm and lights was added to the middle node. For each structure, the mass of the luminaire arm, luminaire, and turbine were added to the top node.

Due to the tapered geometry of each pole, the moment of inertia of the structure was a function of the height. As a result, the stiffness was also a function of height. To simplify calculations, average values of the moments of inertia were used to determine the stiffness.

The wind load was simplified down into a single point load applied to the top of the structure. This was believed to be a conservative approach as the static displacement was larger than if a uniformly distributed load were used. Ultimately, the stiffness parameters were determined assuming a unit load was applied to the top of the structure.

4.4.2 Loading

The dead loads of the traffic signal mast arm and pole were calculated by multiplying the total volume of steel of each element by the density of the steel, which was estimated to be 0.284 pounds per cubic inch. The weight of the existing traffic signal attachments were taken from the City of Lincoln Standard Plans for Mast Arm Poles (L.S.P 85) (City of Lincoln, 2010) and Valmont's City of Lincoln pole designs (Valmont Industries, 2008). The weights of the wind turbines and solar panels were obtained from the manufacturers' specifications (Bergey Windpower, 2001).

For the ice load, the 2009 Standard Specification of Structural Supports for Highway Signs, Luminaires, and Traffic signal specifies to apply a 3-pound per square foot load around the surfaces of the structural supports, traffic signals, horizontal supports and luminaires.

Therefore, the ice load was calculated as the surface area of each element multiplied by 3 pounds per square foot.

Wind data was collected at four locations around Lincoln, Nebraska. The collection process began on May 5th, 2005 and concluded on June 17th, 2010. The average wind speed, wind direction, gust speed and gust direction were recorded. Gust data points were extracted and analyzed separately from the total data set. The average frequency of the gusts was over 2,400 seconds. However, this value was believed to be influenced by unrealistically long lull periods. The most frequently occurring period was 602 seconds and the median period was 612 seconds. Therefore, the forcing frequency of natural wind gusts was too long to consider applying a sinusoidal load. It should be noted that the effect of passing trucks was ruled out because wind direction did not match traffic direction.

Instead of a harmonic forcing function, a single, rectangular pulse was used where the magnitude was equal to approximately 1/3 of the straight-line wind for the region, or 30 mph. The duration of the pulse, t_d , was assumed to be 3 seconds. This combination of magnitude and duration was selected to model a single wind gust.

A bearing pressure caused by the wind can be estimated from the wind velocity and the following equation (given in AASHTO Standard Specifications for Structural Supports and Highway Signs, Luminaires, and Traffic Signals):

$$P_z = 0.00256K_zGV^2I_rC_d \quad (4.1)$$

Where P_z = Design wind pressure (psf)

K_z = Height and exposure factor

G = Gust effect factor

V = Wind velocity (mph)

I_r = Importance factor

C_d = Drag coefficient

Only two of the factors in the above equation varied depending on structural object and shape. The height and exposure factor, K_z , varies with height from about 0.94 to 1.16 for the heights associated with the traffic structures being analyzed (see table 3.5 in the AASHTO document for more details). The drag coefficient, C_d , varies by the type of structural object and in some instances the shape (e.g., round vs. square poles). Details of the drag coefficients can be found in table 3.6 of the AASHTO document (the solar panels were treated as sign/signal attachments when calculating the drag coefficient). These two factors were calculated independently for each component of the traffic signal structure so that the design loads could be applied as a point load at the center of each structural attachment. The design load on a vertical pole was calculated by summing the load on 1 ft segments through its entire length and applying the total load at the center of the pole.

Since there was not data available for the drag coefficient or the effective projected area of the wind turbine, the design wind load was taken as the maximum thrust specified by the manufacturer, which was 200 lbs. This approach was assumed to be conservative as the maximum thrust was calculated for a 120 mph wind while the design wind speed in equation 3.1 was only 90 mph.

For the fatigue design load combination, the natural wind gust pressure was calculated from equation (11-5) of the 2009 Standard Specification for Structural Supports for Highway Signs, Luminaires, and Traffic Signals. The natural wind gust pressure was multiplied by the effective projected areas of the traffic signal elements and solar panels to obtain the natural wind gust load. Again, since an effective projected area was not available for the wind turbine, the

natural wind gust force was conservatively taken as the maximum wind turbine thrust force provided by the manufacturer, 200 lbs.

$$P_{NW} = 5.2C_dI_F \quad \text{AASHTO (11-5)}$$

Where: P_{NW} = Natural Wind Gust Pressure (psf)

C_d = Drag Coefficient

I_F = Fatigue Importance Factor

All of the preceding parameters were selected from the AASHTO reference from which equation 3.1 was taken. Selection was based on the height and shape of the structure. The parameters and resulting pressures for a 27.5-ft traffic signal pole and 40-ft luminaire pole are given in table 4.3.

Table 4.3 Wind Pressure Summary.

Wind Pressure		
	Traffic Signal (27.5')	Luminaire (40')
K_z	1.00	1.04
G	1.14	1.14
V (mph)	30.00	30.00
C_v	0.93	0.93
I_r	0.86	0.86
C_d	1.20	0.50
P_z (psf)	2.73	1.19

4.4.3 Identification of Critical Sections

Under the design loads described in the previous sections, the entire traffic signal structure would have internal stresses imparted on it. However, the critical section of the traffic pole was identified as the base of the pole where the loads and stresses would be maximized.

Therefore, the base reactions were used to evaluate the structural integrity of both the base of the pole as well as the anchor bolts. All other sections and connections were assumed structurally adequate including the connections for the wind turbine and solar panels as well as the welded connection between the pole and the base plate (which is typically over designed).

It should be noted that only the loads and stresses on the superstructure of the traffic signal poles were evaluated. Thus, the existing pole foundations were also assumed adequate and were not evaluated. However, the foundation strength should be checked before the wind turbines and solar panels are applied to existing traffic poles.

4.4.4 Allowable Stress Calculations

The applied stresses in the base of the pole were compared to the allowable stresses determined from the allowable stress design method according to the 2005 Specification for Structural Steel Buildings that is contained in the 13th edition of the American Institute of Steel Construction (AISC) Manual (ANSI/AISC 360-05) (AISC, 2005).

4.4.4.1 Allowable Stress in Pole

The equations used to calculate the allowable stresses in tension, bending, torsion and shear are listed in table 4.4. For a detailed description of each equation and its variables, please refer to the appropriate AISC equation numbers listed in the right column of table 4.4.

In addition to checking the individual applied stresses in the form of axial stress, shear stress, torsion stress, and bending stress against their respective allowable stresses, the combined interaction effect of these forces was also evaluated. Thus, the governing limit state for the strength analysis of the pole section was controlled by equation (H3-6) of the AISC manual, as shown below. The result of this equation is a scalar number which is required to be less than or equal to 1.0 for an acceptable design.

$$\text{Unity Check} = \left(\frac{P_r}{P_c} + \frac{M_r}{M_c} \right) + \left(\frac{V_r}{V_c} + \frac{T_r}{T_c} \right)^2 \leq 1.0 \quad \text{AISC (H3-6)}$$

Where:

- P_r = Required Axial Strength (kips)
- P_c = Design Axial Strength (kips)
- M_r = Required Bending Strength (kip-in.)
- M_c = Design Bending Strength (kip-in.)
- V_r = Required Shear Strength (kips)
- V_c = Design Shear Strength (kips)
- T_r = Required Torsional Strength (kip-in.)
- T_c = Design Torsional Strength (kip-in.)

4.4.4.2 Allowable Stress in Anchor Bolts

The available tensile strength of the bolt was calculated using equation (J3-2), which accounts for shearing effects of the bolts due to the shear and torsion reaction forces. The nominal tensile stress modified to include the effects of shearing stress was calculated from equation (J3-3b) for the allowable stress design method. The nominal tensile stress and the nominal shear stress were calculated in accordance with table J3.2 of AISC 360-05.

$$R_n = F'_{nt} A_b \quad \text{AISC (J3-2)}$$

$$F'_{nt} = 1.3F_{nt} - \frac{\Omega F_{nt}}{F_{nv}} f_v \leq F_{nt} \quad \text{AISC (J3-3b)}$$

Where:

- R_n = Available Tensile Strength of Bolt (kips)
- F'_{nt} = Nominal Tensile Stress Modified to Include Effects of Shearing Stress (ksi)
- A_b = Unthreaded Area of Bolt (in.²)
- F_{nt} = Nominal Tensile Stress (ksi)
- F_{nv} = Nominal Shear Stress (ksi)
- Ω = Safety Factor
- f_v = Required Shear Stress (ksi)

4.4.4.3 Allowable Stress for Fatigue Resistance

The allowable stresses for fatigue limits were taken from table 11-3 of the 2009 AASHTO Standard Specification for Structural Supports for Highway Signs, Luminaires, and Traffic Signals. AASHTO qualified the pole as stress category A and the anchor bolts as stress category D. Therefore, the allowable stress for fatigue design of the pole was 24 ksi and the allowable fatigue design stress of the anchor bolts was 7 ksi.

Table 4.4 Allowable Stress Calculations for the Base of the Traffic Pole

Loading Type	Equation	AISC Equation Number
Bending Moment (non-compact sect.)	$F_{cr} = \left(\frac{0.021E}{\frac{D}{t}} + F_y \right)$	(F8-2)
Bending Moment (slender sect.)	$F_{cr} = \frac{0.33E}{\frac{D}{t}}$	(F8-4)
Torsion	$T_n = F_{cr}C$	(H3-1)
	$C = \frac{\pi(D-t)^2t}{2}$	Note H3.1
	$F_{cr} = \frac{1.23E}{\sqrt{\frac{L}{D} \left(\frac{D}{t} \right)^{\frac{5}{4}}}} \leq 0.6F_y$	(H3-2a)
	$F_{cr} = \frac{0.60E}{\left(\frac{D}{t} \right)^{\frac{3}{2}}} \leq 0.6F_y$	(H3-2a)

Axial Force	$\text{for } F_e > 0.44QF_y: F_{cr} = Q \left[0.658 \frac{QF_y}{F_e} \right] F_y$	(E7-2)
	$\text{for } F_e < 0.44QF_y: F_{cr} = 0.877F_c$	(E7-3)
	$Q = \frac{0.038E}{F_y \left(\frac{D}{t} \right)} + \frac{2}{3}$	(E7-19)
	$F_e = \frac{\pi^2 E}{\left(\frac{KL}{r} \right)^2}$	(E3-4)
Shear	$V_n = \frac{F_{cr} A_g}{2}$	(G6-1)
	$F_{cr} = \frac{1.60E}{\sqrt{\frac{L_v}{D} \left(\frac{D}{t} \right)^{\frac{5}{4}}}} \leq 0.6F_y$	(G6-2a)
	$F_{cr} = \frac{0.78E}{\left(\frac{D}{t} \right)^{\frac{3}{2}}} \leq 0.6F_y$	(G6-2b)

4.5 Evaluation Results and Recommendations

Twenty-two traffic signal designs by Valmont for the City of Lincoln were analyzed with three different luminaire mounting heights, three design configurations, and three load combinations. This resulted in a total of 594 analyses to determine the structural feasibility of mounting the wind turbine and solar panel attachments to existing traffic signal designs. A summary of the evaluation results is shown in table 3.5 in which the Valmont pole designations correspond to the designation keys for the twenty-two different Valmont traffic signals for Lincoln. A star in pole designation indicates a variable character in which any number/character can replace the star. The pound signs in the pole designation shall be replaced by the luminaire mounting height of the traffic signal. For example, a designation key of the 40 ft tall system,

LINC-RS-MA2-44-40-12-1, would fall under the Valmont pole designation LINC-RS-MA*-44-##-*-* in table 4.5.

The last three columns in table 4.5 designate which of the attachment design configurations can be added to the existing pole configurations without overstressing the signal pole or anchor bolts. A blank red box indicates that none of the attachment design configurations are recommended for that particular existing traffic signal. An orange box with a “T” indicates that only Design Configuration C (the wind turbine mounted at the top of the traffic signal pole) is recommended for that particular existing system. A yellow box containing “T, 1P” indicates that Design Configuration B (wind turbine mounted at top of pole and solar panel mounted at mast arm height only) is allowable for use. Finally, a green box than contains “T, 2P” indicates the wind turbine can be mounted at the top of the traffic signal pole along with two, 15 square foot solar panels mounted at the top of the pole and at the mast arm height (Design Configuration A in fig 4.1). For example, the Valmont pole with the designation key LINC-RS-MA2-44-40-12-1 (40 ft high) is allowed to have the BWC XL.1 wind turbine mounted at the top of the pole and a 15 ft² solar panel mounted at the mast arm height.

Table 4.5 Traffic Signal Attachment Feasibility Summary

Valmont Pole Designation	Pole Base Diameter (in.)	Pole Base Thickness (ga or in.)	Anchor Bolt Circle Diameter (in.)	Anchor Bolt Diameter (in.)	Signal Arm Span (ft)	Luminaire Mounting Height, ## (ft)		
						50	40	30
LINC-RS-MA*-18-##-*-*	13	7	17	1.5	18		T, 1P	T, 2P
LINC-RS-MA*-20-##-*-*	13	7	17	1.5	20		T, 1P	T, 2P
LINC-RS-MA*-22-##-*-*	13	7	17	1.5	22		T, 1P	T, 2P
LINC-RS-MA*-24-##-*-*	13	7	17	1.5	24		T, 1P	T, 2P
LINC-RS-MA*-26-##-*-*	13	7	17	1.5	26		T, 1P	T, 2P
LINC-RS-MA*-28-##-*-*	13	7	17	1.5	28		T, 1P	T, 2P
LINC-RS-MA*-30-##-*-*	13	7	17	1.5	30		T, 1P	T, 1P
LINC-RS-MA*-32-##-*-*	13	7	17	1.5	32		T	T, 1P
LINC-RS-MA*-34-##-*-*	13	3	17.5	1.75	34	T, 2P	T, 2P	T, 2P
LINC-RS-MA*-36-##-*-*	13	3	17.5	1.75	36	T, 1P	T, 2P	T, 2P
LINC-RS-MA*-38-##-*-*	13	3	17.5	1.75	38	T, 1P	T, 2P	T, 2P
LINC-RS-MA*-40-##-*-*	13	3	17.5	1.75	40	T, 1P	T, 2P	T, 2P
LINC-RS-MA*-42-##-*-*	13	3	17.5	1.75	42	T	T, 1P	T, 2P
LINC-RS-MA*-44-##-*-*	13	3	17.5	1.75	44		T, 1P	T, 2P
LINC-RS-MA*-46-##-*-*	13	3	17.5	1.75	46		T	T, 1P
LINC-RS-MA*-48-##-*-*	15	0.25	20.5	2	48		T	T, 1P
LINC-RS-MA*-50-##-*-*	15	0.25	20.5	2	50			T
LINC-RS-MA*-55-##-*-*	15	0.31	20.5	2	55	T, 2P	T, 2P	T, 2P
LINC-RS-MA*-60-##-*-*	15	0.31	20.5	2	60	T, 2P	T, 2P	T, 2P
LINC-RS-MA*-65-##-*-*	15	0.31	20.5	2	65	T, 2P	T, 2P	T, 2P
LINC-RS-MA*-70-##-*-*	15	0.31	20.5	2	70	T, 1P	T, 2P	T, 2P
LINC-RS-MA*-75-##-*-*	17	0.31	22.5	2	75	T, 2P	T, 2P	T, 2P

*=Wildcard Character

##=Luminaire Mounting Height

T, 2P	= Turbine and Both Solar Panels Can Be Mounted
T, 1P	= Turbine and the Bottom Solar Panel Can Be Mounted
T	= Turbine Only Can Be Mounted
	= No Attachments Can Be Mounted

As expected, fewer of the 50 ft tall pole configurations were approved for the addition of the wind turbine due to the increase in bending stresses that accompany an increase in moment arm/height. Further, all of the 30 ft tall design configurations were approved for at least a wind turbine, Design Configuration C, and most often the two solar panels as well, Design Configuration A. Thus, the height of the existing traffic structure was a key factor in its ability to sustain the loads from the addition of the energy generating devices.

Fatigue failures (load case IV) were only found in the 1.5 inch diameter anchor bolts (the first eight design configurations in table 4.5). The larger anchor bolts satisfied all of the fatigue limitations, and none of the bolts had strength issues (load cases II and III).

Although none of the poles had fatigue issues, there were numerous instances of excessive stresses resulting from the strength design loading cases (II and III). These pole strength failures were observed to be largely the result of loading case II. Only one configuration was found to violate the allowable stress limit due to load case III. Thus, the wind loads from the turbine and solar panels proved too large for the existing traffic signal pole.

Variations from the approved design configurations noted in table 4.5 would be acceptable as long as they reduce the loads on the traffic signal pole. For example, solar panels may be placed at heights lower than the mounting height used in the analysis (i.e., lower than the top of the pole for Design Configuration A). Additionally, the approved design configurations designate the maximum number of energy generating devices that can be utilized on the structure. If a fewer number of solar panels was desired, it would also be acceptable. Further, if an existing traffic pole does not contain a luminaire above the signal mast arm, it would be more likely to contain adequate strength to accommodate the addition of a wind turbine and/or solar panels. Finally, solar panels with an area less than 15 ft² would also be acceptable for use.

It should be noted that the recommendations illustrated by table 4.5 were made utilizing a couple of design assumptions: i) all existing connections (except for the anchor bolts) and new attachments connections have adequate strength capacity to sustain the additional loads, and ii) the foundation of the existing structure has adequate strength capacity to withstand the additional loading. Both of these assumptions should be evaluated before attaching either a wind turbine or solar panels to an existing traffic signal pole.

Finally, this analysis was based on the recommended evaluation procedures of the 2009 AASHTO Standard Specification for Structural Supports for Highway Signs, Luminaires, and Traffic Signals in lieu of actual physical testing. As a result, the dynamic loading effects of the wind turbine had to be reduced to the manufacturer's prescribed maximum thrust of 200 lbs. Although the fatigue analysis conducted in this study was viewed to be conservative, physical testing of the wind turbine would complete the evaluation and provide greater confidence in the final recommendations.

Chapter 5 Economic Impact Analysis

5.1 Background

The city of Lincoln in Nebraska has 418 signalized intersections under its jurisdiction. The total electricity consumption at these intersections is nearly 92,500 kWh per month. Electricity expenditure is 5% of the city's traffic operating budget. The electricity price charged by local utility, Lincoln Electricity Systems (LES), usually changes once per year. The annual inflation rate for utility prices in Lincoln, as stated by LES personnel, is around 2.5 to 3%. This utility price can inflate by as much as 17% if the Cap and Trade gets approved for the U.S.

This chapter investigated the RWPS as an alternative power source for operating signalized traffic intersections. In this chapter, we provide a framework to investigate the physical and economic feasibility to install an RWPS at a desired location. Methodologies to conduct site selection and economic analysis were developed. A case study with subject of the intersection of Nebraska Highway 2 and 84th Street in Lincoln was used to demonstrate the analysis procedure. The case study site includes one 1.0kW 24V wind turbine and four 6V 305Ah batteries. The batteries are designed to support full operations at the traffic signal for 5-6 hours (or flashing operations for 8-10 hours) at 50% battery discharging level.

The benefits of the proposed RWPS are two-fold: i) the power generated by the system can support the existing traffic signals and any excess power produced can be sold back to the power grid; ii) it also provides a source of backup power in case of grid failures and increase the reliability of traffic operations. This study presents the methodology to ascertain the economic benefits of the RWPS for both the cases described above. The costs and benefits of providing an RWPS are stated in terms of dollar values. The decision on installation of an RWPS at a specific site can thus be made using benefit-cost ratio. In case of budget constraints, the methodology

developed in this study can be used to prioritize the investments based on benefit-cost ratios of the prospective sites.

5.2 Negative Impacts

Noise, aesthetics, visual impairment, ecological problems and other potential negative impacts should be considered for wind generator installation and operation. Small wind generators must be approved by the American Wind Energy Association and the noise of turbine should not exceed 60dBA as measured at the closest neighboring inhabited dwelling unit. Wind Turbine sound level during different operation modes can be obtained from manufacture. These sound levels can then be compared to the background noise level at the subject site to identify the significance of turbine noise. The best way to obtain accurate background noise level is a field study with a sound meter. FHWA Traffic Noise Model (FHWA, 1998) provides estimations of traffic noise at different speed limits and distances, which can be used if a field study is not available. The combined level of noises from wind turbine and traffic can be calculated by equation 5.1.

$$L_{\Sigma} = 10 \log \left(10^{\frac{L_1}{10}} + 10^{\frac{L_2}{10}} \right) \quad (5.1)$$

The RWPS would be installed at the height of the traffic pole, so there is no interference with television reception because of the small size of the turbine and the lower height of the pole. Site-specific topography should be investigated to determine the visual impacts. Another common concern with wind turbine is the increased number of bird kills near the turbine site. Turbine manufacturers may provide references on that issue. The impacts on bird kills are usually a concern for large wind turbines.

In the case study, the sound level of the turbine is approximately 50dBA under normal operation measured at 42 ft downstream of turbine tower, as reported by the manufacturer; while

the typical noise levels for passenger vehicles are 72-74dBA at 55 mph measured at a distance of 50 ft (FHWA, 1998). The cumulative noise of a wind turbine and background traffic calculated using equation 5.1 is 74.017dBA, which is much lower than the Lincoln noise ordinance of 84dBA. The presence of a wind turbine would not significantly increase noise level at the studied intersection with speed limit of 55 mph and average volume about 1,100 vehicles per hour on the main approaches.

A study provided by the manufacture and done by the University of Oklahoma shows the small wind turbine has no statistically significant impact on the bird population (Bergey Windpower, 2001). A briefing paper by the Distributed Wind Energy Association shows that small wind turbines are safe if the well-documented practices are followed. Trees and other structures carry greater inherent danger to individuals and property than does a small wind turbine (DWEA, 2010). Thus, none of the above discussed negative impacts were found to be a significant cause of concern for our test site and hence were not considered in the benefit-cost analysis. Below is another figure example with alternative text.

5.3 System Costs

The total cost includes the cost of the RWPS components and costs of installation, operation and maintenance. The cost of an RWPS will vary by system design and hardware used. The RWPS is supposed to be operated by the traffic operation agency, so the operation cost might be determined by the operator's in-kind cost. A small wind turbine is low-maintenance over its life time. The manufacturer should be able to provide a list of maintenance strategies and associated costs.

In the case study, the project installed cost is \$8,223, which includes one 1.0KW wind turbine, one power grid interactive inverter and charger, one power battery monitor, and four 6V

305Ah batteries. Preventive maintenance recommended by turbine manufacturer includes re-greasing the bearings every 8-12 years and checking blade stiffness every 10 years. For the 15-year analysis period, we assume the total operation and maintenance costs to be 5% of the wind turbine cost. The total project cost would be \$8,352.

5.4 Benefits

The benefits from the RWPS include the electricity production and benefits derived from serving as backup power during grid failures. When signals are not operational, most states require reverting to all-way-stop operation. This operation would result in high delays and substantially riskier operations, especially during peak hours or night time when the visibility is low.

5.4.1. Benefit from Electricity Production

The benefit from electricity production includes the reduction in electricity purchases and sales of any excess production. A feasible site should have enough wind resources to make the RWPS economical. The theoretical energy in wind varies with the cube of the wind speed (Wizelius, 2007). Wind speed increases with increasing height above the ground. Wind maps provide an estimate of the potential resources in a given area. Most of the wind maps available are for the height of 50 meters (164 ft) and higher. A wind map of annual wind speed at 10 m (33 ft) is recommended, as the RWPS will be installed on a traffic signal pole. The National Renewable Energy Laboratory and state energy offices are a good source for wind resources. Wind data from roadway weather stations, such as Clarus Initiative and networks operated by local transportation agencies, can also provide useful information.

5.4.1.1 Power consumption reduction

The electricity production from an RWPS will be used to supply the traffic control signals, which would reduce the electricity purchase from the utility service.

The bin Method (IEC, 2005) can be used to estimate the electricity production with wind data and wind turbine power curve. The power curve provided by the manufacturer typically gives the output at different wind speeds with an assumption of sea level air density of 1.225 kg/m^3 . The estimated energy output should be normalized to sea level air density using a wind speed correction.

Usually, the 10-minute average speed is used in the bin method. The 10-minute average wind speed data will be discretized into speed bins with certain bin width, usually 0.5 or 1 m/s. The power output for each corresponding speed bin is obtained from the turbine power curve. The total output can be estimated by summing up the output from each speed bin. The benefits from electricity production can then be calculated from electricity output and utility price.

In the case study, wind and air temperature data from October 2005 to May 2011 were collected from the same weather station used in the structural analysis. The wind speed data were corrected to eliminate the effect of elevation difference. Figure 5.1 shows the distribution of the 10-minute average speed at the subject site, which indicates abundant wind resources.

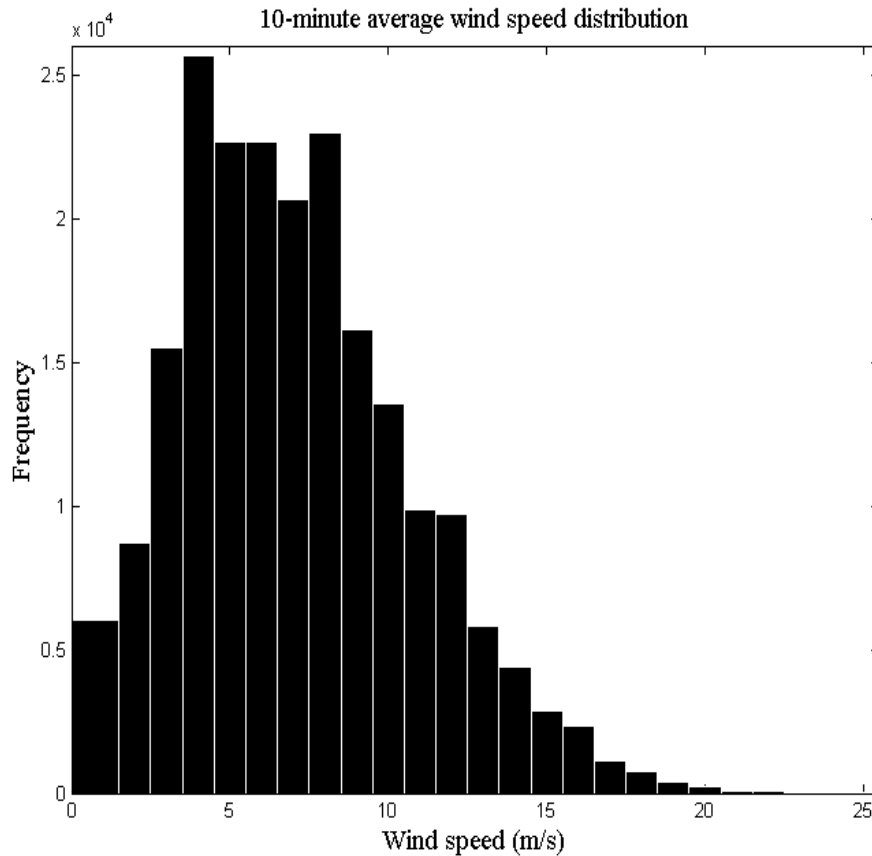


Figure 5.1 10-minute Average Wind Speed Distribution at 84th Street and Highway 2, Lincoln, Nebraska

The average electricity consumption at the subject intersection (24 LED signal heads) was approximately 324 kWh per month. The electricity production from the RWPS is estimated to be 230 kWh per month. At the utility price of \$0.075 per kWh (obtained from local traffic operation agency), the RWPS can save \$210 per year on utility expenditures. It should be noted that this estimation assumes ideal power output as described by turbine power curve.

5.4.1.2 Electricity Sold back

The RWPS is designed to be grid-connected. If it generates more electricity than the amount needed for traffic signals and charging the batteries, the excess production can be sold

back to utility grid. It is necessary to contact local agency and confirm the requirements on grid connection and options for sale of any excess renewable power production. In Lincoln, an application for interconnection should be submitted and approved by the local utility prior to the connection with the utility grid. An agreement was made with the utility agency to sell back the instantaneous surplus of power output at the same rate of purchasing from the utility.

5.4.1.3 Emission reduction

The environmental benefits from a RWPS are twofold. First, the improved efficiency in traffic operations during power outages due to presence of backup power leads to reduction in vehicle emissions. Secondly, the electricity generated by the RWPS is cleaner than that which is generated from fossil fuels. The net electricity generated from fossil fuel and total pollutants from conventional power plants was obtained from EIA annual statistics (EIA, 2011). The emission per kWh generated was estimated from these statistics, as shown in table 5.1. Knowing the electricity generation and unit cost of the pollutant, we can estimate monetary benefits from green energy.

Table 5.1 Emission Savings from Generating Electricity from Wind Energy

	CO₂	SO₂	NO_x
Total emission (thousand metric tons)	2,269,508	5,970	2,395
Net generation (thousand megawatt hours)	2,726,452		
Emission rate (ton/kWh)	8.32 E-04	2.19E-06	8.78E-07

5.4.2 Benefits from Backup Power

The RWPS can provide backup power to maintain normal traffic signal operations during grid power outages. In this study, the benefits of backup power were estimated by comparing the

loss of operational efficiency if such a system was not present. The benefits include delay reduction, safety improvement, vehicle fuel saving, emission reduction and personnel saving. The power outage history and traffic crash records during the power outage would be ideal for this analysis. Crash record databases, however, rarely have power outage details associated with the crashes. Here we use surrogate measures to estimate the impact on traffic safety. Table 5.2 provides a summary of proposed methods that can be used to evaluate the benefits. These methods can be classified into two categories: empirical equation-based analysis or microscopic simulation-based analysis. The trade-off between using empirical equation versus microscopic simulation concerns time and accuracy. The microscopic simulation-based analysis will provide a more accurate estimate but will take longer for model calibration and result analysis. This paper uses the microscopic analysis approach in the case study.

Table 5.2 Methods to Evaluate Benefit Measures

Measurement		Method	
		Empirical equation-based	Microscopic simulation-based
Delay	Signal control(d_s):	HCM method Eq. (18-20), (18-45) & (18-48)	Micro-simulation models (VISSIM used in this study)
	All-way-stop (d_a)	HCM method Eq. (20-30), (20-31) & (20-32)	
	Reduction(d_r)	$d_r = d_a - d_s$	
Crash reduction		Crash data	Traffic conflict using SSAM
Fuel saving		AASHTO method: $g(D_0 - D_I)p$	Emission software using trajectories generated by Micro-simulator (MOVES used in the study)
Vehicle emission reduction		Empirical fuel-based model	Emission software using trajectories generated by Micro-simulator (MOVES used in this study)

5.4.2.1 Delay reduction

Providing backup power at signalized intersections is an effective way to avoid the delay caused by all-way-stop control during traffic signal power failures. Studies have shown that reducing one minute on the average experienced lateness is valued very close to reducing travel time (Tilahun & Levinson, 2010). Delays under different control types for a specific intersection can be estimated respectively by the methodologies provided by the Highway Capacity Manual (TRB, 2010). Another approach is to use microsimulation models to estimate delays under different control types.

5.4.2.2 Safety improvement

Safety at an intersection will be jeopardized if an intersection warranting a signalized control is operated by all-way-stop control. The RWPS can maintain normal signal operation and therefore reduce the risk of crashes during a grid power outage. In our analysis, the deterioration of safety caused by stop-and-go traffic was estimated using traffic conflicts as a surrogate measure. The risks associated with the inability to detect the presence of the intersection during an outage are not considered in our analysis, so the estimates of safety benefits are conservative.

A direct way to estimate the safety benefits would be to use the crash records during power outages. However, this kind of data is rarely available. This paper uses traffic conflict as a surrogate measure of safety. To estimate the number of conflicts, microscopic simulation models can be used to obtain the vehicle trajectories which can be processed using FHWA Surrogate Safety Assessment Model (SSAM) (FHWA, 2008) to obtain the frequency and severity of traffic conflicts under simulated conditions. The dollar value of safety benefits can then be calculated by multiplying the number of conflicts with the cost per conflict. Table 5.3 presents the calculations for the estimated benefit of reducing one conflict.

Table 5.3 Estimated Costs Associated with a Traffic Conflict

Type of crash	Cost for motor vehicle crashes (National Safety Council, 2009)	Rate of crash
Death	\$1,290,000	1.03
Nonfatal disabling injury	\$68,100	51
Property damage only	\$8,200	185
Weighted average cost per crash		\$26,658
Probability of getting involved in a crash given a traffic conflict (Gettman, 2008)		0.00005
Estimated benefits of preventing a traffic conflict		\$1.33

5.4.2.3 Fuel saving

Improving traffic mobility during power failures has a great potential for reducing fuel consumption. Equation 5.2, developed by AASHTO, provides estimated changes in fuel consumption in gallons per minute of delay for different vehicle types and speeds (AASHTO, 2003):

$$\text{change in fuel cost} = g(D_0 - D_1)p, \quad (5.2)$$

where, g is fuel consumption in gallons per minute of delay, $(D_0 - D_1)$ is the change in delay, and p is the price of fuel.

Another way to estimate the change in fuel consumption is through simulation. Some microsimulation software like VISSIM has an optional module for fuel consumption. Some vehicle emission software packages, such as MOVES (Motor Vehicle Emission Simulator), can also estimate the fuel consumption using vehicle trajectories exported from a microsimulator. The price of fuel can then be multiplied to the change in fuel consumption to obtain the dollar values.

5.4.2.4 Emission reduction

Increasing attention has been focused on reducing transportation-related emissions in recent years. Transportation agencies and other stakeholders have highlighted traffic operation improvement as a potential source of emission reduction benefits. Vehicle emissions including CO, NO_x, VOCs, and CO₂ are evaluated in this paper to estimate the environmental cost associated with signal power outages.

An empirical fuel-based model can be used for quick estimations of vehicle emissions as shown in the following list (Cobian et al., 2009):

- CO = Fuel consumption (gallon) × 69.9 g/gallon
- NO_x = Fuel consumption (gallon) × 13.6 g/ gallon
- VOCs = Fuel consumption (gallon) × 16.2 g/ gallon

Another method to estimate emission is to use vehicle trajectory-based vehicle emission models. Many vehicle emission models now are available to estimate the vehicle emissions, such as MOVES and CMEM (Comprehensive Modal Emissions Model). For the case study, a project-level modeling by MOVES was used (Chamberlin, Swanson & Talbot, 2011). VISSIM vehicle trajectories, which include data on speed, location, and acceleration for each vehicle, need to be processed as input of MOVES. All the vehicles are classified by statistically-similar trajectories, which are represented by different links in MOVES. The vehicle specific power is calculated as:

$$VSP = \left(\frac{A}{M}\right) \times v + (B/M) \times v^2 + (C/M) \times v^3 + (a + g \times \sin\theta) \times v \quad (5.3)$$

where v is velocity, a is acceleration, M is the weight, A is rolling resist, B is rotating resist, and C represents aerodynamic drag.

Base on vehicle speed and specific power, all the approaches are translated into operating mode distributions in MOVES. These operating modes include idle, running, start, and braking processes. The intersection can be modeled for the output of each scenario in VISSIM.

The unit cost of the pollutant is needed to estimate the environmental benefits as a dollar value. The monetary costs of air pollutants are typically measured in three ways (Sinha & Labi, 2007): i) as the cost of cleaning the air near the source of degradation, ii) as the cost associated with addressing the effects of degradation, and iii) as the willingness of persons to pay to avoid the degradation. As there is no standard way to measure this in dollar values, the unit cost of pollutants depends more on user preference.

5.4.2.5 Personnel savings

Usually, the police personnel are called to direct traffic during power failures. The presence of an RWPS will reduce police personnel costs and the work load associated with traffic directing. The savings in personnel cost can then be calculated by multiplying the cost rate and total duty time. These data can be found at local police departments.

5.5 Case study

In Nebraska, the state law requires the intersection to be treated as a multi-way stop when the traffic signal control is not operating and no traffic direction is provide (Nebraska Legislature, 2011). Power outage records for Lincoln were obtained from a local utility agency. Overall 2,674 outages were recorded during January 2006 to December 2010. Police activity data were obtained from the Lincoln Police Department. The police traffic directing records were checked to verify the utility data. Three outages were found at the subject intersection in those five years. Two of them occurred between 13:30 to 15:00, and the other occurred during afternoon peak hours. The outage durations were 68, 186, and 90 minutes respectively. It should be noted that

any outages without policing activity could not be verified and were not included in this case study. The benefits estimate would thus be considered conservative.

5.5.1 VISSIM Modeling

Traffic operations during the three outages were simulated in VISSIM. The normal signal operation was considered as a baseline scenario and an all-way-stop operation was used to simulate operations during outages. Relevant features of the test bed include intersection geometry, approach volumes, speed limits, signal timing plans, and detector locations, all provided by the city of Lincoln. Speed profiles on all the four approaches were collected on weekdays for two weeks and used to calibrate and validate the VISSIM model. The model was calibrated using the morning peak (a.m.) speed profile and checked (validated) using the evening peak (p.m.) profile. The Genetic Algorithm (GA) was used in the model calibration to find the appropriate combinations of parameters that would minimize errors between the observed and simulated performance measures (Appiah & Rilett, 2010). The GA calibration procedure started with a randomly generated set of parameter values (within reasonable predefined ranges) or population of chromosomes, each of which represents a potential solution to the calibration problem. Individual chromosomes underwent selection in the presence of variation-inducing operators such as mutation and crossover. A fitness function (mean absolute error ratio) was used to evaluate each chromosome with reproductive success dependent on fitness. The processes of evaluation, selection, crossover, and mutation were repeated for a predetermined number of times or generations. The chromosome (or set of parameter values) which provided the closest match between observed and simulated values in the final population was selected as “optimal” parameter values. The lowest value of the mean absolute error ratio (MAER) after 100 iterations

of the GA algorithm for a population size of 50 was 0.0595. The VISSIM parameter values that corresponded to this MAER value were:

- Number of observed preceding vehicles: 3
- Minimum headway: 0.60 m
- Average standstill distance: 3.38 m
- Additive part of desired safety distance: 4.25
- Multiplicative part of desired safety distance: 2.06

Observed and simulated speed profiles for the a.m. and p.m. peaks are shown in figure 5.2, where the x-label, for example, N_400, indicates average speed at a distance of 400 feet from the stop line on the northbound approach. Observed and simulated speed profiles for the a.m. and p.m. peaks suggested a good match ($MAER = 0.060$ for calibration using a.m. peak data and $MAER = 0.075$ for validation using p.m. peak data) between the observed and simulated speed profiles. This indicates that the calibrated parameter values are appropriate for the studied intersection. Speed profiles are especially important to be used for calibration as traffic conflicts and emissions both used trajectory data for estimation.

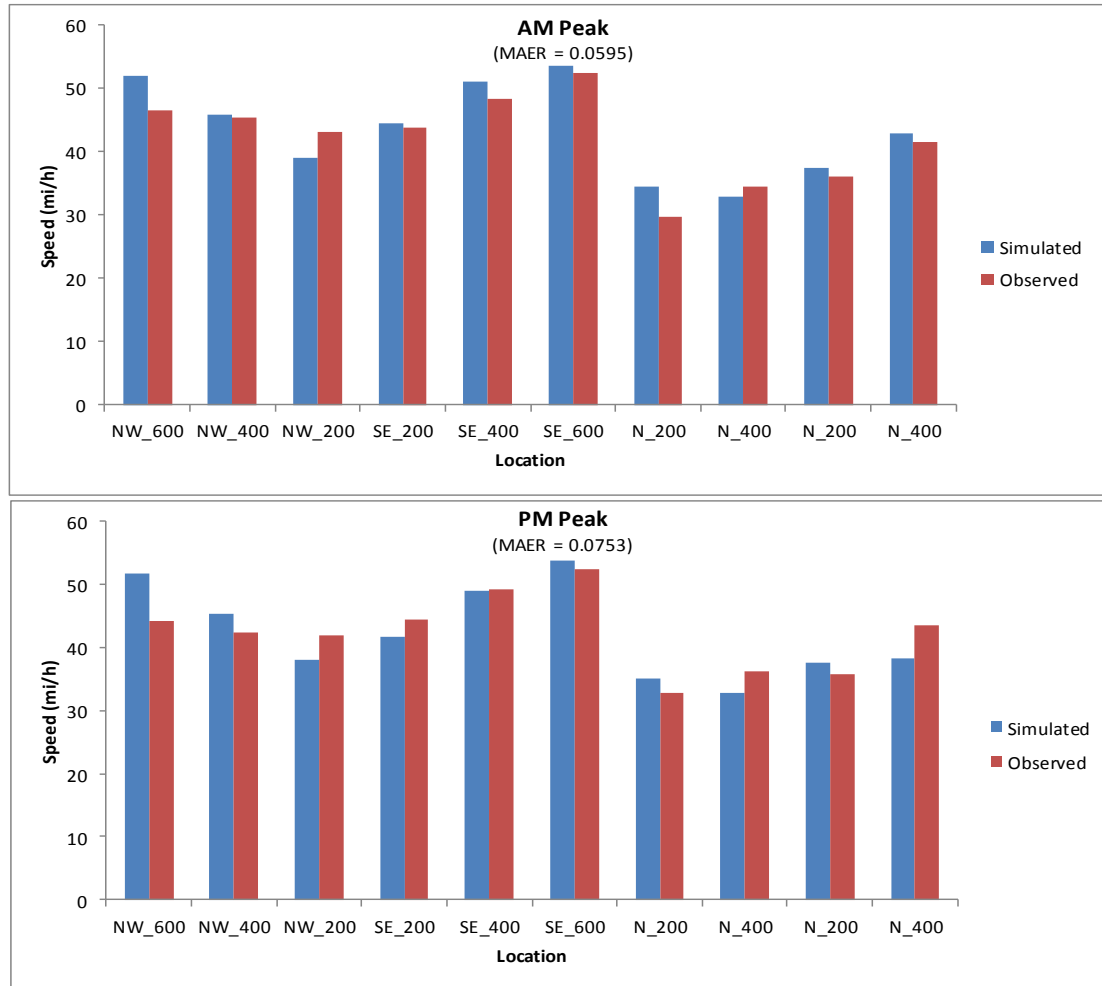
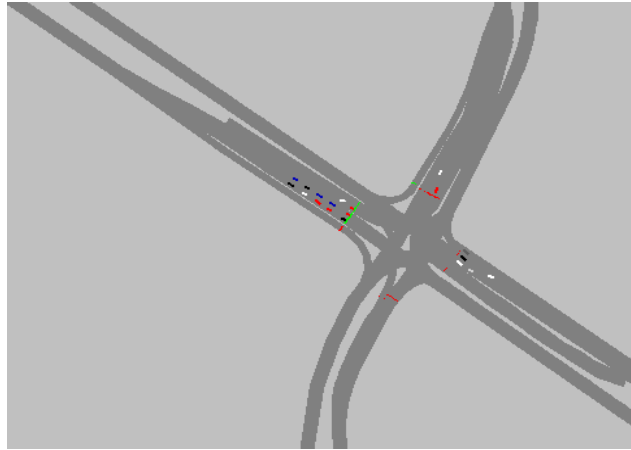
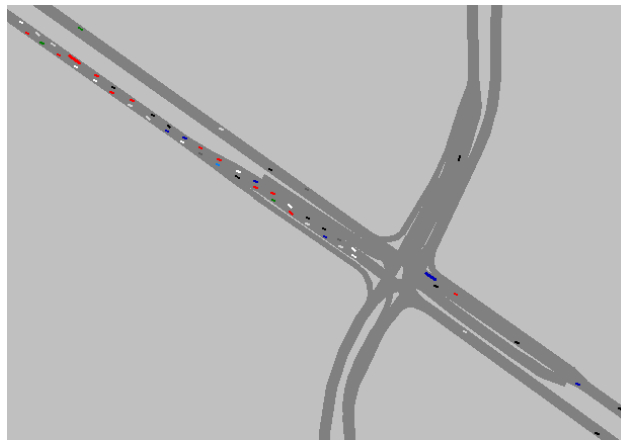


Figure 5.2 Observed and Simulated Speed Profiles for the A.M. and P.M. Peaks

Delay in traffic signal operation and four-way stop operation are compared to find the additional delay caused by power outages at the test site. Figure 5.3 shows the 60th minute simulation stage of traffic signal operation and stop sign operation for the power outage that occurred during afternoon peak hours. The intersection has high volume southeast-bound during afternoon peak hours. In regular traffic signal operation, it can maintain a level of service B. If a power failure occurs and the all-way-stop operation is implemented a substantial queue accumulates on the southeast movement.



a. Traffic Signal Operation



b. Stop Sign Operation

Figure 5.3 The 60th minute simulation stage in traffic signal and stop sign operation

5.5.2 *Economic Efficiency Analysis*

Simulation results show an additional 22 vehicle-hours of delay in all-way-stop control scenarios. The dollar value of delay was estimated by using the local median hourly income from the Nebraska Department of Labor, which was \$15 per hour. The cost of delay from all three outages is about \$330. The SSAM analysis produced an additional 900 conflicts for the three outages. With a cost of \$1.33 per conflict, the safety benefit was about \$1,200.

The fuel consumption per minute of delay at a speed of 45 mph (84th Street.) and 55 mph (Highway 2) for corresponding vehicle mix was obtained from AASHTO (AASHTO, 2003). The average fuel cost at the intersection area was weighted by annual average daily traffic (AADT) at 84th Street (7,100) and Highway 2 (25,550). As shown in table 5.4, the average fuel consumption per minute of delay is 0.0896 gallon at the studied intersection. The average U.S. Midwest retail gasoline price for all grades, all formulations, from January to September 2011 (\$3.60/gallon) was used as the price of fuel for all vehicle classes (EIA, 2011). Nearly \$420 of fuel cost would be saved from these three outages.

Table 5.4 Fuel Consumption per Minute of Delay by Vehicle Type

	Small automobile	Large automobile	SUV	Two-axle single-unit truck	Three-axle single-unit truck	Multiple-unit truck
45 mph	0.025	0.043	0.049	0.206	0.28	0.411
55 mph	0.032	0.054	0.065	0.266	0.362	0.495
Vehicle type ratio	0.42	0.12	0.18	0.14	0.04	0.02
84 th Street	0.07274 gallon per minute of delay					
Highway 2	0.09324 gallon per minute of delay					
Average	$0.0727 \times 7100 / 32650 + 0.09324 \times 25550 / 32650 = 0.0896$ gallon per minute					

Vehicle emissions were estimated by MOVES using the trajectory data obtained from VISSIM. The monetary cost of emissions was measured by the cost associated with addressing the effects of degradation. The Social Cost of Carbon (SCC) is an estimate of the monetized damage cost of an incremental increase in carbon emissions in a given year. The SCC assesses damages to ecosystems, freshwater resources, forests, coastal areas, human health, and industry

(IPCC, 2007). The Department of Transportation used a domestic SCC value of \$2 per ton of CO₂ in the final model year 2011 Corporate Average Fuel Economy rule. The value \$2 was used as the price of CO₂ in the case study. Muller and Mendelsohn estimated the marginal damage cost for several kinds of pollutants (Muller & Mendelsohn, 2009). Table 5.5 shows the marginal damage cost estimations for NO_x and VOCs at the lower (25th percentile), median (50th percentile) and upper (75th percentile) levels. In the case study, the median marginal damage costs were used as the price of the pollutants. At these prices, the annual emission savings from generating green energy was about \$11 with the production of 2,800 kWh per year estimated in section 5.4.1.

Table 5.5 Estimated Marginal Damage Cost of Emission

Pollutant	Lower (\$/ton/year)	Median (\$/ton/year)	Upper (\$/ton/year)
NO _x	180	250	370
VOCs	120	180	280
SO ₂	550	970	1300

According to Lincoln Police Department, the cost of traffic directing is \$53 per hour, which accounts for the cost of vehicles, fuel, facilities, insurance, maintenance, supervision, accounts payable, training, IT services, payroll, and janitorial services. The personnel savings were estimated based on the assumption that police duty time equals the duration of the outage.

The total cost of the three outages is shown in table 5.6. Electricity production by the RWPS during those outages was not considered. About \$2,250 of total benefit would have been

saved in these three outages if the RWPS had been present. The duration of the second outage was about twice that of the third, but the delay caused by it was more than seven times that of the third. The main cause was the high traffic volumes during peak hours in the second outage. Based on the results from all three power outages in the five years, we estimated an annual average for each calculated item, as shown in the last row of table 5.6.

Table 5.6 Estimated Costs of Three Power Outages at the Subject Site

Outage	Duration (min)	Delay (s)	Conflicts	Fuel (liter)	NO_x (kg)	VOCs (kg)	CO₂ (kg)	Police Duty (min)
1	68	6,442.66	157	36.42	0.10	0.13	66.91	53
2	186	63,322.66	543	357.95	1.04	1.27	818.37	171
3	90	8,230.53	200	46.52	0.13	0.15	97.61	75
Annual Average	68.80	15,599.17	178	88.16	0.25	0.31	196.58	59.8

The average annual benefits of using an RWPS at the subject intersection are summarized in table 5.7. The total benefit in the first year of installation is \$670. The total savings of the RWPS is \$15,216 in a 15-year lifecycle, at a 3% inflation rate. The lifecycle payback is 182% (15,216/8,352). Nine and a half years would be taken to reach the breakeven point at the local utility price (\$0.075 per kWh in 2011).

Table 5.7 Estimated Economic Benefits at the Subject Site

	Five- year total	Annual total	Annual benefit (\$)
Duration (min)	344	68.80	
Delay reduction (s)	77,995.85	15,599.17	65.00
Traffic conflicts	899.60	179.92	239.29
Fuel (liter)	440.89	88.16	83.86
NO _x from traffic (kg)	1.25	0.25	0.06
VOC _s from traffic (kg)	1.55	0.31	0.06
CO ₂ from traffic (kg)	982.88	196.58	0.39
Police duty (min)	344	68.8	60.77
Annual benefit as backup power(\$)			449.43
Annual benefit from electricity production (\$)			210
Emission saving from generating green energy (\$)			11.22
First year benefit (\$)			670.65
Inflation rate (%)			3
Lifecycle saving (\$)			15,216
System cost (\$)			8,352
Lifecycle payback			182%
Breakeven (years)			9.6

The lifecycle benefits at a given site will be affected by wind resources, utility rate, and power outage frequency. Holding wind resource, power outage distribution and all others constants, the RWPS would provide more lifecycle benefits if installed at a location with a high utility price. The highest average electricity retail price in the U.S., from January to June 2011, was found in Hawaii, at about \$0.29 per kWh (EIA, 2011). Assuming only the utility price is different, the benefits from the same RWPS units located in New York and Hawaii are compared to the studied intersection in Lincoln. The results are shown in table 5.8. At the highest utility rate, about four times the Lincoln local rate, the lifecycle payback would be almost doubled.

Table 5.8 Economic Benefits of RWPS at Different Utility Prices

	Lincoln site	NY site	HI site
Utility price (\$)	0.075	0.157	0.2958
Annual electricity production (\$)	210	440	828
First-year benefit (\$)	670.65	893.23	1281.26
Lifecycle saving (\$)	15,216	20,266	29,070
Lifecycle payback	182%	242%	348%
Breakeven (years)	9.6	7.7	5.7

The benefits estimated in this analysis are conservative. The designed system lifecycle as claimed by the manufacturer is 25 years—as compared to the 15 years used in the analysis—meaning there would be more energy production and other savings. The three outages observed in the five-year period are only unplanned power outages; the analysis did not consider planned outages. A study conducted by the California Energy Commission found that a typical traffic signal intersection experiences eight to ten local power outages annually (CEC, 2004). It might even be possible to reach the breakeven at the first year of installation if the power outage frequency is high and other conditions are similar. The RWPS will provide a fluctuation-free power which would further reduce the risk of controller malfunction and improve the safety and efficiency of traffic operations.

5.5.3 Extension of Battery Capacity

The battery bank at the test site is designed to supply the traffic control signals for at least 6 hrs at full operation (450 watt load). When wind resource is available during a power outage, the operation time can be further extended. These benefits are not included in the total benefits discussed in table 5.7, but they would be significant if the power outage is longer than 6 hrs. In order to estimate the extension of operation time, we evaluated an average of 4 hrs of production

at the test site. Wind data for a continuous 4 hrs was selected as one sample unit and randomly picked up from data of 1,676 days. A bootstrapping operation was performed by randomly selecting continuous 4 hr data from the available data sets. Figure 5.4 shows the result of the bootstrapping process. It can be seen that the 95%, 50% and 5% percentiles of the estimation converge as the samples increase. The average consumption at the test site is 10.8 kWh per day. The estimated average 4 hr production is 1.28 kWh, which can supply full operation for an additional 3 hrs of operations.

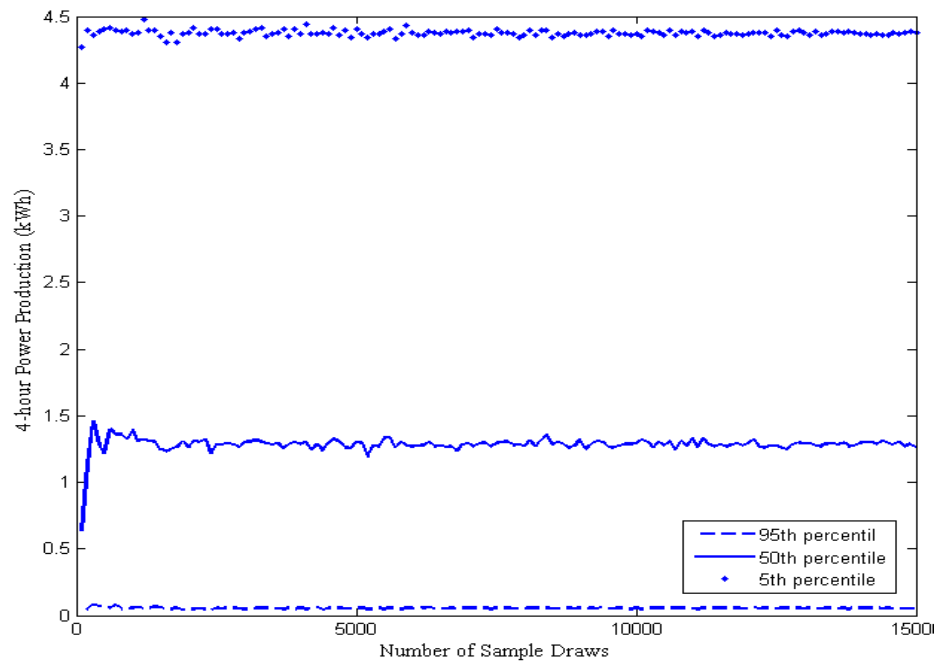


Figure 5.4 Estimated 4 Hour Wind Energy Production with Increasing Sample Sizes

5.5.4 Power Backup Benefits by Time of Day

Simulation scenarios were created in VISSIM to simulate power outages occurring during different times of day (TOD). The duration of simulated power outages are 15 min, 30 min and 60 min. Normal signal operation is considered as a base condition and four-way-stop

operation is compared to study the benefits of the backup system. The simulation model was calibrated by the GA discussed in section 5.5.1. The benefits of an RWPS as backup power in grid outages of different durations and times of day are shown in figure 5.5. The environmental benefits here were estimated by the savings of additional vehicle emissions.

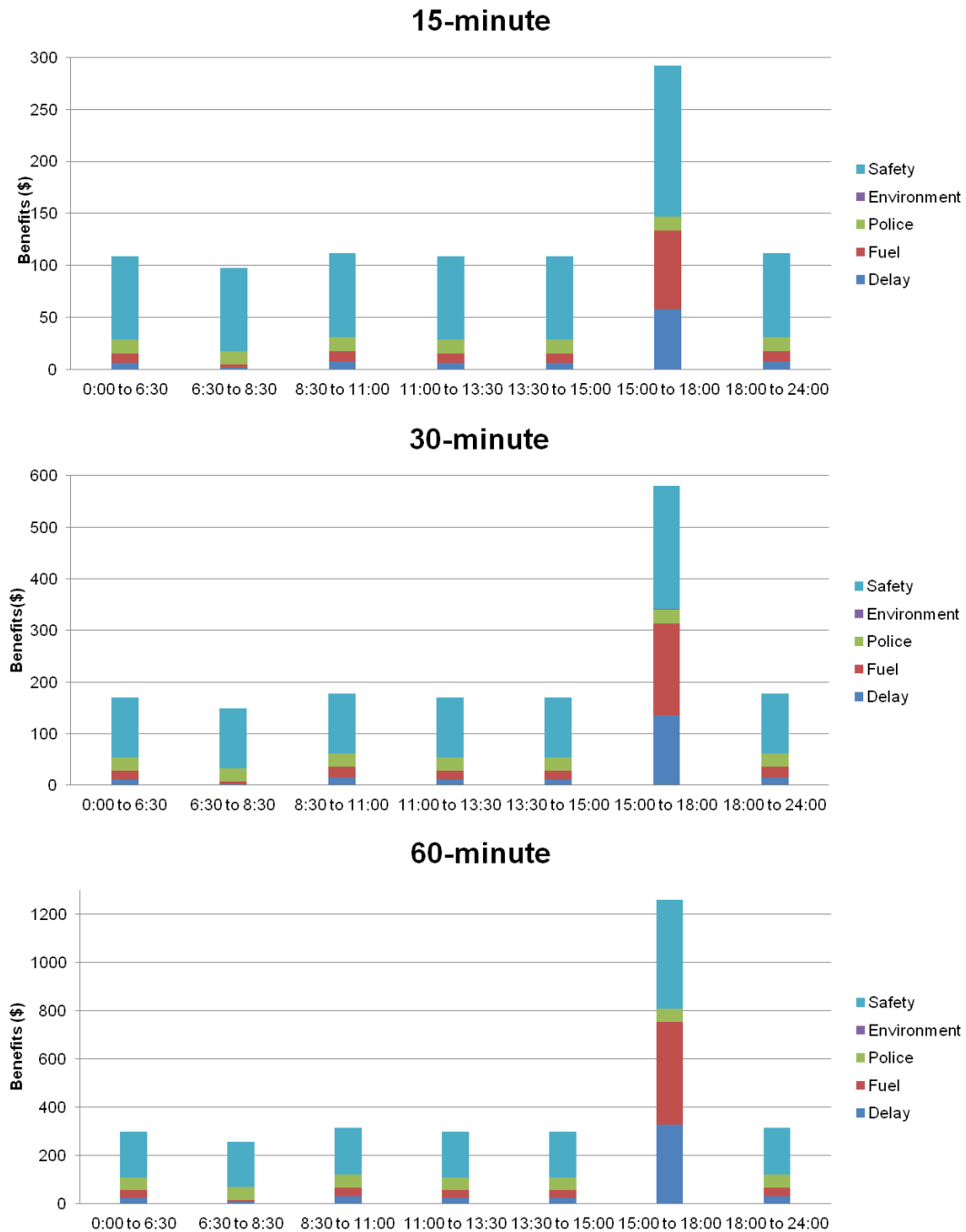


Figure 5.5 Economic Benefits in Avoiding Traffic Signals Power Outages by Time of Day

5.6 Summary

The results from simulation and economic analysis show the RWPS is economically viable for the studied intersection. This case study can directly help the local transportation agencies in Nebraska to determine the benefits and costs to install an RWPS at desired locations. Methodologies were developed to conduct benefit-cost analysis. The benefit-cost ratio can help decision making within the RWPS applications. The intersections can be prioritized based on benefit-cost ratios in order to use available budgets most efficiently. The methodologies used in the benefit-cost analysis can be used to evaluate different battery backup systems for traffic control signals.

Chapter 6 Conclusion

This project assesses the structural and economic impacts of the traffic pole mounted wind power generator and solar panel hybrid system. Structural design analysis would be the first step to verify the poles and foundation that can be used as for the RWPSs. Detailed investigation procedures are given and the analysis on traffic poles currently used in Lincoln proves the feasibility of mounting smaller wind power generators on existing transportation infrastructures.

Methodologies were developed to check the economic feasibility. The benefit-cost ratio can help on decision-making within RWPS applications. The areas with rich wind resource and high utility price would have higher benefit-cost ratios. In addition, areas with frequent power supply interruptions and areas subject to inclement weather, which can extend the dark indication time, would also gain higher benefits when the RWPSs are present as alternative power sources for traffic control signals. The methodologies used in the benefit-cost analysis can be used to evaluate different battery backup systems for traffic control signals. In the 2009 National Manual on Uniform Traffic Control Devices, only the traffic control signals interconnected with light rail transit systems, traffic control signals with railroad preemption or coordinated with flashing-light signal systems are required to have a backup power source. However, the battery backup system would be desirable at each signalized intersection if the cost-benefit ratio is favorable. In the areas where the grid utility is not stable, the traffic intersection operation can benefit from the installation of battery backup systems. The power backup can also protect against electrical surges that can cause damages to traffic controllers and traffic lamps. This protection further reduces the possibility of traffic signal failures.

This project demonstrates the developed methodologies by a case study of providing RWPSs for traffic control systems at high speed signalized intersections in Lincoln, Nebraska.

The proposed system will lead to the following benefits:

- It will reduce the power purchased to operate and maintain the roadway systems, which will reduce traffic operating costs.
- It will provide an alternative power source for the transportation system. This will reduce the risk of signal power failure in case of catastrophic events.
- The system will utilize existing public right-of-way and roadway infrastructure. The electricity production can be used locally and does not need extra investment in power distribution systems.
- The renewable energy production will reduce air pollution and contribute to sustainable development of our society.

A disadvantage of the proposed technology is that the location of the wind is limited by the availability of the wind resources. Some urban and suburban areas may not have sufficient wind resources to provide efficient wind power generation. In an urban area with many tall buildings, the wind flow may experience turbulence and the sunlight might be shielded, resulting in unstable or insufficient resources for power generation. Fortunately, those locations are limited in the United States. The second disadvantage is that there are trees in the proximity of some roadway/traffic signal lights, which reduces the efficiency of the wind power production and has an adverse impact on the secure operation. Additional vegetation management is required to solve this problem.

The RWPS can increase the traffic network reliability and promote the development of sustainable transportation systems. It will change the role of the public right-of-way from an

energy consumer to a renewable energy producer. An energy-zero and green transportation sector can significantly reduce the energy demands in the transportation sector. This will impact the current prices of energy generation, offset the need of building new power plants, reduce the greenhouse gas emissions, and therefore, have a cascading impact on all walks of life.

References

- American Institute for Steel Construction. (2005). *Specifications for Structural Steel Buildings (ANSI/AISC 360-05)*. Chicago, IL: AISC.
- American Association of State Highway and Transportation officials (AASHTO). (2009). *Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals* (5th Edition). Washington, DC: AASHTO.
- American Association of State Highway and Transportation officials (AASHTO). (2003). *User Benefits Analysis for Highways*. Washington, DC: AASHTO.
- Appiah, J. and Rilett L. R. (2010). Joint Estimation of Dynamic Origin-Destination Matrices and Calibration of Micro-Simulation Models Using Aggregate Intersection Turn Count Data. *Proceedings of the 89th Annual Meeting of the Transportation Research Board*. Washington, DC.
- American Public Power Association. (2007). Maryland State Highway Administration-Wind Project. Retrieved from <http://www.publicpower.org/utility/index.cfm?ItemNumber=13711>
- Bergey Windpower. (2001). Small wind and birds OU letter. Retrieved from <http://www.bergey.com/documents/2012/03/small-wind-and-birds-ou-letter.pdf>
- Bergey Windpower. (2003). Basic Tower Requirements for the BWC XL1 Wind Turbine. Retrieved from <http://production-images.webapeel.com/bergey/assets/2010/7/28/67964/XL1.Tower.Rqmts.pdf>
- California Energy Commission. (2004). Senate Bill 84 XX Battery Backup Program for Light Emitting Diode Traffic Signals. Retrieved from http://www.energy.ca.gov/reports/2004-05-05_400-04-006.PDF
- Chamberlin, Robert; Swanson, Ben; Talbot, Eric. (2011). Analysis of MOVES and CMEM for Evaluating the Emissions Impact of an Intersection Control Change. *TRB 91st annual meeting Compendium of Papers DVD*. Washington, DC.
- Valmont Industries. (2008). *City of Lincoln Drawing No. DB00581 Revision E*, Valmont Industries. Inc.
- Canopy Airport. (2010). Canopy Airport Parking. Retrieved from http://www.canopyairportparking.com/index.php?option=com_content&view=article&id=48&Itemid=2
- Cobian, Rafael; Henderson, Tony; Whitlock, Mitra; Sudeshna, Nuworsoo; Sullivan, Edward. (2009). Vehicle Emission and Level of Service Standards: Exploratory Analysis of the effects of Traffic Flow on Vehicle Greenhouse Gas Emissions. *TRB 88th Annual Meeting Compendium of Papers DVD*. Washington, DC.

- Cooler Planet. (2009). Solar Energy to Power Airports and Roadways Soon. Retrieved from <http://solar.coolerplanet.com/News/7310901-solar-energy-to-power-airports-and-roadways-soon.aspx>
- Deluchi, M. (2003). Environmental Externalities of Motor Vehicle Use. *Handbook of Transport and the Environment*. Amsterdam, the Netherlands: Emerald Group Publishing.
- Distributed Wind Energy Association (DWEA). (2010). Small Turbine Safety. Retrieved from http://www.distributedwind.org/assets/docs/PandZDocs/dwea_safety.pdf.
- U.S. Energy Information Administration (EIA). (2011). Annual Energy Review 2010. Retrieved from <http://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf>
- EIA. (2011). Sales (consumption), revenue, prices & customers. Retrieved from <http://www.eia.gov/electricity/data.cfm#sales>
- EIA. (2011). Electric Power Monthly. Retrieved from <http://www.eia.gov/cneaf/electricity/epm/flash/flash.pdf>
- Federal Highway Administration (FHWA). (2008). Surrogate Safety Assessment Model. Retrieved from <http://www.fhwa.dot.gov/publications/research/safety/08049/>
- FHWA. (1998). Traffic Noise Model. Retrieved from http://www.fhwa.dot.gov/environment/noise/traffic_noise_model/old_versions/tnm_version_10/tech_manual/TNM10TechManual.pdf
- Gettman, D., Lili P., Sayed T., Shelby, S. (2008). Surrogate Safety Assessment Model and Validation (Final Report FHWA-HRT-08-051). Retrieved from <http://www.fhwa.dot.gov/publications/research/safety/08051/08051.pdf>
- Hawaii Department of Transportation. (2009). Retrieved from <http://hawaii.gov/dot/news/new-photovoltaic-power-systems-to-save-taxpayers>
- IEC. (2005). International standard IEC 61400-12-1. Retrieved from http://webstore.iec.ch/preview/info_iec61400-12-1%7Bed1.0%7Den.pdf
- IPCC. (2007). IPCC Impacts, Adaptation, and Vulnerabilities: Summary for Policymakers. Retrieved from <http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-spm.pdf>
- Jace Shoemaker. (2010). Massachusetts Turnpike's Rest Area is Getting Greener. Retrieved from <http://www.energyboom.com/wind/massachusetts-turnpike%E2%80%99s-rest-area-getting-greener>
- Kumares C. Sinha and Samuel Labi. (2007). *Transportation Decision Making*. New Jersey: John Wiley & Sons.

- Kwon, Weidemann and Cinnamon. (2009). TDRL Projects: Solar/Wind Hybrid Renewable Light Pole, Gravel-Road Traffic Counter, DLL-Based Traffic Software Development Kit. Retrieved from <http://conservancy.umn.edu/bitstream/96711/1/CTS%2008-21.pdf>
- City of Lincoln. (2010). Mast Arm Poles L.S.P 85, *City of Lincoln Standard Plans*. City of Lincoln, Nebraska.
- National Surface Transportation Financing Commission. (2009). Paying our way: A new framework for transportation finance. Retrieved from http://financecommission.dot.gov/Documents/NSTIF_Commission_Final_Report_Advance%20Copy_Feb09.pdf
- NCDOT. (2009). Sustainable Rest Area. Retrieved from <http://ncdot.technology-view.com/wilkes>
- Nebraska Legislature. (2010). Nebraska Revised Statute 60-6,123. Retrieved from <http://nebraskaalegislature.gov/laws/statutes.php?statute=60-6,123>
- Nebiyu Y. Tilahun and David M. Levinson. (2010). A Moment of Time: Reliability in Route Choice Using Stated Preference. *Journal of Intelligent Transportation Systems*, 14(3), 179–187.
- Nicholas Z. Muller and Robert Mendelsohn. (2009). Efficient Pollution Regulation: Getting the Prices Right. *American Economics Review*, 99(5), 1714-1739.
- Oregon Office of Innovative Partnerships and Alternative Funding. (2008). Oregon Office of Innovative Partnerships and Alternative Funding. Retrieved from http://www.oregon.gov/ODOT/HWY/OIPP/inn_solarhighway.shtml
- Ovidiu Sandru. (2010). 1 MW Solar-Powered Parking lot Opening in Bordentown, NJ. Retrieved from <http://www.greenoptimistic.com/2010/01/15/1-mw-solar-powered-parking-lot-opening-in-bordentown-nj/#ixzz1DZVDiAvQ>
- Sarah A. Hamlen and Rebecca Meadows. (2010). Assessing Your Small Wind Resource. *Montana State University Extension*. Retrieved from <http://msuextension.org/publications/HomeHealthandFamily/MT201011HR.pdf>
- Stankovic Sinisa, Neil Campbell, and Alan Harries. (2009). *Urban Wind Energy*. Sterling, VA: Earthscan.
- Sharman, David. (2010). Getting Real About Small Wind. *Renewable Energy Focus*, 11(1): 30 - 32.
- The Bay Net. (2005). New Wind Turbine in Westminster Part of Smart, Green and Growing Initiative. Retrieved from http://www.thebaynet.com/news/index.cfm/fa/viewstory/story_ID/14100

Taek Mu Kwon, Ryan Weidemann, Dan Cinnamon.(2008). TDRL Projects: Solar/Wind Hybrid Renewable Light Pole, Gravel-Road Traffic Counter, DLL-Based Traffic Software Development Kit. Retrieved from <http://www.its.umn.edu/Publications/ResearchReports/reportdetail.html?id=1670>

Wizelius, Tore. (2007). *Developing Wind Power Projects: Theory and Practice*. Sterling, VA: Earthscan.

Appendix A Summary of Renewable Energy Projects

Year	Project name	Energy source	Installed capacity	cost	Utility saving	CO ₂ reduction	Ownership	Design life
2005	Vauxhall Cross Bus Interchange in London	solar	30 kw	\$5,800,000	generate 30% of the energy required to power the 24-hour bus station			
2007	MD SHA LED sign lighting	wind		\$10,000	cut 80% of the electricity cost of the LED sign		MD SHA	over 20 years
2008	University of Minnesota street light	wind/solar	130 watts solar panel, a 400 watts small wind turbine		sufficient to power the lighting applications		Mn DOT	
2008	Oregon Solar Highway	solar		\$1,280,000	112000 kwh/year; provides 28% of power for the interchange			
2008	Australian highways sound barriers panels	solar			18,700 kwh/year			cover its cost in about 15 years
2009	MD SHA pilot renewable energy project	wind	700 kw/month	\$25,000	700 kwh/month	1,400 lbs /month		20-25 years
2009	photovoltaic power system at Lihue Airport	solar			1,200,000 kw/year	26,000,000 lbs/year		

2009	Northwest North Carolina Visitor Center	solar		\$12,000,000	4,400 kwh/year			
2009	Germany's A3 highway	solar	2,700 kw	\$15,000,000				paid back through cost savings over 16 years
2010	Massachusetts Turnpike	wind	1500 kw		3,000,000 kwh/year; \$15,000 each year over the 20-year lease period		Solaya Energy ,Massachusetts Turnpike owns land	
2010	Canopy Airport Parking	wind/solar /thermal	16,900 watts solar arrays (Figure 1), a 9600 watts wind turbine		saving 70% compared to a similar building without the energy savings additions; provide free charging to electric and hybrid vehicles			
2010	El Paso airport lighting	solar		\$330,000	electricity saving \$40,000 per year		city El Paso	
2010	solar cell parking lot in Bordentown	solar	1 megawatt		more than 1000 megawatts per year	1,900,000 lbs/year		

Appendix B Sample Calculation of Structural Analysis

The following section includes sample calculations for a traffic signal pole (City of Lincoln pole designation LINC-RS-MA*-32-50-*-*), which is a 50 ft luminaire-mounting-height traffic signal with design configuration C (wind turbine only) and load combination II (Dead Load + Wind Load). The signal arm span is 32 ft. All references are to AISC 360-05 unless otherwise noted. The reaction loads and stresses were calculated using traditional structural analysis methods.

<p>Pole Allowable Axial Stress (Slender Section)</p>	$\text{Allowable Axial Stress} = (ASIF) \left(\frac{1}{\Omega} \right) F_{cr}$ <p>Section is slender for compression for $F_e < 0.44QF_y$: $F_{cr} = 0.877F_c$</p> $Q = \frac{0.038E}{F_y \left(\frac{D}{t} \right)} + \frac{2}{3}$ $F_e = \frac{\pi^2 E}{\left(\frac{KL}{r} \right)^2}$ <p> $ASIF = 1.33$ $\Omega = 1.67$ $E = 29,000 \text{ ksi}$ $D = 13 \text{ in.}$ $t = 0.1793 \text{ in.}$ $F_y = 55 \text{ ksi}$ $L = 50 \text{ ft} - 2.5 \text{ ft} = 47.5 \text{ ft} = 570 \text{ in.}$ $K = 2.0$ </p> $\text{Allowable Axial Stress} = 3.16 \text{ ksi}$	<p>Table B4.1 (E7-3)</p> <p>(E7-19)</p> <p>(E3-4)</p> <p>AASHTO Table 3-1 Sect. E1</p> <p>Table C-C2.2</p>
<p>Pole Allowable Shear Stress</p>	$\text{Allowable Shear Stress} = (ASIF) \left(\frac{1}{\Omega} \right) \left(\frac{F_{cr}}{2} \right)$ $F_{cr} = \frac{1.60E}{\sqrt{\frac{L_v}{D} \left(\frac{D}{t} \right)^{\frac{5}{4}}}} \leq 0.6F_y$ $F_{cr} = \frac{0.78E}{\left(\frac{D}{t} \right)^{\frac{3}{2}}} \leq 0.6F_y$ <p> $ASIF = 1.33$ $\Omega = 1.67$ $E = 29,000 \text{ ksi}$ </p>	<p>(G6-2a)</p> <p>(G6-2b)</p> <p>AASHTO Table 3-1 Sect. G1</p>

	$D = 13 \text{ in.}$ $t = 0.1793 \text{ in.}$ $F_y = 55 \text{ ksi}$ Equation (G6-1) was not considered in the design; this is a conservative analysis procedure. <i>Allowable Shear Stress = 13.14 ksi</i>	
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<p>Pole Allowable Bending Stress (Non-Compact Section)</p>	<p>$Allowable\ Bending\ Stress = (ASIF) \left(\frac{1}{\Omega} \right) F_{cr}$</p> <p>Section is non-compact for bending</p> $F_{cr} = \left(\frac{0.021E}{\frac{D}{t}} + F_y \right)$ <p> $ASIF = 1.33$ $\Omega = 1.67$ $E = 29,000\ ksi$ $D = 13\ in.$ $t = 0.1793\ in.$ $F_y = 55\ ksi$ </p> <p>$Allowable\ Bending\ Stress = 50.49\ ksi$</p>	<p>Table B4.1</p> <p>(F8-2)</p> <p>AASHTO Table 3-1 Sect. F1</p>
<p>Pole Allowable Torsional Strength</p>	<p>$Allowable\ Torsional\ Strength = (ASIF) \left(\frac{1}{\Omega} \right) T_n$</p> <p> $T_n = F_{cr}C$ $C = \frac{\pi(D-t)^2t}{2}$ </p> $F_{cr} = \frac{1.23E}{\sqrt{\frac{L}{D} \left(\frac{D}{t} \right)^4}} \leq 0.6F_y$ $F_{cr} = \frac{0.60E}{\left(\frac{D}{t} \right)^2} \leq 0.6F_y$ <p> $ASIF = 1.33$ $\Omega = 1.67$ $E = 29,000\ ksi$ $D = 13\ in.$ $t = 0.1793\ in.$ $F_y = 55\ ksi$ $L = 17.5\ ft = 210\ in.$ </p> <p>$Allowable\ Torsional\ Strength = 1,218.68\ k \cdot in.$ $= 101.39\ k \cdot ft$</p>	<p>(H3-1)</p> <p>Note H3.1</p> <p>(H3-2a)</p> <p>(H3-2b)</p> <p>AASHTO Table 3-1 Sect. H3.1</p>
<p>Pole Combined Torsion, Bending, Compression, Shear Unity Check</p>	<p>$Unity\ Check = \left(\frac{P_r}{P_c} + \frac{M_r}{M_c} \right) + \left(\frac{V_r}{V_c} + \frac{T_r}{T_c} \right)^2$</p> <p> $P_r = 0.23\ ksi$ (from structural analysis) $P_c = 3.16\ ksi$ $M_r = 35.51\ ksi + 6.31\ ksi$ (from structural analysis) $M_c = 50.49\ ksi$ $V_r = 0.44\ ksi$ (from structural analysis) $V_c = 13.14\ ksi$ $T_r = 39.32\ kip \cdot ft$ (from structural analysis) $T_c = 101.36\ kip \cdot ft$ </p> <p>$Unity\ Check = 1.08 > 1.0$, Therefore, the pole fails.</p>	<p>(H3-6)</p>

<p>Bolt Actual Stress Calculated from Base Reactions of Pole</p>	$\text{Axial Bolt Stress} = \frac{P}{NA_b}$ $A_b = \frac{\pi}{4} d_b^2$ $N = 4 \text{ bolts}$ $P = 1.68 \text{ kips (axial reaction from structural analysis)}$ $d_b = 1.5 \text{ in.}$ $\text{Axial Bolt Stress} = 0.24 \text{ ksi (compression)}$ $\text{Moment Bolt Stress} = \frac{M}{2x(2A_b)}$ $x = (R/2)\cos\theta = \text{distance from bolt group centroid to centroid of tensile bolts}$ $R = 17 \text{ in.} = \text{bolt circle diameter}$ $\theta = 45^\circ = \text{principle bolt axis rotation from principle loading axis}$ $M_x = 810.72 \text{ kip} \cdot \text{in. (moment reaction from structural analysis)}$ $M_y = 144.00 \text{ kip} \cdot \text{in. (moment reaction from structural analysis)}$ $(\text{Moment Bolt Stress})_x = 19.08 \text{ ksi (tension)}$ $(\text{Moment Bolt Stress})_y = 3.39 \text{ ksi (tension)}$ $\text{Actual Bolt Stress}$ $= (\text{Moment Bolt Stress})_x$ $+ (\text{Moment Bolt Stress})_y$ $- (\text{Axial Bolt Stress})$ $\text{Actual Bolt Stress} = 22.23 \text{ ksi}$	
<p>Bolt Allowable Tensile Stress (Strength Design)</p>	$\text{Allowable Bolt Stress} = (ASIF) \left(\frac{1}{\Omega} \right) F'_{nt}$ $F'_{nt} = 1.3F_{nt} - \frac{\Omega F_{nt}}{F_{nv}} f_v \leq F_{nt}$ $F_{nt} = 0.75F_u$ $F_{nv} = 0.4F_u$ $ASIF = 1.33$ $\Omega = 2.00$ $F_u = 75 \text{ ksi}$ $f_v = 0.45 \text{ ksi (from structural analysis)}$ $\text{Allowable Bolt Stress} = 37.41 \text{ ksi} > 22.23 \text{ ksi,}$ <p>Therefore, the bolts are satisfactory for strength design.</p>	<p>(J3-3b)</p> <p>Table J3.2 Table J3.2 AASHTO Table 3-1 Sect. J3.7</p>
<p>Bolt Allowable Tensile Stress (Fatigue Design), Load Combination IV, LINC-RS- MA*-32-50-*-*</p>	$\text{Actual Bolt Stress} = 7.47 \text{ ksi (calculated from structural analysis reactions from the natural wind gust load combination)}$ $\text{Bolt Allowable Fatigue Stress} = 7.00 \text{ ksi}$ $\text{Detail Category} = D$ $7.47 \text{ ksi} > 7.00 \text{ ksi, Therefore, the bolts fail for fatigue design.}$	<p>AASHTO Table 11-3</p>

Wind Pressure Calculations (AASHTO)	$P_z = 0.00256K_zGV^2I_rC_d$ $V = 90 \text{ mph}$ $I_r = 1.0$ $K_z = 1.0$ $G = 1.14$ $C_d = \text{Specific to element}$ $P_z = (23.64 \text{ psf})C_d$	(3-1) Fig. 3-2 Table 3.2 Table 3-5 Sect. 3.8.5 Table 3-6
Solar Panel Load Calculations (AASHTO)	$A_{eff} = A \cos \theta$ $A = 15 \text{ ft}^2$ $\theta = 45^\circ$ (angle of inclination) $A_{eff} = 10.61 \text{ ft}^2$ $F = A_{eff}P_z$ $P_z = (23.64 \text{ psf})C_d$ $C_d = 1.2$ (estimated as the same drag coefficient for a traffic signal) $F = 301 \text{ lbs}$	Table 3-6

Fcr = flexural buckling stress