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Abstract

The transportation industry consumes about 28% of the total energy consumed by all sectors in the United States. This paper proposes a renewable wind power system (RWPS) as an alternative power source for signalized traffic intersections. The proposed system can be mounted onto the existing transportation infrastructure to provide reliable green electricity. Large-scale implementation of such a system has the potential to dramatically change the role of the public right-of-way system from an energy consumer to an energy producer, which will reduce the transportation system operating costs and promote the development of greener roadways.

This paper provides a framework to investigate the physical and economic feasibility of installing the proposed RWPS. Methodologies to conduct structural analysis, site selection, and economic analysis are developed and presented. A test intersection in Lincoln, Nebraska, is used to demonstrate the application of evaluation procedures. The proposed RWPS has two benefits: 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, and ii) it also provides a source of backup power in case of grid failures, increasing the reliability of traffic operations. The paper presents the methodology to ascertain the economic benefits of an RWPS for both the cases described above. The costs and benefits of providing a RWPS are stated in terms of dollar values. The decision to install a RWPS at a specific site can thus be made using a benefit-to-cost ratio.

The case study shows the RWPS is economically feasible at the subject intersection in Lincoln, Nebraska. The results also show that installing an RWPS at intersections with frequent power supply failures would result in higher benefit-to-cost ratios. In the event of budget constraints, the methodology developed in this paper can be used to prioritize the investments based on the benefit-to-cost ratios for the prospective sites.

1. Introduction

The transportation industry consumes about 28% of total energy consumed by all sectors in the United States. According to the EIA Annual Energy Outlook 2010, the transportation sector consumes more than 600 million kilowatt hours (kWh) every month. Innovations in green transportation can significantly reduce the sector's energy demand. This can eventually reduce the energy production cost, offset the need of building new power plants, and reduce pollutants from generating electricity with fossil fuels.

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

Renewable electric energy generated by an existing transportation infrastructure will cut the energy purchased to operate and maintain the roadway systems, and will therefore reduce operating costs of the transportation agency. This paper proposes a renewable wind power system (RWPS) which includes a grid-connected wind turbine installed on a traffic signal pole and a battery bank to be housed in an existing traffic signal cabinet. The proposed RWPS has two benefits: 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, and ii) the reliability of traffic operations will be enhanced due to the presence of backup power in the case of the grid failures.

In this paper, the structural and economic feasibility of an RWPS are investigated. Methodologies have been developed to estimate costs and economic benefits of the system. These methodologies can be used by agencies to evaluate the economic practicality of an RWPS and streamline investments to potentially more productive sites. Figure 1 outlines the overall procedure for the analysis. The numbering next to the headers indicates the section that will have an in-depth discussion on that specific topic. The first step of the system evaluation is to conduct a feasibility check to determine the physical eligibility of a subject site. This check phase includes investigations of structural strengths of existing traffic poles, zoning ordinances, site-specific geographic features, and potential negative factors. After the physical feasibility checks, an economic analysis is conducted to study the costs and benefits of the system. The benefits include not only the electricity production, but also the system's role as a backup power source during utility grid power failure. The RWPS is deemed economically desirable at sites where the positive results outweigh the system cost.

The detailed procedures will be described in the following sections. A case study with the subject intersection of Nebraska Highway 2 and 84th Street in Lincoln will be used to demonstrate the analysis procedure. The case study site includes one 1.0 kW 24 V wind turbine and four 6V 305Ah batteries. The batteries are designed to support full operations at the traffic signal for 5 to 6 hours (or flashing operations for 8 to 10 hours) at a 50% battery discharging level.

Figure 1. RWPS project evaluation framework

2. Feasibility check

The criteria for a feasible RWPS site include the requirements on infrastructure strength, zoning laws, and site topography. Potential negative impacts should also be considered prior to the project implementation. The pole specifications can be easily found at local traffic operation agency. The zoning laws can be obtained from local planning departments. Lincoln Public Works and Utilities Department's Engineering Services provided this project with the signal pole specifications and the Planning Department provided the zoning laws. Usually, the state energy office has references and guidelines for the placement of a small wind system. Wind data at the subject site are also needed for conducting the structural analysis.

2.1. Structural analysis

An RWPS installed on a traffic signal pole will increase the load and vibration of the system. Ideally, the dynamic effects that wind loading has on an RWPS should be evaluated through in-field testing. However, any past literature on such testing was not available at the time of this study. Additionally, evaluation of the systems under variable, dynamic loads would be extremely difficult due the enormous number of permutations and combinations of wind magnitude and frequency that will lead to drastically different stresses. Therefore, an alternative method is proposed to evaluate signal poles utilizing the static, allowable stress analysis outlined in the American Association of State Highway and Transportation Officials Standard Specification for Structural Supports for Highway Signs, Luminaires, and Traffic Signals (AASHTO, 2009).

According to Table 3-1 of the AASHTO specifications, four load combinations are necessary to evaluate a pole-mounted RWPS. However, load case I considers only the dead load of the structure. Since the addition of an RWPS would add minimal weight to the traffic pole structure, this base case can be ignored. Analysis is done for the following load combinations:

- II. Dead load + Wind Load
- III. Dead Load + Ice Load + ½ Wind Load
- IV. Natural Wind Gust Load

To check the structural strength, the applied stresses calculated following AASHTO specification can then be compared to the allowable stresses determined from the allowable stress design method according to the 2005 Specification for Structural Steel Buildings, found in the thirteenth edition of the American Institute of Steel Construction (AISC) Steel Construction Manual (ANSI/AISC 360-05). The measurements and equation necessary for the structures check process are outlined in Table 1. All references are to AISC 360-05 unless otherwise noted.

Table 1. Measurements and equation necessary for the structures check

Measurements	Equation	Reference
Pole allowable axial stress (Slender section)	$\text{Allowable axial stress} = (\text{ASIF}) \left(\frac{1}{\Omega} \right) F_{cr}$ $\text{Section is slender for compression}$ $Q = \frac{0.038E}{F_y \left(\frac{D}{t} \right)} + \frac{2}{3}$ $F_e = \frac{\pi^2 E}{\left(\frac{KL}{r} \right)^2}$	<p>Table B4.1</p> <p>(E7-19)</p> <p>(E3-4)</p>
Pole allowable bending stress (Non-compact section)	$\text{Allowable bending stress} = (\text{ASIF}) \left(\frac{1}{\Omega} \right) F_{cr}$ $F_{cr} = \left(\frac{0.021E}{\frac{D}{t}} + F_y \right)$	(F8-2)
Pole allowable torsional strength	$\text{Allowable torsional strength} = (\text{ASIF}) \left(\frac{1}{\Omega} \right) T_n$ $T_n = F_{cr} C$	(H3-1)
Pole combined torsion, bending, compression, shear unity check	$\text{Unity check} = \left(\frac{P_r}{P_c} + \frac{M_r}{M_c} \right) + \left(\frac{V_r}{V_c} + \frac{T_r}{T_c} \right)^2$	(H3-6)
Pole allowable shear stress	$\text{Allowable shear stress} = (\text{ASIF}) \left(\frac{1}{\Omega} \right) \left(\frac{F_{cr}}{2} \right)$	
Bolt actual stress calculated from base reactions of pole	$\text{Axial bolt stress} = \frac{P}{NA_b}$ $A_b = \frac{\pi}{4} d_b^2$ $\text{Moment bolt stress} = \frac{M}{2x(2A_b)}$	

Bolt allowable tensile stress (Strength design)	Allowable bolt stress = $(ASIF) \left(\frac{1}{\Omega} \right) F'_{nt}$	
Bolt allowable tensile stress, Load Combination IV	Bolt allowable fatigue stress	AASHTO Table 11-3

Structural analysis as outlined in Table 1 was conducted on several existing signal poles in Lincoln. Figure 2 shows three studied critical design configurations: A) a wind turbine and two solar panels, B) a wind turbine and a single solar panel, and C) a wind turbine alone. In the future, RWPS systems can be augmented with additional solar panels; therefore, a more comprehensive structural analysis was undertaken. Because higher mounting locations would result in increased loads and stresses on the existing structure, the two-panel configuration was installed with the first panel mounted at the top of the existing pole (outside the required blade clearance) and the second was installed near the mast arm attachment point. When only a single solar panel is used, it should be mounted at the mast arm attachment point.

Figure 2. Design configurations of pole-mounted wind turbine and solar panels

The solar panels were given an area of 15 square feet, and up to two panels could be installed on a single traffic signal structure. The City of Lincoln standard plans for signal mast arms and luminaire poles were used as a basis for consideration. Wind data were collected from a weather station on a signal pole 1,500 feet northeast of the subject site. The collection process began on May 5, 2005, and concluded on June 17, 2010. The average wind speed, wind direction, gust speed, and gust direction were recorded.

The effects of subjecting different load combination were examined in three cases: 1) alternative vortex shedding on a signal mast arm, 2) alternative vortex shedding on a luminaire pole, and 3) direct drag on a traffic signal. The results verified the feasibility of mounting small wind turbines on several existing signal poles, as shown in Table 2. Nearly all the 30-foot poles are structurally strong enough to support a wind turbine and two solar panels. The structural feasibility reduces as the height of the poles increases: for 50-foot poles, neither wind turbines nor solar panels could be mounted.

2.2. Zoning laws

Zoning ordinances dealing with the installation of small wind mills need to be checked prior to installation of an RWPS at the subject intersection. 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.

As for this subject site, there is no statewide zoning law in Nebraska that specifically affects wind turbine tower construction. From the City of Lincoln Planning Department, a special permit may be granted to allow wind energy systems to exceed the height provisions of the district in any zoning district except the agriculture and agricultural residential zones. As the RWPS will be installed at the height of signal poles, no action is needed. Lincoln Public Works confirmed the legality of mounting RWPS on a traffic pole.

Table 2. Summary of traffic signal pole attachment feasibility

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

2.3. Surrounding and topography

The height of the wind turbine tower and nearby buildings and the topography of the site affect the wind energy production. Turbines should be sited upwind of any obstacles to harness the strongest wind and maximize production. Buildings, trees, signs and other obstacles can disrupt wind flow and cause turbulence. Turbulence reduces the power output and causes additional stress on wind turbines and signal poles. The efficiency of wind turbines also decreases if wind direction is not horizontal due to the obstruction created by any obstacles. 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. Field study is needed to check the surrounding and terrain at the subject site. In case an obstruction is present, it becomes critical to have a site-specific evaluation of wind power that can be harnessed.

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

2.4. Negative impacts

Noise, aesthetics, visual impairment, ecological problems, and other potential negative impacts should be considered before RWPS installation and operation. Small wind turbines must be approved by the American Wind Energy Association and the noise of turbine should not exceed 60 dBA as measured at the closest neighboring inhabited dwelling unit. Turbine sound level during different operation modes can be obtained from the manufacturer. 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 an accurate background noise level is field study with a sound meter. The FHWA Traffic Noise Model (FHWA, 1998) provides estimations of traffic noise at different speed limits and distances, which can be used if field study is not available. The combined level of noises from wind turbine and traffic can be calculated by equation 1.

$$L_{\Sigma} = 10 \log \left(10^{\frac{L_1}{10}} + 10^{\frac{L_2}{10}} \right) \quad (1)$$

The RWPS would be installed at the height of traffic pole, causing no interference with television reception because of the small size of turbine and lower height of pole. Site-specific topography should be investigated to determine the visual impacts. Another common concern with wind mills has been the increased number of bird kills near the site of the wind turbine. Turbine manufactures may provide references on this 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 50 dBA under normal operation, measured 42 feet downstream of the turbine tower (Bergey Windpower, 2001), while the typical noise levels for passenger vehicles are 72-74 dBA at 55 mph measured at a distance of 50 feet (FHWA, 1998). The cumulative noise of the wind turbine and traffic calculated using equation 1 is 74.017 dBA, which is much lower than the Lincoln noise ordinance of 84 dBA. The presence of a wind turbine at this site would not significantly increase the noise level at the subject intersection with a speed limit of 55 mph and an average volume of about 1,100 vehicles per hour on the main approaches.

A study provided by the manufacturer and conducted by the University of Oklahoma shows that a small wind turbine has no statistically significant impact on the bird population (Bergey Windpower, 2001). A 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 significant causes of concern for our test site and hence were not considered in the cost-benefit analysis.

3. Economic efficiency analysis

The cost-benefit analysis is conducted to study the economic efficiency after the feasibility checks. This paper aims to develop a methodology which can be easily used by agencies to estimate the cost-benefit ratio of an RWPS project. All the cost and benefits are stated in terms of 2011 dollar values.

4. Costs

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

The installation cost of an RWPS is \$8,223, which includes one Bergey BWC XL.1 24V wind turbine, one Outback power grid interactive inverter and charger, one Outback power battery monitor, and four PVX-3050T 305 Ah 6V batteries. Preventive maintenance recommended by the wind turbine manufacturer includes greasing the bearings every 8 to 12 years and checking blade stiffness about every 10 years. For the 15-year analysis period, we assume the total operation and maintenance cost to be 5% of the wind turbine cost, about \$129. Then the total project cost is \$8,352.

5. Benefits

The benefits from the RWPS include the net sale of produced electricity and benefits derived from the presence of backup power during grid failure. Electric power failures at signalized intersections can cause significant traffic disruption. When signals are not operational, most states require reverting to an all-way-stop operation. This results in high delays and substantially riskier operations, especially during peak hours or during night time when the visibility is low. Thus, the availability of backup power is of immense benefit.

5.1. Benefit from electricity production

The benefits regarding electricity production include the reduction in consumption of grid power and the sale of any excess power generated by the RWPS. A feasible site should have sufficient wind resources to make the RWPS economical. The theoretical energy in wind varies as the cube of the wind speed (Wizelius, 2007). Wind maps provide an estimate of potential resources in a given area. The resources vary with the height of the turbine tower. Wind speed increases with increasing height above the ground. Most wind maps available online are for the height of 50 meters (164 feet) and beyond. A wind map of annual wind speed at 10 meters (33 feet) is recommended for an RWPS to be installed on a traffic signal pole. The National Renewable Energy Laboratory and state energy offices are good sources for wind resources information. Wind data from roadway weather station networks, such as Clarus Initiative or networks operated by local traffic operation agencies, can also provide useful information.

5.1.1. Power consumption reduction

The electricity production from an RWPS will first be used to supply the traffic control signals, which would reduce the electricity purchased from a utility agency.

The Bin Method (IEC, 2005) can be used to estimate the total electricity production from the wind data and the wind turbine power curve. The power curve provided by the manufacturer typically gives the output at different wind speeds with an assumption of zero elevation and sea level air density of 1.225 kg/m³. The power curves have to be modified to account for the height above the sea level and air density. The average air density can be calculated by equation (2) and used to normalize the output at the subject site.

$$\rho = \left(\frac{P_0}{RT}\right) \text{EXP}(-g \times z/RT) \quad (2)$$

where, P_0 is the standard sea level atmospheric pressure (101,325 Pascals), R is the specific gas constant (287 J/kg•Kelvin), T is the air temperature in degrees Kelvin, G is the gravitational constant (9.8 m/s²), and Z is the elevation above the sea level at the subject site.

Usually, 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 power curve. The total output can be estimated by adding the output from each speed bin. The benefits from electricity production can then be calculated from electricity output and local utility prices.

In this case study, 10-minute average wind speed and air temperature data were collected from October 2005 to May 2011 (1,676 days) by the weather station on a signal pole 1,500 feet northeast of the studied intersection. The wind speed data were corrected to eliminate the effect of the elevation difference between the two intersections. Figure 3 shows the distribution of the 10-minute average speed at the test site. Most of the speeds are in the range of 5-10 m/s, which corresponds to abundant wind resources for small wind turbines.

The average electricity consumption at the subject intersection (24 LED signal heads) is 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/kWh (obtained from Lincoln Public Works Department), the RWPS can help to save \$210 per year on utility expenditures. It should be noted that this estimation assumes ideal power output according to the turbine power curve.

5.1.2. Electricity sold back

The RWPS is designed to connect to a utility grid. It is necessary to contact the local utility agency and confirm the requirements on grid connection. If the RWPS generates more electricity than the amount needed to supply the traffic signals and charge the batteries, the excess electricity can be sold back to the utility grid. The dynamics and interconnection requirements for this transaction often vary with location and should be verified by the local utility agency. In Lincoln, an application for interconnection should be submitted and approved by the local agency prior to connection with the utility grid. The local utility agency provides two options to sell back the electricity from RWPS: 1) sell the entire electrical output or 2) use the electrical output of the RWPS to instantaneously supply all or a portion of their own load and sell the instantaneous surplus. In the case study, the second option is selected. The buyback rate was determined to be the same as the rate of purchasing from the utility.

Figure 3. 10-minute average wind speed distribution at 84th St & Highway 2

5.1.2. Emission reduction

The environmental benefits achieved from an RWPS are twofold. The improved efficiency in operation during power outages due to the availability of backup power leads to a reduction in vehicle emissions, which will be discussed in 5.2. Secondly, the electricity produced by the RWPS is cleaner than what is generated by traditional fossil fuels. The net electricity generation from fossil fuel and total pollutants from conventional power plants was obtained from EIA annual statistics (EIA, 2011). The emission per kWh generation was calculated from these statistics, as shown in Table 3. Knowing the electricity generation of the RWPS and the unit cost of pollutant, researchers could estimate monetary benefits from green energy.

Table 3. Emission saving from generating electricity from wind energy

	CO ₂	SO ₂	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

5.2. Benefits from backup power

In the case of a power outage, the operations at a signalized intersection are reverted back to all-way-stop control, which can significantly degrade operations. The presence of an RWPS

provides backup power to extend normal operations during power outages. This paper proposes to estimate the benefits of backup power 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 savings. The power outage history and traffic crash records during power outages would be ideal for this analysis, but databases of crash records rarely have power outage details associated with the crashes. In this paper, researchers use surrogate measures to estimate the impact of power outages on the safety of operations. Table 4 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-offs between using empirical equation versus microscopic simulation based analysis involve time and accuracy. The microscopic simulation based analysis will provide a more accurate estimate of benefits, but will take longer to calibrate the model and analyze the results. This paper details both approaches to help agencies select one of the approaches based on the available resources. The case study conducted for this paper uses the microscopic analysis approach.

Table 4. Methods to evaluate benefit measures

Measurement		Method	
		Empirical Equation	Microscopic Simulation
Delay	Signal Control (d_s):	HCM method Eq. (18-20), (18-45), & (18-48)	Microsimulation models (VISSIM used for the case 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: $g(D_0-D_1)p$	Emission software using trajectories generated by microsimulator (MOVES used for the case study)
Vehicle Emission Reduction		Empirical fuel-based model	Emission software using trajectories generated by microsimulator (MOVES used for the case study)

5.2.1. Delay reduction

During traffic signal power failures, all-way stop control could increase delays, especially at intersections with high speeds and high traffic volumes. The delay in signal control and all-way stop control in the same time period can be estimated by the methodologies provide by the Highway Capacity Manual (TRB, 2010) for isolated signalized intersections and all-way-stop intersection respectively.

Another approach will be to use microsimulation models to estimate delay under the two modes of intersection control.

5.2.2. Safety improvement

Safety at an intersection will be jeopardized if an intersection warranting a signalized control is operated by all-way stop control. An RWPS can maintain normal signal operation, and therefore reduce the risk of crashes during a grid power outage. In this analysis, the deterioration

of safety due to stop-and-go traffic is estimated using traffic conflicts as a surrogate measure of safety. The risks associated with inability to detect the presence of an intersection during power outages are not considered in this analysis, so these estimates of safety benefits are conservative.

A direct way to estimate the safety benefits would be to use the crash history during power outages. However, crash records during power outages are 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 the 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 presents the calculations for the estimated benefit to reduce one conflict.

Table 5. Estimated benefits of preventing a traffic conflict

Type of crash	Cost for motor vehicle crashes (National Safety Council 2009)	Proportion 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

5.2.3. Fuel saving

Improving traffic mobility during power failures has great potential to reduce fuel consumption. Equation 3, developed by AASHTO, provides estimated change in fuel consumption in gallons per minute of delay for different vehicle types and speeds (AASHTO 2003):

$$\text{change in fuel cost} = g(D_0 - D_1)p, \quad (3)$$

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 the Motor Vehicle Emission Simulator (MOVES), developed by the EPA, can also estimate the fuel consumption using vehicle trajectories exported from the microsimulator. The price of fuel can then be multiplied to the change in fuel consumption to obtain the dollar values.

5.2.4. Emission reduction

With more public concerns about global climate change in recent years, increasing attention has been focused on reducing transportation-related emissions. Greenhouse gas emissions and other pollutants from fossil fuels have been considered a critical part of

transportation-related emissions. Transportation agencies and other stakeholders have highlighted traffic operation improvement as a potential source of emission reduction benefits. Vehicle emissions of CO₂, CO, NO_x, and VOCs are evaluated in this paper to estimate the emission cost associated with signal power outages.

An empirical fuel-based model can be used for quick estimations of vehicle emissions as shown (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 vehicle emission is to use vehicle trajectory based vehicle emission models. Many vehicle emission models now are available to estimate vehicle emission, such as MOVES and the Comprehensive Modal Emissions Model (CMEM). For the case study, project-level modeling in MOVES was created by using the vehicle trajectories obtained from VISSIM. 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:

$$VSP = \left(\frac{A}{M}\right) \times v + (B/M) \times v^2 + (c/M) \times v^3 + (a + g \times \sin\theta) \times v \quad (4)$$

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

Based 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 then be modeled for the output of each scenario in VISSIM. The unit cost of the pollutant is then used to estimate the dollar benefits.

The monetary costs of air pollutants are typically measured in three ways (Sinha & Labi, 2007): 1) as the cost of cleaning the air near the source of degradation, 2) as the cost associated with addressing the effects of degradation, and 3) as the willingness of persons to pay to avoid the degradation. As there is no standard way to take these measurements in dollar values, the unit cost of pollutants depends on user preference.

5.2.5. Personnel saving

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

5.2.6. Case study

In Nebraska, state law requires that intersections be treated as multiway stops when the traffic signal control at an intersection is not operating because of a power failure or other cause and no police officer, flag person, or other traffic control device is providing direction for traffic

at the intersection (Nebraska Legislature, 2011). Five-year power outage data for Lincoln were obtained from the local utility agency. There were 2,674 power failures in the service area from January 1, 2006, to December 7, 2010. Police activity data in the same period were obtained from Lincoln Police Department, which recorded all the policing duties of directing traffic during traffic signal failure. Matching the utility data and police activity data, three power outages were found at subject intersection in those five years. Two of them occurred between 13:30 to 15:00, and the other occurred during the afternoon peak hour. The 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 for this case study, making the benefits estimate conservative.

Traffic operations during the three power outages were simulated in VISSIM. The normal signal operation is considered as a baseline scenario and an all-way stop operation is used to simulate operations during power failure. VISSIM models were calibrated and validated using the speed profiles on all four approaches collected weekdays for two weeks. The model was calibrated using the morning peak (AM) speed profile and checked (validated) using the evening peak (PM) profile. The genetic algorithm (GA) was used for simulation model calibration to find the appropriate combinations of model parameters that would minimize errors between the observed and simulated performance measures (Appiah & Rilett, 2010). Observed and simulated speed profiles for the AM and PM peaks suggested a good match between the observed and simulated speed profiles: Mean Absolute Error Ratio (MAER)=0.060 for calibration using AM peak data and MAER=0.075 for validation using PM peak data. This indicates that the calibrated parameter values are appropriate for the test bed. Speed profiles are especially important in the calibration as traffic conflicts and emissions both used trajectory data for estimation.

Simulation results indicated an additional 22 vehicle-hours of delay in the case of an all-way-stop control scenario. The dollar value of the delay was estimated using the median hourly income as the unit cost of delay. From the Nebraska Department of Labor, the median hourly income for the Lincoln area is \$15/hour. The cost of delay from the three outages is about \$330. SSAM analysis produced an additional 900 conflicts for the three power failures. With the cost of \$1.33 per conflict, the safety benefit was about \$1,200.

The fuel consumption per delay minute at a speed of 45 mph (the speed limit at 84th Street) and 55 mph (the limit at Highway 2) for corresponding vehicle mix was obtained from estimates by AASHTO. The average fuel cost at the intersection area was weighted by the Average Annual Daily Traffic (AADT) at 84th Street (7,100) and Highway 2 (25,550). As shown in Table 6, the average fuel consumption per minute of delay is 0.0896 gallon. The average Midwest retail gasoline price for all grades, all formulations, from January to September 2011 (\$3.60/gallon) is used as the cost of fuel for all vehicle classes (EIA, 2011). Nearly \$420 of fuel cost could have been saved from these three outages.

Table 6. Fuel consumption (gallons) 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					
Highway 2	0.09324					
Average	$0.0727 \times 7100/32650 + 0.09324 \times 25550/32650 = 0.0896$					

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 monetized damage cost of an incremental increase in carbon emissions in a given year. 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 (CAFE) rule. The value \$2 was used as the price of CO₂ in this study. Muller and Mendelsohn estimated the marginal damage cost for several kinds of pollutants (Muller & Mendelsohn, 2009). Table 7 shows the marginal damage cost estimation for NO_x and VOCs at the lower (25th percentile), median (50th percentile) and upper (75th percentile) levels. Here the median marginal damage costs were used as the unit cost of pollutants. At these prices, the annual emission saving from generating green energy was about \$11 with the production of 2,800 kWh per year as estimated in section 5.1.1.

Table 7. 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 the Lincoln Police Department, the cost of police direction is \$53/hour accounting 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 to the duration of power outage.

The total cost of the three outages is shown in Table 8. Electricity production from the RWPS during the 344-minute outage was not listed in Table 8. Based on the average annual production of 2,800 kWh, the electricity production during these three outages would save \$0.14 at local rate of \$0.075/kWh. About \$2,250 would have been saved in these three outages if the RWPS had been present. The duration of the second outage is about twice of the third one, but its resulting delays are more than 7 times the duration of those from the third outage. The main

Table 8. Estimated costs of three power outages at the subject site

Outage	Duration (min)	Delay (s)	Conflicts	Fuel (gallon)	NO _x (kg)	VOCs (kg)	CO ₂ (kg)	Police Duty (min)
1	68	6,442.66	157	9.62	0.10	0.13	66.91	53
2	186	63,322.66	543	94.56	1.04	1.27	818.37	171
3	90	8,230.53	200	12.29	0.13	0.15	97.61	75
Annual Average	68.80	15,599.17	178	23.29	0.25	0.31	196.58	59.8

reason is the high traffic volumes during peak hours. Based on the three power outages in the five years, we estimated an annual average for each item, as shown in the last row of Table 8.

The average annual total benefits of using an RWPS system at the subject intersection are summarized in Table 9. The total benefit in the first year of installation is \$670. Assuming a 3% inflation rate and 15-year lifecycle, the total lifecycle savings of the wind power system are \$15,216. The lifecycle payback is 182% (15,216/8,352). Breakeven could be reached within 9.5 years at the local utility price (7.5 cent /kWh, 2011).

Table 9. 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 (gallon)	116.47	23.29	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 resources, power outages distribution, and all other factors constant, the RWPS would provide more lifecycle benefits if installed at the locations with high utility prices. The highest average electricity retail price in U.S. from January to June 2011 is found in Hawaii: about 29.58 cents/kWh (EIA, 2011). Assuming only the utility price is different, the benefits from the same RWPS located in New York and Hawaii are compared to the studied

intersection in Lincoln. The results are shown in Table 10. At the highest utility rate, about four times of Lincoln local rate, the lifecycle payback would be almost doubled.

Table 10. Economic benefits of RWPS at different utility prices

	Lincoln site	NY site	HI site
Utility price (cents)	7.50	15.70	29.58
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 here are conservative. The designed system lifecycle as claimed by the manufacturer is 25 years instead of the 15 years used in the analysis, meaning there would likely be more energy production and other savings throughout the life of the product. The three outages observed in the 5-year studied period are only unplanned power outages; planned outages were not considered. 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 be even possible to reach the breakeven at the first year of installation if the power outage frequency is high and other conditions are the same. The RWPS system will provide a fluctuation-free source of power, which would further reduce the risk of controller malfunction and improve the safety and efficiency of traffic operations.

6. Conclusion

This paper proposed an RWPS as alternative power source for traffic control signals. The proposed system will potential lead to following benefits at suitable sites:

- It will reduce the power purchased to operate and maintain the roadway systems, which will reduce operating costs.
- It will provide a source of backup power for the transportation system. This will reduce the risk of blackouts 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 feasible locations are limited by the availability of wind resources. Some urban and suburban areas may not have sufficient wind resources to provide efficient power generation.

Methodologies were developed to check the feasibility and conduct a benefit-to-cost analysis. This ratio can help in decision-making regarding RWPS applications. The intersections can be prioritized based on the benefit-to-cost ratio to use budgets most effectively. The methodologies of this analysis can be also used to evaluate different battery backup systems for traffic control signals.

The case study proved the RWPS was economically viable at the studied intersection. This case study can directly help the local transportation agency in Nebraska to check the benefits and costs of installing an RWPS at desired locations.

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