Wind Resource Assessment for Highway Luminaire Applications

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***Abstract* – Highway luminaries are a key element to ensure transportation safety during the night. Previous studies revealed that over fifty percent of crashes occurred during the evening even though, in general, there are fewer vehicles-miles during the evening. These results made clear the importance of luminaries in highways, but these luminaries could raise energy cost. Recognizing the high demand of energy caused by highway luminaries and the need for new technologies, this project investigates the potential use of wind turbines in highways to harness the wind energy generated by the motion of a passing vehicle to lower the cost of energy in public illumination. The investigation was conducted through two experiments, a Single-Vehicle Testing and a Multiple-Vehicle Testing. As shown in the results, the measured maximum wind velocities due to the passing of cars (without considering high natural wind speeds) was insufficient to provide the required energy for highway luminaires**

***Keywords*-- Highway luminaries, Traffic Safety, Wind Energy Estimate, Highway Wind Farm (HWF).**

Digital Object Identifier (DOI):
http://dx.doi.org/10.18687/LACCEI2017.1.1.391
ISBN: 978-0-9993443-0-9
ISSN: 2414-6390

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I. INTRODUCTION

Road accidents are a major problem worldwide, especially in low and middle-income countries [1]. Over 1.2 million people die each year on the world's roads [2]. Daily traffic on roads is increasing and road accidents are increasing as well. World Health Organization stated that road traffic injuries are the leading cause of preventable death among people aged 15-29 [2]. In 2012, it was estimated that by 2015, road traffic injuries were the ninth leading cause of death across all age groups globally, and by 2030, it will become the seventh leading cause of death [3]. Studies reported that, in the United States, nighttime crash rates are three times higher than daytime crash rates [4].

Highway luminaries are a critical component of roadway system in respects to safety. Studies in UK and Greece showed that road crash injuries could decrease three times less if road lighting is introduced [5]. Meaning that having better luminance in roadway could lower road accidents, but this will increase energy consumption, which already takes a toll in the total electrical consumption.

Although luminaire systems are very important for traffic safety it is also important to consider the energy consumption of highway lighting. To that end, technologies intended to save energy use efficient luminaires such as Light Emitting Diode (LED) and luminaire that could adapt its intensity depending on the amount of traffic flow called Adaptive Lighting Systems (ALS) [1]. The use of LED in outdoor lighting application has increased interest to decrease energy consumption. The luminaire is accounted for 60%-80% of total electricity consumption of municipality, resulting in the economic burden of maintaining public lighting [6].

The impact of energy consumption by luminaires is a relevant issue in Puerto Rico (PR). The island has approximately about 550,000 light poles illuminating public roads and highways in PR [7]. According to the Puerto Rico Electric Power Authority (PREPA), the total cost for public illumination was $109.1M in 2014 with a significant portion of electricity consumption attributed to the highway and public luminaries from light poles [8]. This cost for public illumination is about 43% of the total cost of electricity in the municipalities.

PR high cost of energy is due to the island full dependence on fossil fuel. As stated by PREPA, petrol-burning plants at this time produce 61% of the electricity in PR. Coal and Natural gas account 24% and 14%, respectively, and alternative energy generates only 1% of the energy production [8]. Reducing the dependence on fossil fuels will also reduce its contribution to environmental pollution and greenhouse effects. A 2010 law in PR established a goal that 12% of the energy produced must be generated through renewable sources or alternative sources by 2015 [9]. It stated that this percentage should increase to 15% by 2020 and 20% by 2035. Currently, is not meeting the requirements to produce the required proportion of renewable energy.

This worldwide need for increasing traffic safety and lowering energy consumption is critical. This paper addresses the opportunity for highway wind farms that could harness the energy from airflow profile around a moving vehicle. The wind may occur as a natural phenomenon, or artificial, roadways airflow can be produced by vehicles i.e. while standing on a roadside and a bus charges by you or car, you may have felt that pressure or wind passing by that even shakes the vehicle. Viewing wind availability as a function of traffic patterns instead of natural phenomena will help us predict the performance of highway wind farms that could harness this energy.

II. WIND ENERGY FOR LUMINAIRE APPLICATIONS

The U.S. Department of Transportation (USDOT) and international teams have conducted studies investigating the implementation of small-scale wind energy units placed in the highway right of way (ROW) [10] [11]. These studies have

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shown the extracting energy from the wind power provided by natural and passing vehicles is possible. The theoretical results from these studies suggested that Vertical Axis Wind Turbien (VAWT) with self-start capacity and low wind speed operation should be used [11]. In the study, no comparison with computational analysis results or field measurements were performed to show the viability, but it proposes a mathematical framework for evaluating the feasibility of harnessing the wind energy from vehicles passing on a highway [11]. This mathematical framework had four main components that need to be considered: i) road selection, ii) atmospheric boundary layer (ABL), iii) model for highways vehicles and iv) turbine blade profile. For the road selection, it considered the average annual daily traffic statistics from the Federal Highway Administration (FHWA), which quantified some traffic on a motorway. An Unsteady Reynolds-Averaged Navier-Stokes (U-RANS) method was selected, and two-dimensional numerical studies were performed. Simplified vehicle models were used, the dimension was scaled down, and degrees of separation from 10m to 50m were tested to determine the optimum length between vehicles [11].

With the results of the computational fluid dynamic (CFD) analysis, C. Lapointe and H. Gopalan concluded that it could be possible to extract energy from a passing vehicle in the highway [11]. They calculated that at least 141W could be extracted from a passing vehicle if that turbine had a power coefficient (CP) of 0.59. The power coefficient of a wind turbine is measured by how efficiently the wind turbine transform the wind energy into electricity [12]. The Betz Limit is the theoretical maximum power coefficient for any wind turbine, and Horizontal Axis Wind Turbine (HAWT) have power coefficient from 35-45% [13]. Therefore, the power generated by the wind turbine should be less than the regular production [6].

Most of these studies have taken into consideration the numerical analysis and CFD simulations, but there is no field measurement or wind tunnel studies to provide validation of the computational results. To determine the energy production that could be extracted from the airflow induced by the passing of a moving vehicle in a highway; it is important to identify the wind resources potential. Identifying the wind resource, we will have a perspective of the average wind speed generated in certain roads given a specific speed limit and traffic to have a proper performance evaluation, sitting, and system design.

III. EXPERIMENTAL ASSESSMENT

The study was divided into two different categories of test: i) Single-Vehicle Testing and ii) Multiple-Vehicle Testing. The single-vehicle testing tries to show the effect on the wind speed of the passing of one vehicle ay a time. The multiple-vehicle testing tries to show the accumulated effect of vehicles passing through a certain point in the highway.

The wind speed smart sensor (S-WSB-M003) shown in Figure 1, is designed for Onset HOBO® data loggers. The anemometer consists of three polycarbonate cup and Teflon bearings. The sensor parameters are saved in the smart sensor, which communicates with HOBO data logger with no need of programming or additional setup. The wind speed sensor can measure wind speed from 0 to 76 m/s (0 to 170mph), with an accuracy of ±1.1m/s (2.4mph) and a starting threshold of ≤1m/s (2.2mph). [14]

Figure 1: Onset HOBO data loggers Wind Speed Smart Sensor

To study the effect of single vehicle testing, the experiment was setup as shown in Figure 2, the anemometer was placed on top of the barrier and approximately 3ft (91.44cm) from the side of the vehicle. The experiment consisted of passing near the barrier at speeds of 45mph (72.42kph) while measuring the wind speed generated by the vehicle.

In the first part of this study, the test was organized on a closed road for single vehicle test. Two types of vehicles were used: compact car and SUV. This dimension of the vehicle were considered because the most common vehicle to pass near the New Jersey barrier would be passenger cars (which would not include vehicle Class 4 and above) [15]. The results from the first test were inconclusive due to natural high wind speeds. A second set of tests at 45 mph, during a no natural wind period, showed that the wind speed generated or the duration of the wind by a single vehicle was not able to surpass the minimum wind speed threshold of the anemometer.

Certainly, the effect on the wind speed in the highway from multiple passing vehicles will be greater than the effect of a single vehicle testing. The findings from previous research of CFD simulations does not correlate with the findings of the single vehicle testing shown here. In the single-vehicle testing, the vehicles did not start the motion of the anemometer. Therefore, the test site was modified to the highway, to test the effect of multiple vehicles. Given the results of single-vehicle, it was expected that a sustained airflow could be formed by the passing of multiple high-speed vehicles in a highway. This wind speed generated by the passing of multiple vehicles should be measurable by the anemometer.

Figure 2: Experimental setup for Single-Vehicle Roadside Measurements

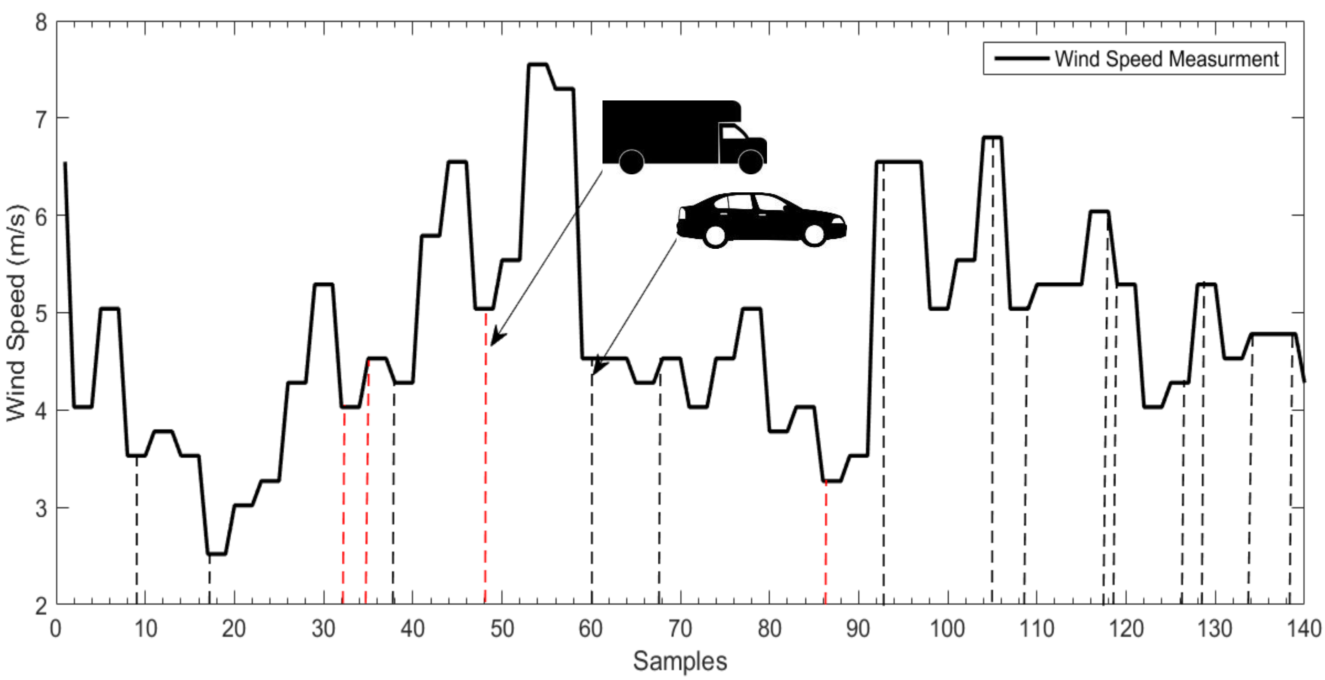
For the first multiple vehicle tests, the highway PR-30 with a speed limit of 55mph (88.5kph) was the site used as a preliminary test to identify the wind availability. The anemometer was set 1ft (30.48cm) from the vehicle parked on the roadside.

From the findings of the Single-Vehicle testing, it was decided to test in the highway to evaluate if the higher frequency of passing vehicle could, in fact, create sustainable airflow that the anemometer could measure. For the Multiple-Vehicle testing, the anemometer was rotating due to the local wind and when a large vehicle passes, wind speed increases are measured by the anemometer. The rotational speed of the anemometer incremented, immediately after a large vehicle passes by.

Figure 3 illustrates the results from the Multiple Vehicle Testing done on the highway. Large vehicle (Class 4 and above) were identified in the figure 3 with red vertical dash lines, and passenger vehicles (Class 3 and below) were identified with black vertical dash lines. It can be seen that most of the times large vehicle to generate higher wind speeds (an example of this result can be seen from samples 50 to 60 and 85 to 95). The wind means average was 4.76 m/s with a maximum wind speed of 7.55m/s.

The induced wind generated by the passing of multiple high-speed vehicles in the PR-30 was just a prove of concept. Due to the results measured from this preliminary test in the PR-30 a second test was conducted. The second test was set up at Luis A. Ferré Highway (PR-52), with a speed limit of 55mph and the highway with the highest vehicle density in the island [16]. The anemometer was placed on top of the barrier and was set 1ft from the barrier as illustrated in Figure 4.

Figure 4: Anemometer set on top of barrier with an offset of 1ft at PR-52



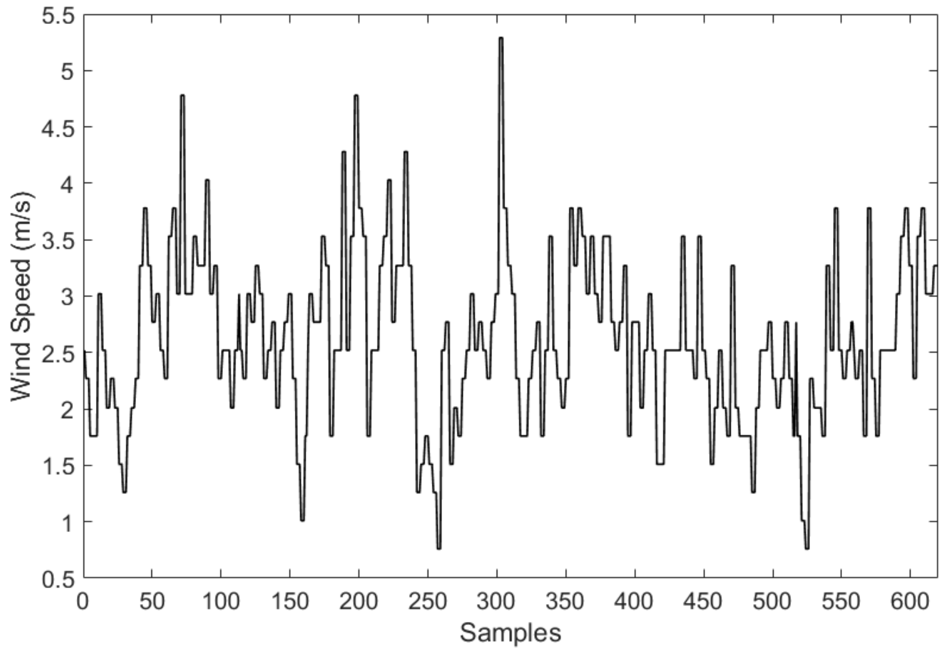


Figure 5: Wind Speed Measurements of Multiple-Vehicle Testing in PR-52

The test results lead to another multiple vehicle test. The anemometer position was not changed; it was set in top of the barrier with an offset of 1ft from the barrier. The multiple vehicle test at PR-52, revealed that there is an airflow induced by the passing of fast moving vehicles in the highway that can be measured by the anemometer. The data obtained shown in Figure 5 had an average wind speed of 2.75m/s and standard deviation of 0.78m/s.

There is one final test needed to prove that the wind speeds are in fact generated by the passing vehicles (or in relation to the vehicles), but it setup is more complex and will require the use of at least three anemometers. This is considered unnecessary, because there is not enough energy production with the wind speeds found in the test. This means, for academic purposes, the actual wind speeds generated by passing vehicles may be found, but in practical terms, the data already gathered show that the winds generated by vehicles in conditions similar to the test shown, will not produce enough energy to power luminaires in highway with current market technology. The next section will show precisely this.

IV. WIND ENERGY ESTIMATION

Estimated wind energy production was obtained using commercially available wind turbine of 75W [17]. The power curve of Darrieus Vertical Axis Wind Turbine is shown in Figure 6. The advantage of VAWT over Horizontal Axis Wind Turbine (HAWT) is their omni-directionality without the need of an external control; VAWT can also operate in turbulent condition making them perfect for urban application. [18]

Figure 6: ALEKO® Vertical Axis Wind Turbine [17]

The power curve of a wind turbine is a key parameter that relates the wind speed and the individual electrical power output of the turbine [19]. The most critical characteristic of wind farm is the wind speed. To maximize the wind production, it is important to determine the wind resources.

The monthly energy production was calculated with the use of the wind measurement from PR-52 testing (Figure 6) and the power curve (Figure 7). The wind measurement histogram is shown in Figure 8. This histogram takes 1 m/s bin intervals and counts the occurrence of the wind speed measurement from the data in Figure 5. The number of occurrence is then multiple by the power available by the turbine for the given wind speed interval and then is sum up.

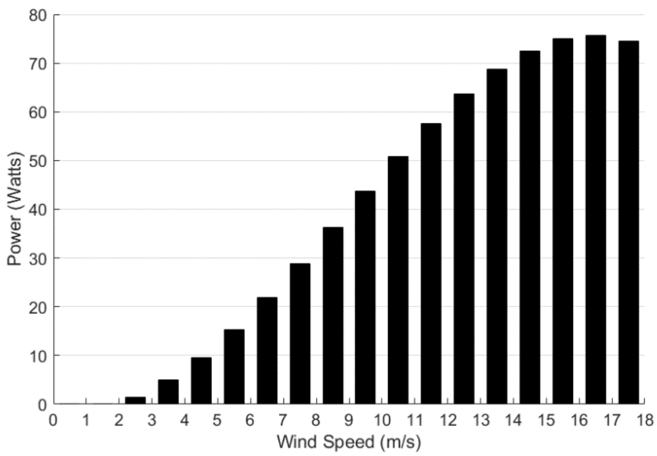


Figure 7: Commercially available 75W VAWT Power Curve

This power production is then added; this data was extrapolated from 40-minute reading to 12-hour daily operation in one month. Table 2 shows the results from this calculation. The energy production for the monthly energy production was calculated with Equation 1 and capacity factor (CF) with Equation 2 [12]. The capacity factor is the average power generated, in this case 2.2kWh divided by the rated peak power 37.0kWh resulting in 5.89%.

$$E = \sum_{i=1}^{N_{speed}} P_{Oi} \times t_i = 2.2\ kWh \qquad (1)$$

$$CF = \frac{Energy - Site}{Energy - Rated} = \frac{2.2kWh}{37.0kWh} = 5.89\% \qquad (2)$$

(m/s)

Table 1: Wind Energy Production from PR-52 Highway data

Power Average	Capacity Factor	Energy per Month
3W	5.89%	2.2kWh

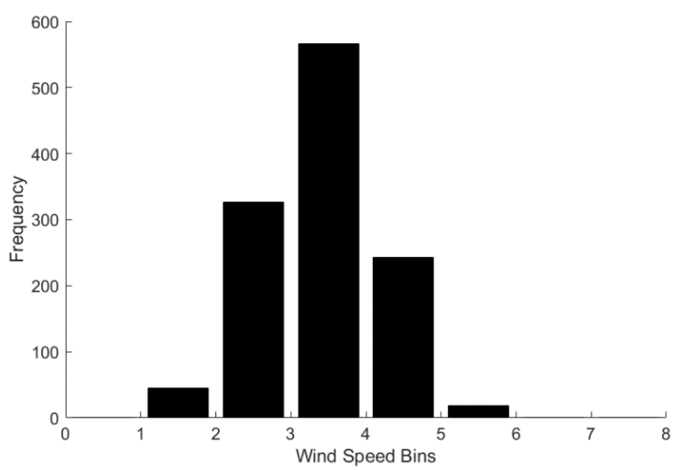


Figure 8: Wind Speed Histogram of Multiple-Vehicle Testing in PR-52

Figure 8 demonstrates the available and existing luminaire for highway light poles located in Puerto Rico. The energy consumption was obtaining for a month operation with 12-hour daily operation. The calculation of this energy consumption is useful to determine if the single turbine could deliver the required energy to the luminaire. From the measured wind speed and 75W commercially available turbine it could only extract 15.3% of the required power to illuminate the lowest consuming LED with an energy consumption of 14.4kWh.

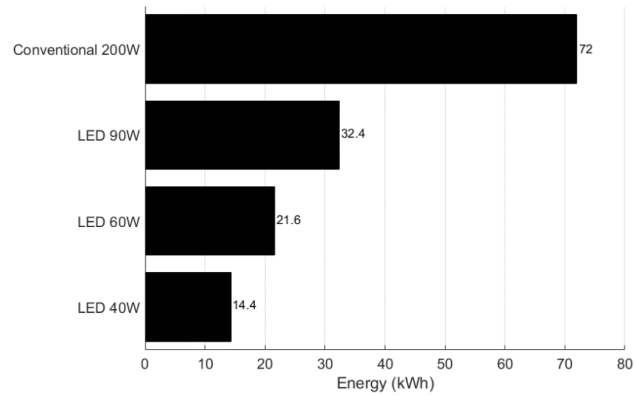


Figure 9: Energy consumption for luminaries available for light pole per month with 12 hours of operation

V. CONCLUSIONS

In conclusion, highway wind farms may be used to improve traffic safety while reducing the cost of energy for luminaire applications only if natural wind speed is consistently high to maintain energy production by itself. The single-vehicle testing was not successful in calculating the wind speed generated by a single vehicle, because the airflow did not surpass the lower threshold to rotate the anemometer. Experimental testing in highway showed better results, which showed anemometer readings increment with airflow induced by the passing of vehicles. The highway testing provided better perspective of how the induced airflow from a passing vehicle is not large enough to harness energy. From the different types of luminaire which energy consumption vary from 14.4kWh per month to 72kWh per month. Experimental data from wind energy assessment for a commercially available wind turbine showed limited capability to power luminaire applications with the use of a single 75W VAWT. This single turbine would only provide 2.2kWh vs. required energy 14.4kWh per month for a 40W LED. It needs to be consider the use of multiple wind turbines and study the feasibility of this type of wind farms.

Previous research, by other authors, concluded that high amount of energy could be extracted from high-speed moving vehicles in the highway. C. Lapointe and H. Gopalan concluded that it could be possible to extract energy from a passing vehicle in the highway [11]. The CFD model consisted of a tunnel with inlet wind speed, the wind left behind the vehicle was the wind affecting the turbine. However, the CFD models does not replicate what happens in the highways when high-speed vehicle passes near the turbine. To properly replicate CFD, vehicle model should move at the stipulated speed, which is different from the previous CFD models that consider wind speed of stipulated vehicle speed. Certainly, some energy can be extracted from the highway, but it is impractical to do so for highway luminaires with the technology in the market today.

ACKNOWLEDGEMENT

The authors would like to thank the economic support of the Dwight David Eisenhower Transportation Fellowship Program (DDETFP) of the Federal Highway Administration.

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