FEASIBILITY OF USING VERTICAL AXIS WIND TURBINES (VAWT) PLACED ON HIGHWAY MEDIANS

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Abstract. As concerns grow over limited resources, fluctuating energy prices, global warming, and environmental degradation, the need for renewable energy sources has becomes paramount in maintaining and meeting the current energy demands. Among the renewable and clean energy technologies, wind energy is one of the most efficient and cost-effective sources of renewable energy production, costing 1-2 cents per kilowatt-hour after the production tax credit by governments. While natural wind speeds over various continents in the world span from 0 to 20 m/s, Vertical Axis Wind Turbines (VAWT) placed on highway medians make it possible to utilize consistently higher wind speeds due to vehicle motion. Additionally, the energy generated by these wind turbines is reported to increase multi-fold due to the shearing winds generated on both sides of the medians by the on-going traffic, and offer a great opportunities to reduce costs as well as carbon footprint. The objectives of this project are to characterize vehicle-induced wind patterns to assess and empirically quantify the potential for wind energy-based electric generation for highway services, such as lighting and signage, in areas for which the electrical grid is either unavailable or for which interconnection would be complicated and expensive. In addition, we seek to optimize the number and positioning of VAWT turbines to achieve optimal results using criteria determined to be important, such as output power, ease of installation/repair, proximity to consumers, additive effects from positioning e.t.c. We seek to apply a computational fluid dynamics approach, real-life traffic, geographical and weather data and subsequently investigate the economic feasibility of implementation of this technology.

Contents

1. Introduction to the Project

The utilization of wind energy is technologically driven and has gained significance as one of the best alternatives to the traditional methods of generating electricity with a viable potential to mitigate and reduce global warming effects on the environment. As a result, wind turbines have evolved technologically over the years with considerable potential to generate and contribute to the global energy productions as it represents a low-carbon alternative to conventional power-generation technologies that depend on fossil fuels. Wind energy is trending as one of the main sources of clean, renewable energy that would allow a rapid transition away from current fossil-fuel-based energy. However, if wind power is to drive a significant share of global energy supplies, the efficiency and energy density of wind turbines need to be improved. Despite the urge potential, harnessing the power of wind turbines depends on many variables ranging from environmental factors to design specifications. One typical way of improving wind turbines power is through highway installation, particularly at a high wind gust zone. The deployment of wind turbines on the highways has a considerable potential to generate electricity from traffic-generated turbulence between the turbine and passing vehicles.

While travelling along the highway at high speeds, vehicles produce large amounts of wind energy in their wakes which is not being captured. By placing vertical axis wind turbines (VAWT) on highway medians, we could capture some of this energy and use it to power lights, charging stations, or other projects. In this project we identified factors that affect the performance of VAWTs, computed estimated power output on the 401 Highway and identified some other potential sites and future directions.

2. Turbine characterization and cost

The optimal performance of a wind turbine depends on the type, design, and structural specifications of the turbine among other factors. As a result, many different designs of wind turbines have emerged over the years. However, contemporary wind turbines can be identified based on the shaft orientation and rotational axis as either the horizontal-axis variety (HAWT) or the vertical-axis design such as the Savonius type, the Darrieus type, or the Giromill type(VAWT).

This project focus on the feasibility study of vertical axis wind turbine due to the marginal cost of the turbine and the ability to accept turbulent flow by air displacement from vehicular movement irrespective of the wind direction. VAWTs are designed to capture the wind kinetic energy irrespective of wind orientation, thus, setting aside the need for re-positioning along with the wind and thereby offering great benefits in places where the wind direction keeps varying. VAWTs are characterized by lower aerodynamics noise and fit in more readily into urban settings. This structural configuration considerably reduces the operating costs while improving stability and reliability. In addition, VAWTs have distinct operating features such as the ability to operate under irregular wind flow, slow cut-in speed, and low maintenance cost than comparably sized axial flow turbines. Based on the literature survey in support of this project, we identified Banki and Colite DS series turbine systems as potential wind turbines that can be placed on highway medians for power generation. Besides harvesting wind omni-directionally simultaneously, they are better suited for large array installation, that is, more able to stage multiple turbines on medians to capitalize on synergistic fluid interactions between the turbines. Collectively, these characteristic features imply that arrays of VAWTs can possibly gain power densities an order of magnitude higher than those of isolated wind turbines. However, harnessing wind power from any direction to create energy using these turbines is an attractive option and despite the intensive research in the field, the underlying performance parameters of the turbines and the question of scalability are not yet settled. One of the few studies that investigated the performance augmentations of pairs of VAWT was that of Dabiri [3], which were experiments in a desert with six $10m$ tall times $1.2m$ diameter VAWTs were conducted. The experiments investigated the effects of turbine spacing and direction of rotation. It was observed that while HAWTs experienced an overall decrease in power by $20\% - 50\%$ when placed in close proximity to each other (1.65 turbine diameter separation), the VAWTs enhanced the overall performance by $5 - 10\%$. In this regard, Banki and DS series wind turbines can be paired and interact synergistically to enhance the total power production when placed in close proximity.

The Banki and DS series turbines have cut-in wind speeds of about $1-3ms^{-1}$ and rated wind speeds that are less than $15ms^{-1}$. Table 1 provides more information on the specifications of the four models that were used as a basis of wind data interpolation for power generation.

Table 1. Colite VAWT specifications.

Model	**Banki**	**DS-300**	**DS-1500**	**DS-3000**
Cut-in wind speed (m/s)	1	< 3	< 3	< 3
Rated Wind speed (m/s)	10	13.5	12	12
Maximum Speed (m/s)	12	15.5	15	15
Rated Output (kW)	0.2-0.8	0.3	1.5	3
Rotor Diameter (m)	1	1.24	2.8	4
Rotor Height (m)	0.1	5.06	6.9	8.16
Turbine Cost ($)		3,585	18,825	26,625

3. The Data

In this project we identified several factors that could positively and negatively affect VAWT power output. For example, it is known that VAWTs perform better in laminar flow, and that the wake from vehicles is highly turbulent. Moreover, in [7] they showed that the power output from cars and SUVs is essentially negligible when compared to the power output from trucks. In light of this, we realized that since most trucks travel in the right (slow) lane, it made more sense to consider placing VAWTs on the shoulders of highways. Thus we only considered one way traffic. The East-bound direction on the 401 had 21% more traffic than the West-bound direction, and was used for this study. It should be noted that the wind generation modeling results presented in this report are based on a single VAWT. When considering VAWTs deployment, it should be recognized that the wind power technology is scaleable and thus multiple turbines can be deployed over a small area to produce additional electricity.

3.1. **The 401 Highway.** The 401 is the largest highway in Canada. Exploring data from [6], we found that in 2006, nearly 8000 vehicles travel on the 401 at Keele St every hour. On weekdays, nearly 2000 of those are trucks.

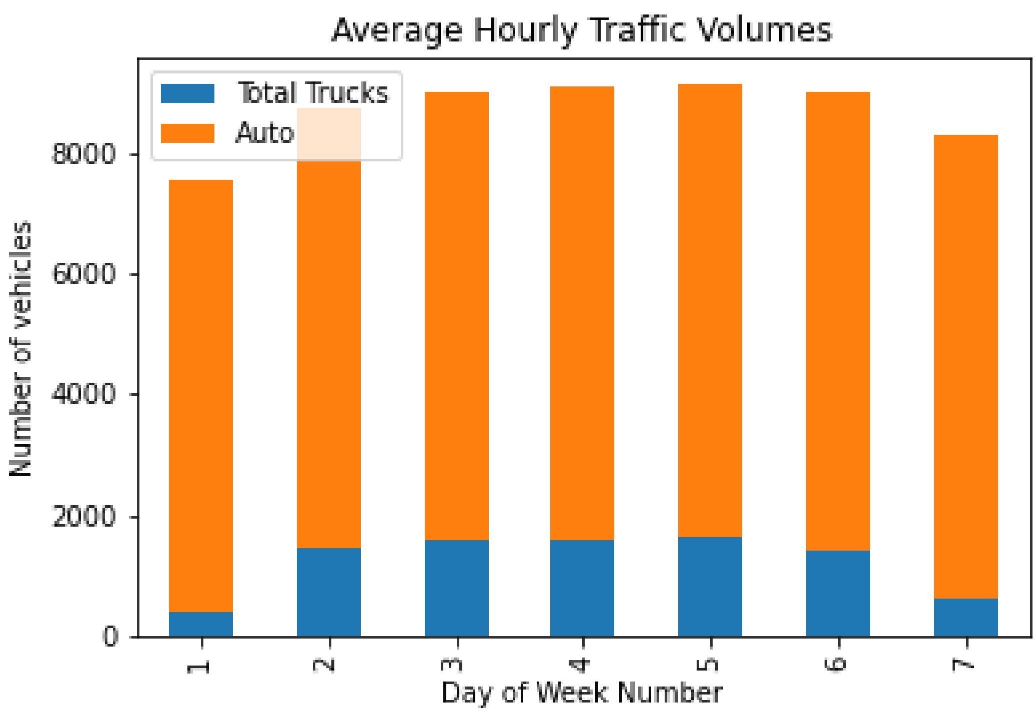

Figure 1. Average hourly traffic volumes on the 401 at Keele St made using Python.

To improve this data for our computations, we scaled it up by 12% to match population growth in the Greater Toronto Area. Next, we wanted to understand the lane by lane composition of the traffic. Based on [1], in a 6 lane highway about 50% of trucks are in the rightmost lane, while only 5% are in the leftmost lane. Extrapolating this for an 8 lane highway, we assumed about 40% of trucks are in the rightmost lane and 5% are in the leftmost lane. We applied this to our data set. Finally, the data from [6] was taken hourly over a two week period. We wanted to add in some seasonality to reflect the fact that there are more passenger vehicles on the road in the summer and less in the winter. We assumed the two week period took place in the Spring/Fall, repeated the data to have values for each day of the year, increased car volumes by 10% for days between June and September, and decreased car volumes by 10% between January and March, while keeping truck volumes constant.

This area of the 401 is a good candidate site because it has the largest truck volumes in all of Ontario. Moreover, due to the proximity to Lake Ontario there are higher windspeeds than in other areas. However, a metropolitan area has access to many other sources of power already, and the influence from buildings and other roadways may dampen the amount of wind the VAWTs can harvest. This analysis suggests that potential energy generation would vary from location to location and based on many factors, including the number of traffic lanes, median or center barrier type, traffic volume, vehicle type, and season.

3.2. **Other Potential Sites.** The data in [6] contains hourly traffic volumes for all main highways in Ontario. This would be a good data set to compute power output for other sites in Ontario. We also considered traffic data from the BC 5 highway which was reported on the Government of British Columbia website. We selected the daily data from 2018, and approximated some missing data by averaging the values from the previous years, we didn't have enough time to do the similar analysis we did for the 401 Highway, but it is a good candidate for future research on this project.

While other provinces did not have as robust traffic data, there are many other sites that could be good placement for VAWTs. For example, any areas with high wind speeds, in energy deserts, or with reasonable weather (not too much ice or snow) would make good candidates. However, in any case, we found the most important feature is high truck volume.

3.3. **Wind Data.** The National Renewable Energy Lab has developed the wind toolkit database [4] for onshore North American winds from 2007 to 2014. Wind speed, wind direction, and other meteorological are available at 5 minute intervals over a 2km x 2km grid. Each variable is available at various heights throughout the atmospheric boundary layer from 10m to 200m above the Earth's surface. Examining the wind data set, it is obvious that the turbulent wind flow exhibits high temporal and spatial variability. Therefore, the magnitude of a turbulent flow is best measured by maximizing data resolution (i.e., minimizing the sampling intervals). As a result, 10m wind velocity for the most recent year (2014) was used for this analysis. The 10m wind velocity was further scaled down to 2m height via a log-wind profile with a mean canopy height of 1m, this reduced the mean wind velocity by 40% from 2.95 m/s to 1.76 m/s. Furthermore, the wind was assumed to be constant over each 5 minute interval. Despite the wind and traffic data being from two different years, they were assumed to be independent, and no further adjustments were made.

4. Modelling

4.1. **Traffic Simulation.** The hourly truck and passenger vehicle rate on the 401 were each treated as a Poisson parameter and decomposed to the expected number of events per 2 second interval. If a truck, being a longer vehicle, was present within the 2 second interval, no other vehicle could be present; however the number of passenger vehicles, being smaller, were unrestricted. While there is is a non-zero probability that more than 1 truck is present within the 2 second interval, given that the average truck rate was 0.14 trucks per 2 second interval, there is less than 1% chance that the mean interval would contain more than 1 truck.

4.2. **Wind-derived Power.** As referenced in [7], the most applicable vertical axis turbines for are solonius or banki style turbines. The turbines studied are approximately 1m tall and 1m in diameter. While larger turbines certainly exist, sight-lines, safety, and space concerns limit the size of the turbine.

Given that the air is not moving at a standstill after passing through a turbine, a turbine doesn't capture 100% percent of the potential energy. Under ideal conditions a wind turbine captures between 30 and 50% of the potential wind energy. A typical manufacturer's rating for a 1m x 1m turbine is 300W at 10m/s, half of the 600W potential energy.

Unfortunately, in reading many small turbine reviews, the manufacturer's rating does not match up to reality. A variety of other conditions, notably turbulent wind can greatly decrease the power production. Engineering design studies [5, 8] refer to a 1m x 1m turbine with a manufacturers rating of 300W at wind speeds of 10m/s produces a maximum of 40W under turbulent wind conditions.

Furthermore, a feasibility study in Kuwait [2] measured the wind produced by vehicles along a highway to be 5.1 m/s. For a 40W turbine, with a 1m/s cut-in speed, this corresponds to 6W, which is the power production found in a truck found in [7]. Note that [2] suggests using a 3m high and 1.8m diameter turbine, they found this turbine to produce 50W at wind speeds of 5m/s. However, for this analysis, we will use the 1m x 1m turbine, producing a maximum of 40W at wind speeds of 10 m/s, the power curve used for this turbine is taken from [8, 5] and is shown in figure 2.

Research [7] finds that a single vehicle creates two gusts of wind, one from the air being pushed by the front of the vehicles, and another from the air being sucked in behind the vehicle as it passes the turbine. In this model, a single vector of wind, parallel to the flow of traffic was created over each 2 second interval. The wind vector was then added to the prevailing wind taken from [4]. The new wind vector was then converted to power using the power curve illustrated in Figure 2.

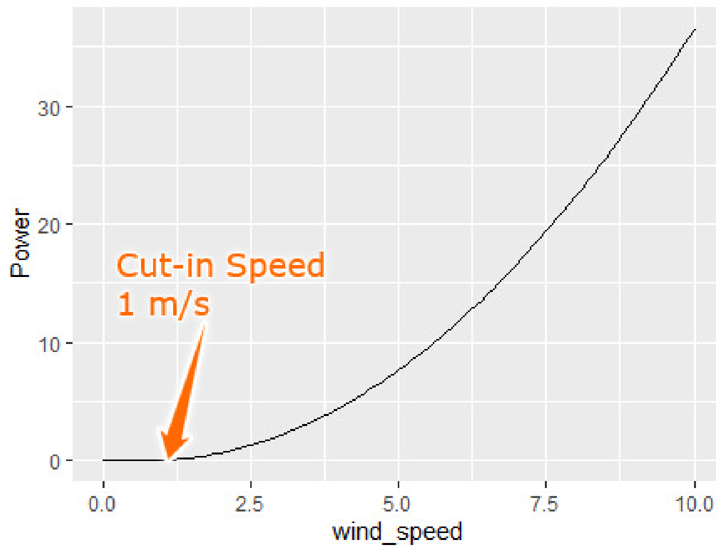

FIGURE 2. Power curve of 1m x 1m turbine in turbulent Conditions. The turbine has a manufacturer rating of 300W at 10 m/s, but experimental data suggests a peak of 40W.

	Single Vehicle	Two Vehicles	Three Vehicles	Theoretical Limit
Truck	6.48	9.71	11.32	12.92
Car	0.49	0.74	0.86	0.98

TABLE 2. Average Power(W) from a single turbine from multiple vehicles in series used in the vehicle-derived model.

4.3. **Vehicle-derived power.** Instead of modelling the wind velocity, we can model the energy produced. Research [7] shows that a truck can produce an average of 6W, with a peak up to 15W. Passenger vehicles produce a much smaller power output; however in the presence of other vehicles, they can contribute up to 1W of power.

To model this output, a variety of power decay curves were evaluated. Linear decay was found to overestimate the power, as multiple vehicles passed the turbine, it would produce higher and higher amounts of power. Exponential decay successfully reduced the maximum power output, but produced long tails under 1W of power. As a result, a combination exponential decay with rate 0.9 and linear decay with rate -1W/2s interval were chosen. The exponential reduced the peak power, while the linear decay reduced the length of the tail. Figure 3 illustrates an example of this power generation, and table 3 shows the mean power generation of multiple vehicles in series. In this model, the wind was treated independently to the power, and power generation due to the prevailing wind was added as per Figure 2.

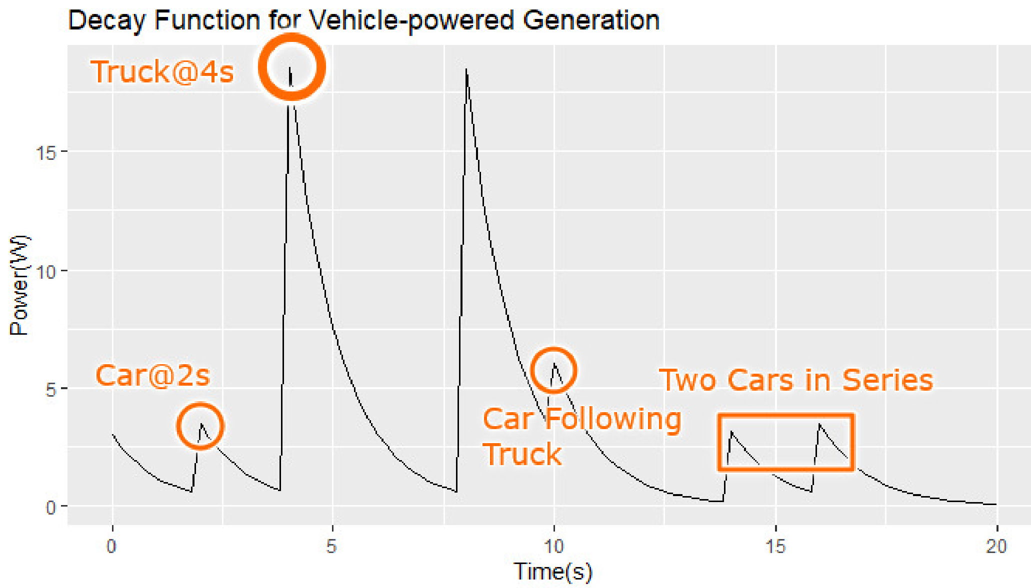

FIGURE 3. Vehicle Power generation used in the vehicle-derived model. As each vehicle passes the turbine, it produces a jump in power, which then decays according to a linear combination of exponential(0.9) and linear decay(-1W/2s interval).

5. Results

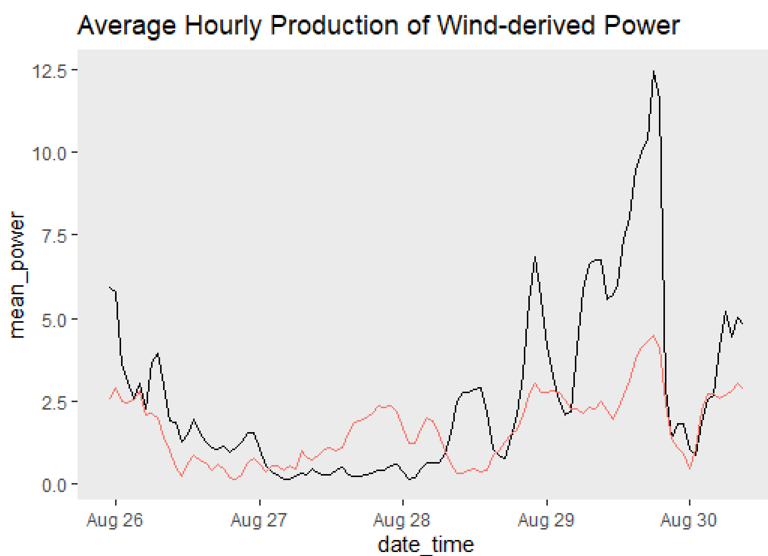

FIGURE 4. Sample of hourly wind-derived power production from August 26 to August 30. The mean prevailing wind speed (m/s) is overlaid in red

	5th Percentile(W)	Mean(W)	95th percentile(W)	Peak Hour(W)
Vehicle-derived Power	0.34	3.88	11.48	17.68
Wind-derived Power	0.05	5.98	21.75	34.83

TABLE 3. Mean annual power production from a single turbine from Vehicle and Wind derived power models.

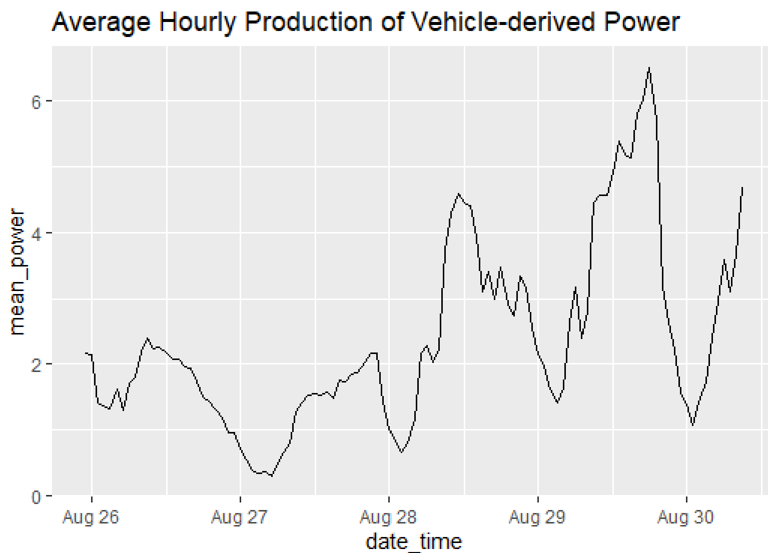

FIGURE 5. Sample of hourly vehicle-derived power production from August 26 to August 30

Table 3 shows the The wind-derived power production model produces on average 5.98W of power per year, while the vehicle-derived produced an average of 3.88W. The wind-derived model also had higher peak hourly power production. However, it had a lower 5th percentile, due to the model assumptions, where prevailing wind and vehicle produced wind were treated as independent vectors. If the prevailing wind was against the flow of traffic, the resulting vector would be low in magnitude, resulting in low power production. Figures 4 and 5 show a sample of 4 days from the year simulated. Increased traffic during the day creates increased traffic flow and thus higher power. Overnight fewer cars pass by the turbine, and the power production decreases accordingly. Figure 4 shows an overlay of mean wind speed in red, the higher windspeeds between August 29 and August 30 contribute to the increased power output.

6. Conclusions

Overall, we see a mean power production of 3.88W with the vehicle-derived power model, or a mean power production of 5.98W with a wind-derived power model. Unfortunately, this cannot power a light bulb, nor a Tesla. Given the size of the turbine studied, the potential for wind power generation is limited, as noted above, for a 1m $\times$ 1m block of wind moving at 10m/s there is a maximal potential energy of 600W. The most effective turbines can potentially capture half of that power, with turbulence and other conditions reducing that again. the CFD studies in [7] show that solitary truck produces 6W of power, and so a model producing an average of 4-6W of power, given the overnight lulls in traffic, could be seen as reason to study this further. If a larger turbine was selected, capable of producing more power at a lower speed, a series of turbines could produces a significant amount of power. However, turbine power scales linearly with area, so a much larger turbine would be necessary. Nevertheless, the generated data facilitates the correlation of energy potential to traffic flux, providing a basis for determining an optimum placement of wind energy generating systems along highways.

There is plenty of future work to continue from this project. This study neglects to take into account the effects of other lanes, the potential for trow way traffic, nor the effects of the surrounding building on wind flow. There were also many approximations during the process of turning the summary data into granular 2 second intervals. The traffic speed was assumed to be constant, thus neglecting the effects of rush hour and traffic jams.

Furthermore, the stochastic modelling of the traffic was relatively simple. Anecdotal evidence of driving on highways suggests that traffic comes in flows, with gaps between slower traffic. Modelling the traffic using Markov chains with a higher probability of passenger vehicles being stuck behind trucks could lead to a more accurate model. Additionally Figures 4 and 5, look like a stochastic process. Using these outputs and designing an optimal trading strategy for battery storage or selling back to the grid would be an interesting follow-up question. In addition, we could also investigate the optimum layouts of small vertical axis wind turbines and perform parametric optimization of three-dimensional analysis of dynamics fluid body interaction for a Banki rotor pair in various configurations. The performance augmentation of turbine pairs would help to estimate the possibility of boosting the derived wind power on highways.

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