Converting Waste Vehicle Aerodynamic Energy into Electricity

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Abstract—**With the number of vehicles traveling every year increasing, it is becoming more important to make every trip as efficient as possible. This leads to the question, is it possible to recover a fraction of the energy that vehicles use? This paper explores the winds produced by road vehicles traveling at high speeds and, by extension, the winds produced by high speed rail and the design of a device that successfully captures and converts this wind into usable electricity. ANSYS Fluent and Solidworks Flow Simulation were used to obtain the induced wind profiles of the vehicles. A novel small scale Savonius wind turbine was then designed and constructed around reasonable perimeters for this application and tested for efficiency. The results of the simulations and experimental testing are provided to prove the proposed wind energy harvesting concept has potential for commercial use.**

Keywords—Aerodynamic energy, energy harvesting, high speed rail, passing vehicle, Savonius wind turbine

I. INTRODUCTION

There has been a growing interest in harvesting renewable energy from transportation infrastructures and public right-of-way to promote sustainable transportation development, save infrastructure cost, and provide a potential revenue source [1], [2]. In this application, wind turbines and photovoltaic panels are commonly used to produce electricity from natural wind and solar resources, which rely on the availability of the natural resources. Today's society is intertwined with high speed road traffic. Current trends have caused an increase in the purchase of larger vehicles like SUV's and light duty trucks [3]. The shipping of products by road is continuing to rise [4]. Even though not popular in America, high speed rail is a growing industry in other countries. With all these vehicles traveling at high speeds it is worth considering if a portion of the energy caused by the induced winds could be harnessed and used to generate electricity. However, little work has been done to study the generation of clean electricity from the aerodynamic energy produced by the vehicles moving on highways and railways. For this application, high traffic density traveling at high speed is the ideal situation.

Such a seemingly intuitive application does not go without some precedence. Previous work has not been as in depth or considered this method of electricity generation [5], [6]. A chassis mounted wind turbine is considered in [5], but that approach is hardly ideal due to the fact that any electricity production will be offset by the vehicle's reduced efficiency. This paper will focus on a way to harness the vehicles waste energy while mitigating the negative impacts on the vehicle's efficiency. A tandem vehicle situation is considered in [6], but only a simplified aerodynamic model is used. Varying distances away from the vehicles, different kinds of vehicles, and different speeds are also not considered. Most importantly, a practical way to harness vehicle produced aerodynamic energy is not addressed in [6]. This paper will simulate multiple traveling speeds on multiple vehicles and gather data at reasonable distances away from the vehicle, as well as consider the most efficient design to harness these gusts of wind. Several patents exist for harnessing the wind produced by vehicles, but the idea has not been capitalized upon [7], [8]. These patents show that the idea has been considered, but much additional work needs to be conducted to have a product ready for production. Furthermore, the concept of placing piezoelectrics into the road that would then generate electricity when vehicles passed over has been considered [9], [10]. Harnessing waste energy from moving traffic is an important step in improving transportation efficiency. This paper goes beyond past consideration as well as exploring different aspects of vehicle variety, safety concerns, complex aerodynamic situations, idealizing turbine design, and ultimately the cost effectiveness of this concept.

This paper performs a computer simulation study to prove the aerodynamic energy produced by the vehicles moving on highways is sufficient for electricity generation. Based on the simulation results, a novel prototype wind turbine is designed and constructed for harvesting aerodynamic energy. Laboratory tests are carried out on the prototype to prove the feasibility of the proposed wind energy harvesting concept, which has significant potential for powering highway electronics and providing nearby rural areas with local renewable electricity. This will be beneficial to the communities and the infrastructure in the rural areas where the access to cost-effective, reliable, and renewable electricity is difficult. This new form of wind energy will be reliant on human traffic and free from the uncertainties of the weather, giving areas without access to great wind and solar resources an option for clean energy or potentially offering

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electricity at times when solar and traditional wind energy production are low.

II. SIMULATION OF VEHICLE INDUCED WIND PROFILES

A. Modeling of Road Traffic

Five different vehicles were used for simulations to better represent the variety of vehicles that travel on the road. A Toyota Corolla, Honda CR-V, Ford Explorer, and Chevrolet Silverado were used because they have the best or second best sales in each of their respective categories of small sedan, small crossover, SUV, and light duty truck [11]-[13]. Models of these passenger vehicles were constructed using Solidworks. Isometric pictures of the vehicles as well as the length, width, and height specifications of the vehicles were used to make a side, front, and top cuts that produced a model resembling the vehicle. These rough models were considered accurate enough for the purposes of this work. To simulate larger commercial traffic, a three-dimensional model of a Mercedes semi-truck with trailer was obtained from grabcad.com [14]. The semi model was determined to be usable after several modifications.

The situation of a vehicle passing and inducing winds along its side is a complex transient scenario. After speaking with both physics and mechanical engineering professors, it was decided that the much simpler and less time intensive steady-state model could be used. ANSYS Fluent was initially used to create the simulation. The first test car simulation was the Toyota Corolla. The fluid domain around the car was three car lengths in front of the car, two on a side, two above, and six behind. Down the center line of the car a symmetry plane was inserted to reduce the mesh and the time of the simulation. A fine mesh was used for the surface of the car that inflated into a coarse mesh at a rate of 20%. An area of influence was inserted at three feet to seven feet away from the car, ten feet high, and half a body length in front of the car to half a body length behind. This area of influence created a finer mesh in the designated area that would be beneficial for generating electricity. A pressure based viscous-laminar realizable k-epsilon model was used with standard air as the domain fluid. The SIMPLE solution method was used to determine the solution. Reference lines were placed at three feet to eight feet away from the side of the car at one foot intervals and above the ground from one foot to ten feet at one foot intervals. These lines ran the length of the domain parallel to the vehicle's direction and are where the wind speed values were taken. The Z-axis was the direction that the car was traveling, with the X-axis to the side of the car and the Y-axis above. To obtain the correct Z velocities, the car speed needed to be subtracted from the observed velocity. This means that the road boundary had to be an ideal boundary, so that the observed velocity was not slowed by friction to a small value only to be increased to a large value when adjusting for the vehicle's velocity. This method is by no means the most accurate way to conduct a fluid dynamics simulation, but a student version of ANSYS was being used so the mesh was limited to 620,000 cells.

After conducting the Corolla simulation in ANSYS Fluent, the same simulation was conducted in Solidworks Flow Simulation. Standard Solidworks settings were used with a drawn in road, a medium to fine quality mesh, and the same fluid domain and reference lines that were used in ANSYS Fluent. After running tests in both ANSYS and Solidworks multiple times with varying meshes, it was determined that the differences in the simulation were almost negligible. Solidworks become the preferred software because the simulations took a fraction of the time, the size of the model was not limited, and the data was easier to analyze. After the software was chosen, simulations were conducted at 75, 70, 65, and 60 miles per hour (MPH) for all five models.

For this design to be practical, only wind speeds beyond four feet away from the vehicle will be considered. This coincides with the minimum shoulder width for a freeway in accordance with the Federal Highway Administration [15]. When a vehicle passes a turbine, wind reflecting off the turbine has potential to negatively affect a vehicle's fuel efficiency. At four feet from the traveling vehicle, this wind reflection is expected to have negligible effects on fuel efficiency, but more testing is needed for confirmation. For high speed rail, the turbines can be safely placed closer to the moving vehicle, due to the fact that the train constantly travels on the same path. But with decreasing distance and increasing the speed, the wind reflecting off the turbine will likely negatively affect the efficiency of the train. A vehicle speed of 75 MPH is focused on in this paper because vehicles will not likely travel much faster than 75 MPH consistently. Additionally, if the induced wind speeds were not substantial at this speed they would not be substantial at lower speeds. For simplification purposes, values of the smaller vehicles (Corolla and CR-V) and the larger vehicles (Explorer and Silverado) were averaged together because of their similar results. Values seven feet away were almost negligible, so the values of the X, Y, and Z wind velocities four feet to six feet away from the vehicle were averaged together to form the magnitude of the vector of the wind that would be blowing on a turbine. Small vehicles were found to produce an average of five MPH that lasted for around one second (Fig. 1). Larger vehicles produced close to eight MPH for around one second (Fig. 2). Semis produce close to an average of 40 MPH for nearly four seconds (Fig. 3). The high wind speed and the duration produced by semi traffic dwarfs everything else to the degree that it might be preferable to ignore smaller traffic and focus solely on heavy truck traffic. Additionally, the winds at four feet are substantially higher than those at six feet. The majority of the winds produced by semis are parallel to the semi with a large spike in wind going perpendicularly away from the semi when it initially passes (Fig. 4). The simulations also showed that at 60 MPH and four feet away, the semi produces winds close to 45 MPH that last around four seconds, increasing the applicability of the proposed concept (Fig. 5). The lasting wind effects past two vehicle body lengths beyond the vehicle are due to ground effects caused by the ideal road in the simulation and would be mitigated by further and more refined simulations. Additionally, the magnitude of wind speeds one foot high would be slightly decreased by a better simulation model.

B. Road Traffic Simulation Results

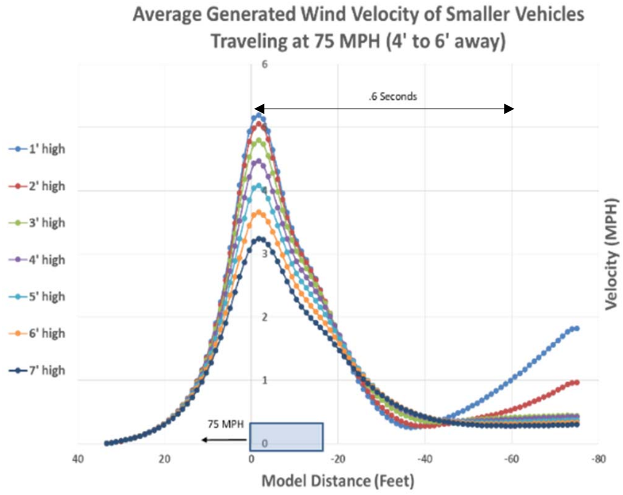

Fig. 1. Small vehicle wind profiles (Note: The blue boxes on the graphics are to give a sense of where the vehicle is in relation to the wind velocities).

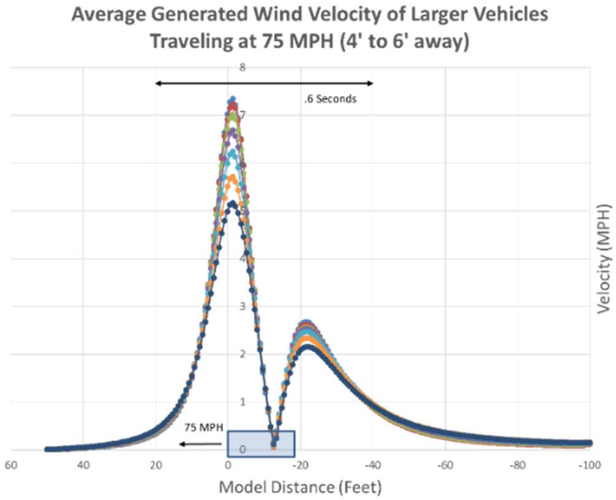

Fig. 2. Large vehicle wind profiles.

As intuition suggests, the closer to the vehicle, the faster the wind speeds. Unfortunately, the wind velocities decreases rapidly farther away from the vehicle. The area where the wind speeds will be usable are less than seven feet away from the vehicle and within seven feet of the ground. The relatively small gusts associated with the smaller vehicles have minimal electricity generation potential, whereas the high velocity gusts from semi-truck traffic have potential to generate substantial amounts of electricity.

III. Design of a New Wind Turbine to Harness Waste Aerodynamic Energy of Passing Highway Vehicles

A. *Wind Turbine Type Selection*

The simulations of road vehicle wind profiles proved that there would be significant wind along roadways to power a small wind turbine. The question remained, "What would be the best way to capture this unused energy?"

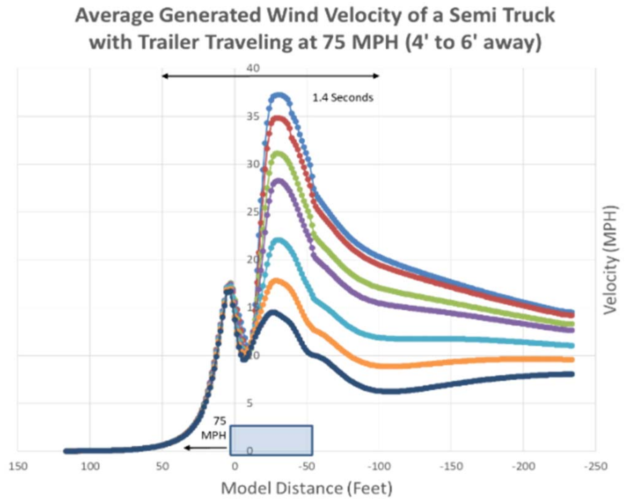

Fig. 3. Semi-truck wind profile.

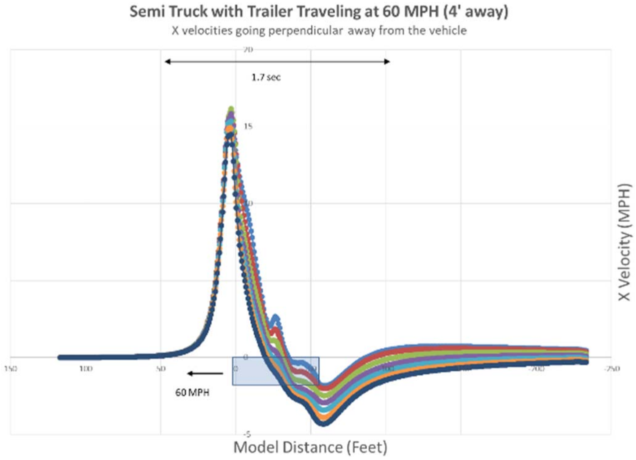

Fig. 4. Semi-truck perpendicular wind speeds at 60 MPH.

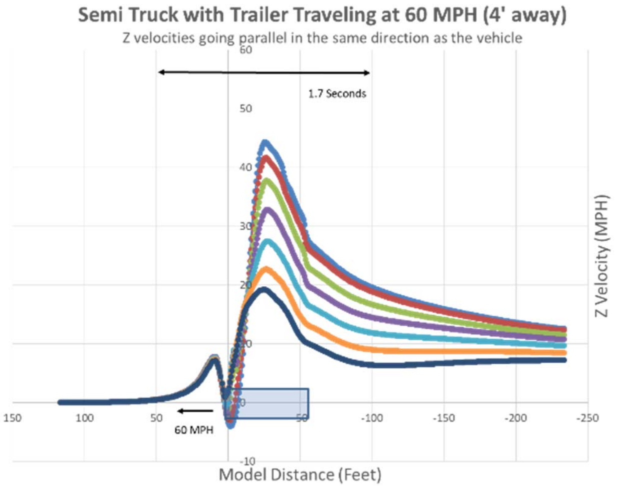

Fig. 5. Semi-truck parallel wind speeds at 60 MPH.

Upon analysis of the data, the area from four to six feet away from traffic and from one to six feet above the ground were determined to be the parameters of the turbine. Several different wind turbines were considered for this application. At the moment of the vehicles passing, the produced wind changes directions rapidly. This abrupt change in wind direction would not be usable by conventional horizontal axis wind turbines and decrease the overall efficiency, especially if the turbine is mounted in a fixed direction. Whereas a vertical axis wind turbine has the ability to harness wind from every direction. Horizontal axis wind turbines have the highest coefficient of performance, C_p, which is the amount of electric energy generated divided by the total energy in the wind hitting the rotor and can be expressed as follows,

$$C_p = \frac{P}{\frac{1}{2} * A * V^3} \tag{1}$$

where P is the power generated by the turbine in Watts, A is the area swept by the rotor in meter^2, and V is the wind velocity in meter per second. Despite its high efficiency, a horizontal axis turbine design would not be the best turbine for this application. A Darrieus style vertical axis wind turbine has difficulty self-starting and harnessing the gusts that this application would produce. A Two-stage Savonius turbine design was chosen, due to its more rigid structure, ability to harness winds from any direction, ability to harness gusts, provide constant positive torque, and its relatively low cost to make. A Savonius style turbine also has addition qualities that may make it even better suited for this application. Higher velocities will hit the positive torque side while lower velocities hit the negative torque side. A Savonius turbine can harness winds from multiple directions at the same time, allowing it to be placed in a median where it can harness wind from traffic going both directions. These attributes are further discussed in the conclusion.

B. *Prototype Design*

A half-scale turbine was designed, assembled, and tested. A 3D rendering of the designed turbine is shown in Fig. 6. The turbine itself is made of 20 gauge steel, the framework is one inch steel tubing, and the alternator is a 160 Watt permanent magnet synchronous generator that was previously used in the lab. The materials were chosen for low cost, ease of assembly, and total weight. The turbine was heavier than ideal at around 12 pounds, but the heavy frame would not be greatly moved by a passing vehicle yet was light enough to have one person move. The dimensions of the turbine are 30 inches tall by 15 inches wide with a 0.17 overlap ratio (distance the blades overlap each other over the total length of one blade). The two stage two blade design was chosen for its combination of efficiency, weight, and ease of construction [16], [17]. The blades were molded closely to half circles due to their moderate efficiency and ease of manufacturing [18]. The aspect ratio (the height of the turbine divided by the width) of two was determined to be the best combination of efficiency and size [16]. Since the overlap ratio does not heavily influence efficiency, the value of 0.17 was chosen for ease of assembly [19].

In an attempt to increase efficiency, 3D printed plastic blades were also tested. The blades consisted of a half circle design twisted 45 degrees to increase efficiency by up to 7% [17]. This reduced the weight of the rotor by 3.5 pounds. With a lighter rotor weight the turbine should be more susceptible to gusts. The turbine with twisted blades is shown in Fig. 7. The initial prototype was focused on being inexpensive and able to be easily modified. Future prototypes will focus on improving efficiency by testing different blade shapes, configurations, and materials. Ultimately, a new alternator or generator will be designed specifically for this application, which will greatly improve the overall performance.

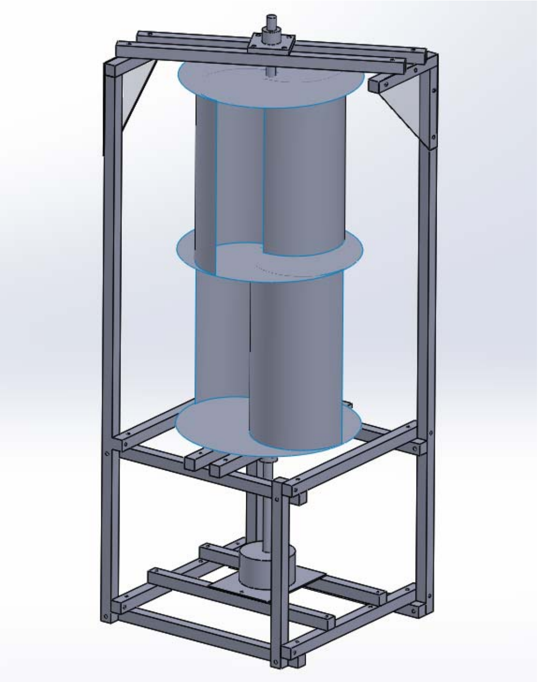

Fig. 6. Solidworks model of the wind turbine designed.

Fig. 7. Prototype with curved blades.

IV. EXPERIMENT RESULTS AND CALCULATIONS

A. Results

The UNL wind tunnel was used to test the prototype turbine with two different styles of blades. A picture of the tested setup is shown in Fig. 8. After testing the turbine at various loads and wind speeds, a 7.5 ohm balanced Wye load was found to produce the most power. The wind tunnel was only able to produce wind speeds up to 9.6 MPH, so testing of the semi-truck induced wind speeds was impossible. Various small design changes were made to increase the efficiency of the turbine during testing.

The average coefficient of performance obtained from testing both blades was 0.23. The highest results were 0.3 and 0.31 for steel and plastic blades, respectively, as shown in Fig. 9. The average values exceeded the expected 0.2 value for a rough design, but the curved blade design fell short of the 0.33 expected value. A full sized turbine would have dimensions of 40 inches wide and 80 inches tall. With the 35 MPH wind gusts associated with passing semi traffic (Fig. 3), the expected power output would be 0.9 to 1.2 kW. The turbine was found to have a starting speed of 6.75 MPH, meaning it will be able to generate electricity from background winds, which will increase the power output of the turbine.

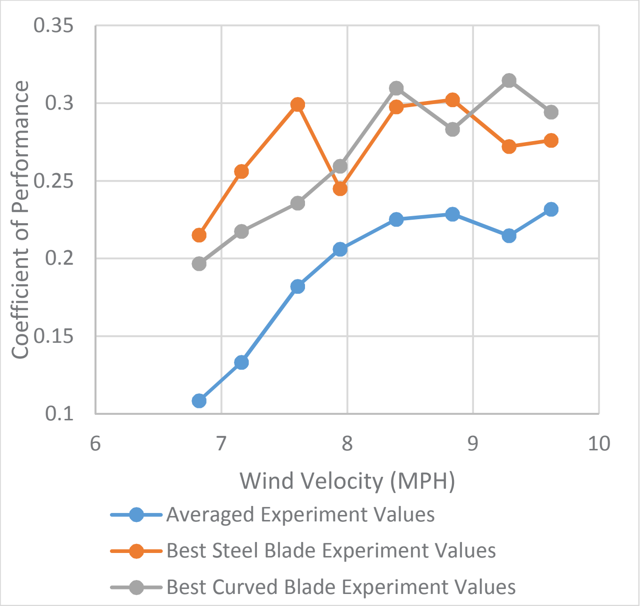

Fig. 9. Coefficient of performance vs. wind velocity of the prototype wind turbine.

B. Calculations

For an example of how much electricity this turbine could produce, if the full scale turbine were to have a C_p of 0.25, a gust from a semi-truck could reach up to 47 MPH at four feet away, which would be equivalent to 2.7 kW. These gusts have potential to make this turbine economically competitive against traditional methods. According to the Nebraska Department of Roads, a location on I-80 West of Omaha with a 75 MPH speed limit has 22,300 cars, 8,500 trucks, and 5,250 large trucks pass in one direction every day [20]. If the full-size model wind turbine is placed alongside the roadway, this translates to 0.06 kWh produced by cars, 0.09 kWh produced by light trucks, and 15.8 kWh produced by semi traffic in one day according to the following equation,

$$E = \frac{1}{2} C_p \cdot A \cdot T \cdot V^3 \cdot n \tag{2}$$

where E is energy produced in kWh, T is time of the wind gust in hours, V is the induced wind speed, and n is the number vehicles. If the wind was blowing at the average Nebraska ground wind speed of 7 MPH, the total electricity produced would be 16.8 kWh every day. Additionally, background winds have potential to increase the energy output due to the turbines ability to harness winds from any direction simultaneously. The gust and the ambient winds will form a vector, resulting in the effective output power of the turbine being,

$$P = \frac{1}{2} C_p \cdot A \cdot (V^2 + v^2)^{\frac{3}{2}} \tag{3}$$

where v is the background wind velocity. These background winds generally are more prevalent in rural areas which will only increase the applicability of this design.

Fig. 8. Picture of testing system.

Because semi-trucks produce 95% of the electricity, and a single semi produces 1,200 times more electricity than a single car, semi traffic should be focused on for future research. To give an example of how cost effective this design could be, say this turbine cost $2000 to install and maintain. The turbine would be placed alongside a busy freeway where traffic passed at 75 MPH and 5500 semi-trucks passed daily, which mean almost 6.1 hours of 47 MPH gusts would occur alongside the vehicles. At the cost of 5 cents per kWh, this turbine would pay for itself in six years.

These turbines could power street lights or other highway electronics. This could lead to electronic infrastructure only in certain areas, possibly cutting down on infrastructure costs. Additionally, larger turbines could be designed to generate substantial power, which could then be returned to the electric grid. A system of small turbines has several benefits over their traditionally larger counterparts. With turbines being small and close to the ground, manufacturing, transportation, and installation costs will all be much less than conventional large turbines. Maintenance costs should also be much lower due to the turbines being closer to the ground. With many turbines, maintenance required on a few turbines will hardly affect the overall amount of electricity being generated. Installation of turbines could be done simultaneously with the building of new roads.

V. HIGH SPEED RAIL APPLICATION

Another promising application of this design would be to place the turbine alongside high speed trains. With trains running in a much more consistent position, turbines could be safely placed closer to the moving vehicle, increasing power output. Trains produce a much larger wind profile than road traffic, so turbines can be made larger. With the overall length of the train being greater than any road traffic, the duration of the gust will be much longer, producing more energy per vehicle [21]. With only one vehicle type, turbines could be further specialized to become ideal for that single wind profile. Predicting the power output over a given day will also be easier considering the scheduled nature of train traffic.

With wind profiles be much more readily available than individual road traffic models, simulations for train wind profiles were excluded. At a distance of four feet from the edge of a moving train, the peak intensity of the wind gust can be up to 20% of the train's velocity with wind effects lasting up to ten seconds [21], [22]. At two feet from the train, the intensity spikes around 40% of the train's velocity for the same duration [21], [22]. Consider a high speed train traveling at 217 MPH (350 km/h). Also use the turbine in the previous example but with double the height and width to take advantage of the larger scale of the train. A turbine placed four feet away from the train would produce 0.021 kWh every time a train passes. If the turbine were place two foot away it would produce 0.17 kWh with every passing train. To achieve the same 15.8 kWh per day production as in the highway example, close to 100 trains would need to pass per day.

Such large scale turbine may be less than ideal for this application, but a series of smaller turbines may prove to be a much better option. Large turbines will likely negatively affect the aerodynamics of high speed trains if they are placed too near the moving train. Additionally, the number of turbines that can be placed alongside trains is virtually unlimited. The electricity produced by these turbines could be used to increase the overall efficiency of high speed rail or to power other local needs.

VI. CONCLUSIONS AND FUTURE WORK

This study explored the possibility of using the wind produced by passing highway vehicles to power a wind turbine and produced promising results. Much more testing and analysis needs to be completed before this method is considered a viable option for electricity production. New blade curvatures, dimensions, and materials need to be tested. Real world testing needs to be conducted to verify simulation results. Additional fluid dynamic questions will need to be addressed. Cross winds and gusts should have a compounding effect due to the design, but it is unknown to what degree. With having a starting speed of 6.75 MPH, most background winds should increase the power produced by passing vehicles. Also, the way the turbine is designed allows greater wind speeds to add positive torque while the farther away lesser wind speeds contribute less negative torque, which should improve the efficiency of the turbine for this application. This means there is more wind pushing the turbine to rotate and less wind fighting the rotation. This situation is difficult to model, but will increase the efficiency of the turbine by an unknown amount. Ideally, this turbine would be placed on a median a safe distance away from fast moving semi traffic on both sides (Fig. 10). Again, a compounding effect should take place, but it is unknown if these opposing winds will negatively affect each other. This concept is very promising because if the wind turbine theoretically captures double the wind speed, it increases power production by a factor of 8. Additionally, the application of high speed rail needs to be further considered. Much more wind speed and power will occur with each passing train compared to a semi-truck, but the frequency of how often a train passes will be even more relevant. A taller and thinner turbine design will likely result in less aerodynamic impact on the train while decreasing costs of individual turbines.

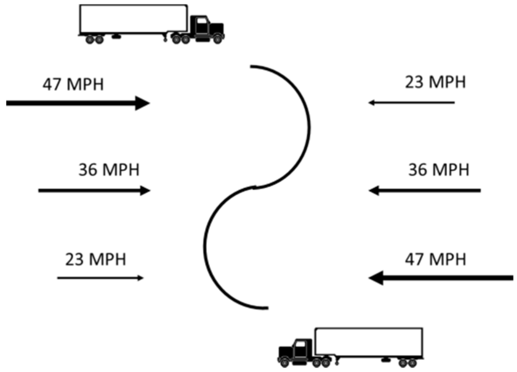

Fig. 10. Opposing traffic concept.

In conclusion, it is possible to generate electricity from the wind of passing vehicle traffic, and it has potential to compete with other forms of renewable energy. The amount of power produced is largely dependent on semi-truck traffic. With proper development, this new form of wind energy could become a viable source of clean energy and improve the overall efficiency of the transportation industry.

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