Energy Harvesting from Moving Vehicles on Highways

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Abstract— **Due to the high emissions from the consumption of natural fossil fuel resources, developing and commercializing the sustainable and environment-friendly renewable energy systems are highly demanding topics. The wind turbines are commonly used to convert wind kinetic energy into electric energy. The induced wind along the highways has a great potential to be harvested through the wind turbines on the sideways. In this paper, the aerodynamic effect of traffic along the highway is analyzed to generate the induced wind profile in estimating the potential energy generation. Computational fluid dynamics (CFD) analysis is used to measure the wind velocity profiles generated through the vehicles in different scenarios. Based on these wind velocity profiles energy that can be captured from the harvesting units are estimated. Feasibility of the system is tested to power highway lighting apparatus.**

Keywords—renewable energy, wind turbine, energy harvesting, highway traffic.

I. INTRODUCTION

In recent years, the consumption of all forms of energy around the world increased rapidly due to the increasing population, urbanization, and development of the living standards. Around 42% of global CO_2 emission in 2013 was the by-product of electricity and heat mainly from fossil fuel resources [1]. Over-utilizing the fossil fuel resources cause volatility in fuel prices, and serious environmental problems such as acid rain, global warming, and desertification. Thus, research and development in environmentally friendly renewable energy systems are very crucial. In 2014, global wind power capacity expanded to 369,553 MW. Currently, at least 84 countries around the world are using wind power in their energy portfolio to fulfill their energy demands [2] which makes 4% of worldwide electric power usage [3].

The amount of energy available from the wind is highly related to the wind speed which is higher at high altitude and coastal areas. However, the wind energy generated from low-speed wind can also be a source of energy, especially for the distributed energy needs. The turbulence due to the traffic on the roadways is a source for low-speed wind generation that would be considered for energy harvesting [4]. Before investing in this technology, it is very crucial to estimate or measure the wind profile through the vehicle wake from the highways and the amount of energy that could be harvested through the wind turbine systems.

The research in this area is limited and constrained to a specific consideration. In [5 -6], the induced wind speed of a heavy-duty vehicle was only measured from the bridge over the highway to get the wind profiles. Researchers in [7] conducted a CFD analysis which is limited to a single vehicle model. In [7], the potential of a small wind turbine along the highway is discussed to propose a location for the vertical axis wind turbine (VAWT) on the highway as illustrated in Fig. 1.

VAWT has a simplified geometry with no yaw mechanism or pitch regulation and has neither twisted nor tapered blades. Furthermore, VAWT not only could extract wind energy from all directional but also is cheap and less noisy, which makes VAWT most suitable for the urban and small-scale application.

Fig. 1. VAWT on the divider [7].

In this paper, the energy harvesting system is proposed to harvest energy from the traffic along the highway. The CFD simulation with two different scenarios containing different vehicle models is proposed to simulate the induced wind profiles by moving traffic. Energy estimated using these profile data with addition to the natural wind speed shows a potential availability of energy which could be utilized for LED lighting system.

II. INDUCED WIND VELOCITY PROFILE ESTIMATION

In order to estimate the amount of energy that can be extracted from the highway, the wind velocity profiles induced by traffic along the highway needs to be collected. In this section, the method for collecting induced wind velocity profile using a CFD analysis is presented comprehensively. The induced wind velocity profiles are mainly dependent on the size and the driving speed of the vehicles. The challenge in the design is to create more realistic scenarios to provide accurate wind velocity profile. A Sedan, SUV, VAN, and the Lorry are the four types of vehicle models used to generate wind velocity profiles. To improve the accuracy of the simulation results, all the vehicle models are developed based on their blueprints from the manufacturers. Fig. 2 shows the different car models used for the analysis. The 3D models have the same dimensions, streamline structure with the exclusion of some of the fine details such as back up mirrors. The analyses have the following two different scenarios: a single-vehicle with 65 mph and multiple vehicles clustered in one lane. Multiple vehicles in two lanes, and multiple vehicles in two ways are not considered for the analyses.

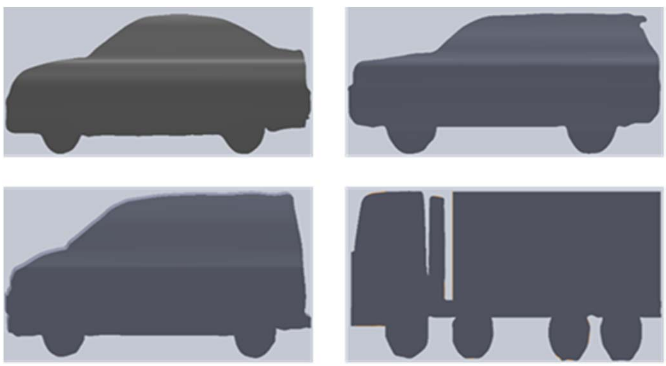
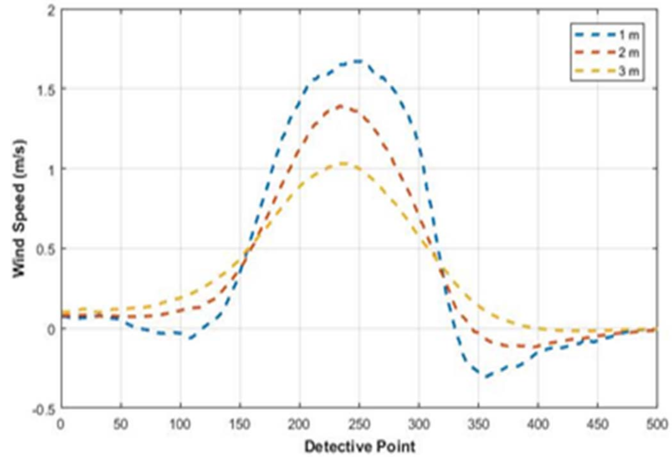


Fig. 2. 3D car models.

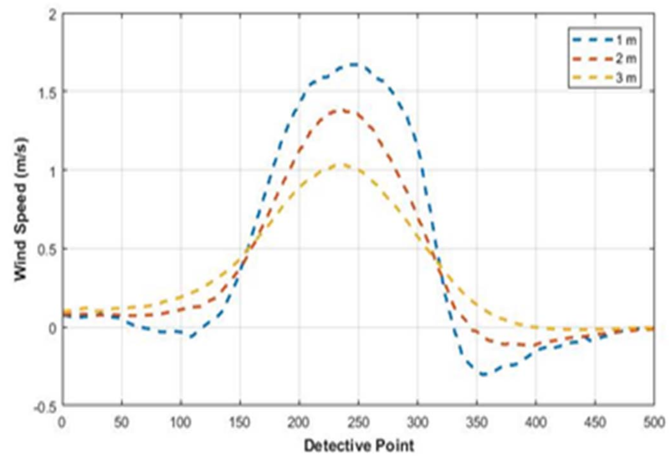
A. Single lane single vehicle

For Sedan vehicles, Honda Accord is selected for modeling. The car models which were built using the 3D blueprints were imported to ANSYS Fluent for CFD analysis. The enclosure of 0.1 m from the bottom, 5 m from the lateral, 3 m from top and 10 m from both front and back were drawn to model the wind flow and aerodynamic effect. Input and output of the enclosure are defined with input being the front of the vehicle. Viscous laminar flow is selected to model the wind flow. For the boundary condition, the inlet is selected as a velocity inlet with 29.06 m/s (65 mph) and the outlet is selected with a simple outflow.

Fig. 3 presents the CFD results for a selected Sedan model. The induced wind velocity measured at a 1 m height from the highway with a lateral distance of 1 m, 2 m, and 3 m away from the vehicle as shown in Fig. 3(a). Whereas Fig. 3(b) presents the wind velocity at a 1 m distance away from the vehicle at 1 m, 2 m, and 3 m height. This pattern of measurement points has been followed for the other vehicles as well throughout the paper. It can be seen that the peak velocity is obtained when the measurements are taken at a 1 m height from the highway with the distance of 1 m away from the vehicle. The maximum induced velocity of around 1.7 m/s is measured for the Sedan model.



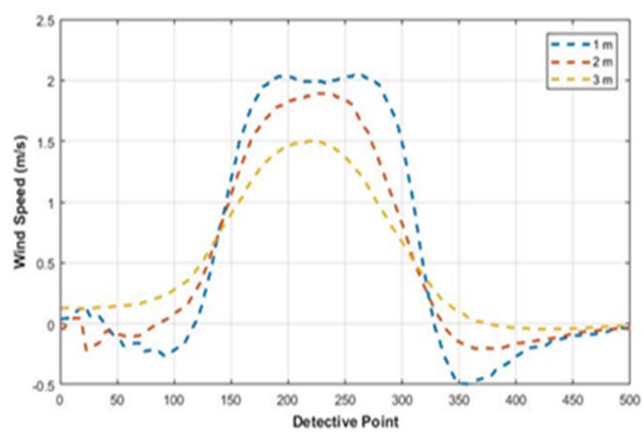
(a) Induced wind velocity at 1 m height.



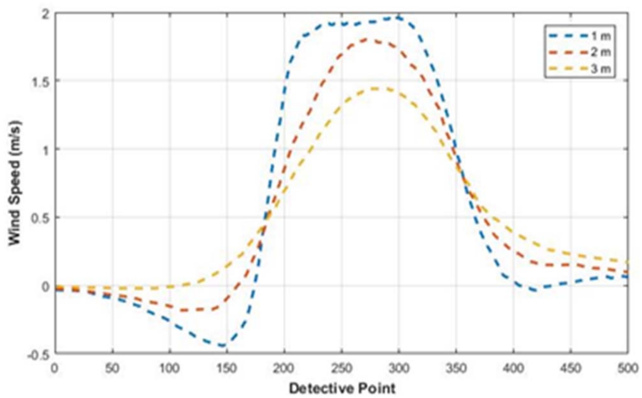
(b) Induced wind velocity at a 1 m lateral distance.

Fig. 3. Induced wind velocity by Sedan.

For an SUV, Toyota Fortuner is selected for analysis. Fig. 4 presents the CFD simulation results for the SUV model. The maximum induced wind velocity, in this case, is 2.0 m/s and is higher than the Sedan which should be expected for a larger size vehicle.



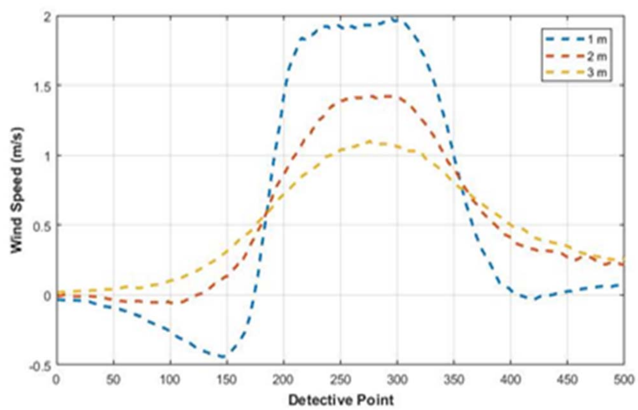
(a) Induced wind velocity at 1 m height.



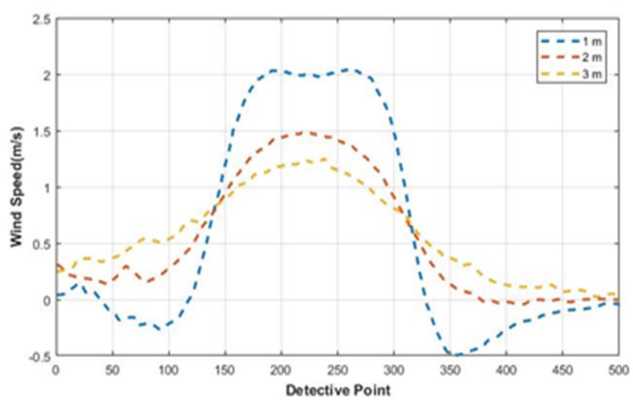
(b) Induced wind velocity at a 1 m lateral distance.

Fig. 4. Induced wind velocity by SUV.

For a VAN, Volkswagen Caddy is selected for analysis. Fig. 5 presents the CFD simulation results for the VAN model.



(a) Induced wind velocity at 1 m height.

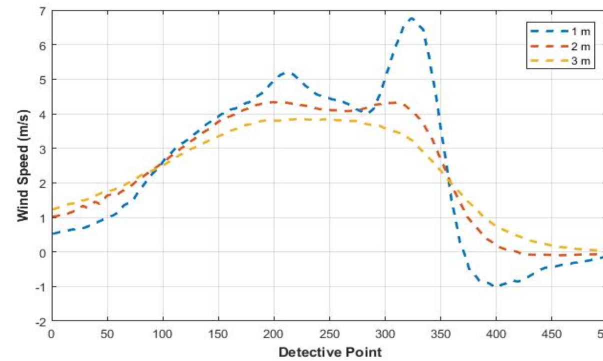


(b) Induced wind velocity at a 1 m lateral distance.

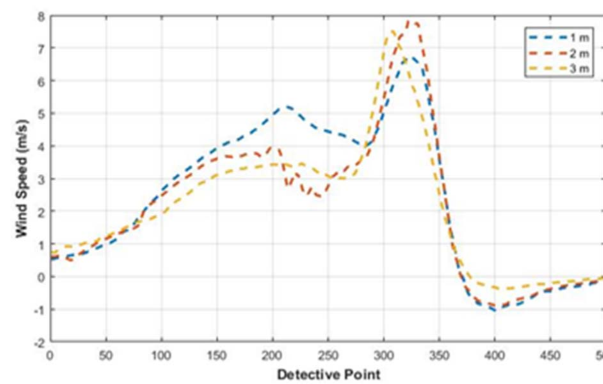
Fig. 5. Induced wind velocity by Van.

The VAN has a similar cross-section area as an SUV, hence the maximum induced wind velocity is also around 2 m/s. However, the VAN demonstrated in longer-lasting turbulence, due to the longer body length than the SUV.

For Lorry, Volvo NFL is selected for analysis. Fig. 6 presents the CFD simulation results for the Lorry model. With the same driving speed, the Lorry would produce the strongest turbulence because of the largest cross-sectional area among the other vehicles. Since the height of the Lorry is larger than the previous three car models the maximum induced wind velocity of around 8 m/s is measured at a height of 2 m above from the ground.



(a) Induced wind velocity at 1 m height.



(b) Induced wind velocity at a 1 m lateral distance.

Fig. 6. Induced wind velocity by Lorry.

B. *A cluster of vehicles in a single lane*

A cluster of vehicles passing on the highway is modeled in the CFD simulations. The distance between the vehicles is determined through the commonly known *three-second* rules. The *three-second* rule (also known as the *two-second* rule in some states) is a rule of thumb by which a driver can maintain a safe trailing distance at any speed [8-9]. Fig. 7 presents the vehicle sequence used in this analysis in which the four different vehicle types are apart by a safe distance of 80.4 m based on the highway speed limit of 60 mph. The traffic moving pattern, for simplification, is Sedan, SUV, VAN, Lorry. The sequence is repeated continuously.

Fig. 7. Cluster traffic and safe driving distance.

The vector results for one lane cluster condition are shown in Fig. 8. Fig. 9 presents the related wind velocity profile. According to the results, if the vehicles maintain safe driving distance, the generated wind velocity was reduced slightly in driving direction but at the same time, it might boost in another direction. The negative values refer to the turbulence swirling in the direction opposite to the driving. Table I shows the maximum induced wind velocity by different vehicle models.

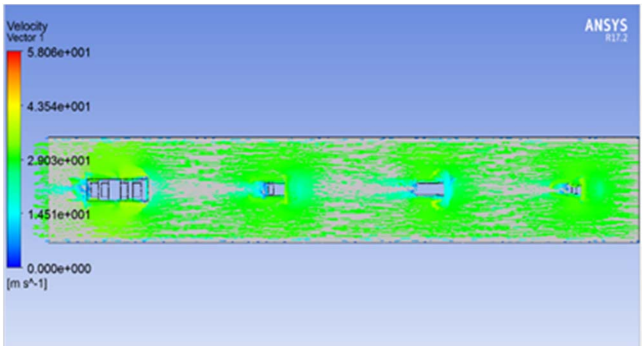
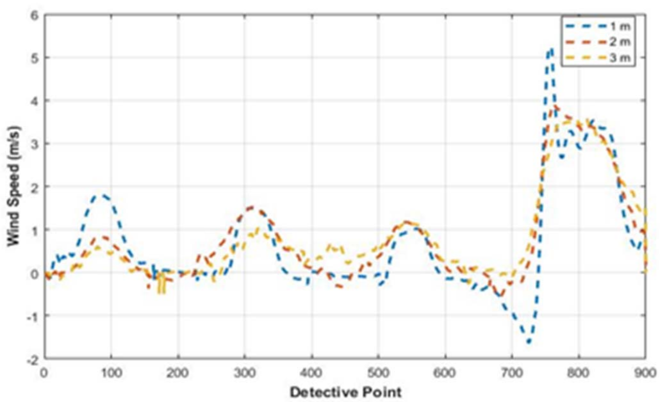
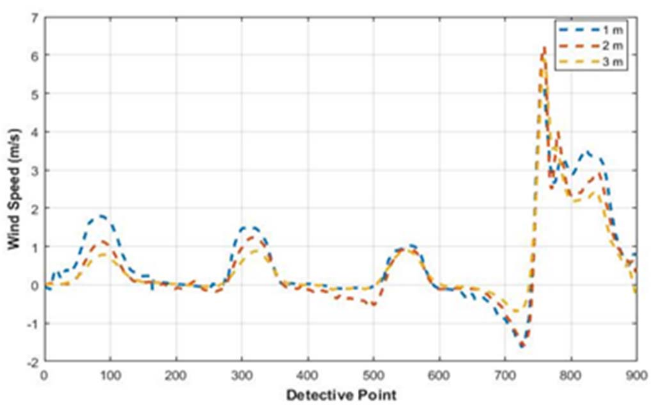


Fig. 8: Vector results for a single lane condition.



(a) Induced wind velocity at 1 m height.



(b) Induced wind velocity at a 1 m lateral distance.

Fig. 9. Induced wind velocity by the cluster in a single lane.

TABLE I. MAXIMUM WIND VELOCITY INDUCED.

	Sedan	SUV	VAN	Truck
Peak (m/s)	1.6	2.0	2.0	8

III. ENERGY ESTIMATION

The energy that can be harvested along the highways is estimated based on the wind velocity profiles determined in the previous section. The wind power p that can be harvested by the wind turbine is related to the wind velocity V_w by (2):

$$p = \frac{1}{2} C_p \rho A V_w^3 \tag{2}$$

where, A is Cross-section area of the turbine; ρ is Wind density; C_p is Betz Limit (the maximum power that can be extracted from the wind). According to Betz's law, the theoretical limit for a power conversion ratio in an undisturbed wind stream is 59.3%. The factor 16/27 (0.593) is known as the Betz coefficient which is also referred to as the Betz Criterion or the Betz Limit [11].

For energy estimation, the Betz coefficient C_p is taken 0.59 (maximum value under ideal condition), the air density is taken under sea level for 25℃ which is 1.1839 kg/m3. The cross-section area of a 200 W turbine would be approximately 1 m^2. Therefore, (2) can be simplified for the given conditions as:

$$p = 0.35517 V_w^3 \tag{3}$$

North east Ohio region's I-71 highway is selected to predict the energy that can be harvested from the moving vehicles. The total traffic flows yearly along the selected highway from ODOT Fact Book [10] is 16,853,107 of which the small size vehicles account for 13,798,859 and the heavy vehicles are 3,054,217. Also, the annual average daily traffic for small size vehicle and for the Lorry is 56,034 and 12,403 respectively. According to this data, it can be assumed that for a busy hour of traffic the velocity pattern given in Fig. 7. a is repeated continuously.

In addition to that wind speed form the moving vehicles, the background natural wind speed should also be considered for the analysis. In Cleveland, OH, the average surface wind speed for August is around 7.5 mph (3.35 m/s), the highest wind speed is 35 mph (15.65 m/s), and the highest gust can reach up to 43 mph (19.22 m/s) [13]. VAWT can receive wind from all direction. For simplifying the complex wind vector calculation, the average wind is assumed to only boost or weaken the traffic generated turbulence in driving direction. Then the overall turbulence velocity along the chosen highway is given in Table II. The negative value in the table is the wind-induced by the turbulence in the direction opposite to the driving.

TABLE II. OVERALL TURBULENCE VELOCITY.

	Sedan	SUV	VAN	Truck
Boost (m/s)	4.95	5.35	5.35	11.35
Weaken (m/s)	-1.75	-1.35	-1.35	4.65

The total amount of energy generated from the highway with both traffic-induced turbulence and highway inherent natural wind is shown in Table III. This shows the energy that can be harvested along the highway is sufficient enough for small applications such as street lighting systems.

TABLE III. ENERGY ESTIMATION FOR THE DIFFERENT VEHICLE MODEL.

	Sedan	SUV	VAN	Truck
Peak Power (W)	43.1	54.4	54.4	519.3

IV. PRACTICAL SYSTEM DESIGN

This section provides energy harvesting design through vehicle wakes in the highway to power an LED lighting system. Low wind speed profiles make the VAWT a perfect fit for this application. For the wind turbine generator, a duo-outer-rotor coreless axial-flux permanent magnet (AFPM) generator is selected and the specifications of which are shown in Table IV. Compared to the normal AFPMs, the coreless AFPMs has no hysteresis and gear notch effect which makes them have very low starting torque. The stator uses disc coreless structure to replace the traditional core structure reducing the overall volume and the weight of the generator providing a higher ratio of power to volume and power to weight compared to traditional AFPM generator. A solar feed battery-based LED lighting system was selected as a load. LED lighting is designed for low voltage supply systems with low energy consumption. The solar battery-based LED lighting system is the most familiar self-feed energy harvesting system with the turbine system. The specifications of the battery-based LED lighting system is shown in Table V.

TABLE IV. CORELESS AFPM GENERATOR SPECIFICATIONS.

Rated Power	200 W
Rated Rotate Speed	200 rpm
Rated Voltage	12 VAC
Frequency	33.3 Hz
Starting Torque	0.05 Nm
Rated Torque	11.6 Nm
No. of Phase	3

TABLE V. BATTERY-BASED LED SYSTEM.

LED Power Rating	50 W
Battery Capacity	6.5V/120 Ah
Luminous Flux	8,000 Lm
Placement Height	6 m-8 m

V. CONCLUSION

The availability of wind energy along the highway due to the traffic for energy harvesting is studied in this paper. A method to estimate the induced wind profiles accurately for different vehicle models considering two different scenarios using CFD analyses is presented. Energy estimation is performed to find the amount of energy induced by different vehicles in a single day which could be utilized for a battery-based LED lighting system. Heavy-duty vehicles having higher wind velocity profiles induce higher energy due to their large cross-section is observed. The amount of energy that can be harvested from the highway shows promising results and should be experimentally verified. Based on the energy requirements by the LED lighting system the wind turbine energy harvesting system is sized.

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