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Energy Recovery of Moving Vehicles' Wakes in Highways by Vertical Axis Wind Turbines

In this study, energy recovery from moving vehicles wake by vertical axis wind turbine (VAWT) was investigated. The wind turbine is designed to be located at the highways medians to generate electricity. Transient simulation was performed to evaluate the performance of the VAWT. Various factors were studied such as car velocity, gap distance between the VAWT and car position, and angular velocity of the blades. The results showed that maximum energy output from VAWT is about 107.1 J from the car wake. At 126 km/h average car velocity, the daily energy generation, number of batteries, number of lamps, and daily reduction in CO_2 emission were 53.5248 kWh, 38 batteries, 18 lamps (with 60 m spacing between each lamp), and 24.08616 kg, respectively.

Keywords: *Highway wind turbines, Energy recovery, Vehicles wake,CFD, Renewable Energy.*

1. INTRODUCTION

Renewable energy is becoming one of the major trends worldwide in the last two decades. Only in 2019, installation of 67 GW of wind energy and the same amount of solar energy were achieved globally. According to a 2013 study of the International Energy Agency (IEA), 42% of global carbon dioxide is emitted from fossil fuel used to generate electricity and heat [1]. The term renewable refers to several sustainable resources of energy such as photovoltaics, solar concentrators, hydroelectric, biomass, geothermal, and wind energy [2]. Wind energy takes up the highest percentage of the overall modern renewables (Except for hydropower which is well established and invested long ago, particularly from dams) [3]. Needless to say, the traditional wind energy technology is one of the oldest technologies, which dates back thousands of years ago, namely by using windmills by Persians and other ancient civilizations [4]. Modern wind energy technology was established only 200 years ago with the pioneering wind farms in the United States [4].However, Denmark was the pioneer country in the development of commercial wind turbines [5].

The perfection of this technology grew up fast in the last few decades with the increasing demand for renewable energy and climate change challenges.

In wind farms, wind speed is classified into six categories to determine the feasibility of the wind power site. Table (1) shows wind speed classification at 50m height [6]. The average wind speed in most areas of Iraq is within the range of (5.1 – 5.6m/s) at 50m height, which is class 1 in Table (1) (some exceptional spots are in the southeast, northeast, and west of the country, where wind speed is categorized within class 4) [7]. Therefore, Iraq has a poor wind energy resources in general [8].

Table 1. Wind speed classification at 50 m height [6].

Class	Wind Speed (m/s)	Resource Potential
1	0 – 5.588	Very Poor
2	5.588 – 6.393	Poor
3	6.393 – 7.018	Marginal
4	7.018 – 7.510	Good
5	7.510 – 8.002	Very Good
6	8.002 – 8.807	Excellent

Despite that natural wind speed in Iraq is potentially low, manmade disturbance, such as wind gusts from moving vehicles can be successfully invested. This type of energy retrieving has been prototyped and deployed by several groups in the last few years [9, 10, 11]. Figure (1) illustrates a scheme of wind turbine on highway median strip. Moving vehicles on highway lose energy due to aerodynamic drag. This aerodynamic energy loss is approximately about 13% to 23%, depending on vehicle type [12]. Energy (*E*) required to overcome the aerodynamic drag, if the vehicle travels a distance (*d*) is determined from the following equation:

$$E = 0.5 * \rho * A_f * C_d * V_c^2 * d \tag{1}$$

where: ρ is air density, A_f is vehicle frontal area, C_d is drag coefficient, and V_c is vehicle velocity. This energy is delivered to the airand producing crosswind gusts (so-called wakes). Some studies found that moving vehicles can produce wind speed of up to 24m/s, depending on velocity and size of the vehicle [10]. Wind speed drops down to 4.5m when the gap between vehicle and wind blade is 0.5 to 1.5m at height of 0.5 to 1.5m from the ground [1]. The results showed that, the maximum recorded wind speed about 4.5 m/s was observed at 1.0 m from the lateral distance of the road shoulder.Since this wind speed is very low (within Class 1category), a

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low self-start and high torque wind turbine is recommended in this type of applications.

There are many studies that focused on developing aerodynamic models for VAWTs with particular emphasis on stream tube approach and the CFD solution or analytical investigation to assess theblades performance [13, 14]. As described previously, one can deduce that blowing wind from moving vehicles is significantly feasible source of energy. In a 2011 investigation carried out in Malaysia, a loss of wake energy from moving cars in highways is estimated to be ~1.2 million tons of oil equivalent, which corresponds to 11.36 MWh of energy [12]. Winds from vehicles are basically considered ground level winds. Wind turbines with vertical axis such as Savonius or Darrieus can be utilized at this low level. Generally, VAWT design does not require the turbine to be facing the wind and it captures winds from any direction, which is perfect in highway applications where wind blows from the two sides of the road. In addition, VAWT has low noise compared to horizontal axis wind turbines [15], so that they can be used in urban areas including highways passing through the cities. Savonius works on drag forces so it produces important torque with low rotational speed, high self-start, and low power efficiency, whereas Darrieus works on lift forces so it produces important rotational speed with low torque, low self-start, and high power efficiency [16]. Nevertheless, none of these turbines works ideally on the road because wind speed in highways is usually low and intermittent. Therefore, combined VAWTs can be a good choice in highways. In combined VAWT, low self-start and high torque are obtained. Banki wind turbine (so-called: cross-flow turbine) has low self-start (around 1.2m/s) and relatively high torque [17].

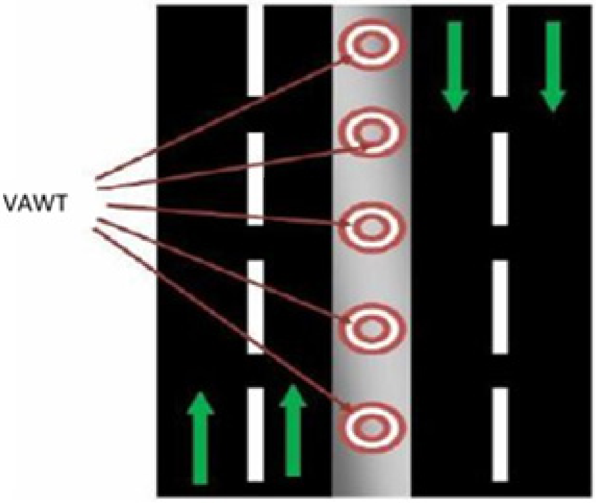

Figure 1. Vertical axis wind turbines on highway median. This figure is reproduced from [9] under permission of Creative Commons Attribution License.

Busy highways with medium traffic jam are perfect streets to install small VAWTs at low level to capture the gusts of wind from passing vehicles in addition to natural wind that may blownow and then at any direction. Since this configuration is an intermittent source of energy, batteries are required to store energy during the day, which can be reused at night to light lampposts in the highway.

Scarce literature is available on highway wind turbines. No literature has been published on using Banki wind turbines in highways to the best of author's knowledge. This article aims to investigate the aerodynamic simulation of highway moving sedan cars using ANSYS Fluent Software, and then calculating the generated energy and recovering it using vertical axis Banki wind turbine. The conversion of this energy into electricity stored in batteries to use it in lighting up lampposts in the highways is another thrust of this article. The motivation of this study is to contribute towards clean energy production.

2. DESIGN AND SIMULATION

2.1 Design Challenges

Operational noise level, space, turbine price, and safety are the major challenges during the system design. Therefore, all of these challenges should compromise the retrieving energy and the environmental impact [14].

2.2 Numerical Method

In this study, 2-D transient numerical simulation based on finite volume methodis presented by using the commercial Fluent software. A moving mesh model was applied to perform the simulation according tothe car movement (translation) and turbine rotation. In this model simplification, the location of the VAWT is designed to be planted on the median of the highway to capture the wakes of cars on both sides of the median and to contributeto the output of the turbine.

2.3 Geometry and Mesh Generation

The overall dimension of the model and a schematic representation of this model are shown in figure (2). A Banki wind turbine is selected for the energy recovery in this study as shown in figure (3). To increase turbine stability when wind direction and velocity change, the 20-bladed design is chosen.

Rectangle computational domain was selected as a highway prototype with a length and width (60m × 30m), respectively. The turbine is placed in the domain center and at a distance of 30m from the left boundary as shown in figure (2). The boundary conditions employed consist of a car velocity and a pressure outlet on all other walls.

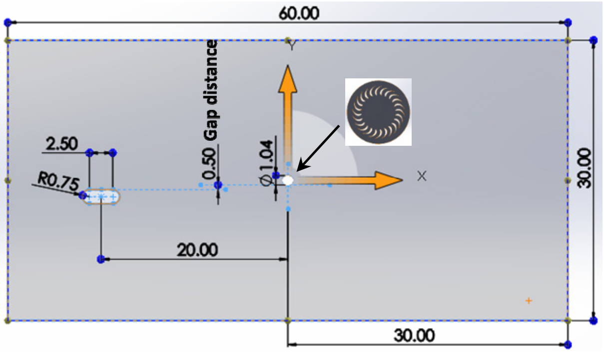

Figure 2. A scheme of Computation domain of highway wind turbine

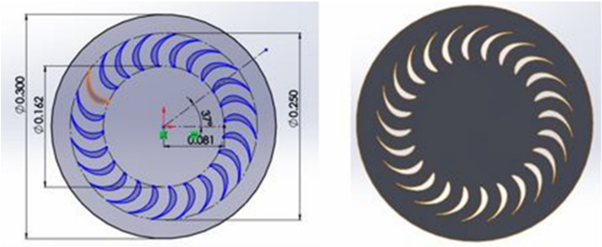

Figure 3. Schematic representation of Banki's blades geometry.

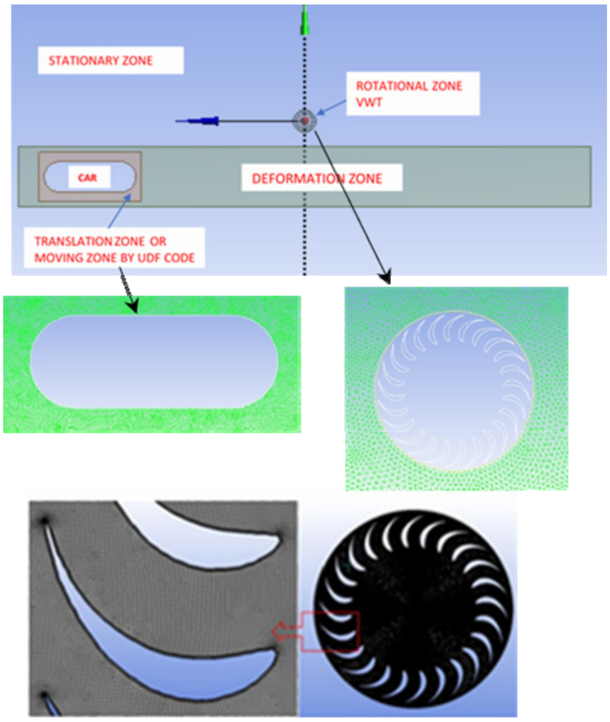

Figure 4. Mesh generation of domains and blades for different view.

The simulation domain contains the car domain (translation), wind turbine domain (rotation), and a stationary domain. Different interfacesare chosen between domains to allow the transport of the flow properties with no slip boundary conditions.

The total elements number was about 1.5 M which is close to blade profiles and the car to increase results accuracy of the boundary layer flow. Also, according to same reason, mesh density in the rotational domainis higher than other domains (see figure 4). Also, for solution stability a best courant number was chosen according to cell size and time step.

Several simulation cases were investigated using various parameters, namely: car velocity, wind turbine angular velocity, and the gap distance between the rotor and the car as shown in Table (2).

Table 2. Type of cases in this study.

Total cases 2×3×4=24	Case 1 Gap distance = 0.895			Case 2 Gap distance = 0.5		
	Rotor angular velocity ω (rad/sec)					
	1	2	3	1	2	3
Car velocity	20	20	20	20	20	20
	30	30	30	30	30	30
	40	40	40	40	40	40
	50	50	50	50	50	50

3. GOVERNING EQUATIONS

The governing equations are based on 2D transient finite volume incompressible Reynolds Averaged Navier-Stokes (RANS) equations. these equations in conservative forms are [18 to 21]:

$$\frac{\partial u_i}{\partial x_j}=0 \tag{2}$$

$$\frac{\partial}{\partial x_j}\left(\rho \overline{u_i u_j}\right)=-\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_i}\left(\overline{\tau_{ij}}-\rho\overline{\dot{u}_i\dot{u}_j}\right)+Su_i \tag{3}$$

where

$$Su_i=-\rho\left[2\vec{\Omega}\times\vec{u}+\vec{\Omega}\times\left(\vec{\Omega}\times\vec{r}\right)\right] \tag{4}$$

$$\overline{\tau_{ij}}=\mu\left(\frac{\partial\overline{u_i}}{\partial x_j}+\frac{\partial\overline{u_j}}{\partial x_i}\right) \tag{5}$$

To solve this case of wind turbine performance numerically, the turbulence model was added in RANS CFD solvers. Therefore, the SST k-ω turbulence model was applied in numerical simulation

3.1 Fluent User Defined Function

ANSYS Fluent provides User Defined Function (UDF) that can be loaded to define different boundary conditions, initialized conditions, source terms, material properties, etc. C programming language is used to write any code as UDF. In our case study, transient car velocity is implemented in the numerical simulation cases to avoid the calculation instability. The car moves with constant velocity in each case and the mesh will be changed in each time step according to the car position in the domain, so a new mesh must be updated in each time step (as shown in figure 5). Therefore, dynamic mesh with layering part isused in this case. The UDF source file is compiled and builtin a shared library for the resulting objects. The process needs a C++ program language compiler.

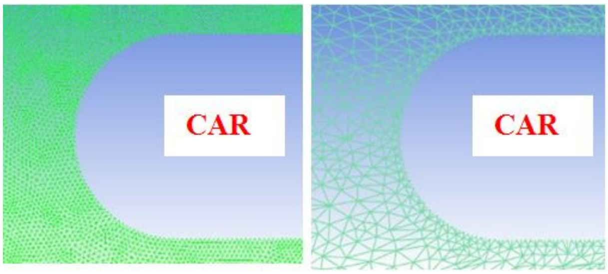

Figure 5. Mesh deformation during the simulation. Left: Mesh at the beginning. Right: Mesh at the end

4. RESULTS AND DISCUSSION

The velocity contours are demonstrated in figures (6&7) to provide a clear sight of the flow around the rotor. Figure (6) shows transient velocity contour simulation at car velocity = 50m/s, angular wind turbine velocity ω = 1rad/s, and gap distance = 0.895m at different transient positions of the car (the car distance from the rest). As the vehicle moves forward, a strong wake region occurs behind the car with strong deformation in the flow due to counter-rotating vortices. More effect on the flow structure occurs when the gap distance between the car and wind turbine decreases as shown in figure (7).

Instantaneous torque arises on the wind turbine blades at different car velocities and angular velocityfor each gap distance valueas shown in figures (8&9). Figure (8) shows instantaneous torque for gap distance of 0.895m, while figure (9) illustrates the torque at 0.5m gap distance. According to these figures, the torque value increases with car velocity.

Figure (10) shows the maximum torque value of the wind turbine for various rotational speeds and car velocities. Maximum power (Watts) generated from the wind turbine can be seen in Table (3).

Table 3. Maximum power generated by Banki wind turbine used in this study.

Car Velocity (m/s)	Car Velocity (km/h)	Pm (W) @ 1rad/s	Pm (W) @ 2rad/s	Pm (W) @ 3rad/s
20	72	6	8	8.40
30	108	24.38	38	39.90
40	144	59.09	88	92.40
50	180	66.02	102	107.10

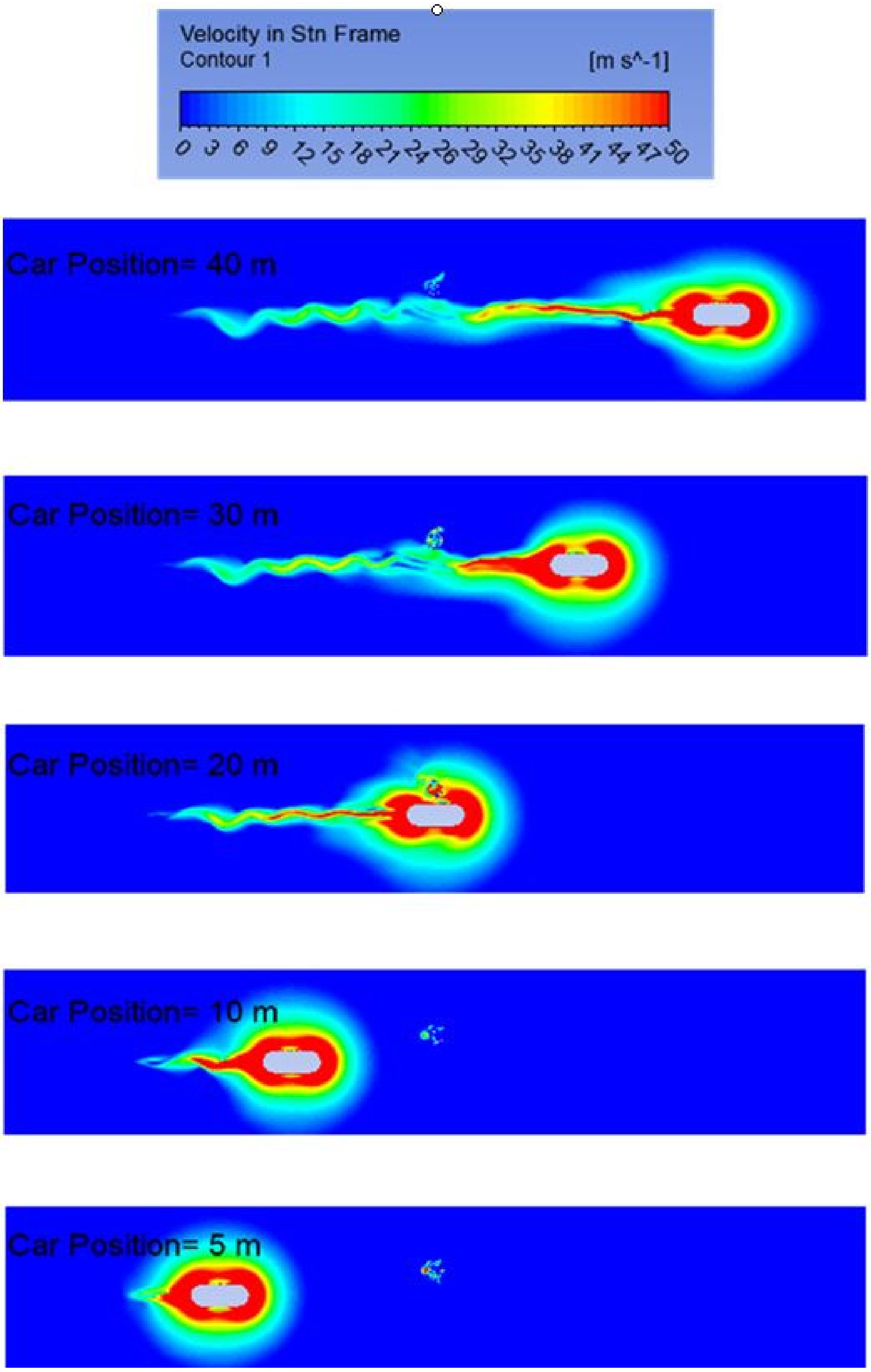

Figure 6. Transient velocity contour simulation at car velocity = 50 m/s angular rotor velocity ω=1 rad/s and gap distance = 0.895 m.(Zooming in view, 4 m/s <car velocity < 10 m/s), (Real velocity range, 0 m/s <car velocity < 30 m/s).

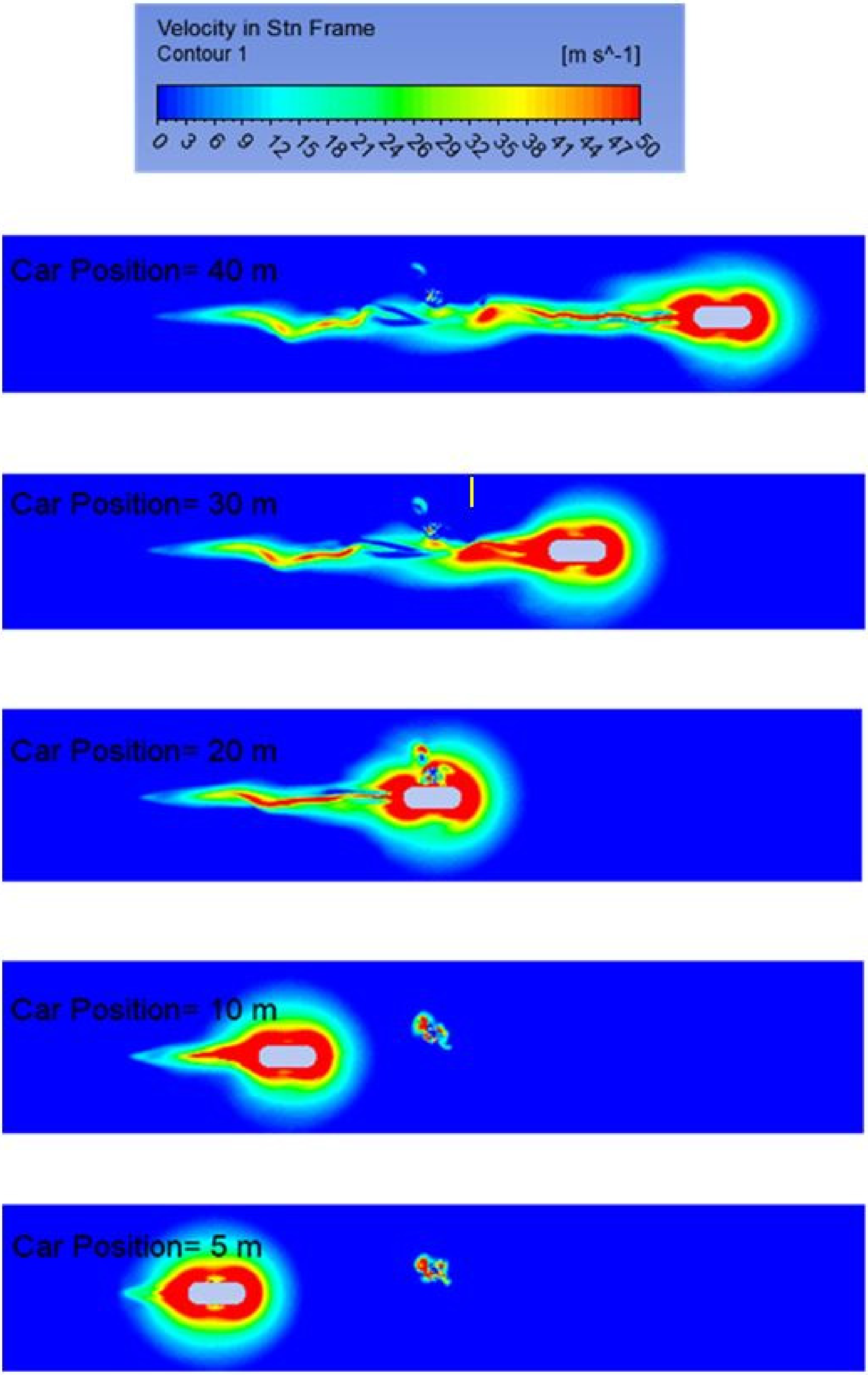

Figure 7. Transient velocity contour simulation at car velocity = 50 m/s angular rotor velocity ω=1 rad/sec and gap distance = 0.6 m.(Zooming in view 4 m/s <car velocity < 10 m/s) (Real velocity range 0 m/s <car velocity < 30 m/s).

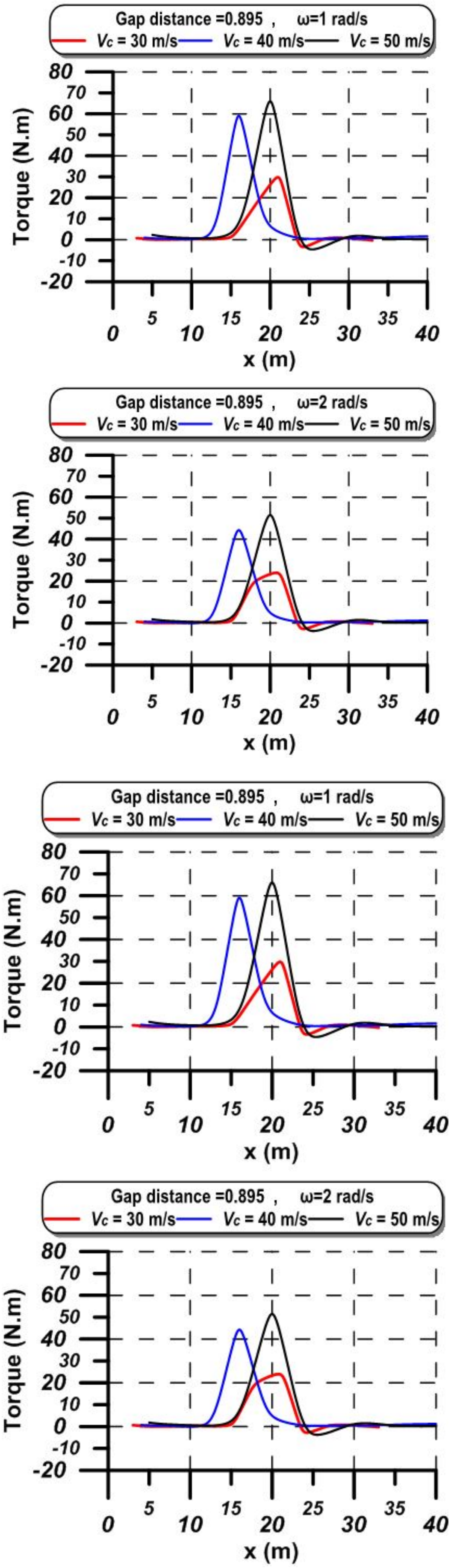

Figure 8. Instantaneous torque of the wind turbine for different car velocities and angular velocity, gap distance = 0.895 m.

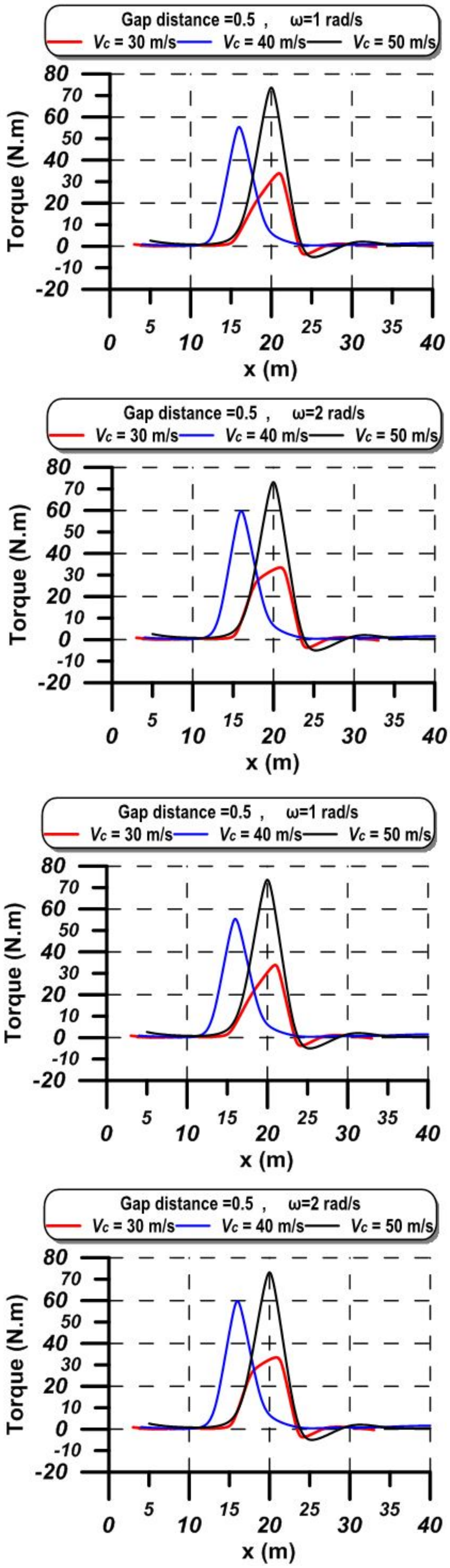

Figure 9. Instantaneous torque of the wind turbine for different car velocities and angular velocity, gap distance = 0.5 m.

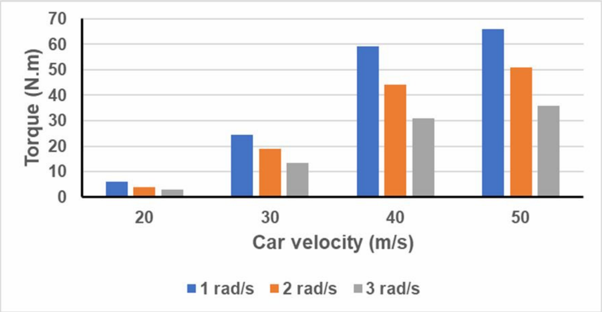

Figure 10. Max torque of the wind turbine for different rotation speeds and car velocity.

4.1 Energy Storage Calculations

Maximum power generated by the turbine for four assumed car velocities is tabulated in Table (3) (only sedan car is considered in this simulation. Other types such as minivans, station wagons, SUVs, pickups, and trucks are neglected). The postulated turbine introduces a maximum rated power at angular velocity of 3rad/s as shown in Table (3). The maximum power (*Pm*) obtained by any VAWT is calculated according to:

$$Pm = Max.Torque \times \omega \tag{6}$$

where max. torque is obtained from figure (10), with max. angular velocity that equals to 3 rad/s, maximum power (*Pm*) calculated as shown in table (3).

The electrical power (*Ep*) extracted from each turbine is calculated from the maximum power (*Pm*) multiplied by time interval (t) in which wind exerts that power on the turbine blade:

$$Ep = Pm \times t \tag{7}$$

Since the maximum rated electrical power of the postulated turbine is obtained with the blade angular velocity of 3rad/s, the extracted electrical powerwill be calculated at this condition. Our assumption is that the highway cars' frequency is 1car/min each way of 12 hoursof daytime running road plus 0.2 car/min each way of 12 hoursof nighttime running road (night traffic is considered less frequent).

The batteries used in the calculations are 12VDC output voltage, 200Ah capacity (2.4kWh stored energy) type Newmax deep discharge lead-acid Gel battery. The depth of discharge (DOD) of this battery is 60% with 1000 charge-discharge cycle. Light lamp used in the calculations is 250W LED street light lamp with 22500 lumens and 50000 hours rated life. Vehicles with various assumed velocities shown in Table (4) are randomly passing the VAWT, therefore, we will consider an average velocity of 126km/h as shown in Table (4). The average energy generated in 24 hours is 53.5kWh. The number ofNewmax batteries required to store this energy is 38 batteries for each installed turbine. Light lamps are working ~12 hours a day (night operation). For a 250W lamp, the consumed energy in 12 hours is 3kWh. Therefore, the 38 batteries can run 18 light bulb for 12 hours (considering the DOD of the battery is only 60%). Using higher DOD batteries such as lithium ion batteries can reduce the number of batteries drastically. However, this type of batteries is still expensive and hazardous with a high chance of explosion.

The space between each lamppost (D) depends on several details including road width, pole height, and luminous of each lamp. Based on these details, the following formula can be used to calculate the space between each lamppost [22]:

$$D = \frac{k \times L}{F \times W} = \frac{0.04 \times 22500}{5 \times 3} = 60m \tag{8}$$

where: L is luminous flux of the bulb which is 25200lm in this study, F is required lux level (equals to 5 in highways), k = 0.04 which is a constant correlated to depreciation and utilization factors, and W is the road width (W = 3m in Iraqi highways).

Since lamppost space is 60m, the total roadlength that can be lit with each VAWT is (60 × 18 = 1080m = 1.08 km). This result reveals that each turbine can lighten around one kilometer of the highway throughout the night.

Table 4. Daily generated energy calculations and specific carbon dioxide.

Car Velocity (km/h)	*Ep* (kWh)	No. of Batteries	No. of Lamps	CO_2 Emission (kg)
72	7.2576	5	3	3.26592
108	34.473	24	12	15.51312
144	79.833	56	27	35.92512
180	92.534	65	31	41.64048
Ave 126	53.524	38	18	24.08616

4.2 Estimated Reduction in CO_2 Emission

The specific carbon dioxide emission is 0.45kg of CO_2 for each kWh of consumed electricity from the grid [23]. Hence, lighting 1 kilometer of the highway for 12 night hours with 18 lampposts using 53.5kWh of energy collected from VAWT installed on highway median will avoid 24kg emission of CO_2 a night, corresponds to 8.8 tons of CO_2 emission annually. This is a feasible value from the environmental side of view, in addition to the free source of energy that is collected from the moving vehicles.

5. CONCLUSIONS

The simulation results and calculations obtained encourage us to recommend using wind turbines to recover energy from car wake and to the production of clean renewable energy under normal operation conditions. The wind turbine designed to be located at the highways medians to generate electricity and it will power up highway lights or can be used for commercial applications. Including other types of vehicles changes the results of this study dramatically, especially when including heavy goods vehicles (HGVs) such as trailers. A combination of various types of vehicles' aerodynamics is under progress.

6. ACKNOWLEDGEMENT

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NOMENCLATURE

A_f	Vehicle frontal area (m2)
C_d	Drag coefficient
D	Vehicle travels distance (m)
E	Energy (J)
Ep	Electrical power (kWh)
Pm	Maximum power (W)
V_c	Vehicle velocity (m/sec)

$\vec{r}$	Position vector
P	Static pressure (Pa)
X	Axial distance (m)
μ	Viscosity (Pa.s)
ρ	Air density (kg/m^3)
ω	Angular velocity (rad/s)
$\vec{u}$	Relative velocity of fluid
RANS	Reynolds Averaged Navier-Stokes
SST	Shear Stress Transport
VAWT	Vertical axis wind turbine
$\vec{\Omega}$	Rotational speed (rpm)
$\overline{\tau_{ij}}$	Average shear stress

ОБНАВЉАЊЕ ИЗВОРА ЕНЕРГИЈЕ ИЗ ВРТЛОЖНОГ ТРАГА ВОЗИЛА У ПОКРЕТУ НА МАГИСТРАЛИ КОРИШЋЕЊЕМ ВЕТРОТУРБИНА СА ВЕРТИКАЛНОМ ОСОМ ОБРТАЊА

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Истражује се поновно добијање енергије из вртложног трага возила у покрету коришћењем ветротурбина са вертикалном осом. Ветротурбина је пројектована за локацију по средини магистрале да би се производила електрична енергија. Симулација неустаљеног протока саобраћаја је извршена у циљу евалуације перформанси турбине. Анализирани су следећи фактори: брзина возила, растојање између турбине и положаја возила, и угаона брзина лопатица.

Резултати су показали да је максимална излазна енергија турбине из вртложног трага око 107,1 J. При просечној брзини возила од 126 km/h, укупна дневна производња енергије, број батерија, број стубова расвете и дневна редукција емисије CO2 имали су следеће вредности: 53, 5248 kWh, 38 батерија, 18 стубова расвете (по 60 м растојања између стубова) и 24, 08616 kg.