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# Numerical investigation of wind turbines and turbine arrays on highways

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High-speed moving vehicles can produce strong wakes which contain considerable amount of localized wind energy. Previous studies have proved the feasibility of using vertical axis wind turbines (VAWTs) to recover energy from the wake of vehicles on highways. However, two key problems remains unsolved considering the highway wind turbines. What is the best type of VAWTs for highway wind energy recovery? And what is the best gap between VAWTs if they are planted in an array? This study aims at solving the above two problems using three-dimensional computational fluid dynamics (CFD) simulations. First, the performance of three different rotors are evaluated and compared, it is found that the Banki rotor operates best in the wake of a moving vehicle. Then, simulations are performed on an array that composed of three Banki rotors. The performances of the array is evaluated at different rotor gaps and the optimal rotor gaps are provided for different situations.



## 1. Introduction

Wasted energy recovery has gained worldwide interest due to the increasingly severe energy crisis in recent years. Among the various wasted energies, highway wind energy produced by moving vehicles has not been valued until recent years [1–5]. High-speed vehicles moving on highways produce strong disturbance to the air and transmit energy to the wake in the form of localized wind energy [6]. The potential of highway wind energy is high, considering the large mileage and the high traffic flow. The highway wind energy is most likely to be used to power the surveillance cameras on highways that are remote from the grid. By connecting the highway wind turbines to the surveillance cameras, independent self-powered monitoring systems are formed, thus avoiding the cost caused by the laying and maintenance of the cables.

According to the relative alignment between their axis of rotation and the wind direction, wind turbines can be generally classified into two types, the horizontal axis wind turbines (HAWTs) and the vertical axis wind turbines (VAWTs). The main advantage of VAWTs over HAWTs is the capability to generate power under any wind directions. This advantage makes VAWTs more suitable for the highway wind energy generation considering that the wind directions on both sides of the turbine are opposite due to the opposite directions of vehicles, and the opposite aerodynamic forces could be used to drive the VAWT [4]. VAWTs can be classified into two types, the drag-type and the lift-type, according to the generation mechanism of the blade driving force [7]. The Savonius turbines and the Darrieus turbines are the typical designs of the drag-type and the lift-type VAWTs, respectively.

There have been some studies on the design of highway wind turbines. Krishnaprasanth et al. designed a maglev turbine for highway wind power generation [2]. Taskin et al. designed a combined solar and wind system to be planted in the medians of the highways, the system uses a multi-stage Savonius rotor to generate power from the wind produced by cars [1]. Several researchers put the ideal of highway wind turbine into the prototype stage, including a Savonius turbine [5] and a hybrid wind turbine composed of a Darrieus rotor and a Savonius rotor [3,4]. These prototype studies showed the feasibility of using wind turbines to generate power from the wakes of moving vehicles, but the mechanisms of the interactions between the vehicle and the rotor were unclear.

Unlike natural wind flows, the wake of moving vehicles is highly turbulent and contains complex separation flows. Many studies

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have been done to model the wake of moving vehicles, and most of them employed a simplified vehicle shape, the Ahmed model, which was proposed by Ahmed et al. [8] and had been generally used in the automotive industry to investigate the influence of the flow structure on the drag. Guilmineau numerically investigated the flow around the Ahmed body at base slant angles of 25$^{\circ}$ and 30$^{\circ}$ [9]. This numerical investigation considered the influences of turbulence models and found that the EASM model predicts the best results. A later research by Guilmineau et al. presented a DES approach based on the shear stress transport (SST) $k$-$\omega$ model for the simulation of flow around the Ahmed body [10]. They performed detailed comparisons of the wake between the CFD results and the experimental data. Another remarkable work was done by Uystepruyst and Krajnovic [11], in which they utilized a combined deforming and sliding mesh method that could simulate the motion of real-life vehicles with high accuracy.

Considerable effort has been exerted to evaluate and optimize the performance of VAWTs, mainly including the Darrieus turbine and the Savonius turbine. Driss et al. [12] used 12 parameters to define a Savonius turbine and got a segment of circular arc with the blade arc angle of 120° as the blade. Al-Faruk et al. [13] studied the influence of the blade overlap ratio, the blade arc angle and the aspect ratio on the performance of Savonisu turbines. at the same time. Tian et al. [14] introduced an optimization procedure of a modified Savonius blade which had different concave and convex shapes. Hashem and Mohamed [15] evaluated the aerodymamic performance of Darrieus turbines with 24 new airfoils as the sectional profiles of the blades. Bedon et al. [16] created an optimization method to develop high performance airfoil shape which increased the aerodynamic performance of the Darrieus wind turbine. Arpino et al. [17] presented a new Darrieus turbine which adopted three couples of blades for the rotor, each composed by a main and an auxiliary aerofoil.

Modeling of VAWTs in the wake of moving vehicles is relatively difficult due to the complexity of the vehicle wake. Lapointe and Gopalan [6] performed a two-dimensional steady CFD study on the flow field of mini wind turbines placed near highways, they studied the flow field velocity distributions around the turbine under the assumption that the inflow velocity was fixed and the vehicles were stationary in space. Tian et al. [18]carried out three-dimensional transient CFD simulations on a VAWT installed on highways, the influences of vehicle type and road condition on the performance of the VAWT were studied. Overall, the modeling studies of VAWTs on highways are far less and more complex than those operates in natural wind flows.

Although efforts has been devoted to the conversion of highway wind energy, two key problems remain unsolved and impede the development of highway wind turbines:

(1) What is the best type of VAWT for highway wind energy recovery? Because the bi-directional flow conditions on highways are different from common uniformed wind field, common VAWTs, such as the Savonius and the Darrieus turbine, may not be the best choice.
(2) What is the optimal gap between the VAWTs if they are planted in an array? In large-scale applications, the VAWTs will be likely planted in arrays on the medians of highways, the gap between two adjacent VAWTs is an important factor which affects the performance of the turbine array.

This study aims at solving the above two problems with a three-dimensional transient CFD approach. Firstly, comparative study of three widely used VAWTs, a Banki rotor, a Savonius rotor and a Darrieus rotor, are performed to find the best VAWT for highway wind energy recovery. Then, simulations of a turbine array are performed to find the optimal gap.

## 2. Model simplification

The array of VAWTs will be planted on the median of the highway, then the wakes of vehicles on both sides of the median will contribute to the output of the turbines, as shown in Fig. 1. In this study the dimensions of the highway is chosen according to the Chinese Highway Engineering Technique Standard. The width of the median of a six-lane highway is 1 m and the width of each lane is 3.75 m. The required velocity is 110–120 km/h for the passing lane.

### 2.1. Geometries

The vehicle considered in this study is a simplified car model, as shown in Fig. 2. The car geometry is developed from a common compact-size car with rounded front and sharped rear end. The overall dimension of the car model is 4.5 m × 1.8 m × 1.5 m (length × width × height), which is close to the real size of a compact car.

In order to find the best type of VAWTs for highway wind energy recovery, three widely used VAWTs, including a Darrieus rotor, a Savonius rotor and a Banki rotor, are considered in this study. The reason for choosing these three rotors is that they are typical representatives of three types of VAWTs. It is known that the Darrieus rotors are lift type VAWTs and the Savonius rotors are drag type VAWTs [19]. The Banki rotors belong to the category of cross-flow VAWTs [20].

The geometry of the three rotors are shown in Fig. 3. The Banki rotor has 20 straight arc-type blades. The Darrieus rotor has three helical blades extruded from the NACA0015 foil. The Savonius rotor has two helical blades derived from a half-circle. A helical angle of 60° is chosen for the helical blades of the Darrieus and the Savonius rotors to make the aerodynamic forces on the rotors more stable [21].

The cross-sectional shapes of the three rotors are all derived from the existing literatures [20,22,23]. In order to scientifically compare their performance, the three rotors are scaled to the same diameter (1 m) and height (1.5 m). The main geometric dimensions of the three rotors are shown in Table 1. The definition of the symbols in Fig. 3 and Table 1 can be found in Refs. [20,22,23].

### 2.2. Dimensionless coefficient

In order to clearly describe the parameters and the coefficients,

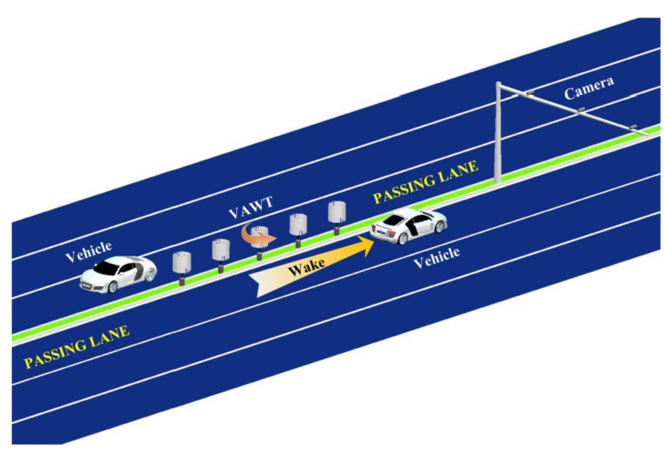


**Fig. 1.** Schematic of the highway wind turbine.