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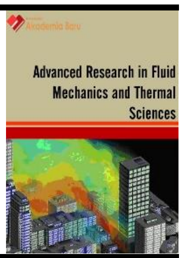

Numerical Investigation of Wake Energy Induced by Cruising Passenger Vehicles on Highway

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ABSTRACT

Wind energy developed from the wake induced by the cruising vehicles has a large potential in harvesting energy through the wind turbine system that could be possibly used in supplying power for lightings along highway. This paper presents the feasibility study of the potentiality of vertical axis wind turbine to be placed along the median of highways in Malaysia. The velocity of the wake from the moving vehicles observed in the median of the highway is the important output parameter in this research. Transient Computational Fluid Dynamics (CFD) simulation is done using time-efficient dynamic mesh approach called overset mesh as to represent the real condition of flow induced by moving vehicles in highway. There are four cases simulation carried out, that are, are one car on single lane, one car on both side lane, two cars on single lane and two cars on both side lane. The vehicle geometry is set as standard sedan car and the speed is ranging between 90km/h and 110km/h. From the findings, It is observed that the wake of two moving cars from both sides lane is to be the case that produces the highest wake velocity with 12 m/s. The finding also shows that the higher the speed of the car the higher the velocity of wake induced, and the sequent car contributes in escalating the wake induced velocity.

1. Introduction

The tendency among motorists to involve crash on motorways with insufficient road illumination is relatively high and this is known as one of the major causes of accident on Malaysian motorways, other than reckless factor among them. In the 10th Malaysian Plan (2011–2015), the government has spent approximately USD 4.7 billion on improving the road infrastructure which includes providing reliable lighting for the highway network in order to decrease the accident rates in the country [1]. However, the connection of a robust lighting system on such network to the national electricity grid will definitely increase the load on the power generation stations, which are mainly fuelled by natural gas and diesel. Along with the persisting increase in global oil price, and the uprising political instability in the major oil producing countries, a country such as Malaysia would definitely consider

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sustainable energy resources as successful alternatives to support its rapidly developing economy. Therefore, with a Malaysian highway network of 49,935 km in total length, the kinetic energy from the turbulent induced by the speeding passenger vehicles on highway seems not negligible and is highly potential towards sustainable and renewable energy. Several research papers were taken efforts to convert these kinds of the winds to generate electricity; especially, the winds that exist on the street isles due to possibility to utilize wind generated by the moving vehicles from both directions of the street [2,3].

Numerous efforts have been devoted by researchers to access on the potentiality of the highway energy harvesting through different types of turbine. Recently, Santhakumar *et al.,* [4] conducted an experimental work to understand the behaviour of a Savonius wind turbine (SWT) on two-lane highways located in Coimbatore district, India. They placed a Savonius wind turbine (SWT) on the sides of the highway during the south-west monsoon season in three different directional roads. Ismail *et al.,* [5] conducted a research to analyse and optimize the Darrius wind turbine based on air velocity and twist angle blade. They found that those two parameters have significant influence on the turbine torque, turbine rotation speed and turbine power capacity. The method of research that they used consists of air velocity observation, wind turbine design, and simulation of wind turbine design. The found that the Darrius wind turbine with the twist angle of 30° which has chosen has the torque value is 0.285 Nm that capable to increase the rotation speed is 6.42 rpm, and generate the turbine power capacity is 0.221 W. Bani-Hani *et al.,* [6] performed an experimental study of using a three-bladed helical Vertical Axis Wind Turbine (VAWT) specially designed and manufactured for producing electrical energy from wind energy of moving cars on highways for lighting purposes such as the highway lights, traffic signals, and light guide lines. The wind speed of vehicles passing on a highway and wind power from the VAWT is measured at a number of anemometer heights on the highway sides. They found that the VAWT prototype has produced up to 48 W of power from vehicles moving on the highway, which produce an average wind speed of 4.4 m/s. The wind turbine power curve is produced from the measured data and based on the best fit to the power curve, the efficiency of 34.6% is obtained. Santhakumar *et al.,* in 2017 [7] investigated the behaviour of a vertical axis Savonius Wind Turbine (SWT) in four-way lane highways during South-West and North-East monsoons. Starting behaviour of the SWT was studied by measuring and calculating the starting torque coefficient. The proposed SWT's cut-in speed was achieved at a velocity of 3.5 m/s. Experiments were carried out on a four-way lane highway through the placement of turbine at two different positions (middle and sides of the highway). Also, the experiments were repeated during different monsoons to understand the behaviour under different wind directions. The obtained experimental data clearly illustrates that the SWT's nominal rotational speed varies at different monsoons, when located at the sides of the road. From the data analysis, it can be understood that the wind directions play a key role for harnessing maximum amount of energy in highway wind-energy generation. Maximum augmented rotational speed of around 64% was achieved by placing the SWT at the median of Four-way lane highways in different monsoons. Tian *et al.,* [8] employed a vertical axis wind turbine (VAWT) to recover energy from the wakes of moving cars. They designed the turbines to be planted by the side of the car lane and driven by the wake produced by the car. Transient CFD simulations were performed to evaluate the performance of the VAWT. The influence of two main factors on the performance of the VAWT, the velocity of the car and the gap between the car and the rotor, were studied. The simulations confirmed the feasibility of this plan, and in the tested cases, the VAWT was able to generate a maximum energy output of 100.49 J from the wake of a car. The results also showed that the performance of the VAWT decreased with the velocity of the car, and the increased gap between the car and the VAWT. Al-Aqel [9] Vehicle-induced turbulent airflow by the traffic in the highways is one of the sources of wind energy which can be harvested to supply the power to the highway lighting and telecommunication signaling. Their work focuses on the assessment of potentiality of implementing small scale wind turbines along the highways in Malaysia. The study was started by conducting wind speed measurements adjacent to the highway at Lebuh SPA (Sungai Udang - Paya Rumput - Ayer Keroh Highway), a major highway in Malacca state, Malaysia [9]. Three positional parameters have been investigated for suitable placement of the wind turbines. They are: the lateral distances from the road shoulder, the heights from the ground, and the orientation of the wind turbines relatives to the road. The former two parameters were set at 0.5 m, 1.0 m and 1.5 m for each position; while the latter was varied at perpendicular, 45°, and parallel to the road. The measurements were conducted using hot-wire anemometers. The results showed that the optimum positions for the wind turbine is at 1.0 m from the lateral distance and the height above the ground, respectively, and the optimum orientation is found to be 45° from the road at which the horizontal axis wind turbines (HAWT) can be directed. The large size vehicles such as lorries and busses were observed to produce higher wind speed as compared to the smaller ones. The results were further verified by using numerical simulation work through ANSYS Fluent. Bonilla *et al.,* [10] Highway luminaries are a key element to ensure transportation safety during the night. Previous studies revealed that over fifty percent of crashes occurred during the evening even though, in general, there are fewer vehicles-miles during the evening. These results made clear the importance of luminaries in highways, but these luminaries could raise energy cost. Recognizing the high demand of energy caused by highway luminaries and the need for new technologies, this project investigates the potential use of wind turbines in highways to harness the wind energy generated by the motion of a passing vehicle to lower the cost of energy in public illumination. The investigation was conducted through two experiments, a Single-Vehicle Testing and a Multiple-Vehicle Testing. As shown in the results, the measured maximum wind velocities due to the passing of cars (without considering high natural wind speeds) was insufficient to provide the required energy for highway luminaires. Tian *et al.,* [11] chose vertical axis wind turbine (VAWT) as the renewable energy system to recover energy from the wake of vehicles on highways. The VAWT is designed to be placed on the medians of the highway and produce power from the wakes of vehicles on both sides. Three-dimensional CFD simulations based on the Reynolds-Averaged Navier–Stokes equations are performed to evaluate the performance of the VAWT and to determine the mechanism of interactions between the moving vehicle and the turbine,. Five typical situations, including one car on the passing lane, one bus on the passing lane, two opposite moving cars on the passing lane, one car on the fast main lane, and one bus on the fast main lane, are considered and studied. From the results the found, the VAWT could generate power from the wakes of vehicles on the passing lane and the maximum average power coefficient is 0.00464, which corresponds to an average power of 139.60 W.

According to the literature done here, it is found that VAWT of Savonious and Darrieus rotors are typically selected for highway application due to its appropriability and applicability. In the aspect of VAWTs, the Darrieus and the Savonius rotors have been studied in depth. Considerable effort has been exerted to model the dynamic forces on the Darrieus turbine [12, 13]. Variable pitch control mechanism [14] and twisted blades [15] have been adopted to further improve starting torque and efficiency, and reduce shaking of the Darrieus turbine. Despite their lower efficiency compared with Darrieus types, Savonius wind turbines have higher starting torque and good starting performance, as well as the ability to operate under complex turbulent flows [16]. The Savonius turbine also has been studied experimentally and numerically to examine the effects of various design parameters, such as rotor aspect ratio, overlap, bucket number, rotor endplates, and bucket stacking [17-19]. In addition, some researchers attempted to enhance the performance of the Savonius turbine by changing its structure. Kamoji *et al.,* [20] analyzed the aerodynamic characteristics of a modified

Savonius turbine with helical blades. Kacprzak *et al.,* [21] studied the performance of modified turbines with spline-type and Bach-type blades, and they found a 16% increment in efficiency when spline-type blades were used. Tian *et al.,* [22] evaluated the performance of the Savonius turbine with new blades derived from the Myring Equation. Faiz *et al.,* [23] evaluated the performance and generated power of the wind turbine with new blades derived from the Betz's theory.

The issue comes behind the investigation of the highway wind-energy generation is the unsteadiness of traffic flow, while, in the numerical aspect is that the wake flow induced by the moving vehicles is highly turbulent, making the modelling time-consuming as it demands transient simulation. Therefore, the main goal of this research is aimed at predicting the wake and flow induced by the moving vehicles on highway at a low cost in terms of simulation time. The idea behind the research work done in this paper is to provide the input flow information to the wind turbine analysis installed along highways. The overset mesh is used in the CFD numerical modelling as to represent the real condition of flow induced by moving vehicles in highway and even found to be an time-efficient approach.

2. Methodology

2.1 Simulation Cases

A standard-size sedan car is chosen to be the passenger vehicle model for the analysis. The geometry of the car is 4.16m length, 1.68m width, 1.33m height as per illustrated in Figure 1.

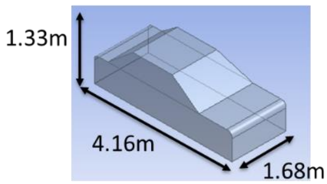

Fig. 1. Vehicle geometry

Four cases are simulated in this research work in which the cuboid-shape computational domain as shown in Figure 2 has been adapting in all cases, for the fact that it managed to create more structured mesh in the domain. The domain is divided into two parts. The first part is the translating zone and the second part is the dynamic mesh zone (exterior domain). The translating zone moves along with the car.

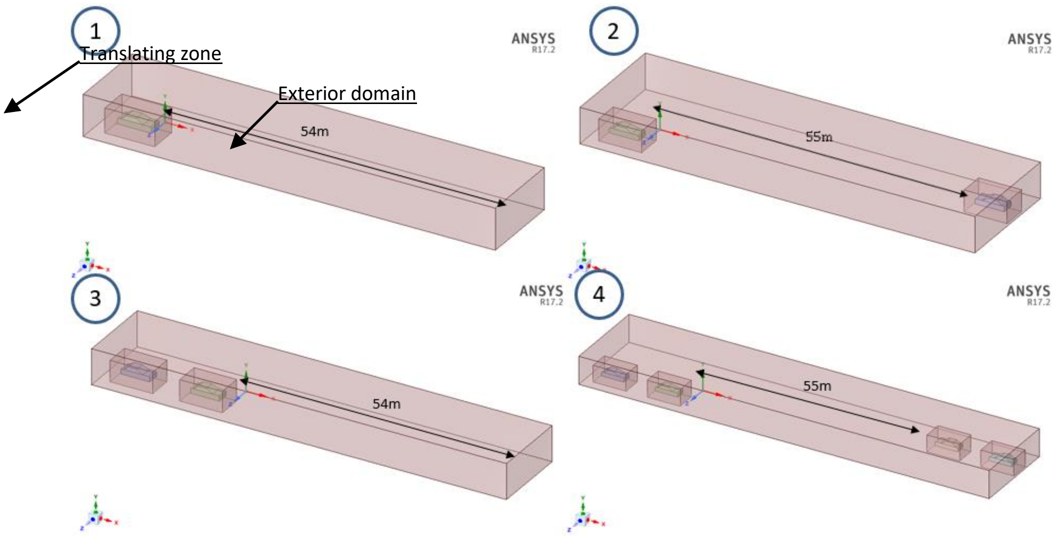

Fig. 2. Computational domain of all simulation cases

2.2 Boundary Condition Specification

There are some constant parameters between all of the cases for example the distance between the car to the side wall, the distance of the car to the opposite lane and many more. For the translating zone, it is set to be 1 meter at every surface of the car including its bottom part. Refer Fig. **3** for the constant parameters that have been set.

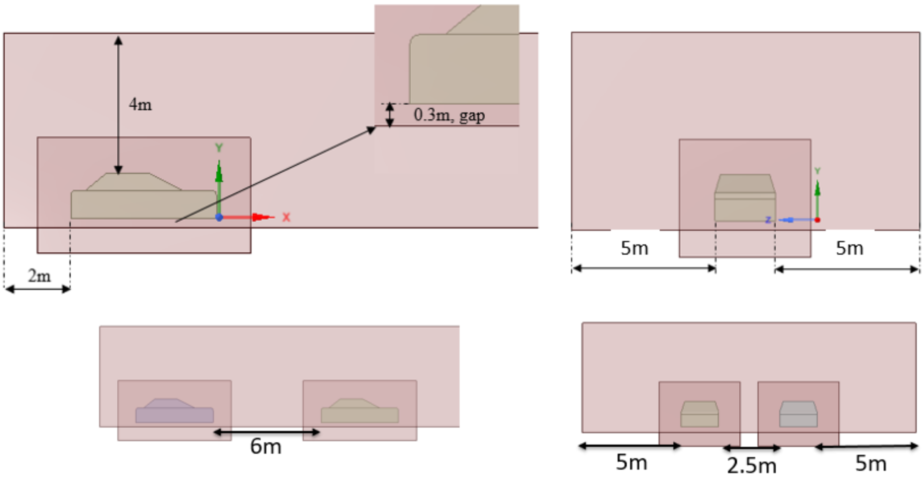

Fig. 3. Constant parameter for all the cases

Running the overset-type mesh requires to a thorough specification of the boundary condition in ensuring for workable simulations. Refer Fig. **4** for the boundary condition specified on the computational flow domain. There is no specification for inlet. This simulation is a dynamic mesh simulation where the car is moving in translation motion, thus there is no inlet boundary condition required. Apart from that, the enclosure of the car is specified to be overset instead of a wall to activate overset mesh function for the simulation.

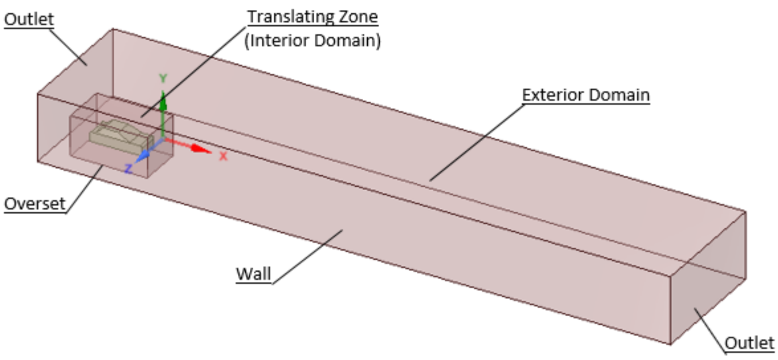

Fig. 4. Boundary condition specification

2.3 Meshing Process

In this study, the computation mesh is generated by using the ANSYS Mesher. All the computed zones are meshed with structured grids. CutCell method have been chose for the meshing process. The CutCell method is a structured mesh where it converts a volume mesh into a predominantly cartesian mesh consists of mostly hexahedral elements and the faces are aligned with the coordinate axes. Fig. **5** shows the meshed domain of exterior zone and translating zone. The size of the meshing at translating zone is set to be much finer than the exterior domain. The purpose of doing this is to ensure for an accurate result near the car. Aside from that is the car could move in high velocity which is 90km/h to 110km/h, to catch the wake intensity at surrounding of the car, the translation zone requires a smaller size of mesh as in Fig. **5**.

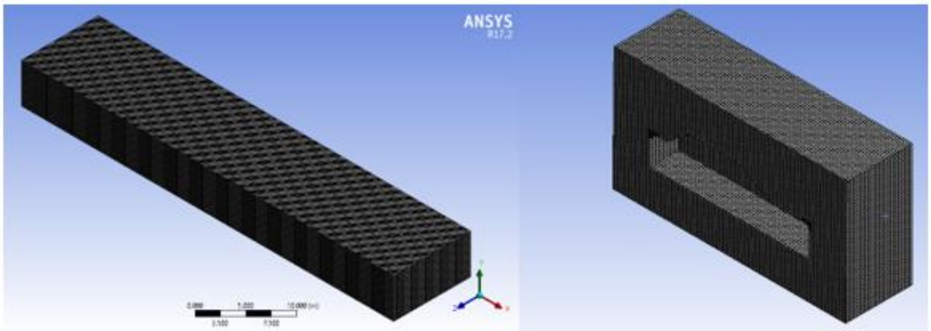

Fig. 5. Meshing for the exterior domain and translating zone

2.4 CFD Simulation Process

As for the fact that the car model has to be moving at high velocity, this simulation hence employs smoothing dynamic mesh option to real capture the velocity of the wake of the moving vehicle. The general setting of the simulation are as in Table 1.

Table 1
General setting for the simulation

Type	Setting
Simulation	Transient
Turbulence Model	k-ω SST
Cell Zone	Air
Dynamic Mesh	Smoothing
Scheme	Coupled, Second Order Upwind

The turbulence model that been chosen is k-ω with Shear Stress Transport (SST). This turbulence model was chosen for the fact that it combines the best characteristic of epsilon, ε and omega, ω equations making it a perfect model in calculation. Apart from that, it activates the Wilcox model (K-omega) near the wall and the k-epsilon model in the free stream making the simulation to be more accurate. As the overset mesh is employed, overset interfaces are hence neccesary to be created in which the background zone and component zone have to be defined. From this simulation, the exterior domain and the translating zone were respectively set as the background zone and the component zone. Fig. **6** illustrates the overset mesh before and after initialization. From the figure, it shows that the excessive part of the translating zone is disappeared and terminated. This is due to the fact that Fluent automatically establishes the necessary connectivity between the meshes when the flow is initialized. In this process, cells that fall outside the background zone are classified as dead cells. Thus, it creates the 0.3 meter gap between the car and the road (exterior domain) for the tyre effect.

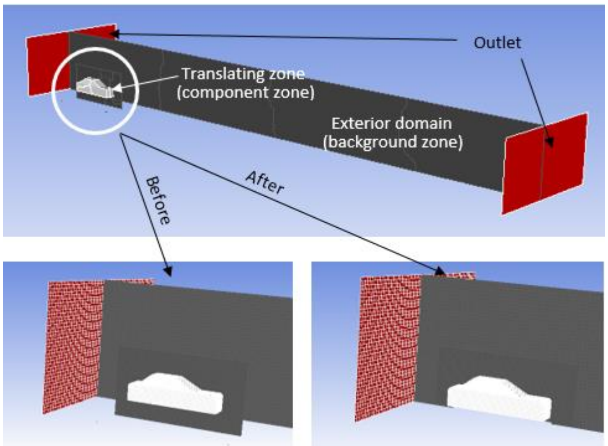

Fig. 6. Before and after initialized of overset mesh

2.5 Grid Independence Test

Prior to simulation, a grid independence study is performed to evaluate the influence of mesh resolution on the results. The grid independence study involves two main stages, i.e, the construction of the computational meshes according to the reasonable estimation of cell size and the investigation of the sensitivity of the computed flow field to the output result. After the data from the first mesh is extracted, the mesh is refined before the second simulation runs. This process is repeated until the result of the simulation found to be or nearly similar as the previous ones. Four grid models have been simulated with different number of cells. The first mesh consists of 514,524 cells, while the second mesh is 836,346 cells followed by the third with 1,256,804 cells and the last with 1,669,693 cells. The grid independence study is based upon the result of wake velocity at a point which is similar for all tested meshed models. Fig. **7** shows the grid indepence study result. It shows that the result converged at the third run where the difference of wake velocity between third mesh and fourth mesh is approximately 1.2%. Thus, from this point onward, the number of cells for all of the simulations are follow the third mesh which is 1,256,804 cellss.

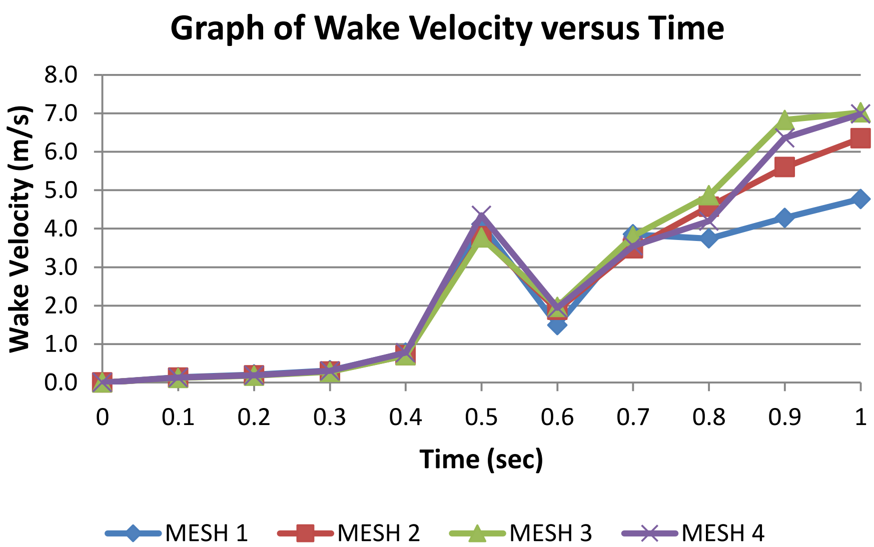

Fig. 7. Grid independence test results

3. Results

In this section, how the moving vehicles with different cruising speeds contribute to the induction of wake velocity on highways will be discussed. Each of four cases is specified to have three different car speeds, that is 90km/h, 100km/h and 110km/h. The first simulated case is one car on a single lane, one car on side lane, two cars on single lane and two cars on both side lanes.

3.1 Distribution Comparison Between One Car and Two Cars Moving on Single Lane

The simulations between one car (Case 1) and two cars (Case 3) moving at 3 different speeds are considered and compared. The data were extracted from the point which is located at 0.7 meter above the ground, 1 meter from the side of the car and 15 meters from the front of the car. Fig. **8** illustrates the graph of wake velocity against simulated time, for both cases. Case 3 is found to produce highest wake velocity which is nearly 10 m/s. When compared with the case 1, the increases in wake velocity is more than 250%. This is due to the fact that there are two sources of wake induced which is from the first car followed by the sequent car. From this regard, we could draw a statement saying that the sequent car contributes in developing the velocity of the wake induced. Fig. **9** shows the velocity contour of both cases at time where highest wake velocity is achieved.

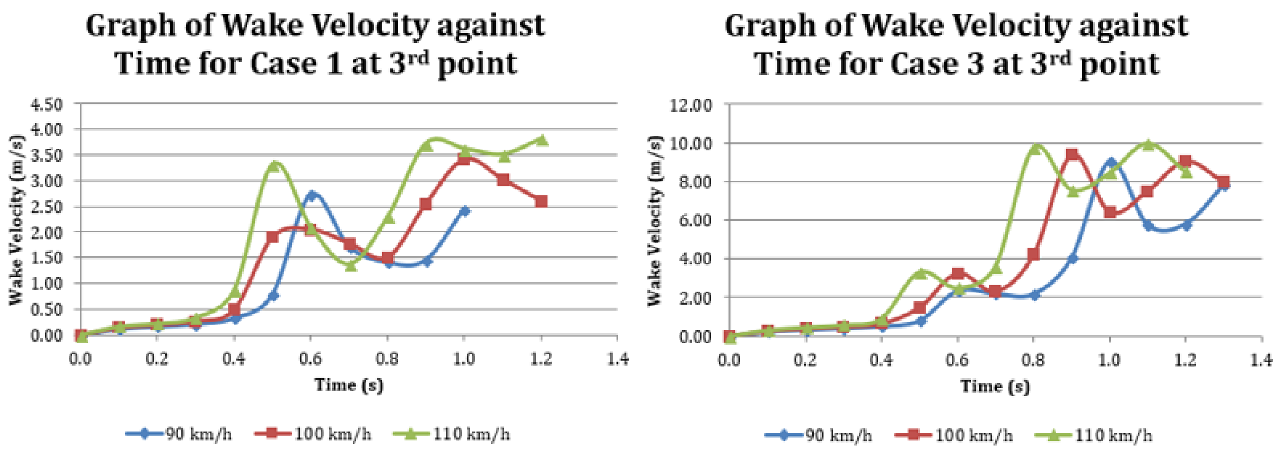

Fig. 8. Wake velocity distribution for Case 1 and Case 3

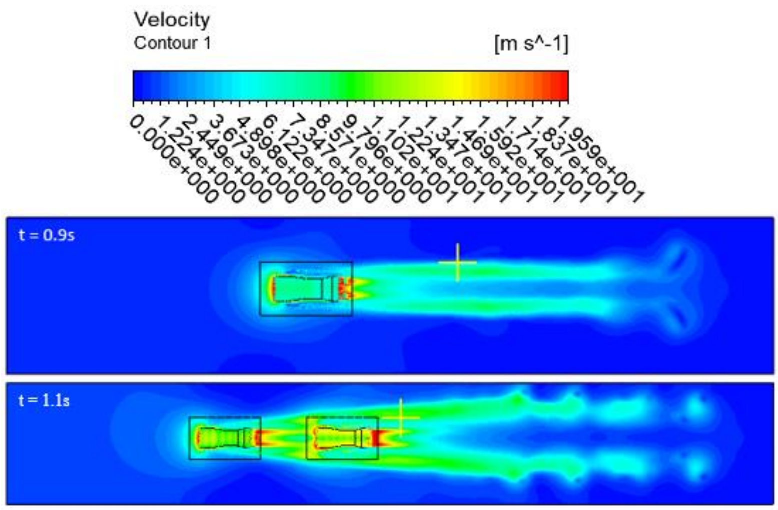

Fig. 9. Highest wake velocity contour for Case 1 (top) and Case 3 (bottom)

3.2 Comparison Between One Car and Two Cars Moving on Both Side Lane

Here is the result comparison between one car (Case 2) and two cars (Case 4) moving on both side lanes. The data is extracted at a point located at the middle between the two opposite car, 0.7 meters high above the ground and slightly shift to 1 meter from the either one side of the car. Similarly, the cases of high car velocity is found to produce high velocity of wake induced. Fig. **10** is the wake velocity result of Case 2 and Case 4.

From the graph, it can be seen clearly that Case 4 shows the highest wake velocity production than in Case 2 which is approximately 12 m/s. The increases for this case reaches 20% from the highest wake velocity in Case 3. Hence, a conclusion could be made that when cars from opposite lanes passing to each other, it produces higher wake velocity than that cars moving on a single lane. This is due to the fact that the car is influenced by the wake of the other cars after the meeting point and they form a region of vortices at the median. The wake induced is merged and forms vortices and increases the wake velocity. Figure 11 shows the velocity contour of Case 2 and Case 4 at time where the highest wake velocity achieved.

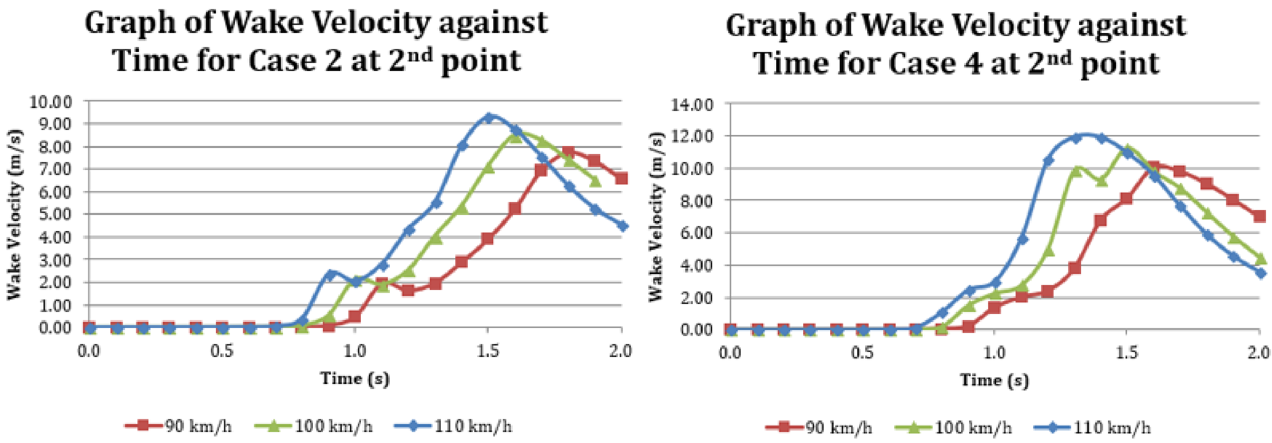

Fig. 10. Wake velocity distribution for Case 2 and Case 4

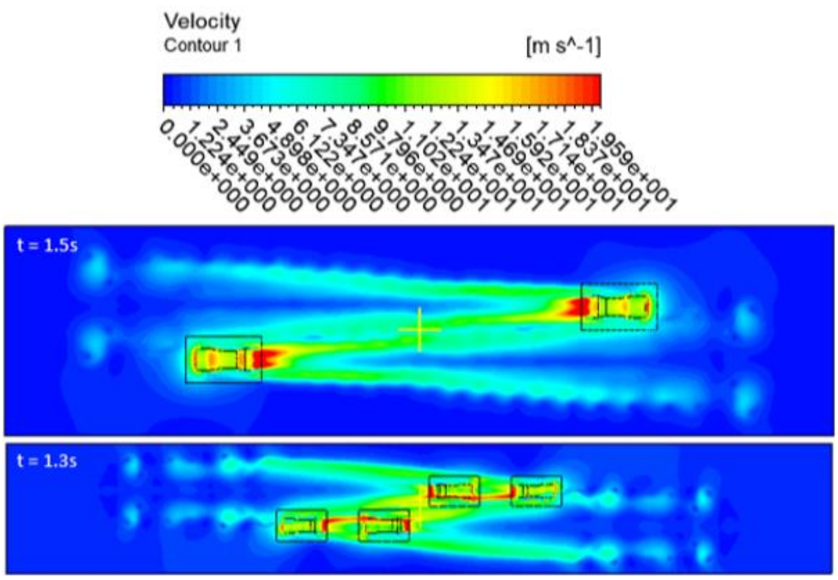

Fig. 11. Highest wake velocity contour for Case 1 and Case 3 respectively

3.3 Wake Velocity Profile for Case 2 and Case 4

The idea behind the wake velocity profile is that it could be the input of flow information to the vertical-type wind turbine analysis installed along highways. Fig. **12** refers to the wake velocity profile and design specification for the VAWT. Similarly, the data is extracted at the time where the highest wake velocity occurred, and the same point of previous cases. As for the velocity profile, the data is taken from the ground until it reaches to a height of 1.4 meters.

From the graph, it could be advised that the turbine is unnecessarily to be placed too low to the ground for the fact that the wake induced velocity within that height is too low when compared that at the middle. Thus, the height of the support for the wind turbine is suggested to be approximately 0.2 meter above the ground.

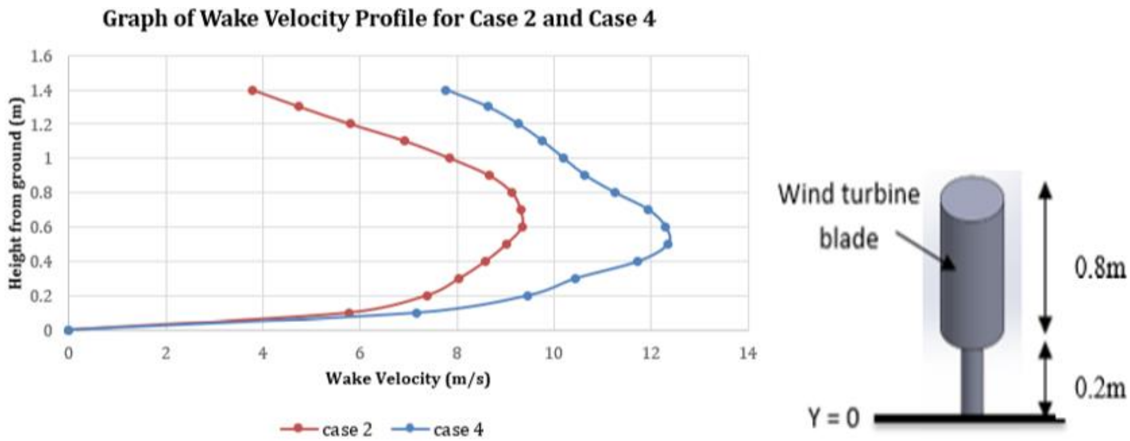

Fig. 12. Wake velocity profile for Case 2 and Case 4 and the design of the turbine

4. Conclusions

The wake velocity induced by the cruising passenger vehicles in highways is investigated using numerical results from a CFD simulation. A total of four cases corresponding to two different setup, i.e., single lane and two opposite lanes with three variation of vehicle cruising speed are numerically investigated. The turbulent wind flow is solved using the standard k-ω SST model. In the following, a few important findings from our analysis can be highlighted as follows.

I. The induced wake velocity by cars moving on both side lanes is found to show much greater compared to that by cars moving on a single lane.
II. Sequent car highly contributes in escalating the velocity of induced wake hence it provides high energy to rotate the wind turbine.
III. The greater the speed of the car, the higher the velocity of wake induced by the car.

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