Proposed Design of Wind Turbine for Highway Energy Harvesting

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Abstract

This study explores the feasibility of deploying wind turbines alongside highways to harvest untapped wind energy generated by vehicular traffic, with a focus on Malaysia's North-South Highway. The research aims to analyze local wind meteorology data, identify suitable wind turbine designs for roadside applications, and propose mechanically optimized configurations to enhance energy harvesting efficiency and safety. The methodology involves a comprehensive literature review on wind patterns, structural considerations, and turbine types from international contexts, followed by the simplification and design of vertical axis wind turbines (VAWTs), specifically Darrieus and Savonius models, using SolidWorks software. Computational fluid dynamics (CFD) simulations were conducted at a wind speed of 30.56 m/s (equivalent to Malaysia's highway speed limit of 110 km/h), evaluating parameters such as blade count, materials (e.g., high-grade steel alloys), airflow density, pressure, velocity, and power output. Data from the Malaysian Meteorological Department (2019–2022) informed site-specific assessments, particularly for the Pagoh to Yong Peng section. Findings indicate that VAWTs are most appropriate for highway installations due to their adaptability to turbulent, low-speed winds. The Darrieus turbine outperformed the Savonius and a previous design, achieving an average velocity of 27.460 m/s, a pressure of 101797.48 Pa, and a power output of 3.163 kW, exceeding the Betz limit of 1.875 kW and demonstrating superior energy capture efficiency. This research contributes to renewable energy integration in transportation infrastructure by providing evidence-based recommendations for VAWT deployment, highlighting mechanical optimizations for safety and performance. It informs policymakers, engineers, and developers on sustainable practices, potentially reducing reliance on fossil fuels while enhancing highway energy self-sufficiency.

1. Introduction

Wind turbines represent an advanced technology that converts wind energy into clean, renewable electricity. These structures, often tall and equipped with blades resembling large propellers, capture wind flow to generate power for homes, businesses, and communities [1]. At the core of a wind turbine is the rotor, which features three

or more blades made from lightweight materials such as fiberglass or carbon fiber. These blades are shaped to create lift through differences in air pressure, causing rotation as wind passes over them [2]. Modern turbines include sensors to monitor wind conditions, adjust blade angles for optimal performance, and incorporate safety features like brakes to handle high winds [2].

The advantages of wind turbines extend beyond electricity production. They reduce dependence on fossil fuels, which contribute to air pollution and climate change, thereby supporting environmental sustainability [3]. However, wind energy faces challenges, including its intermittent nature, as turbines produce less power on calm days and require backup systems like batteries or generators [4]. Another concern is the potential impact on wildlife, particularly birds and bats, which may collide with turbines during migration; ongoing research explores solutions such as speed adjustments and acoustic deterrents [5]. Despite these issues, wind energy offers a promising path to a sustainable future, with advancing technology and falling costs enhancing its viability [6].

A key gap in current applications is the underutilization of wind energy generated by vehicle movement along highways, where consistent traffic creates turbulent winds that could be harvested. International studies highlight this potential. In India, guidelines from the Indian Roads Congress (IRC) define road standards, including lane widths of 2.7 to 4.6 meters and side clearances, supporting the placement of vertical axis wind turbines (VAWTs) in medians or roadsides [7]. Research in Bhopal has used algorithms and on-site measurements to profile wake winds from vehicles, noting stronger effects from large trucks and buses. Simulations with computational domains (e.g., 220 D × 30 D × 8 D) confirm feasible airflow around turbines [7]. In the United States, wind energy costs $41–$74 per MWh, competitive with natural gas, and highways provide public rights-of-way (ROW) for VAWT installations, aligning with Department of Transportation goals for renewable energy [8–13]. European countries like the UK, France, and Germany feature single-lane widths of 2.5–3.65 meters, while speed limits in Australia (100–110 km/h) and Germany (up to unlimited on some autobahns) indicate adaptable conditions for turbine deployment [14, 15].

These examples reveal a knowledge gap in adapting such systems to Malaysia, where highways like the North-South Expressway experience similar traffic patterns but lack integrated wind harvesting. The proposed solution involves deploying VAWTs, which suit turbulent, low-altitude winds better than horizontal axis wind turbines (HAWTs), to capture this unused energy while addressing mechanical challenges like structural stability and safety. This study aims to analyze wind meteorology data from Malaysia, identify suitable wind turbine designs for highway applications, and propose installations along the North-South Highway. The focus is on mechanical aspects, including optimal configurations for viability and performance, to contribute to renewable energy integration in transportation infrastructure.

2. Methodology

This study systematically evaluates the potential for installing wind turbines along Malaysia's North-South Highway to capture wind energy generated by vehicle traffic. The methodology focuses on analyzing wind data, selecting suitable turbine designs, and developing mechanically viable configurations for roadside applications. The approach combines data collection, literature review, computational modeling, and site-specific assessments to ensure practical implementation.

The initial phase involved gathering wind meteorology data from the Malaysian Meteorological Department for 2019–2022, focusing on the Batu Pahat region, particularly the Pagoh to Yong Peng highway section. This data uses a color-coded scale to depict wind speeds ranging from 0.3 to 10.7 m/s, providing a clear visual representation of wind patterns across eight sectors [16]. A thorough literature review was conducted to explore wind patterns, structural considerations, and turbine applications in international highway projects, such as those in India and the United States, where vertical axis wind turbines (VAWTs) have been tested for similar purposes [7, 13].

Two VAWT designs, Darrieus and Savonius, were chosen for their suitability in capturing turbulent, low-altitude winds caused by vehicles. These designs were developed using SolidWorks software, enabling precise modeling of turbine components, including blade geometry, material selection, and structural supports [7]. Fig. 1 illustrates the Darrieus turbine in an isometric view, featuring three blades with tri-grip supports at both ends for stability, while Fig. 2 shows the Savonius turbine, equipped with rounded plates to maintain blade alignment. Both turbines incorporate a central aluminum rod and a square base secured with four M16 hex bolts to ensure structural integrity [7]. The turbines were designed to stand at 1.5 meters and positioned outside highway barriers to enhance safety and avoid traffic obstruction.
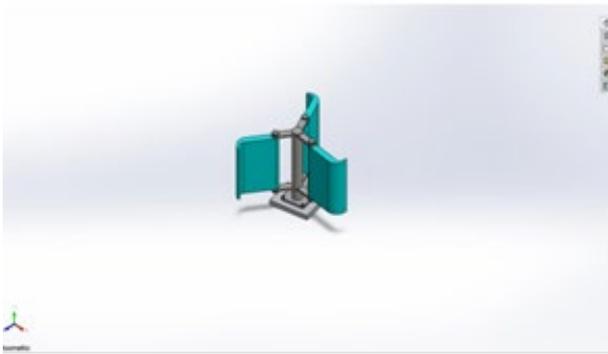
**Fig. 1** *Darrieus type wind turbine in isometric view*

Fig. 2 *Savonius type wind turbine in isometric view*

Computational fluid dynamics (CFD) simulations were performed using SolidWorks to assess turbine performance under highway conditions. The simulation setup, shown in Fig. 3 and Fig. 4, used a wind speed of 30.56 m/s (matching Malaysia's 110 km/h highway speed limit) with wind directed from the left [9]. A computational domain of 220 D × 30 D × 8 D (length × width × height) was used, with a 3% block ratio to ensure stable airflow, as supported by prior studies on vehicle wake effects [7]. The simulations evaluated blade count (three per turbine), material properties (high-grade steel alloys with corrosion-resistant coatings), airflow density, pressure, and velocity to optimize design efficiency.
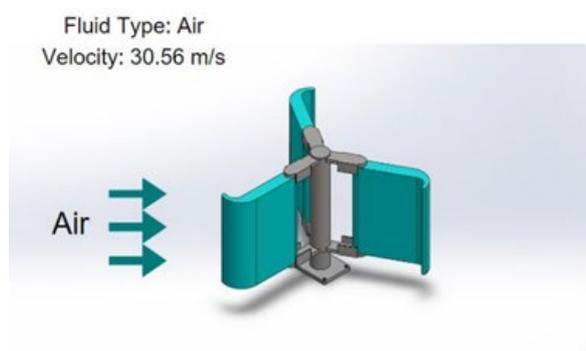
Fig. 3 *Darrieus turbine simulation data*
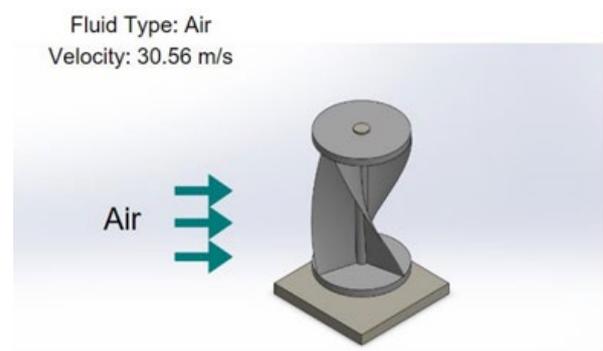
Fig. 4 *Savonius turbine simulation data*

Material selection focused on high-grade steel alloys for structural components due to their strength and resistance to wind-induced fatigue. Stainless steel spacers were chosen to resist corrosion and maintain proper spacing from roadside infrastructure, ensuring durability in Malaysia's humid climate [7]. The Pagoh to Yong Peng section was selected as the installation site for its low accident risk and accessibility for maintenance, which supports safe and efficient operation [13].

The methodology culminated in a comparison of the performance of the Darrieus and Savonius turbines with that of a previous design based on CFD results. Metrics such as average velocity, pressure, fluid density, and power capture were analyzed to determine the most effective turbine for highway energy harvesting. The results guide recommendations for VAWT deployment, emphasizing configurations that enhance safety, durability, and energy efficiency for highway energy harvesting.

3. Results and Discussion

This section presents the findings from the wind data analysis and computational fluid dynamics (CFD) simulations of the proposed wind turbines. The results compare the performance of the Darrieus and Savonius vertical axis wind turbines (VAWTs) against a previous design, focusing on key parameters such as wind flow, fluid density, pressure, velocity, power capture, and the Betz limit. These outcomes highlight the mechanical advantages and energy harvesting potential for highway installations along Malaysia's North-South Highway.

3.1 Malaysia Meteorology Wind Data

Wind speed data from the Malaysian Meteorological Department for the Batu Pahat region (2019–2022) offers vital details about local conditions suitable for turbine deployment. Fig. 5 displays the wind speed distribution using a color-coded scale: pink represents the highest speeds at 10.7 m/s, yellow indicates 8.0–10.7 m/s, light

green shows 5.5–7.9 m/s, dark green denotes 3.4–5.4 m/s, blue covers 1.6–3.3 m/s, and red signifies the lowest speeds of 0.3–1.5 m/s [16]. This visualization reveals varying wind activity, with moderate to high speeds predominant in certain sectors, supporting the feasibility of VAWTs in capturing vehicle-induced winds along the Pagoh to Yong Peng highway section.
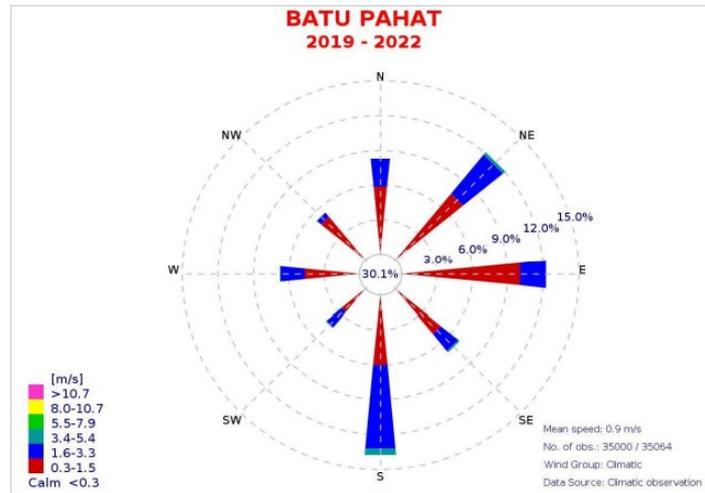

Fig. 5 *Wind speed data in Batu Pahat*
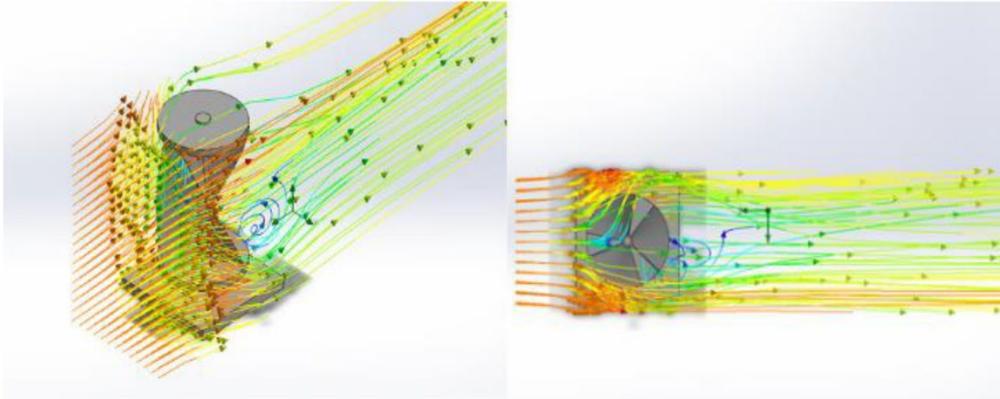
3.2 Wind Flow Analysis

The wind flow simulations provide a detailed view of airflow behavior around the turbines. Fig. 6 presents isometric and top views of wind flow for the previous turbine design, showing general distribution patterns [16]. In comparison, Fig. 7 depicts the Darrieus turbine's wind flow, revealing smoother and more efficient airflow with reduced turbulence due to its blade design. Fig. 8 illustrates the Savonius turbine's flow, which exhibits greater drag but stable rotation in variable winds [16]. These results indicate that the Darrieus design optimizes energy capture in highway settings by minimizing disruptions from vehicle wakes.
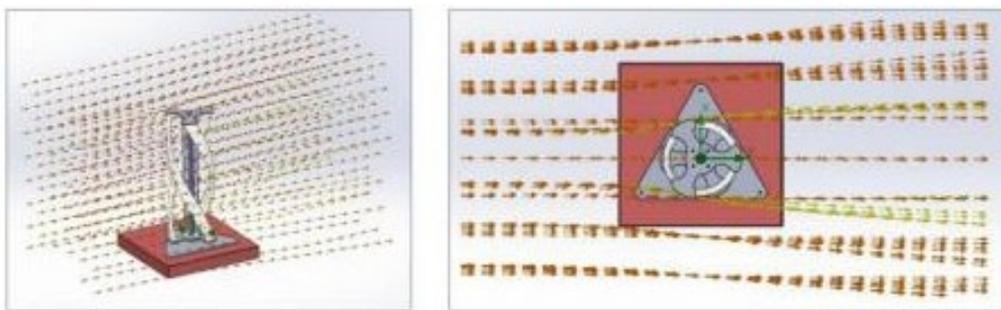
Fig. 6 *Previous turbine wind flow results in isometric and top views [16]*
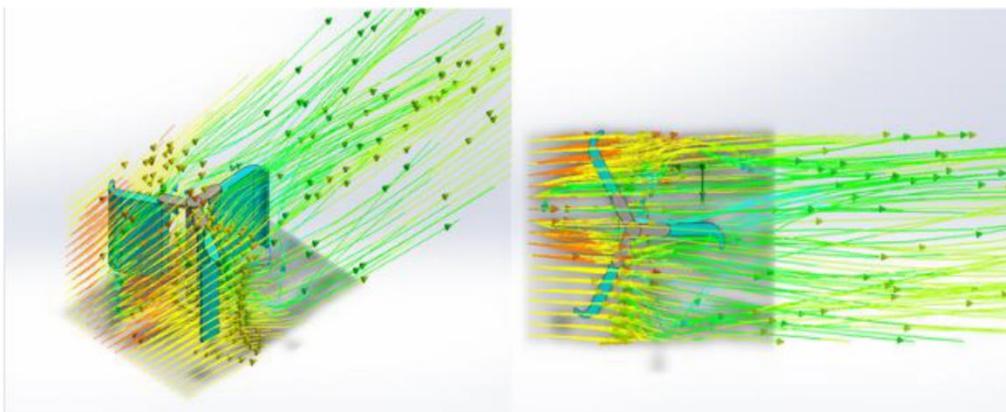

**Fig. 7** *Darrieus wind turbine wind flow results in isometric and top views*

Fig. 8 *Savonius wind turbine wind flow results in isometric and top views*

3.3 Fluid Density Analysis

Fluid density results from the CFD simulations highlight differences in airflow characteristics. Fig. 9 shows the density distribution for the previous turbine, with an average of 1.18 kg/m³ [16]. Fig. 10 presents the Darrieus turbine's density at an average of 1.20 kg/m³, while Fig. 11 displays the Savonius turbine's density, also averaging 1.20 kg/m³ [16]. The slightly higher densities for the proposed VAWTs suggest improved airflow stability, which enhances mechanical reliability and reduces wear on turbine components in humid Malaysian conditions.
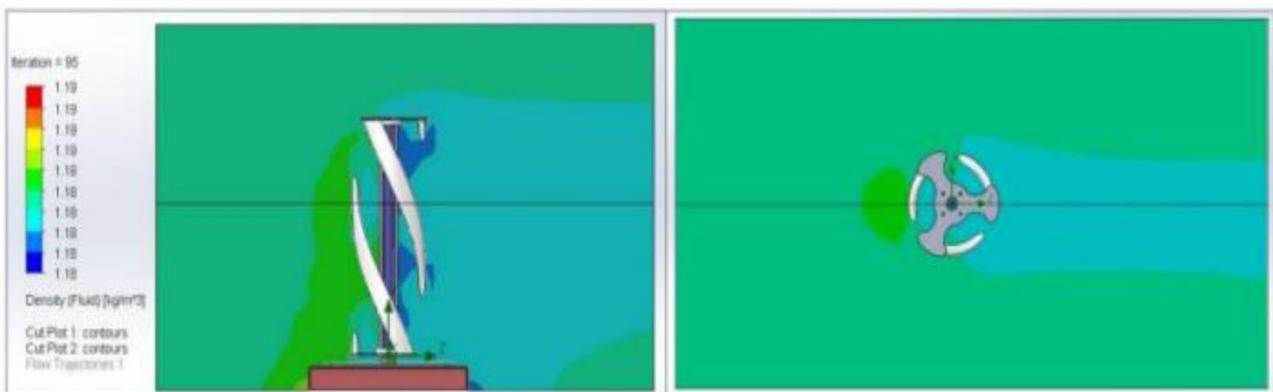
Fig. 9 *Airflow density simulation result from a previous wind turbine [16]*
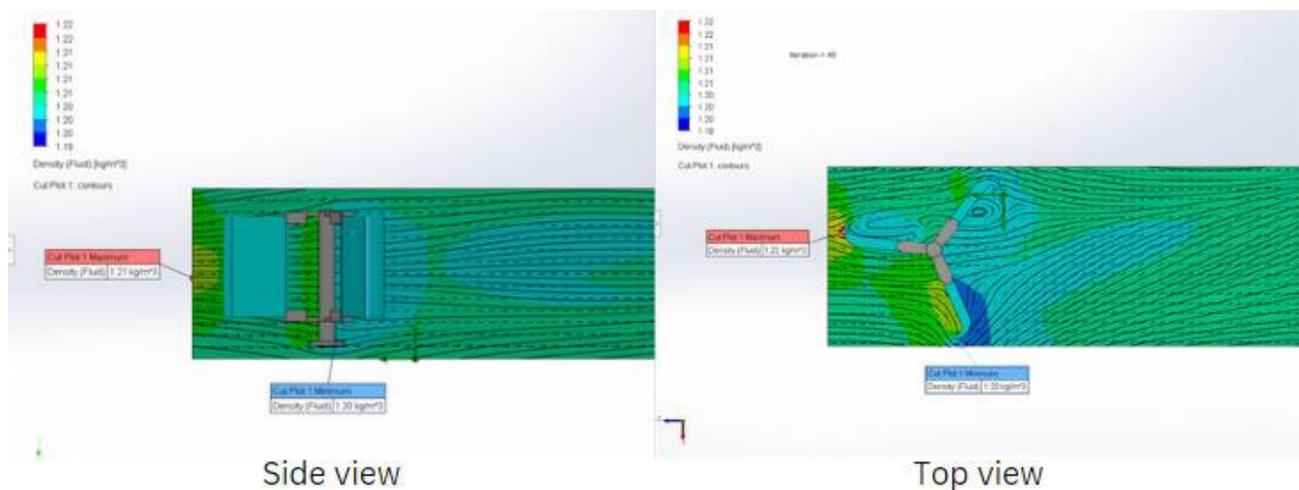
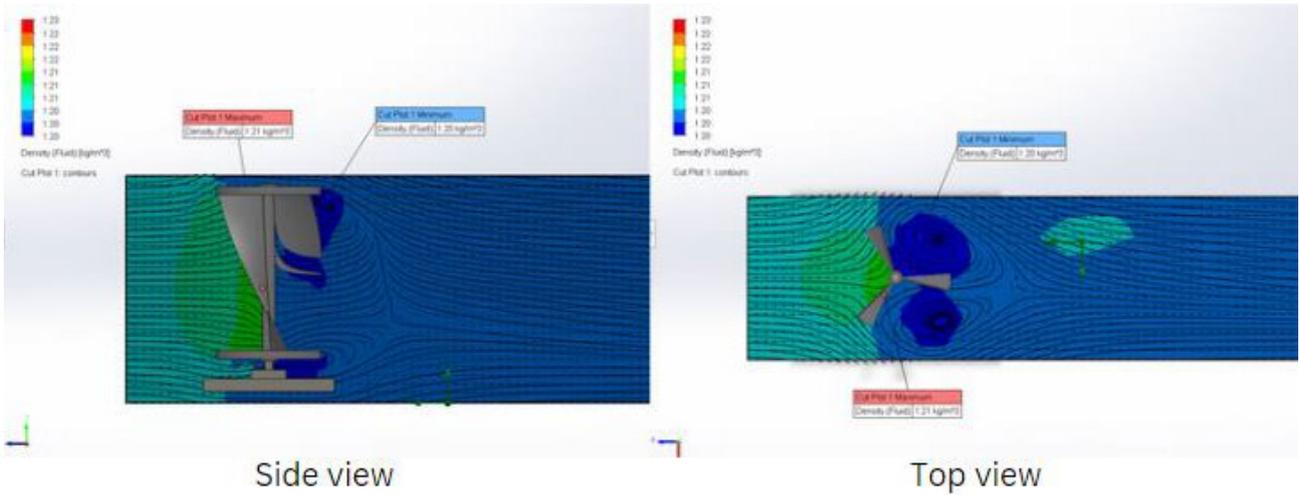**Fig. 10** *Airflow density simulation result for Darrieus wind turbine*

Fig. 11 *Airflow density simulation result for Savonius wind turbine*

3.4 Pressure Analysis

Pressure distributions offer insights into aerodynamic efficiency. Fig. 12 illustrates the pressure results for the previous turbine, with an average of 101618.76 Pa [16]. Fig. 13 shows the Darrieus turbine's pressure at 101797.48 Pa, and Fig. 14 depicts the Savonius turbine's higher average of 102157.45 Pa [16]. The higher pressure in the Savonius design suggests that it interacts more effectively with wind flow, which may result in improved torque generation; however, the Darrieus turbine maintains a balanced pressure for overall efficiency.
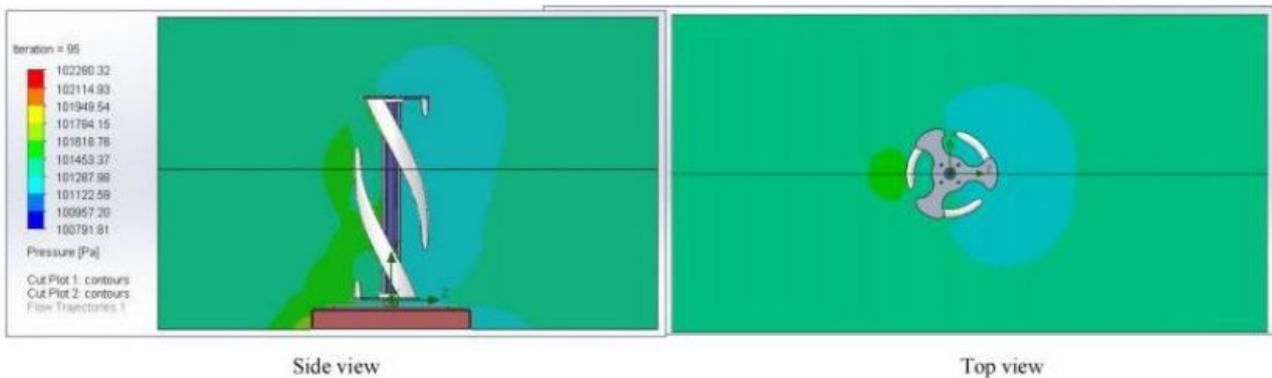

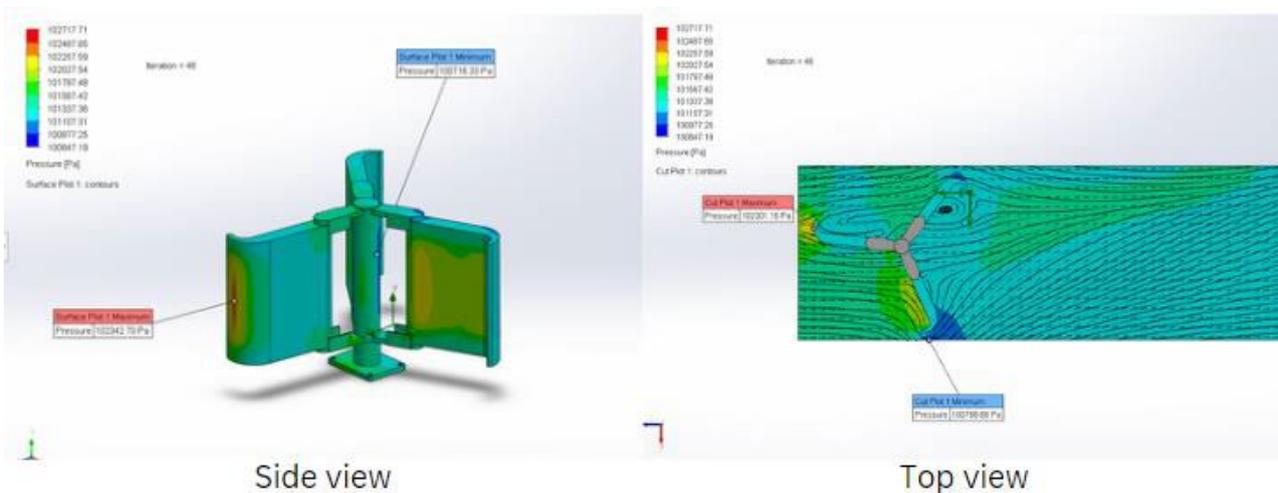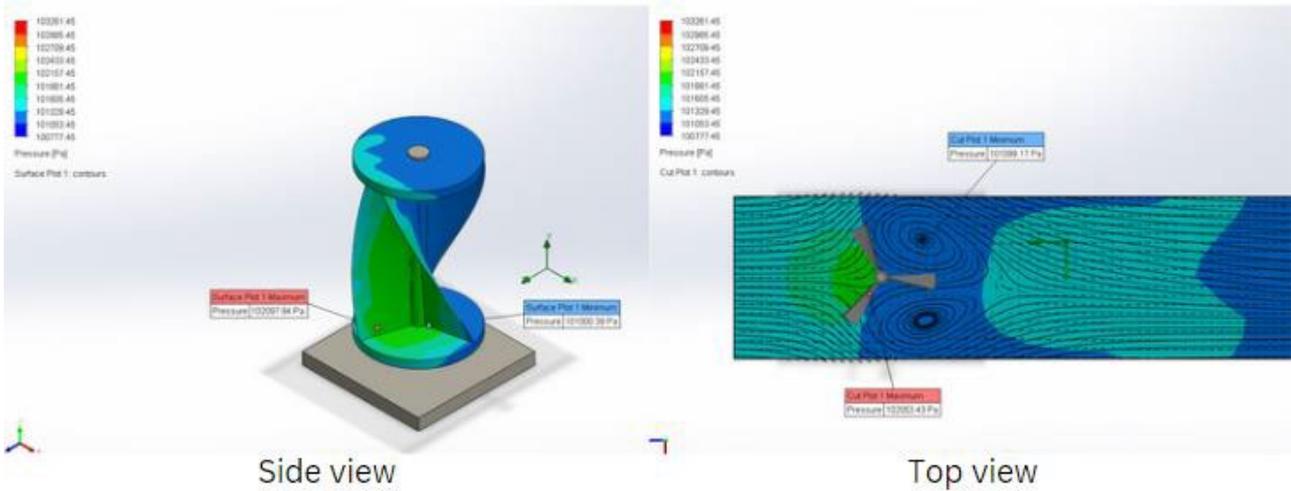**Fig. 12** *Pressure (Pa) simulation result for previous wind turbine [16]*
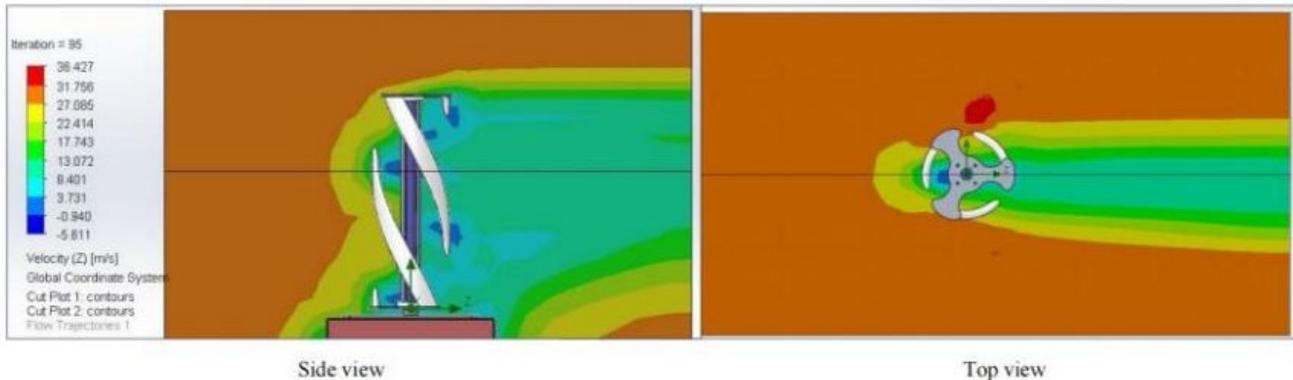

**Fig. 13** *Pressure (Pa) simulation result for Darrieus wind turbine*

Fig. 14 *Pressure (Pa) simulation result for Savonius wind turbine*

3.5 Velocity Analysis

Velocity gradients reveal how wind speeds vary around the turbines. Fig. 15 presents the velocity for the previous turbine, averaging 22.414 m/s [16]. Fig. 16 shows the Darrieus turbine's higher average velocity of 27.460 m/s, while Fig. 17 illustrates the Savonius turbine at 24.693 m/s [16]. These findings demonstrate that the Darrieus turbine accelerates airflow more effectively, improving energy conversion in low-altitude highway winds.

Fig. 15 *Velocity gradient simulation result for previous wind turbine [16]*
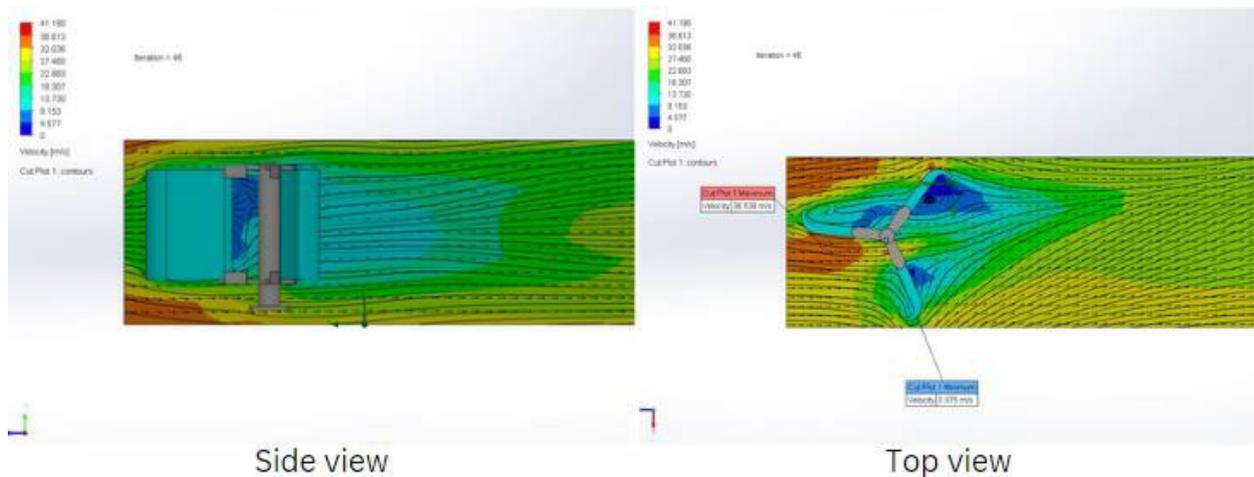
Fig. 16 *Velocity gradient simulation results for Darrieus wind turbine*
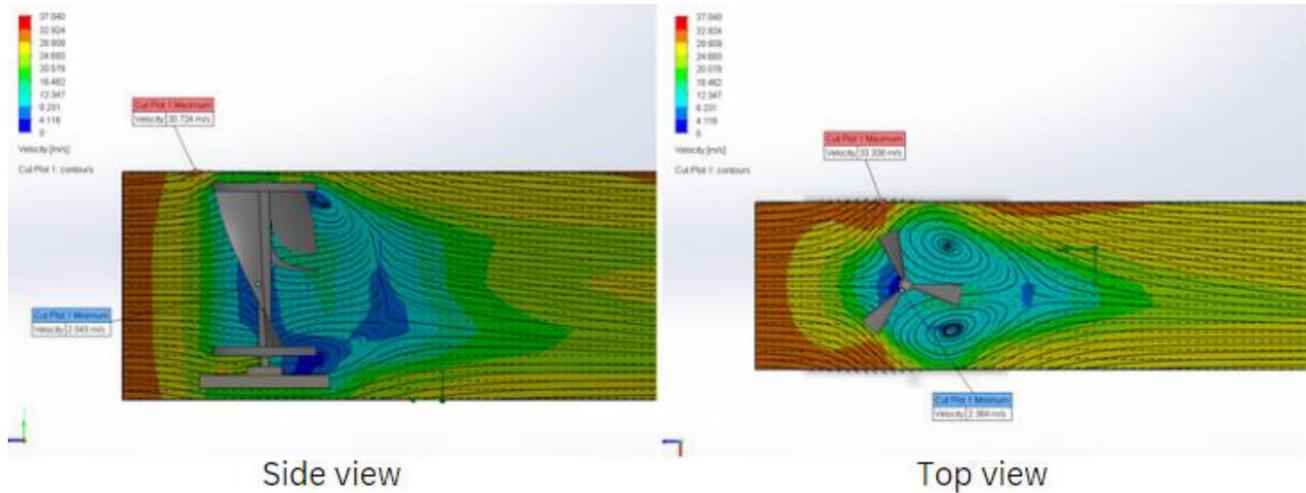
Fig. 17 *Velocity gradient simulation for Savonius wind turbine*

3.6 Power Captured

Power output was calculated using the equation for wind energy capture as follows:

$$P = \frac{1}{2}\rho A V^3 \qquad\qquad (1)$$

where V is wind velocity (m/s), P is power output (W), ρ is air density (kg/m³), and A is the rotor swept area (m²). The previous turbine and Savonius design each produced 0.791 kW, while the Darrieus turbine achieved 3.163 kW [16]. This substantial increase in the Darrieus output underscores its superior blade configuration for harnessing turbulent winds, making it more suitable for generating usable electricity along highways.

3.7 Betz Limit

The Betz limit represents the theoretical maximum efficiency for converting wind energy into mechanical power using a wind turbine. For the previous wind turbine design, the Betz limit is calculated to be 0.469 kW. Similarly, the Savonius turbine also has a Betz limit of 0.469 kW. In contrast, the Darrieus turbine demonstrates a significantly higher Betz limit of 1.875 kW. These values indicate the maximum power each turbine can theoretically capture from the wind under optimal conditions. The higher Betz limit for the Darrieus turbine suggests that it has a greater potential for energy conversion efficiency compared to the other two designs, making it a more effective option for harnessing wind energy.

3.8 Overall Results

Table 1 summarizes the performance metrics: the previous turbine operates at 22.414 m/s with 0.791 kW output (Betz limit 0.469 kW); the Darrieus at 27.460 m/s with 3.163 kW (Betz limit 1.875 kW); and the Savonius at 24.693 m/s with 0.791 kW (Betz limit 0.469 kW) [16]. These comparisons confirm the Darrieus turbine's superiority in velocity, power, and efficiency, addressing mechanical challenges like stability and safety for highway integration. The results demonstrate that VAWTs, particularly the Darrieus type, offer a viable solution for energy harvesting on Malaysia's highways, reducing reliance on fossil fuels while enhancing sustainability.

Table 1 *Overall results comparison for previous wind turbine designs, Darrieus and Savonius wind turbines*

Name	Types of wind turbine	Number of blades	Wind turbine velocity (m/s)	Power captured (kW)	Betz limit (kW)
Previous design wind turbine	VAWT	3	22.414	0.791	0.469
Darrieus wind turbine	VAWT	3	27.460	3.163	1.875
Savonius wind turbine	VAWT	3	24.693	0.791	0.469

4. Conclusion

This research examined the feasibility of deploying wind turbines along Malaysia's North-South Highway to harness untapped wind energy from vehicular traffic. The study achieved its objectives by analyzing meteorological wind data from the Malaysian Meteorological Department (2019–2022), identifying suitable vertical axis wind turbine (VAWT) designs through literature review and comparative analysis, and proposing mechanically optimized configurations using SolidWorks modeling and computational fluid dynamics (CFD) simulations. The focus was on the Pagoh to Yong Peng section, emphasizing safety, structural integrity, and performance under highway conditions equivalent to a wind speed of 30.56 m/s.

The results indicate that VAWTs are well-suited for highway applications due to their adaptability to turbulent, low-altitude winds. Among the evaluated designs, the Darrieus VAWT emerged as the most suitable, outperforming the Savonius type and a previous turbine model. Specifically, the Darrieus achieved an average velocity of 27.460 m/s, a pressure of 101797.48 Pa, a fluid density of 1.20 kg/m^3, and a power output of 3.163 kW, surpassing its Betz limit of 1.875 kW. In contrast, the Savonius and previous designs yielded lower outputs of 0.791 kW each, with Betz limits of 0.469 kW. The Darrieus's superiority stems from its enhanced aerodynamic efficiency, which enables better acceleration of airflow, reduced turbulence, and superior energy capture in variable highway wind patterns, while maintaining mechanical stability through features like tri-grip blade supports and corrosion-resistant materials.

Future work could involve developing full-scale prototypes for on-site testing, conducting long-term performance monitoring under real environmental variations, and exploring hybrid systems combining VAWTs with solar panels for enhanced energy reliability. These steps would further validate the approach and support broader adoption in sustainable transportation infrastructure.

Acknowledgement

Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm their contribution to the paper as follows: **study conception and design:** *Ahmad Danial Ezman Azhar, Nurhayati Rosly;* **data collection:** *Ahmad Danial Ezman Azhar;* **analysis and interpretation of results:** *Ahmad Danial Ezman Azhar, Nurhayati Rosly;* **draft manuscript preparation:** *Ahmad Danial Ezman Azhar, Nurhayati Rosly. All authors reviewed the results and approved the final version of the manuscript.*

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