

Research Article

Exploring Vehicle-Induced Turbulence as a Supplemental Energy Source for Sustainable Urban Infrastructure

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Abstract

The growing energy requirements of modern urban areas, particularly for public infrastructure such as street lighting and signaling systems, have intensified the need for innovative and sustainable renewable energy solutions. Among emerging concepts, vehicle-induced turbulence (VIT) has gained attention as a potential yet underexplored source of supplemental energy in densely populated urban environments. This study investigates the feasibility of harvesting VIT using vertical axis wind turbines (VAWTs) strategically integrated into roadside infrastructure to capture the airflow generated by moving vehicles. Unlike conventional power systems that rely heavily on grid electricity or fossil fuels, the proposed approach aims to provide a sustainable and cost-effective solution that reduces both operational expenses and environmental impacts. Computational Fluid Dynamics (CFD) simulations were conducted using ANSYS to analyze airflow behavior, pressure distribution, and aerodynamic characteristics around the turbine blades under various flow conditions. The turbine geometry and blade tilt angle were optimized based on the simulated wind velocity profiles derived from real-world vehicle flow patterns. Experimental validation through small-scale prototyping confirmed that optimal airflow angles, particularly around 120°, produce sufficient mechanical torque to rotate the turbine effectively. Results demonstrate that integrating small VAWTs into urban infrastructure, such as lighting poles, highway dividers, and sound barriers, can significantly enhance local energy recovery while improving the reliability of off-grid lighting systems. Overall, this research highlights the promising potential of VIT-based microgeneration systems to complement existing renewable energy sources, contributing to the realization of cleaner, smarter, and more resilient urban energy networks.

Keywords

Vehicle-Induced Turbulence (VIT), Vertical Axis Wind Turbine (VAWT), Computational Fluid Dynamics (CFD), Sustainable Urban Infrastructure, Renewable Energy Harvesting

1. Introduction

Renewable energy has become an essential component in addressing rising global energy demands and reducing reliance on fossil fuels. Among the available alternatives, solar and wind energy are widely recognized for their scalability

and sustainability [1, 2]. In the Malaysian context, street lighting systems consume a significant portion of municipal electricity expenditure, and innovative solutions are required to reduce their operational costs [3]. One promising yet un-

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Received: 23 October 2025; **Accepted:** 12 November 2025; **Published:** 11 December 2025



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derutilized resource is the airflow disturbance generated by moving vehicles, commonly referred to as vehicle-induced turbulence (VIT) [4, 5]. Capturing this turbulent airflow represents a novel opportunity to supplement power generation for street lighting while simultaneously contributing to emission reduction efforts [6, 7]. To maximize energy harvesting potential, careful consideration of the airflow incidence angle is necessary, as it directly influences aerodynamic performance and conversion efficiency [8-10].

The selection of an appropriate wind turbine is another critical factor when exploiting turbulent and low-speed wind resources. Vertical axis wind turbines (VAWTs) have distinct advantages over horizontal axis wind turbines (HAWTs) in environments with fluctuating wind speed and irregular flow directions, making them more suitable for VIT conditions [11-13]. Among VAWT configurations, the Savonius and Darrieus designs are often considered due to their simplicity and adaptability [14, 15]. In this study, both turbine types were modeled using Fusion 360 software, with blade geometries adjusted according to the recorded VIT patterns. Computational simulations were then conducted in ANSYS to evaluate airflow behavior and turbine performance.

To complement the numerical analysis, scaled-down prototypes of the turbines were fabricated using 3D printing technology and coupled with a 5 V DC generator for performance testing. Key output parameters, including rotor speed and voltage, were measured using a tachometer and multimeter. Although the setup did not employ a complete Data Acquisition (DAQ) system, it offered a practical means of validating performance trends under controlled conditions. Future work will incorporate advanced DAQ systems to capture more comprehensive datasets for continuous monitoring.

The overarching objective of this research is to evaluate the feasibility of harnessing VIT as a supplemental renewable energy source for urban applications. By comparing the performance of different VAWT designs under turbulence-driven airflow, this study seeks to identify the most effective configuration for integration into sustainable street lighting infrastructure.

2. Experimental Methods

2.1. VIT Data Collection

The field measurements were carried out along Jalan Gambang, near Kampung Seri Fajar in Gambang, Pahang. Data were collected over four consecutive days during peak traffic periods, specifically between 5:00 p.m. and 6:00 p.m., when vehicle density was highest. As illustrated in Figure 1 and Figure 2, an anemometer was mounted on a wooden support at a height of 1.2 m from the ground and positioned 0.5 m from the road shoulder. This arrangement was adapted from a previous undergraduate project conducted at the same institution, which investigated airflow patterns induced by passing vehicles at heights appropriate for small-scale verti-

cal axis wind turbine deployment. While there is no standardized international guideline for anemometer placement in this specific application, the adopted configuration provides practical insight into airflow conditions experienced by road-side infrastructure.

The objective of this stage was to determine the optimal measurement location in terms of height and lateral distance from the road where vehicle-induced turbulence reaches its maximum velocity. Following this, an additional experiment was performed to identify the most effective flow incidence angle. For this purpose, five anemometer setups were installed simultaneously, each oriented at a different angle relative to the oncoming vehicle trajectory: 90°, 100°, 110°, 120°, and 130°. The orientation angles were measured from the roadside toward the vehicle direction, as depicted in Figure 1. Wind velocity readings were recorded concurrently from all instruments using smartphone-based data logging applications for subsequent analysis and interpretation.

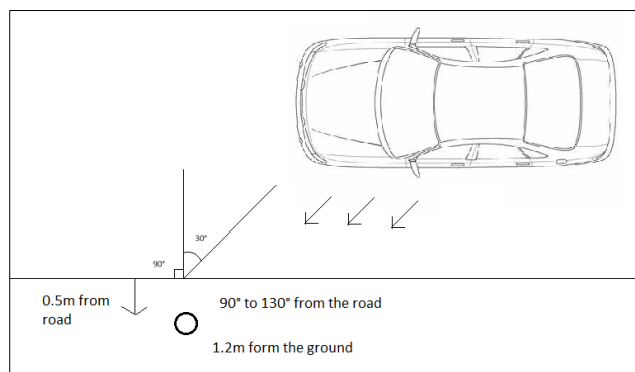


Figure 1. The setup for VIT data collection.



Figure 2. The setup for the anemometer.

2.2. Design of the VAWTs

After completing the vehicle-induced turbulence (VIT) measurements, the angle associated with the highest average wind speed was adopted as the reference for turbine blade

design. Two vertical axis wind turbine (VAWT) configurations were selected for this study: the Savonius-type and the Darrieus-type. These turbines were chosen due to their proven effectiveness in environments with low wind velocity and fluctuating directions, which closely resemble the characteristics of VIT airflow.

The Savonius turbine is well known for its simple structure, ease of construction, and strong self-starting capability at low wind speeds [16, 17]. This makes it particularly effective in conditions where turbulence dominates, and continuous startup is necessary. On the other hand, the Darrieus turbine, although requiring higher wind speeds to self-start, provides superior aerodynamic efficiency and higher energy conversion rates once in operation [18, 19]. By comparing these two designs, the study aims to balance the trade-offs between startup performance and overall efficiency in VIT-driven applications.

The blade profiles were developed in Fusion 360 software, with their orientations adjusted based on the measured VIT incidence angle. To maintain consistency in performance evaluation, both turbine types were designed with identical dimensions: a radius of 200 mm and a height of 250 mm. Figure 3 and Figure 4 depict the 3D models of the Savonius-type and Darrieus-type turbines, respectively. These standardized models provided the foundation for subsequent computational fluid dynamics (CFD) simulations and experimental testing.

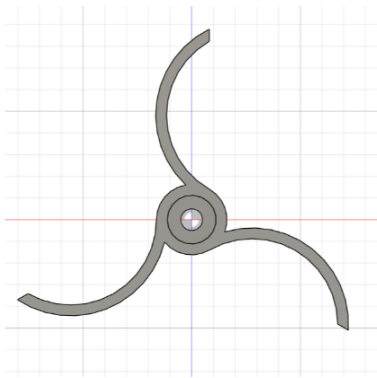


Figure 3. The blade design of Savonius-type wind turbine.

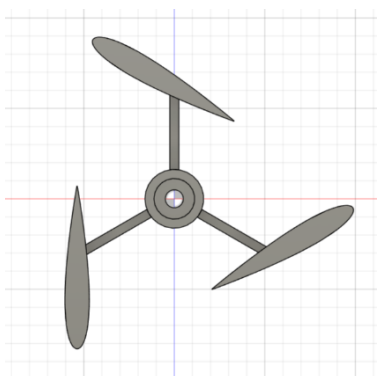


Figure 4. The blade design of Darrieus-type wind turbine.

2.3. Simulation using ANSYS Software

Computational analysis of the turbine models was performed using ANSYS Fluent to investigate the aerodynamic interaction between vehicle-induced airflow and turbine blades. The simulation environment was constructed to replicate the turbulent flow characteristics observed in the experimental data. As shown in Figure 5 the computational domain was designed to include inlet, outlet, and wall boundaries, ensuring realistic representation of flow development around the rotor.

The governing flow behavior was modeled using the Navier-Stokes equations for incompressible flow:

$$\nabla \cdot \mathbf{u} = 0 \quad (1)$$

$$\rho \left(\frac{\delta \mathbf{u}}{\delta t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = -\nabla p + \mu \nabla^2 \mathbf{u} \quad (2)$$

where $\mathbf{u}$ is the velocity vector, ρ is the fluid density, p is pressure, and μ is the dynamic viscosity.

A turbulence model (realizable $k-\epsilon$) was adopted due to its robustness in predicting recirculating flows and turbulent wakes generated by the rotor. Boundary conditions were defined such that the inlet velocity corresponded to the measured vehicle-induced turbulence (VIT) magnitudes, while the outlet was set to atmospheric pressure. The turbulence intensity and angle of incidence were adjusted based on field measurements. A structured mesh was applied near the turbine blades to capture boundary layer effects, while a coarser mesh was used in the far-field region to reduce computational cost.

To assess turbine performance, the coefficient of performance (C_p) and torque coefficient (C_t) were evaluated:

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

$$C_t = \frac{T}{\frac{1}{2} \rho A R V^2} \quad (4)$$

where P is the extracted power, T is the torque generated by the turbine, A is the swept area, R is the turbine radius, and V is the free-stream velocity. These parameters provide standardized metrics for comparing the aerodynamic efficiency of the Savonius and Darrieus configurations.

Simulation outputs included velocity contours, pressure fields, and streamlines, which were analyzed to evaluate drag forces, torque generation, and wake formation. The comparative analysis revealed the aerodynamic strengths and limitations of each turbine type under turbulence-driven airflow, offering design insights for their potential deployment in VIT-based energy harvesting applications.

A	
1	Fluid Flow (Fluent)
2	Geometry ✓
3	Mesh ✓
4	Setup ✓
5	Solution ✓
6	Results ✓

Fluid Flow (Fluent)

Figure 5. The setup for the ANSYS (fluid flow).

2.4. Hardware Development

Following the completion of the 3D models, the Savonius and Darrieus turbine designs were fabricated using an Ender 3 V2 3D printer (Figure 6). The printing process utilized Fabbx-ible 1.75 mm PLA filament, chosen for its durability, ease of processing, and lightweight properties, which are suitable for prototype-scale experimentation. Each full turbine assembly required approximately 40 hours of continuous printing, ensuring dimensional accuracy and smooth surface finish for aerodynamic testing.

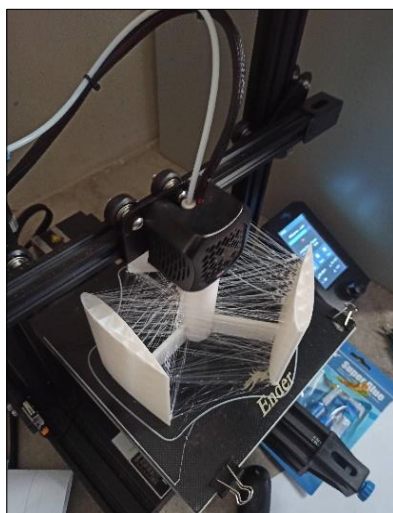


Figure 6. The 3D printing of the wind turbine.

Once the printing process was completed, the individual components were carefully post-processed and assembled into complete turbine structures. The rotor shafts were then directly coupled to a small-scale DC generator, enabling the conversion of mechanical rotation into electrical output. This transition marked the progression from computational and theoretical analyses toward the physical validation of turbine performance under experimental conditions.

The fully assembled prototypes are presented in Figure 7 and Figure 8, corresponding to the Savonius-type and Dar-

rieus-type turbines, respectively. These prototypes served as the basis for subsequent laboratory testing, where their operational characteristics including rotational speed, voltage output, and overall stability were evaluated under simulated VIT air-flow conditions.



Figure 7. The prototype of Darrieus-type wind turbine.



Figure 8. The prototype of Savonius-type wind turbine.

2.5. Prototype Data Collection Setup

Upon completion of the turbine assembly, an experimental setup was established to measure the rotational speed (RPM) and electrical output voltage of the prototypes, as illustrated in Figure 9. For safety considerations and to minimize external disturbances that could arise in roadside testing, the ex-

periments were conducted under controlled laboratory conditions. A hairdryer was employed as the wind source, providing two distinct operating levels (denoted as Power 1 and Power 2) to replicate variable airflow conditions.



Figure 9. The setup for the data collection of the prototype.

During testing, a tachometer was positioned above the rotor to record the turbine's rotational speed, offering direct insight into its dynamic response under airflow excitation. Simultaneously, a multimeter was connected to the DC generator to capture the corresponding voltage output. This dual measurement approach allowed for a comprehensive evaluation of both mechanical and electrical performance.

To further examine the influence of incident flow angle, the hairdryer's position relative to the turbine was systematically adjusted within the range of 90° to 130°. Data were recorded for each angle and airflow condition, enabling performance comparisons between the Savonius and Darrieus prototypes. The resulting dataset provided valuable experimental validation of the turbine designs, supporting their potential suitability for vehicle-induced turbulence (VIT) energy harvesting applications.

3. Results and Discussion

The result for this project can be classified into three parts which are the VIT pattern, the software result, and the hardware result.

3.1. The VIT Pattern

Figure 10 presents the daily average wind speed values recorded at different incidence angles. The results indicate that the orientation at 120° consistently produced the highest mean wind velocity, reaching 9.17 km/h, which is noticeably higher than the other tested angles. This finding highlights the sensitivity of vehicle-induced turbulence (VIT) to the direction of measurement and confirms the

importance of proper angular positioning when designing energy harvesting devices.

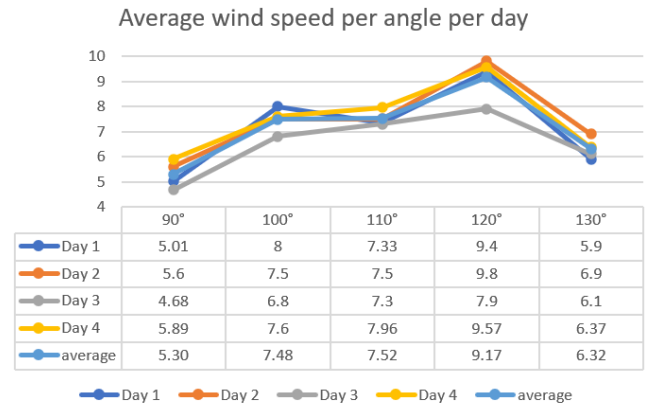


Figure 10. The average wind speed per angle per day graph.

The 120° orientation is particularly significant because it aligns with the angle at which airflow deflection from passing vehicles produces the most concentrated turbulent stream toward the roadside. This observation provides a practical benchmark for determining the angle of incidence (AOI) to be used in subsequent turbine designs. The AOI can be derived mathematically using the weighted average of wind speeds at different angles, expressed as:

$$AOI = \frac{\sum_{i=1}^n (\theta_i \cdot V_i)}{\sum_{i=1}^n V_i} \quad (5)$$

where θ_i represents the tested incidence angle and V_i is the corresponding average wind velocity.

By applying this formulation, the optimal AOI for turbine placement was validated at approximately 120°, ensuring that the blade orientation in the simulation and prototype design reflects the most favorable wind flow conditions. This result serves as a crucial foundation for the subsequent aerodynamic evaluation and performance testing of the Savonius and Darrieus VAWTs under simulated VIT conditions.

3.2. Software Results

3.2.1. 3D Result

Building upon the VIT measurements, the determination of the angle of incidence (AOI) served as a crucial step in translating airflow characteristics into practical turbine design parameters. The analysis identified 120° as the angle producing the maximum average wind speed of 9.17 km/h. Applying the AOI relation ensured that this dominant wind direction was effectively aligned with the turbine blades. Consequently, the blade tilt was optimized at 30°, providing the necessary alignment between wind inflow and blade ori-

entation to maximize aerodynamic efficiency.

Figure 11 and Figure 12 illustrate the resulting wind turbine designs with the incorporated blade tilt. These representations highlight how empirical field data (VIT measurements) were systematically integrated into the turbine design process. Such a data-driven approach demonstrates how the adaptation of blade geometry, particularly angle modification, enhances the aerodynamic performance and enables the turbines to exploit localized wind phenomena effectively.

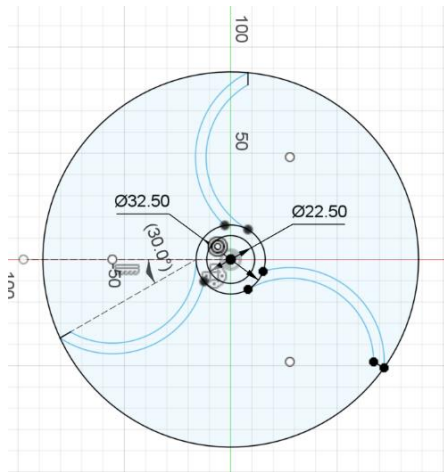


Figure 11. The final drawing of Savonius-type wind turbine.

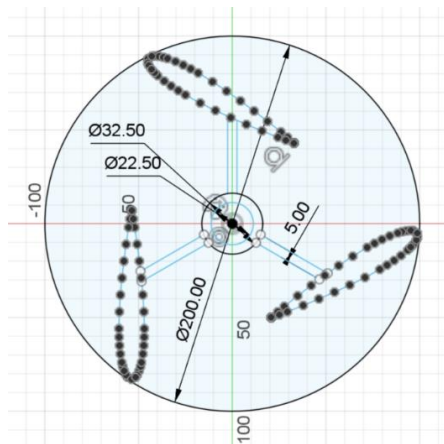
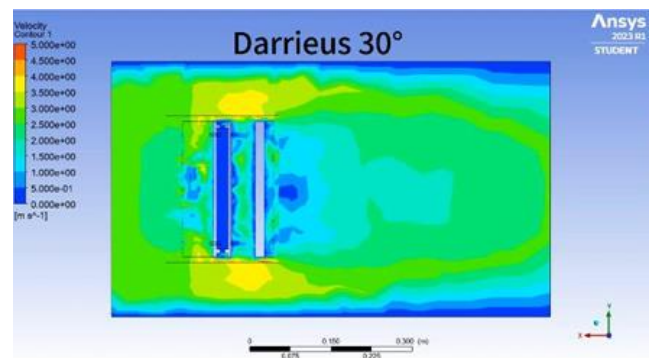
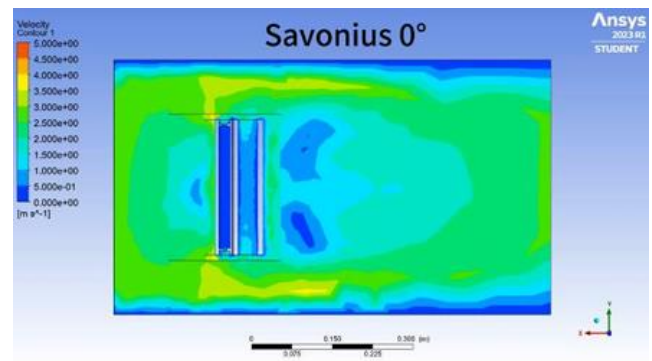
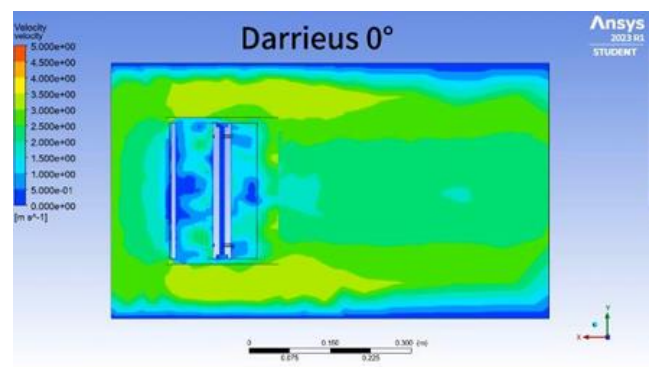


Figure 12. The final drawing of Darrieus-type wind turbine.

3.2.2. ANSYS Result

As illustrated in Figure 13, the CFD simulation highlights distinct airflow behaviors between the two turbine designs. The Savonius-type turbine exhibits a broader region of lime green, representing airflow deceleration and accumulation behind the rotor. This pattern indicates that the airflow tends to pass through the blades, subsequently forming a wake zone where air is concentrated. Such visualization provides valuable insight into the post-turbine flow characteristics, which are directly linked to the aerodynamic interaction between wind and blade surfaces.

In terms of operational performance, the Savonius-type turbine demonstrates a higher rotational speed compared to the Darrieus-type turbine under identical test conditions. This outcome suggests that the Savonius configuration is more effective in capturing the kinetic energy from vehicle-induced turbulence and converting it into mechanical rotation. The superior rotational response highlights the influence of blade geometry and flow interaction on energy conversion efficiency. Conversely, while the Darrieus-type turbine is typically designed for higher wind speeds and smoother flow conditions, its relatively lower performance in this setup emphasizes the suitability of the Savonius-type turbine for low-speed, turbulent environments such as road-side VIT applications.



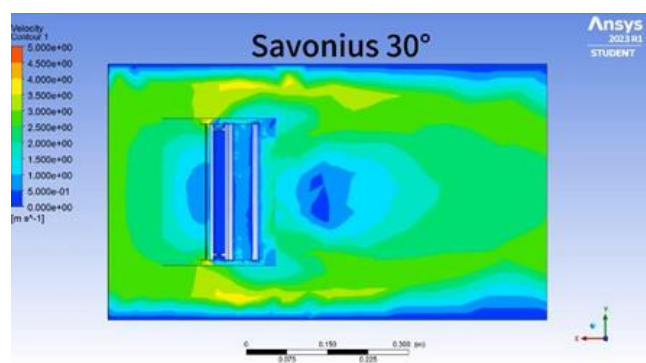


Figure 13. The ANSYS simulation results.

3.3. The Hardware Results: RPM and Voltage of the Wind Turbines

As shown in Figure 7 and Figure 8, the fabricated prototypes of the Savonius-type and Darrieus-type VAWTs were mounted on an 8 mm diameter shaft, directly coupled to a 5V DC generator for performance testing. The comparative results of both turbine designs are summarized in Table 1.

The experimental data reveal that the Savonius-type turbine achieved a maximum rotational speed of 470 RPM, producing an output voltage of 0.27 V. In contrast, the Darrieus-type turbine recorded a peak speed of 410 RPM with a corresponding voltage of 0.24 V. These findings confirm the earlier CFD analysis, where the Savonius-type design exhibited superior aerodynamic interaction with low-speed, turbulent airflow.

Although the measured voltage levels are relatively low due to the small prototype scale and laboratory conditions, the results provide important insights into scalability. When adapted to larger, commercial-scale dimensions, with optimized materials and structural reinforcements, the Savonius-type configuration has the potential to deliver higher power output while maintaining efficiency under vehicle-induced turbulence (VIT) conditions. This highlights the suitability of the Savonius turbine for integration into urban energy-harvesting applications, such as powering roadside lighting or sensors.

Table 1. The results of RPM and voltage for both VAWTs.

Darrieus-Type				
Power 1			Power 2	
Angle	RPM	Voltage (V)	RPM	Voltage (V)
90°	48.00	0.03	61.50	0.04
100°	136.00	0.08	163.50	0.09
110°	243.00	0.14	280.00	0.16
120°	372.00	0.21	410.00	0.24

Darrieus-Type				
Power 1			Power 2	
130°	230.00	0.13	270.00	0.16

Savonius-Type				
Power 1			Power 2	
Angle	RPM	Voltage (V)	RPM	Voltage (V)
90°	136.00	0.08	342.00	0.20
100°	178.00	0.10	359.00	0.21
110°	220.00	0.13	470.00	0.27
120°	362.00	0.21	414.00	0.24
130°	217.00	0.13	343.00	0.20

4. Conclusions

The performance of Savonius-type and Darrieus-type VAWTs under vehicle-induced turbulence (VIT) was comprehensively evaluated through CFD simulations using ANSYS and validated with laboratory-scale prototypes. The simulation results provided critical insights into airflow interaction and turbine efficiency, while the prototype testing confirmed that the Savonius-type turbine exhibits superior rotational speed and voltage generation under turbulent, low-speed wind conditions.

This combined methodology integrating numerical modeling and experimental validation demonstrates the feasibility of harnessing VIT as a supplementary renewable energy source. The outcomes highlight the potential of small-scale wind turbines to support urban energy demands, particularly for powering streetlights and roadside infrastructure, thereby reducing dependence on conventional grid electricity and contributing to sustainable city development.

Looking forward, further research will focus on scaling up turbine designs and improving structural integration with urban infrastructure such as lighting poles and highway medians. Testing under diverse traffic flows and environmental conditions will also be essential to refine efficiency and reliability. Moreover, hybrid approaches that combine vehicle-induced wind energy with solar PV systems are expected to enhance system robustness, offering a more comprehensive pathway toward smart and sustainable urban energy solutions.

Abbreviations

VIT	Vehicle-Induced Turbulance
VAWTs	Vertical Axis Wind Turbines
HAWTs	Horizontal Axis Wind Turbines

CFD Computational fluid dynamics
DAQ Data Acquisition

Acknowledgments

The author would like to thank the Faculty of Electrical & Electronics Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA), for providing the necessary facilities and continuous support in conducting this research.

Author Contributions

Muhamad Zahim Sujod is the sole author. The author read and approved the final manuscript.

Funding

This work is not supported by any external funding.

Data Availability Statement

The data is available from the corresponding author upon reasonable request.

Conflicts of Interest

The author declares no conflicts of interest.

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