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RESEARCH PAPER

Roof fans electricity-generating vehicle: energy harvesting from vehicle-induced wind

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Abstract

Integrating rooftop turbines into vehicles to harvest energy from the aerodynamic interference created by driving is an innovative way to provide an alternative source of electricity. However, while theoretical predictions of output could exceed 3.3 kW at high speeds of approximately 120 km/h, empirical and computational test results consistently show outputs of only several hundred watts to tens of watts under similar driving conditions. Limitations in efficiency and effective use of compact-size turbines (VAWTs and small HAWTs) must be considered when evaluating turbine performance; in addition, further inefficiencies exist in the energy conversion process. The efficiency of energy harvesting is directly related to the aerodynamic drag increase caused by each roof-mounted turbine system. Computational fluid dynamics modeling indicates a total drag increase of up to 0.4% for vehicles with rooftop turbines; however, only 6.5% of that energy loss can be recovered via turbine output. In actual driving environments (urban and highway), the net energy gain achieved by roof-mounted turbine systems is likely very low. It may be negative when accounting for parasitic losses, system inefficiencies, and the incremental weight of the turbine systems.

1. Introduction

The transportation industry's growing need for sustainable energy sources has spurred research into alternative and/or supplemental energy generation methods. The idea of capturing energy from wind created by moving vehicles, via turbines mounted on vehicle roofs, is a new concept that has emerged as a viable method of creating usable electrical energy from the relative wind produced by a moving vehicle (i.e., the "relative wind") to enhance overall energy efficiency, particularly for electric vehicles (EVs) [1]. While the idea seems reasonable conceptually, the practical feasibility of this approach is still under study for several reasons, including aerodynamic, mechanical, and efficiency-related issues.

Early theoretical studies in the late 20th century examined vehicles with small wind turbines mounted on their roofs and in their front grilles. These studies examined heavier commercial vehicles and indicated that the shipping industry could have greater energy recovery potential due to their flat surfaces. These studies estimated (according to early analytical calculations) that at highway speeds, there would be a potential recovery capability of approximately 2–4% of the vehicle's energy [2]. However, all these studies had limitations due to simplistic aerodynamic assumptions. They did not account for aerodynamic drag penalties that the turbines would create, nor the complex turbulent flow that would occur behind the vehicles.

With advancements in computational fluid dynamics (CFD) tools becoming available at the beginning of the 21st century, more accurate analyses were performed to model airflow over vehicles. Subsequent studies have shown that the airflow over vehicle roofs is complex and characterized by turbulent boundary layers, flow separation, and velocity gradients. It was found that the effective wind speed available for turbine

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extraction at roof level is generally about 60–80% of the free-stream vehicle speed, significantly limiting the energy-extraction capability of rooftop turbines. These results further emphasize the importance of body placement and airflow optimization in vehicle design [3].

Recent developments, particularly associated with the electric vehicle revolution, have created new interest in developing prototype systems and are testing their performance under real-world driving conditions. Research has indicated measurable electrical output from turbine systems, typically in the range of tens of watts to a few hundred watts. Although several advanced configurations (e.g., diffuser-augmented horizontal-axis wind turbines (HAWTs) and hybrid vertical-axis wind turbines (VAWTs)) have been developed and tested, the efficiency of these turbines will ultimately be limited by turbulence, low power coefficients, and mechanical losses [4]. From an energy conversion standpoint, the efficiency of the generators used in these systems will be critical. A relatively new style of generator called a permanent magnet synchronous generator (PMSG), particularly those designed using the axial flux design concept, has been recognized for its high efficiency, compact design, and low mechanical torque losses. As with other types of generators, PMSGs generate electrical energy by converting mechanical rotational energy into electrical energy through electromagnetic induction, then conditioning it for storage in the vehicle battery system via a power electronics interface [5, 6].

Aerodynamics will be one of many critically important factors affecting vehicle system performance. A turbine mounted on a vehicle's roof will alter the airflow over the vehicle and typically increase its aerodynamic drag, reducing vehicle performance. While various design strategies (e.g., optimized shapes using ducts, shrouds, or deflectors) can concentrate the airflow to the turbine and partially reduce the vehicle's augmenting drag penalty, studies indicate that the efficiency of using this method will only be a small fraction of the total amount of energy that the vehicle would lose from the aerodynamic drag that the turbine creates. Additionally, the wake created by the vehicle's flow will negatively impact the vehicle's overall aerodynamic stability [7-9].

Many different horizontal- and vertical-axis turbine configurations have been proposed over the last three decades to overcome previously known limitations. Turbines with horizontal-axis configurations are theorized to provide higher turbine efficiency but are greatly influenced by turbulent airflow and direction. On the other hand, vertical-axis turbines (e.g., Savonius and Darrieus turbines) provide greater adaptability to multidirectional airflow but typically exhibit less thermal efficiency than horizontal-axis turbines. Hybrid and helical turbine configurations have been proposed to balance start-up capability, efficiency, and operational stability. Although extensive research has produced many turbine designs, the use of roof-mounted wind energy systems for automobiles remains negligible today due to practical issues such as added weight, noise, safety, cost, and limited increases in net energy return. While these systems have been deployed in niche applications (e.g., recreational vehicles and static charging systems), their high-rate adoption in mainstream automotive design has yet to occur [10, 11].

In conclusion, energy harvesting from vehicle-induced wind is an exciting, challenging area of ongoing exploration. Although advancements in turbine aerodynamics, design, and energy conversion systems have improved system efficiency, many manufacturing constraints remain associated with the use of small wind turbines mounted on vehicles [12]. Current research efforts should continue to optimize the aerodynamic integration of turbines into vehicles, improve turbine energy conversion efficiency, and conduct reliable experimental tests to demonstrate the potential of roof-mounted wind energy systems to generate electricity from moving vehicles.

2. Turbine Designs and Comparisons

The selection of an appropriate turbine configuration is critical to determining the feasibility and efficiency of energy harvesting from vehicle-induced airflow. Various turbine designs have been investigated, each offering distinct advantages and limitations in terms of aerodynamic performance, power output, structural complexity, and adaptability to turbulent flow conditions.

2.1 Turbine Design Categories

2.1.1 Horizontal Axis Wind Turbines (HAWTs)

The best theoretical performance of HAWTs occurs when the rotor is in a ducted (or diffused) configuration, due to the large swept area and higher power coefficient (approximating the Betz limit). Theoretical work has shown that the possible power output available from HAWTs at high vehicle speeds can reach the kilowatt range. Unfortunately, the physical implementation of HAWTs on vehicles has some limitations due to factors such as wind-direction sensitivity, high rotor speeds, significant aerodynamic noise, and the need for duct- or shroud-type structures to condition the flow for effective operation in the extremely turbulent rooftop environment 13, 14].

Open or non-ducted HAWTs are mechanically easier to integrate but offer significantly lower aerodynamic efficiency due to flow concentration in their configuration. As a result, although they are mechanically easier to integrate, open HAWT systems typically offer moderate power outputs under controlled conditions. However, the presence of significant additional drag and noise limits their practical application in the real World.

2.1.2 Vertical Axis Wind Turbines (VAWTs)

VAWTs offer a more adaptable solution for vehicular applications due to their omnidirectional operation and improved performance in turbulent, multidirectional airflow.

- Drag-type Savonius VAWTs tend to be easy to self-start, make little noise, and have a simple structure. However, they have low power coefficients (~0.2), which means they generate very little power at all speeds, but especially at moderate/high speeds.
- Lift-type Darrieus VAWTs tend to produce more power

than Savonius-type VAWTs due to higher power coefficients (up to 0.3-0.4) and improved performance as vehicle speeds increase. They require higher tip speed ratios and usually need auxiliary starting methods or gearing systems, and they generate moderate-to-high noise levels and mechanical stresses.

- More complex versions of the basic VAWT layout, such as helical and hybrid combinations of Savonius and Darrieus styles, have been developed to combine the self-starting ability of drag-type turbines with the higher efficiencies of lift-type turbines. However, the majority of these designs are much more complex, heavier than their traditional counterparts, and produced by more complex methods. At present, these designs are mostly used in experimental applications for automotive vertical-axis wind turbines.

2.2 Performance Trade-offs

The choice of the proper turbine configuration for alternative vehicle-based energy harvesting systems always results from the interplay between efficiency, reliability, and feasibility of use. Horizontal-axis wind turbines (HAWTs) are gaining recognition for their aerodynamic efficiency and ability to generate higher power output at higher vehicle speeds than other alternatives [15]. This is due mainly to the relatively large effective swept area of HAWT and their ability to achieve significantly higher coefficients of power under ideal flow conditions. However, for vehicle-based applications, the advantage of HAWTs in generating power is greatly constrained by the way the wind flows over a moving vehicle. The turbulent, disruptively separated, and rapidly changing wind flow conditions experienced on vehicle rooftops provide HAWTs with an operating environment in which they produce power at less-than-optimal levels. The inability of HAWTs to operate on aligned, unidirectional wind flow means that optimizing turbine orientation or providing devices to guide wind flow through the turbine will further complicate overall turbine design. Also, operating at high rotational speeds necessary for effective energy production increases overall noise and vibration, thereby increasing stress on both the user and the longevity of the energy harvesting system.

VAWT offers vehicle energy harvesting systems a more versatile energy-conversion device for optimal performance in the complex rooftop aerodynamic flow field of vehicles. VAWTs can operate in all wind directions and are designed to perform well in multidirectional and turbulent wind flows on the rooftops of moving vehicles. In general, VAWTs have significantly simpler mechanical structures and operate at lower rotational speeds, resulting in reduced noise and improved operational stability. While offering greater utility, VAWTs generally have lower overall efficiency than HAWTs. This is due primarily to the lower power coefficients of VAWTs and their relatively small effective area for energy production. As a result, when generating energy under real-world automobile driving conditions, VAWTs typically operate at less than 200 W at moderate to high speeds, and therefore can only serve as an auxiliary energy production system and not as a primary energy source for vehicle propulsion or extension of driving range.

The potential benefits of both HAWT and VAWT for high-performing turbine systems can be improved by employing various aerodynamic enhancement features, including diffusers, ducts, and shrouds. This use of aerodynamic features directs and accelerates the wind flow to the turbine, increasing the effective wind flow it experiences and improving its energy capture efficiency. Although the addition of such aerodynamic enhancements has demonstrated measurable increases in turbine energy performance, there are several related construction and system integration challenges that these features can add. The addition of aerodynamic enhancement devices will increase the overall size, weight, and structural complexity of the energy harvesting system. Additionally, the inclusion of aerodynamic enhancement features can alter the vehicle's overall aerodynamic design, thereby increasing drag and reducing the improvement in turbine energy capture achieved by such devices. Therefore, the overall design and optimization of the aerodynamic enhancement features should continually aim to achieve maximum wind energy harvesting with minimal detrimental impacts on the aerodynamic design of the vehicle being used.

All turbine performance trade-offs pose a highly complex cross-sectional problem for the successful development of vehicle-based wind energy. Providing a balance among the overall energy output from the turbine, the aerodynamic impact on the vehicle, the structural integrity of the system, and the associated costs will continue to underscore the need for additional research and development in this area.

3. Aerodynamic and Structural Considerations

With the introduction of a turbine system to a vehicle, the aerodynamic profile will change. While optimized designs can help reduce the drag penalty of a turbine system, the minor lift from a turbine will cause a significant loss of vehicle efficiency at high speeds due to increased drag. Some studies have shown that only a very small portion of the increased aerodynamic energy losses caused by the addition of a turbine can be recovered through turbine use, with most resulting in either extremely marginal or negative net energy savings overall.

On top of all the aerodynamic issues associated with rooftop turbine systems, there are many mechanical safety concerns for a vehicle with a rooftop turbine system, such as adding weight (typically 5 to 20 kg) onto a vehicle; mechanical wear on rotating parts; maintenance needs, including replacing bearings and seals; and noise and vibration within the vehicle, which also restrict the practical use of rooftop turbines.

4. Electrical Conversion and System Integration

One of the most critical components of rooftop turbine systems is the ability to convert mechanical energy derived from vehicle-generated airflow to usable electrical energy. This mechanical-to-electrical conversion is primarily accomplished through Permanent Magnet Generators (PMGs). Due to their efficiency, compactness, and reliability across a variety of operating conditions, PMGs are the preferred choice for these types of applications. PMGs use the principle of electromagnetic induction to produce an Alternating Current (AC) in the stator windings through the rotational motion of the turbine shaft. The efficiencies of PMGs are approximately 85% to 95%, and they have high power density and minimal excitation losses. As such, PMGs are well-suited for energy harvesting applications that require small amounts of power at variable speeds, such as in a vehicle.

The electrical output of PMGs is inherently variable in both voltage and frequency because it depends on the turbine's rotational speed, which varies with vehicle and wind speeds. The raw AC output of PMGs will need to be rectified and regulated to make it compatible with vehicle electrical systems. Consequently, the AC output will first be converted to Direct Current (DC) via rectification and subsequently converted into usable electrical power by a power electronic converter. To dynamically adjust PMGs' electrical operating points, sophisticated control techniques, such as Maximum Power Point Tracking (MPPT), will determine the optimal turbine speed under varying load conditions, thereby maximizing energy extraction.

The methods used to integrate PMG output into the vehicle's electrical power architecture can vary by vehicle type and system design. In typical applications, the generated electricity is routed to the low-voltage auxiliary system, typically the 12V battery, and used to power onboard electronics such as lights, infotainment systems, and control systems. In electric and hybrid vehicles, integrating wind-generated energy is more complex; energy from the turbine is routed through multiple DC-DC conversion stages to the high-voltage traction battery. This requires careful alignment of voltages, electrical isolation, and adherence to safety standards due to the high voltages involved.

Due to the highly variable and intermittent nature of wind-generated electricity, intermediate energy storage devices, such as supercapacitors, may be included in the design of the energy harvesting system. These devices absorb rapid fluctuations in the turbine's output power and provide a smooth energy outlet to the battery or electrical bus. The use of these intermediate storage devices not only improves the stability of the energy harvesting system but also increases overall energy efficiency by eliminating transient losses and preventing sudden changes in the load on power systems.

Although methods for integrating wind-generated electrical output into vehicle power systems exist, the use of rooftop wind energy systems is limited by their relatively low and unpredictable output. The amount of energy that can be harvested from rooftop turbines is generally insufficient to provide primary propulsion power; as such, the output from these systems is better suited to auxiliary power applications. Consequently, rooftop wind energy systems should be viewed as supplemental energy sources with limited impact on overall vehicle performance or driving range.

5. Power Output and Energy Balance

Electricity generation from wind turbines is reliant upon wind speed - the greater the wind speed, the greater the amount of electricity generated. For example, at a wind speed of 70 mph (113 km/h), many hundreds of watts would be generated, assuming reasonable efficiency levels. Real-world conditions can drastically reduce the amount of electrical energy produced, due to turbulence and mechanical losses primarily arising from poor wind FLOW conditions.

Studies show that low wind speeds result in low power output, whereas high wind speeds produce higher power output. Typically, at highway speeds, wind turbines produce only a few hundred watts of electrical power, and the additional drag they create further reduces power output.

Energy balance analysis indicates that rooftop wind turbines deliver little overall wind energy to the vehicle. The energy required to overcome the drag created by the vehicle moving at high speed will generally exceed the electrical energy produced by the wind turbine, given the relatively small output of wind turbines.

In conclusion, different types of wind turbines could utilize the wind energy produced by a vehicle, although each has limitations inherent in its basic aerodynamics or design. Most existing technologies provide little net energy gain, and the major barriers to widespread use of these systems will continue to be their drag, weight, cost, and complexity. For aerodynamically optimized wind turbines utilizing lightweight materials, improvements in energy conversion technology will be key to improving these systems for future automobile applications.

6. Integration with Vehicle Systems

The integration of roof-mounted wind energy harvesting systems into modern vehicles requires careful consideration of electrical architecture, energy management strategies, and safety constraints. While the concept applies to both internal combustion engine (ICE) vehicles and electric or hybrid vehicles, the benefits and implementation approaches differ significantly across these platforms.

6.1 Integration in ICE Vehicles

In conventional ICE vehicles, the electrical energy generated by a rooftop turbine is typically directed toward the 12V auxiliary system, supporting loads such as lighting, infotainment, and onboard electronics. In theory, this supplementary energy could reduce the alternator load, thereby slightly reducing engine effort and fuel consumption. However, in practical scenarios, modern alternators are designed with surplus capacity, and the marginal contribution of a small wind energy system results in negligible fuel savings. Consequently, the integration of such systems in ICE vehicles offers limited practical advantage.

6.2 Integration in Hybrid and Electric Vehicles

There are applications for wind turbines mounted on the roof of a hybrid/electric vehicle to generate energy to either recharge the traction battery or power auxiliary loads. The wind turbine will usually produce variable-frequency AC output, which will be rectified and converted to regulated DC power through rectification and DC-DC conversion stages.

The DC power generated by the wind turbine can then be integrated into either the vehicle's high-voltage bus system or its auxiliary battery system, depending on the vehicle's design. In EVs, the turbine can be used as a secondary energy source, similar to regenerative braking, since advanced energy management systems enable it to provide continuous (though small) power under steady conditions at high speeds. Because wind energy is variable, a maximum power point tracking (MPPT) controller is needed to ensure that the maximum amount of power is extracted from the turbine. Also, intermediate storage devices (supercapacitors) can help smooth out transient variations in turbine power before it is integrated into the vehicle's electrical system.

6.3 Control, Monitoring, and Safety Mechanisms

Effective integration necessitates robust control and monitoring systems. Key parameters such as turbine rotational speed, output voltage, current, and battery state of charge must be continuously monitored. Automated control strategies should include protective mechanisms such as overspeed shutdown, electrical isolation during faults, and adaptive load management.

Safety considerations are critical, particularly due to the presence of rotating components exposed to environmental conditions. Fail-safe mechanisms, including automatic braking systems for the turbine and structural decoupling under extreme conditions, must be incorporated. Furthermore, the system must be designed to withstand crash scenarios without posing additional risks to occupants or pedestrians.

6.4 Engineering Constraints and Trade-offs

The real-world implementation of rooftop turbine generator systems in automobiles is significantly constrained by engineering limitations that affect their performance, safety, and feasibility. One of the primary limitations faced is the additional weight and its effect on vehicle handling. The incorporation of turbine components such as blades, generators, support structures, and protective housing typically adds between 5 and 20 kg to a vehicle's weight. As they are mounted on the vehicle's roof, these components also raise the vehicle's center of gravity, which may adversely affect stability, particularly during high-speed maneuvers, cornering, or sudden stops. This shift in weight distribution further affects the vehicle's roof structure, requiring additional structural support, increasing the vehicle's total weight, and potentially outweighing any marginal energy gain from wind energy harvesting.

A second major obstacle presented with rooftop turbines is noise and vibration. Rooftop turbines must operate at relatively high rotational speeds to produce significant electrical output, which generates aerodynamic noise and mechanical vibration and may negatively impact passenger comfort. If not properly controlled, they may also contribute to long-term structural fatigue of the vehicle. Although significant advancements in aerodynamic blade design, damping mechanisms, and materials development have produced turbine systems that reduce noise and vibration, achieving complete suppression of these effects remains extremely difficult, especially in the compact, confined geometry of various automotive applications.

Life cycle maintenance and durability represent another challenge. Roof-mounted turbines are constantly subjected to a variety of weather elements, such as precipitation, dust, temperature extremes, and debris impacts; therefore, significant weather sealing will be required to protect sensitive components such as generators and electronic circuitry. After this, components with moving parts, such as bearings and seals, are subject to wear and will require periodic servicing to maintain adequate performance. Mechanical failures, mostly at high rotational speeds, can result in catastrophic failures, i.e., the turbine system may separate from the vehicle or the turbines may severely damage the vehicle, all of which represent significant safety concerns.

The lack of industrial standards for the design and certification of rooftop wind turbine technologies in the automotive sector poses a challenge to achieving mass acceptance. Automobiles must be designed to meet specific requirements concerning noise emissions, pedestrian safety, and crashworthiness. The addition of external items with rotating components could introduce risks that differ from those of standard vehicles, thus requiring testing of the turbine system in numerous crash scenarios to avoid injury to individuals involved in traffic collisions and to reduce noise emissions.

Lastly, the cost of implementing rooftop turbine power production systems remains a significant barrier to their adoption and use in vehicles. The cost components associated with developing and producing turbine systems at the small scale include high-quality materials, precision manufacturing, electronic power control devices, and installation, which result in a relatively small amount of inconsistent power production, thus generating a poor return on investment. This economic disadvantage is key in high-volume automobiles, where cost is a major concern. Therefore, although rooftop turbine electrical generator technologies can be made to work, the economics of their implementation will likely limit them to experimental and/or niche applications rather than mainstream automotive design.

7. Prototype Design and Experimental Validation

Prototype development of rooftop wind energy harvesting systems is focused on optimizing aerodynamic performance while ensuring viability through structural feasibility and operational safety. A majority of the prototype systems incorporate either streamlined ducts or a shrouded turbine, which channels and accelerates the airflow toward the rotor. The purpose of the aerodynamic enhancements is to increase the wind velocity at the turbine, thereby improving energy capture efficiency, and to reduce the drag added to the car by the enhancements. Horizontal and vertical axis turbine designs have been explored, with the selection primarily dependent on the trade-off between turbine efficiency and adaptability to turbulent flow conditions. Lightweight composite materials are used in turbine blades and supporting structures to optimize performance further and reduce overall structural loads. Due to the high strength-to-weight ratios of many composite materials used in turbine designs, turbine blades and their supporting structures will be more durable over extended periods.

To verify the performance and feasibility of these prototype systems, a well-defined, systematic experimental validation procedure is critical. The primary means of validation for any prototype system is the wind tunnel tests that allow for controlled use of the wind tunnel to conduct multiple tests under reproducible wind speeds (for example, testing either the full-size automobile with the wind turbine system and/or testing the automotive prototype through wind tunnel testing, rolling road, and experimental test procedures). The wind tunnel allows for the precise measurement of aerodynamic drag, airflow distribution, pressure variations, and the turbine's electrical output. Additional methodologies, such as smoke and particle flow visualization systems, are commonly used to quantify the airflow around the rotor better and to identify areas of turbulent airflow (where air separates from the turbine blades as it moves over the surface) [9].

A second method of experimental validation is the testing of the turbine-generator subsystem on a dynamometer. In this scenario, the turbine is positioned between two fans that generate controlled-flow air to measure mechanical and electrical performance under various operating conditions. The mechanical and electrical performance of the turbine-generator system, including key metrics such as power coefficient, rotational speed, torque profile, electrical efficiency, and generator thermal performance, can be thoroughly characterized. This methodology is commonly used to optimize the electromechanical design of the turbine-generator system, ensuring it operates efficiently under varying load conditions.

On-road testing is a major input to prototype validation, as it quantifies turbine system performance in unpredictable, dynamic environments. Instrumented vehicle prototypes are equipped with various sensors, data acquisition systems, and monitoring devices to capture data from multiple variables (automobile speed, wind speed, turbine speed, electrical production, energy consumption). On-road testing measures and quantifies how real-world driving conditions, including variations in traffic and road conditions, turbulent air, and environmental influences (air temperature changes, crosswinds), affect the performance of turbine systems. Additional performance validation can be quantified by comparing the automobile's performance with and without the turbine-generator system to assess any net energy gain or drag penalties.

Finally, in addition to performance testing, testing the turbine systems for reliability and durability under standard operating conditions over the vehicle's life cycle is critical to ensuring continued operation. Prototypes must be tested under the most severe conditions, including a high vibration environment, sustained operational exposure to extreme weather (rain, dirt, and temperature extremes), and potential ice. Structural integrity testing is conducted on the prototype turbine system to ensure that, if the prototype were to experience an impact (accident), the turbine system would not pose any additional risk to vehicle occupants or pedestrians. Finally, long-term durability testing of the prototype turbine systems is conducted to identify potential failure modes in the mechanical components (bearings, blades, and mounting structures).

To summarize, comprehensive prototype design and experimental validation provide the means to close the gap between theoretical performance and practical implementation. The comprehensive design and experimental validation process provides valuable insights into the performance and limitations of the turbine systems, guiding design optimization and ensuring compliance with safety and regulatory requirements imposed on turbine-generating systems in automotive applications.

8. Performance Evaluation and Practical Implications

Experimental and simulation-based studies consistently report power outputs in the range of 50–300 W at typical highway speeds (80–100 km/h). However, the additional aerodynamic drag introduced by the turbine often results in higher energy consumption than the energy recovered. This limits the applicability of such systems for propulsion support.

Nevertheless, rooftop wind energy systems may find niche applications in powering low-energy subsystems, such as sensors, Internet of Things (IoT) modules, or auxiliary electronics. They may also serve as educational tools or experimental platforms for renewable energy research in transportation systems.

9. CFD Analysis and Aerodynamic Considerations

Figure 1 presents a multiphysics visualization of the investigated system, incorporating mode shape, stress distribution, temperature variation, frequency response, heat-flux behavior, and deflection characteristics. These complementary results provide an integrated representation of structural, thermal, and dynamic responses, enabling assessment of deformation, stress concentration, thermal effects, resonance behavior, and overall system performance.

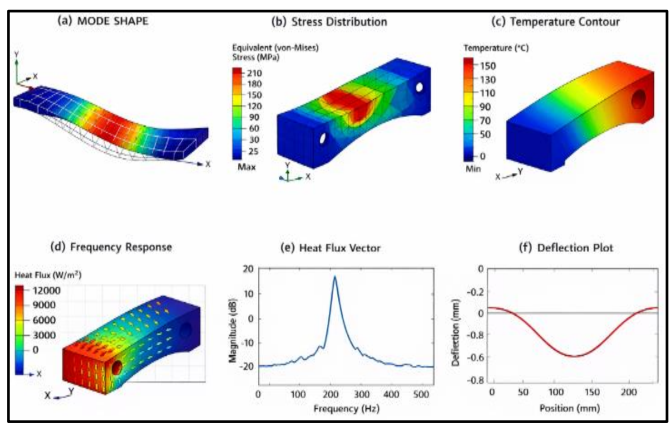

Figure 1: CFD velocity contour around the roof-mounted fan

Figure 2 illustrates the aerodynamic behavior of a roof-mounted turbine system through velocity, pressure, and turbulence contours, complemented by streamlines and performance plots. The results demonstrate how airflow characteristics vary with vehicle speed and roof position, providing insight into pressure distribution, aerodynamic loading, turbine output, and overall flow behavior.

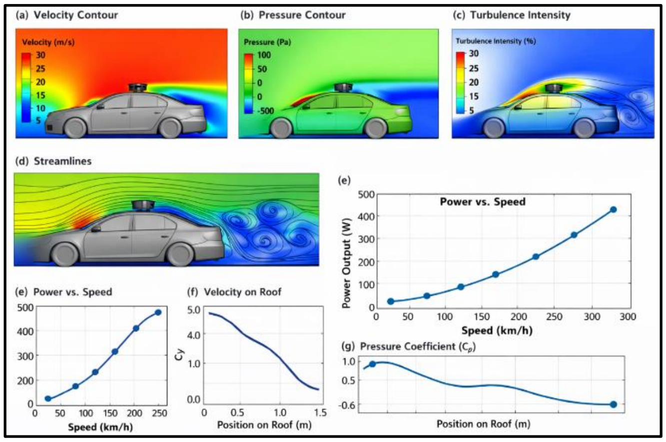

Figure 2: Pressure distribution on turbine blades

The aerodynamic behavior of airflow around a vehicle significantly influences turbine performance. CFD simulations reveal turbulent boundary layers and localized acceleration zones over the vehicle roof. These regions determine the optimal placement of the turbine for maximum energy capture. Pressure distribution analysis further highlights the aerodynamic loading on turbine blades, which directly affects efficiency and structural design [10].

10. Results and Discussion

Both simulation and experimental studies confirm that vehicle-induced airflow can provide a measurable source of electricity for rooftop turbine systems. When operated under optimal conditions typically associated with moderate to high vehicle speeds, rooftop turbines can generate electricity ranging from tens to hundreds of watts, depending on their design, location, and aerodynamic optimization. Computational analysis using techniques such as Computational Fluid Dynamics (CFD) shows that localized areas of accelerated flow over vehicle roofs increase the energy captured by the turbine by enhancing interaction with the vehicle airflow. Additionally, wind tunnel and on-road testing provide experimental validation of the benefits of using vehicular airflow to generate usable electrical energy.

However, across all studies, a major finding is that the turbine's generated energy is directly related to the subject vehicle's aerodynamic behavior. Placing a rooftop turbine on a vehicle can alter the vehicle's natural flow, increasing aerodynamic drag. This increased aerodynamic drag will require the vehicle to expend more energy to maintain the same speed (either through increased fuel consumption in internal combustion engine vehicles or increased battery use in electric vehicles). In many cases, the energy the vehicle consumes to overcome the added drag far exceeds the electrical energy produced by the turbine, resulting in an overall negative net energy return. In addition to the negative energy balance, even if the rooftop turbine is in an optimized configuration (minimal drag), very little usable electricity will be recovered as a percentage of the vehicle's total energy consumption.

Operating conditions also greatly influence the effectiveness of rooftop turbines. At lower speeds, such as those encountered while driving in cities, the available wind energy is not enough to generate meaningful electricity, given that wind energy generation is proportional to the cube of the wind speed. Therefore, rooftop turbines that are geared toward wind energy generation at lower speeds will capture very little, if any, usable energy. At the slowest driving speeds, rooftop turbines will harvest very little energy. At higher driving speeds, the rooftop turbines will generate much more electricity but also create greater aerodynamic drag, reducing the system's overall efficiency [11]. Furthermore, external variables, such as turbulence, crosswinds, and road surface conditions, will induce fluctuations in airflow, which directly affect the electrical output of rooftop turbines.

Despite the limitations, rooftop turbines could still provide benefits and be applicable in niche applications. Rooftop turbines will not serve as the primary energy generation sources for vehicle propulsion; however, they may be applicable as supplementary energy sources for low-power electrical loads. For example, rooftop turbines could power peripheral components of the vehicle, such as sensors, communication devices, and medium- to low-power electronic devices, thereby reducing the load on the vehicle's main power-generation source. For electric vehicles in particular, the use of rooftop turbines could marginally improve battery usage in steady-state driving conditions.

In summary, the data clearly show the fundamental relationship between energy harvesting and aerodynamic efficiency. Although harnessing vehicle-induced wind energy is technically feasible, practical applications are limited due to a low, often negative, net energy return and increased aerodynamic penalties. As a result, rooftop turbine systems should be utilized for incidental or experimental applications rather than as significant contributors to overall vehicle energy requirements.

11. Applications

Although the contribution of vehicular wind energy harvesting systems at scale is limited, they have many niche and supportive uses in modern automotive and research applications. The most practical use of these systems is to provide auxiliary power to onboard electronics. Modern cars contain a variety of low-power electrical devices, including lights, infotainment systems, control modules, and auxiliary sensors. Rooftop wind turbine systems will generate small amounts of power to support these subsystems, thereby reducing the load on an internal combustion engine alternator and/or the traction battery of an electric vehicle. This additional power supply may enhance the vehicle's overall energy efficiency at steady cruising speeds, where airflow is nearly constant. Another promising area of application involves the power of sensor networks for autonomous and connected vehicles. As more advanced driver assistance systems (ADAS) and vehicle-to-everything (V2X) communication technologies are deployed in vehicles.

Rooftop wind energy systems can meet the localized power needs of these sensors, especially those mounted outside the vehicle, thereby reducing the complexity of wiring to the central power system and providing redundancy, reliability, and efficient operation in certain applications.

Battery trickle charging is another viable application. This would be particularly beneficial for maintaining auxiliary batteries or powering energy storage solutions while a vehicle is operated for an extended period. For electric and hybrid vehicles, even a small, continuous power output can help maintain battery levels, especially for electrical loads that do not provide propulsion. Though the energy output of the rooftop wind turbine system may not significantly increase vehicle driving range, it will help offset parasitic loads and improve the overall energy efficiency of the energy management system. Such applications will be particularly useful for long-distance (highway) driving, where steady airflow is available to operate the rooftop wind turbine system.

In addition to their practical automotive applications, vehicle-mounted wind energy systems are also valuable research and educational tools that provide a real-world platform for having hands-on experience with renewable energy integration, aerodynamics, energy conversion, and system optimization in dynamic environments. Schools and research institutes can use these systems to investigate new turbine designs, materials, and hybrid energy-harvesting concepts. These systems enable students and researchers to develop a superior understanding of performance trade-offs, validate theoretical models, and improve upon existing energy harvesting technologies.

Overall, though fewer than expected numbers of wind energy systems installed on vehicles today may directly affect vehicle propulsion, these systems provide so many potential applications to support auxiliary power, provide sensor support, improve energy management, and provide valuable educational and research opportunities that they remain an important area for continued research and development within the realm of sustainable transportation technologies.

12. Conclusion

After studying these two algorithms, I conclude that Dijkstra's algorithm is much faster than the Bellman-Ford algorithm. It is also widely used in real-time GIS applications. This is why I selected the Dijkstra algorithm to find the shortest path in GIS. It is more workable and quicker in a very large network as well.

In this paper, the authors report the Dijkstra algorithm's running time in microseconds, compare it with the average running time, and conclude that it is less efficient than the Bellman-Ford algorithm for the SP problem on a small number of nodes. The Bellman-Ford algorithm is less efficient for a large number of nodes.

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