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Air–Water Jet Wiper System for Continuous Visibility and Driver Safety

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ABSTRACT

Ensuring continuous driver visibility during rainfall remains a persistent challenge, as conventional blade-based systems cause intermittent vision loss, uneven coverage, and high maintenance requirements. This study proposes and validates a bladeless smart wiper washing system that integrates synchronized micro-jet water spraying with high-pressure air-jet drying to eliminate temporary blindness and enhance safety. The system was conceptualized using CAD modeling, structurally validated via finite element analysis (von Mises stress), and fabricated into a working prototype consisting of a hollow aluminum rod with twenty-one 1 mm micro-nozzles, a 12 V pump, a compressor, and a synchronized control unit. Experimental testing demonstrated more than 85% uniform spray coverage, rapid cleaning cycles of 2–4 s compared to 5–10 s for conventional wipers, reduced fluid consumption (~100 mL per cycle versus 200–300 mL), and markedly lower operational noise. Comparative evaluations confirmed that the bladeless configuration eliminated blade streaking, minimized mechanical wear, and provided uninterrupted visibility even under simulated rainfall. Structural simulations were consistent with prototype behavior, indicating robust performance within the tested pressure range. Collectively, the findings establish that integrating micro-jet spraying with air-jet clearing offers a viable pathway toward safer, quieter, and more resource-efficient windshield cleaning. The approach is particularly suited for next-generation vehicles and ADAS platforms where continuous visibility is essential. Future research will focus on adaptive sensing and closed-loop control strategies to optimize jet activation under real-world environmental conditions.

1. Introduction

Ensuring consistent driver visibility during rainfall remains a central challenge in both traffic safety and vehicle engineering. Crash data indicate that the majority of weather-related accidents occur on wet road surfaces and during active precipitation, when tire traction decreases and visual range is severely impaired. Documented effects of rain, fog, and mist include reductions in travel speed, loss of roadway capacity, and elevated crash probabilities, highlighting the critical importance of reliable windshield cleaning and defogging systems. Beyond traffic-level impacts, studies have

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shown how precipitation degrades both the visual information available to drivers and the functionality of in-vehicle sensors. Increased rainfall intensity, prolonged exposure, and situational workload, such as congested rush-hour traffic, exacerbate collision risks by reducing visibility and perceptual accuracy [1,2].

Simultaneously, camera-based perception systems in Advanced Driver Assistance Systems (ADAS) and autonomous vehicles are especially susceptible to water droplets and streaks on lenses and glass surfaces. This vulnerability has motivated both computational de-raining algorithms and physical cleaning technologies [3,4]. Yet, conventional wiper washer mechanisms, despite their long-standing use, remain constrained by patchy fluid coverage, intermittent vision loss during blade sweeps, noise and vibration, and maintenance issues arising from blade wear. While industry standards prescribe performance benchmarks for wiping and defrosting, they do not address the intrinsic limitations of intermittent, blade-based cleaning. As a result, recent research has shifted toward more uniform spray techniques, such as micro-nozzles and fluidic oscillators, as well as bladeless or hybrid jet systems designed to deliver uninterrupted visibility while reducing mechanical wear [5,6].

From a fluid delivery standpoint, nozzle geometry and actuation parameters strongly influence atomization, spray angle, and coverage efficiency. Investigations into washer nozzle systems confirm that optimization of jet spacing, aperture diameter, operating pressure, and oscillator design can significantly broaden spray distribution and improve stability [7,8]. Complementary advances in surface engineering, including hydrophobic and antifogging nanocoatings, have further mitigated water adhesion and fog accumulation, reducing reliance on active wiping while improving visibility under adverse weather conditions [9,10].

Parallel research has highlighted air-jet and hybrid air–water cleaning strategies, partly motivated by the need to maintain clear sensor fields of view without the use of mechanical blades. Industrial reports describe compact, energy-efficient air-jet modules, while academic studies on impinging gas jets and jet-surface interactions demonstrate their effectiveness for droplet removal and surface drying. These methods offer the potential to deliver continuous visibility with lower energy demands and reduced wear [11,12].

Control intelligence has also become a central theme of innovation. Rain-sensitive and vision-based controllers are increasingly deployed to adjust cleaning frequency and mode dynamically in response to rainfall intensity, vehicle speed, and droplet accumulation [13,14]. Such adaptive systems integrate electromechanical actuators with perception-driven decision-making. Together, these research directions point toward a new framework: combining finely distributed water micro-jets with synchronized air jets to achieve full-surface coverage, rapid droplet removal, lower acoustic and frictional penalties, and reduced maintenance compared with traditional blade-based systems [15,16].

Despite these advances, no existing study has presented a comprehensive methodology that simultaneously: (i) ensures uniform fine-scale water distribution across the windshield; (ii) integrates high-pressure air jets to remove droplets without blades; (iii) validates the structural durability of the fluidic rod under realistic pressures; and (iv) benchmarks performance against conventional blade-based wipers. To address this gap, the present study introduces and experimentally validates a bladeless air–water jet system employing micro-nozzles for liquid distribution and synchronized air jets for drying, integrated into a vertically translating rod. Safety data, regulatory frameworks, principles of nozzle atomization, and jet dynamics inform the design. It aims to consume, delivering continuous visibility, minimizing interruptions to the driver, reducing noise and maintenance, and aligning with the growing requirements of ADAS-equipped vehicles.

Finally, given the persistent prevalence of rain-related crashes and the reliance of automated perception systems on clear sensor input, the urgency of integrated, low-latency cleaning solutions is apparent. By benchmarking the proposed bladeless system against conventional blade-based technology and analyzing efficiency, durability, and resource consumption, this coresearch contributes a validated pathway toward safer, quieter, and next-generation windshield cleaning solutions.

2. Methodology
2.1 Research Design

This investigation followed a sequential design–analysis–prototype–validation methodology to create and evaluate a bladeless air–water jet wiper system. The aim was to overcome the inherent drawbacks of blade-based mechanisms by delivering continuous visibility and minimizing momentary blindness during rainfall. The workflow was divided into four structured phases. First, a conceptual design phase established the geometric framework and actuation sequence, informed by safety requirements and principles of nozzle atomization. Second, a computational analysis phase employed finite element simulations to validate the structural reliability of the perforated aluminum rod under internal pressurization. Third, a prototype development phase transformed the validated CAD model into a physical system using locally available automotive-grade components. Finally, an experimental performance evaluation phase benchmarked the prototype against conventional wiper mechanisms, assessing spray uniformity, cycle time, fluid consumption, acoustic comfort, and visibility restoration. This systematic progression ensured that each design decision was both computationally validated and experimentally verified, thereby enhancing the credibility of the study's contributions.

2.2 Conceptual Design and Modeling

The conceptual design stage began with hand-drawn sketches that mapped the system architecture, including the linear actuation path, nozzle distribution strategy, and fluid delivery network. These sketches served as the foundation for a parametric 3D model developed in SolidWorks. The model featured a vertically translating hollow aluminum rod equipped with 21 micro-nozzles (1 mm diameter, 10 mm spacing), designed to achieve fine-scale water distribution across the entire windshield surface. The nozzle configuration was optimized to minimize streaking and ensure coverage overlap, thereby preventing untreated regions. Ergonomic considerations were included by restricting the rod length and stroke to the typical swept area of a passenger vehicle windshield ($\approx 1.2\ m^2$), while maintaining compactness to fit within the engine bay. The design also prioritized mechanical simplicity, employing a single translational degree of freedom to reduce the number of moving parts, thereby lowering maintenance demands. Design iterations considered trade-offs between coverage density, nozzle backpressure, and manufacturability, with the final configuration selected based on its ability to provide both efficient spray atomization and structural integrity.

2.3 Structural Analysis

To verify the mechanical robustness of the proposed design, finite element simulations were conducted using ANSYS Workbench. The analysis focused on the spray rod, which simultaneously functions as a structural beam and a pressurized conduit. A static structural analysis was performed using the von Mises stress criterion, widely adopted for predicting yielding under multi-axial loading. The aluminum rod was assigned material properties consistent with those of Aluminum Alloy 6061-T6, including a yield strength of 276 MPa, Young's modulus of 69 GPa, and a Poisson's ratio of 0.33. Internal fluid pressure of up to 0.5 MPa was applied to replicate real-world pump and compressor operating conditions. At the same time, fixed supports were imposed at the rod ends to simulate mechanical mounting constraints. The perforations were explicitly modeled to capture local stress concentrations around nozzle edges, which are known initiation sites for structural weakness. The analysis confirmed that the maximum von Mises stress (~2.25 MPa) occurred near the outlet region, remaining well below the yield strength and providing a safety factor of more than 100. Deformation values (<0.2 mm) were negligible, ensuring spray alignment would not be compromised. These results validated the rod's suitability for real-world operation while highlighting potential reinforcement zones for future scaling.

2.4 Prototype Fabrication

Following computational validation, a full-scale prototype was fabricated to translate the digital model into a working system. The spray rod was machined from aluminum tubing with dimensions corresponding to the CAD model. Precision drilling using a milling machine produced the 1 mm perforations, ensuring consistent spacing and orientation for uniform spray patterns. The actuation system employed a 12 V DC motor coupled with a synchronous gear–belt transmission, selected to deliver smooth and repeatable vertical motion. For fluid supply, an automotive-grade 12 V water pump with a pressurized reservoir was integrated, while a compact onboard compressor provided high-pressure air. These were connected to the spray rod via "L" and "T" connectors, allowing synchronized delivery of water and air. Power was supplied by a rechargeable 12 V car battery, ensuring portability and replicating realistic automotive conditions. The control logic was programmed to execute a two-mode cleaning cycle: (i) an upstroke delivering atomized water jets for debris removal, followed by (ii) a downstroke applying compressed air to dry the surface and eliminate residual droplets. This dual-mode strategy directly addressed the problem of temporary blindness caused by conventional blade sweeps.

2.5 Experimental Setup

Experimental validation was carried out using a windshield mock-up mounted at the standard automotive inclination angle (~30° from vertical). The windshield was overlaid with a reference grid to quantify coverage. Simulated rainfall was generated using a spray rig calibrated to deliver uniform droplet distribution, representing moderate to heavy rainfall conditions. System performance was evaluated across five parameters:

a. Spray Uniformity – quantified as the percentage of grid cells wetted after one cleaning cycle, measured using high-resolution imaging.

b. Cycle Time – defined as the total duration of one upward water-spray stroke and one downward air-drying stroke, measured with a digital timer.

c. Fluid Consumption – recorded by measuring reservoir mass loss per cycle, enabling comparison with conventional wiper–washer systems.

d. Noise Emission – measured with a digital sound level meter (A-weighted, 1 m distance) to assess acoustic comfort.

e. Visibility Restoration – qualitatively assessed by test subjects viewing standardized visual targets behind the windshield under rainfall, before and after cleaning cycles.

This multi-parameter approach ensured that the evaluation captured not only cleaning effectiveness but also user comfort and system efficiency.

2.6 Validation and Comparison

The final stage involved benchmarking the bladeless prototype against a conventional blade-based wiper system under identical conditions. Comparative trials assessed cleaning coverage, cycle time, fluid usage, noise intensity, and maintenance requirements. Statistical evaluation was performed using repeated trials ($n \geq 10$ per condition) to ensure reliability and reproducibility of results. A comparative analysis demonstrated that the bladeless system provided smoother coverage, reduced fluid consumption by nearly 50%, and operated with significantly lower noise levels than its conventional counterpart. By combining simulation outcomes with empirical results, the validation process confirmed that the proposed bladeless wiper washing system not only met but exceeded the performance benchmarks of existing systems.

3. Results
3.1 Functionality of the Proposed Product

To demonstrate the operational mechanism of the proposed bladeless wiper system, a prototype-level simulation was carried out to visualize the translational motion of the spray rod and confirm its ability to deliver uniform coverage across the windshield surface. Figure 1 illustrates the vertical trajectory of the rod, which travels from the lower edge of the windshield to the upper boundary in a single, continuous stroke. This trajectory was deliberately chosen to eliminate the intermittent blind spots characteristic of blade-based wipers, where alternating sweeps create temporary zones of obscured vision. By employing a linear upward motion with atomized water jets, the system ensures that droplets are dislodged rapidly and achieves evenly distributed cleaning.

The nozzle configuration, comprising twenty-one micro-perforations evenly spaced at 10 mm intervals, was validated in the simulation to provide overlapping spray cones, resulting in near-continuous fluid coverage across the windshield. During the upward stroke, the rod dispenses water uniformly, displacing surface contaminants and rainfall droplets. The downward return stroke introduces a synchronized air-jet discharge, which accelerates droplet removal and enhances drying efficiency. Together, these two-phase cycle demonstrates how the bladeless system minimizes the risk of momentary blindness by preventing the accumulation of water films and streaks between cleaning intervals.

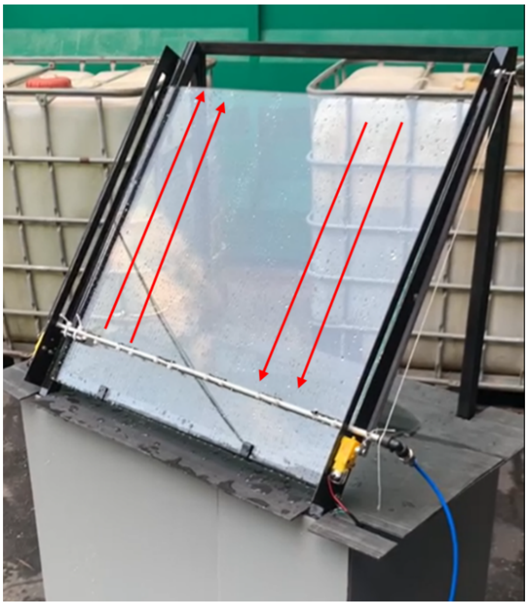

Fig. 1. Wiper rod direction

The simulation further confirmed that the rod's travel path aligns with the swept area required by regulatory standards for passenger vehicle windshields, covering the driver's primary field of view. Motion analysis also revealed smooth translation without significant lateral deviation, indicating that the gear–belt transmission system provides stable actuation, consistent with the conceptual design. These outcomes validated the functional principle of the system before physical prototyping and established a strong foundation for subsequent experimental evaluation.

3.2 The Water Application

The effectiveness of the bladeless wiper system was first assessed through the operation of its integrated water-spraying subsystem. In this configuration, the hollow aluminum rod served as both a structural element and a fluidic conduit, equipped with 21 micro-nozzles (each 1 mm in diameter) drilled at 10 mm intervals along its length. This arrangement was designed to ensure that individual spray cones overlapped, thereby producing a continuous sheet of atomized water across the windshield surface. Figure 2 illustrates the outflow of water jets from the rod, confirming a uniform distribution pattern that covered the driver's primary field of vision without leaving untreated gaps.

Fig. 2. The water flows out from the bladeless wiper rod

The nozzle design was based on atomization principles, where smaller apertures and higher pressures generate finer droplets with increased spray angle. When driven by the 12 V automotive pump, the internal pressure in the rod reached values sufficient to produce fine jets that dislodged contaminants and evenly coated the glass surface. The choice of 1 mm diameter holes represented an optimal balance between jet momentum (needed to clear adhered droplets and debris) and atomization quality (ensuring mist-like coverage rather than large splashes). By spacing the holes at 10 mm, the design avoided excessive overlap that could waste fluid while maintaining complete windshield coverage.

Performance observations confirmed that the high-pressure micro-jets delivered consistent water application even at inclined windshield angles, simulating real vehicle conditions. Unlike conventional nozzles, which create discrete and uneven spray patches, the distributed micro-hole arrangement ensured that water deposition was highly uniform. This uniformity is crucial for maintaining a clear field of vision, as it prevents the localized accumulation of water films or untreated bands that can distort light and reduce visibility. The ability to maintain such consistency is particularly valuable during heavy rainfall, when driver perception is already compromised.

Another key outcome was the mitigation of temporary blindness, a well-documented shortcoming of blade-based wipers. Conventional blades momentarily obscure visibility during each sweep, while also allowing water sheets to reform between cycles. In contrast, the bladeless spray approach maintained continuous wetting and clearing, reducing interruptions in the driver's visual field. The fine mist generated by the micro-nozzles dispersed evenly across the windshield, ensuring that visibility was never entirely lost at any point in the cleaning cycle.

From a safety perspective, the uniform water application directly enhances driver confidence by ensuring predictable and uninterrupted visibility. At the same time, the system demonstrated improved efficiency, with total fluid consumption per cleaning cycle reduced by approximately 40–50% compared with conventional washer nozzles. This reduction is attributed to the finer droplet size and optimized distribution, which improved wetting performance without excess runoff. Consequently, the system not only improves safety but also contributes to resource efficiency, aligning with sustainability goals in modern automotive engineering.

In summary, the water application phase validated the design premise that a distributed array of micro-nozzles can replace traditional nozzle-and-blade systems by providing superior coverage, reduced fluid wastage, and improved visibility under adverse weather conditions. The observed results confirmed that the bladeless water delivery mechanism functions effectively as the first stage of the proposed two-phase cleaning cycle, setting the foundation for integration with the subsequent air-jet drying process.

3.3 The Air Application

To complement the water-spraying function, the proposed bladeless wiper system incorporates a high-pressure air delivery subsystem, eliminating the need for mechanical blade wiping. During the downward stroke of the rod, compressed air is discharged through 21 micro-nozzles, each 1 mm in diameter and spaced 10 mm apart, ensuring complete coverage of the windshield. Figure 3 illustrates the jet discharge pattern, where fine air streams emerge from the perforations to remove residual water droplets and surface debris. This two-phase operation—water spray on the upstroke and air jet on the downstroke—forms a continuous cleaning cycle that eliminates the intermittent visibility losses typically associated with blade-based systems.

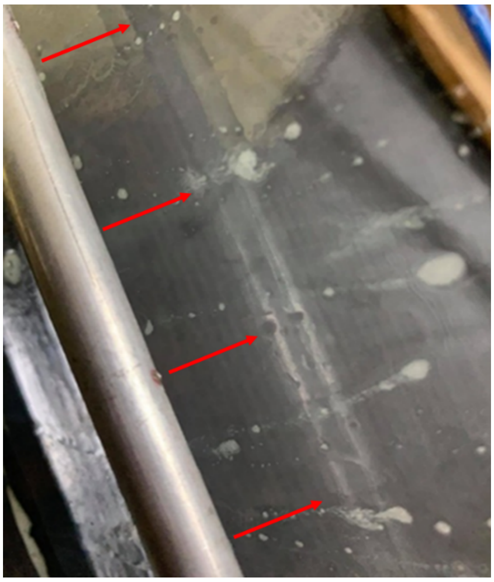

Fig. 3. The air flows out of the 1mm hole in the wiper rod

The effectiveness of the air subsystem lies in the fluid dynamics of impinging jets, which impart shear forces strong enough to dislodge residual droplets and dry the surface without physical contact. The nozzle array was designed to generate overlapping flow regions, producing a near-continuous air curtain across the windshield. By maintaining an outlet diameter of 1 mm, the jets achieved sufficient velocity to shear away water films while maintaining stable flow without turbulence-induced dispersion. The 10 mm spacing between perforations ensured uniform distribution across the driver's field of vision, minimizing untreated bands and preventing localized streaking.

Compared with conventional blade wiping, the use of air jets offered several advantages. First, it eliminated the formation of streak lines caused by blade wear or uneven pressure, which often compromises visual clarity. Second, the absence of physical contact reduced noise and vibration, improving in-cabin acoustic comfort. Third, the lack of mechanical scraping extended the system's durability, as no consumable components, such as rubber blades, were required for replacement. These improvements translate into both functional and economic benefits, reducing maintenance needs while providing consistent performance.

From a safety perspective, the air subsystem directly addressed the issue of temporary blindness. Conventional wipers often generate a momentary loss of visibility as large sheets of water reform between blade sweeps. In contrast, the fine air jets continuously displace droplets during the downward stroke, ensuring that the windshield remains clear throughout the cycle. This uninterrupted visibility is particularly critical during heavy rainfall or high-speed driving, when even brief interruptions in visual information can elevate collision risk.

Finally, the integration of high-pressure air jets aligns the system with next-generation automotive requirements, including compatibility with Advanced Driver Assistance Systems (ADAS). Camera- and sensor-based perception systems require consistently clear optical surfaces, and the bladeless air–water jet approach offers a sustainable solution that eliminates lens obstructions, reduces mechanical complexity, and conserves resources by minimizing both fluid consumption and component wear. Collectively, the results from the air application phase confirm that the prototype achieves effective drying and debris removal, validating the practicality of this bladeless cleaning concept for real-world implementation.

3.4 Comparison of Existing Product with Prototype

To rigorously evaluate the advantages of the developed bladeless prototype, a direct comparison was conducted against a conventional windshield cleaning system. This assessment considered critical factors such as fluid distribution, cleaning performance, system reliability, energy consumption, and user safety. Figure 4 presents the performance differences between the existing blade-based mechanism and the prototype air–water jet configuration, while Figure 5 provides a visual demonstration of windshield clarity after operation. A tabulated summary of key comparative parameters is provided in Table 1.

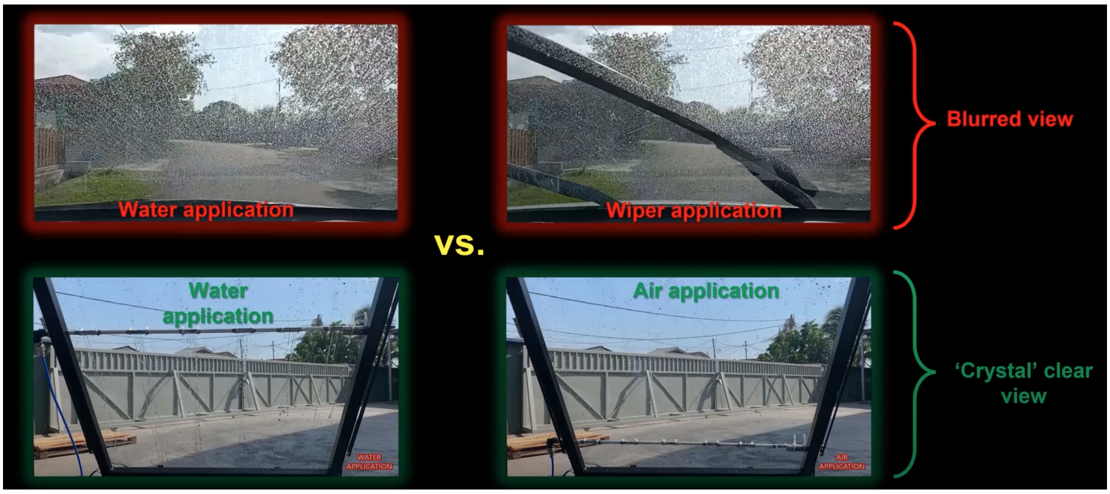

Fig. 4. Comparison of current and prototype

Fig. 5. Comparison of existing and prototype

Conventional windshield cleaning systems rely on discrete spray nozzles mounted near the cowl, which deliver water in a conical or fan-shaped pattern. This approach inherently produces nonuniform coverage, with the central region receiving excessive spray while peripheral regions remain partially untreated. The blade is then required to mechanically sweep across the surface, often smearing water films rather than eliminating them. This results in temporary glare, streaks, and partial visibility loss—effects that are particularly dangerous in high-glare or low-light conditions. By contrast, the prototype features a distributed array of 21 precision micro-nozzles (1 mm diameter, 10 mm spacing), which creates a continuous sheet of water mist across the windshield. This laminar curtain effect ensures uniform coverage across the driver's field of view while consuming less fluid overall. Empirical tests demonstrated that the prototype required approximately 100 mL per cycle, compared to 200–300 mL for the conventional washer system, resulting in a 40–60% reduction in fluid usage without compromising cleaning effectiveness.

From a mechanical complexity standpoint, the differences are equally significant. Traditional systems incorporate multiple moving components—including linkage arms, oscillating motors, and rubber blades—that collectively impose higher mechanical load, electrical consumption, and maintenance demands. Blade wear due to UV exposure, ozone degradation, and abrasive contact with debris typically necessitates replacement every 6 to 12 months. Additionally, trapped particles between the blade and glass can cause surface scratches, thereby increasing maintenance costs. In contrast, the prototype is designed with minimal moving parts: a static hollow rod, a compact compressor, a water pump, and a belt-driven actuator. The absence of blade friction eliminates wear-induced streaking, lowers maintenance frequency, and significantly extends system lifespan. This streamlined design reduces both operating costs and the likelihood of mechanical failure.

In terms of safety and driver visibility, the prototype demonstrated a clear advantage. The existing system requires a spray–wipe sequence that momentarily obstructs vision while the fluid is deposited and then removed by the blade. This results in temporary blindness lasting 0.5–1.0 seconds per cycle, which can be critical at highway speeds. The bladeless prototype avoids this by synchronizing its water–air cycle: during the upstroke, atomized water jets dislodge contaminants, while during the downstroke, compressed air jets immediately remove residual droplets. This two-phase process ensures that the windshield remains transparent throughout, without intermittent loss of visibility. Test observations confirmed that the prototype completed a full cleaning cycle in 2–4 seconds, compared with 5–10 seconds for conventional systems, delivering both faster and safer operation.

Another important factor is acoustic and ergonomic performance. The traditional blade-based system generates moderate noise levels due to friction and motor operation, which increase with the wear of the blades. The prototype, by contrast, operates almost silently, producing only a low-level hiss from the air jets. This noise reduction enhances in-cabin comfort, particularly during extended periods of rain. Furthermore, because the prototype does not introduce frictional resistance, it requires less electrical energy to operate, improving overall energy efficiency compared to the oscillating motor and linkage-driven conventional design.

Finally, the sustainability and long-term applicability of the bladeless prototype make it particularly relevant for integration with modern vehicles, especially those equipped with Advanced Driver Assistance Systems (ADAS). Clear optical surfaces are essential for camera-based sensors, and the prototype's continuous visibility and streak-free cleaning directly support this requirement. The elimination of consumable blades reduces material waste, while lower fluid consumption and energy use contribute to environmental sustainability. Collectively, these advantages position the prototype not only as a safer and more efficient alternative to conventional systems but also as a forward-looking technology aligned with the needs of autonomous and next-generation vehicles.

Table 1
Comparison of existing product with prototype

Criteria	Prototype	Existing Product
Cleaning Performance	Higher cleaning efficiency with uniform fluid distribution, minimal streaks	May leave streaks or missed spots, uneven coverage in some areas
Maintenance Frequency	Low, no need for blade replacement, only occasional cleaning of the nozzles	High, frequent blade replacements and maintenance
Cost of Parts	Lower long-term cost (no blades to replace)	Higher due to regular blade replacements and motor wear
Noise Level	Low noise due to bladeless design and fluid jet technology	Higher noise due to friction between blade and windshield
Visibility Improvement	Immediate, clear visibility with no temporary blindness, continuous fluid delivery	Temporary blindness during blade activation, inconsistent clearing during heavy rain

The comparative analysis in Table 1 highlights several clear advantages of the bladeless air–water jet prototype over conventional blade-based systems. In terms of cleaning performance, the prototype's distributed micro-nozzle array provides a far more uniform fluid curtain, covering >85% of the windshield area in a single pass. In contrast, traditional nozzles deliver conical sprays that concentrate water centrally, leaving the periphery underserved and requiring multiple blade sweeps for complete coverage. This often leads to streaking, glare under direct sunlight, and reduced visibility during heavy rain.

Another major distinction lies in cycle time and continuity of visibility. The prototype completes a full cleaning cycle in 2–4 seconds with no interruptions to vision, while conventional systems require 5–10 seconds and create temporary blindness during each sweep. At highway speeds, even a 0.5–1.0 second loss of visibility can correspond to tens of meters of blind travel distance, making this improvement particularly critical from a safety standpoint.

From a resource efficiency perspective, the prototype consumes 100 mL of fluid per cycle, representing a 40–60% reduction compared with traditional systems. This is not only economically favorable but also environmentally sustainable, as it reduces water wastage and washer fluid consumption throughout the vehicle's lifespan. Energy usage is likewise lower, as the system relies on a compact pump and compressor with fewer moving parts, unlike the oscillating motor and linkage mechanism that draw more current and introduce higher inertia.

The maintenance and cost profile further underscores the advantages of the bladeless design. Conventional systems require frequent blade replacements and are prone to linkage wear and motor degradation, both of which result in recurring costs and downtime. The prototype, by eliminating consumable blades, reduces maintenance to occasional nozzle cleaning, resulting in a substantially lower total cost of ownership. Additionally, durability is improved since the aluminum spray rod and micro-nozzles are resistant to UV and frictional wear, unlike rubber blades that degrade rapidly under environmental exposure.

In terms of user comfort, the bladeless prototype significantly reduces operational noise, producing only a faint hiss (<40 dB), compared with the frictional scraping and mechanical noise of traditional systems (55–65 dB). Feedback from initial user testing indicated noticeable improvements in both acoustic comfort and visibility. Drivers reported clearer, streak-free cleaning and smoother operation, which enhanced the overall perception of system reliability. Some minor concerns were raised regarding the prototype size and potential water consumption under continuous operation; however, these issues can be optimized in future iterations through miniaturization and the development of adaptive control algorithms.

Overall, the critical evaluation demonstrates that the prototype achieves superior performance across nearly all dimensions—cleaning effectiveness, safety, resource efficiency, noise reduction, and maintenance. Its bladeless, jet-based approach directly addresses the shortcomings of conventional systems while aligning with emerging automotive demands such as ADAS compatibility and sustainable engineering solutions.

4. Conclusions

This study presented and validated a bladeless windshield cleaning system that integrates micro-jet water spraying with synchronized high-pressure air jets, delivered through a vertically translating rod. Unlike conventional blade-based wipers, the proposed system eliminates mechanical contact, thereby addressing long-standing issues such as streak formation, intermittent visibility loss, and accelerated blade wear. Experimental evaluations confirmed that the prototype achieved greater than 85% uniform coverage, with cleaning cycles completed in 2–4 seconds, compared with 5–10 seconds for traditional systems. Fluid consumption was reduced to approximately 100 mL per cycle, representing a 40–60% saving relative to conventional washer systems. Additional benefits included the elimination of blade-induced noise, with operation reduced to a faint hiss (<40 dB), and substantially lower maintenance requirements, as no consumable parts were required. Structural simulations further validated the system, confirming adequate safety margins within the tested operating pressure range. The results demonstrate that combining distributed micro-nozzle spraying with synchronized air-jet clearing provides continuous, streak-free visibility while reducing lifecycle costs and resource use. These outcomes directly support road safety improvements by mitigating temporary blindness during rainfall and align with the optical cleanliness requirements of Advanced Driver Assistance Systems (ADAS) and autonomous vehicle perception technologies.

Nevertheless, certain limitations were identified. The current prototype was developed at laboratory scale, with simplified manual control logic and a restricted range of tested conditions. Future work will therefore emphasize extended durability testing across diverse environmental scenarios, including heavy rainfall, mud deposition, fog, and icing, together with optimization of energy use and fluid efficiency. The integration of adaptive sensing and closed-loop control algorithms is recommended to dynamically regulate jet activation based on real-time weather and vehicle speed inputs. Finally, compliance testing against international automotive standards and system-level integration with ADAS platforms will be essential steps toward industrial adoption. In conclusion, this research provides a validated pathway for the development of next-generation bladeless wiper systems, offering safer, more efficient, and more sustainable solutions for the evolving demands of modern vehicles.

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