Interior Windshield Moisture Management Using a Vapor-Assisted Wiping Model: System Architecture and Design

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***Abstract*—Fogging and moisture accumulation on the interior side of vehicle windshields continue to affect driving visibility despite the development of various defogging and climate-control approaches. While previous studies have mainly addressed the problem through HVAC optimization, airflow management, or intelligent monitoring systems, direct moisture handling at the interior glass surface remains less explored. In response to this gap, the present study proposes an interior windshield moisture management model based on vapor-assisted wiping. The model integrates a water reservoir and vapor generation unit, a guided vapor delivery pathway, and a regulated wiping interface that includes a porous moisture-distribution structure. These components work together to control vapor transfer before it reaches the windshield, allowing the wiping action to operate with a moderated moisture layer rather than uncontrolled vapor flow. The proposed system architecture explains how moisture generation, routing, and surface interaction are coordinated to support stable visibility inside the vehicle cabin. This model offers an alternative approach that complements existing defogging strategies and may contribute in future work to the development and evaluation of more effective interior windshield visibility enhancement systems.**

***Keywords*—Interior windshield; moisture management; vapor-assisted wiping; windshield defogging; vehicle visibility enhancement**

I. Introduction

Maintaining optimal visibility through a vehicle's windshield is a fundamental requirement for operational safety. While conventional wiping systems effectively manage the exterior surface, the interior side remains susceptible to visibility degradation caused by condensation, fogging, and particulate accumulation [1]. These phenomena are typically triggered by thermal gradients between the vehicle cabin and the external environment, or during periods of high ambient humidity, directly impacting the driver's visual field [2].

Reduced visibility caused by moisture accumulation on the interior glass surface can significantly affect driver perception and reaction time, increasing the risk of accidents [3]. To address this issue, several studies have explored defogging performance and HVAC optimization as key factors in improving visibility and thermal comfort inside vehicles [4]. In addition, airflow design and defrosting duct performance have been investigated to enhance the efficiency of moisture removal from the windshield surface [5]. Despite these efforts, maintaining stable and immediate visibility remains a challenge, especially under rapidly changing environmental conditions.

Current mitigation strategies primarily rely on HVAC (Heating, Ventilation, and Air Conditioning) systems, which often lack the immediacy or uniformity required for rapid de-fogging [6]. Furthermore, these indirect environmental controls are not designed for direct surface interaction, limiting their efficacy in stabilizing visibility under volatile atmospheric conditions [7], [8].

Consequently, there is a clear operational necessity for a dedicated solution that manages interior windshield moisture through direct surface interaction, tailored for the unique constraints of the vehicle cabin. While the automotive industry has introduced various defrosting and cleaning technologies, these are predominantly bifurcated into exterior-only wipers or general climate control systems [8]. Such conventional mechanisms often fail to address localized condensation effectively, as they prioritize ambient air regulation over direct glass surface management [9]. This technical gap results in persistent fogging even when HVAC systems are fully active, underscoring the need for a synchronized system that integrates moisture application with mechanical wiping to ensure instantaneous and sustained optical clarity [10], [11].

While vapor-assisted cleaning is established in industrial and exterior automotive applications, its integration into the vehicle cabin presents unique technical constraints [12]. Interior moisture management requires precise regulation to avoid unregulated condensation or dripping, which could further obstruct the driver's field of view [13]. Consequently, the functional challenge shifts from mere vapor generation to the controlled delivery and uniform distribution of moisture. This necessitates a structured architectural approach that synchronizes vapor guidance with mechanical wiping, ensuring that the interaction with the glass surface enhances, rather than compromises, optical clarity within the enclosed environment [14].

To address these limitations, this study introduces an integrated vapor-assisted wiping model designed specifically for interior windshield moisture management. Moving beyond the fragmented approach of treating vapor generation and wiping as independent processes, the proposed model organizes them into a coherent operational architecture where moisture delivery and surface interaction are precisely coordinated. The core of this model lies in the transition from free vapor discharge to a guided distribution mechanism. By incorporating a structured moisture-diffusion interface, the system regulates vapor transfer and ensures uniform distribution prior to glass contact. This prevents uncontrolled condensation and allows the mechanical wiping action to interact with a moderated moisture layer rather than an unmanaged vapor flow. Such a synchronized configuration stabilizes the cleaning process, ensuring consistent optical clarity within the constrained environment of the vehicle cabin. Instead of focusing on complex mechanical implementations, the study emphasizes the architectural organization of the system and the operational interaction between its components.

The main contributions of this study can be summarized as follows:

- This study introduces a vapor-assisted wiping model designed to improve moisture management on the interior windshield surface and support clearer visibility through coordinated vapor delivery and wiping action.
- A system design is presented to explain how the main components work together to guide, regulate, and apply moisture in a controlled way during operation.
- The proposed model provides a practical framework that can support future development, testing, and refinement of interior windshield visibility enhancement systems.

Unlike previous approaches that focus primarily on environmental control, this study emphasizes direct surface-level moisture management through a coordinated vapor-assisted wiping mechanism.

This research is positioned as a conceptual engineering design study that focuses on system architecture rather than experimental validation. The objective is to provide a structured framework for interior windshield moisture management that can guide future implementation, simulation, and performance evaluation. Accordingly, the contribution of this work lies in the design rationale and integration of system components rather than in empirical testing at this stage. The current study is limited to a conceptual design without experimental validation. Future work will focus on simulation, prototyping, and quantitative evaluation to assess system performance under different operating conditions.

The remainder of this study is organized as follows: Section II presents the related work on windshield fogging and defogging approaches. Section III describes the proposed vapor-assisted wiping model and system architecture. Section IV explains the design rationale and conceptual advantages. Section V presents the discussion. Section VI discusses limitations and future work. Finally, Section VII concludes the study.

II. Related Work

This section reviews existing approaches to windshield fogging and defogging, focusing on climate control systems, airflow optimization, and intelligent monitoring solutions.

Recent studies have explored HVAC-based solutions to improve windshield defogging and cabin conditions. In [4], the authors analyzed the relationship between defogging performance, thermal comfort, and energy consumption, showing that optimized HVAC operation can enhance visibility while maintaining energy efficiency. Similarly, in [15], the authors proposed a high-efficiency HVAC system with integrated defogging and dehumidification functions for electric vehicles. More recently, in [16], the authors introduced a predictive cabin conditioning strategy that anticipates environmental changes to improve system responsiveness.

In addition, broader investigations into HVAC design and indoor airflow patterns have been conducted. In [17], the authors examined the role of HVAC systems and window configurations in shaping airflow patterns and air exchange rates within enclosed environments. Their study emphasizes the importance of system design in controlling humidity distribution. However, similar to other environmental approaches, the focus remains on air-level regulation rather than direct surface-level moisture management.

Other studies have focused on airflow behavior and its impact on windshield defogging. In [18], the authors conducted numerical simulations to analyze airflow distribution across the windshield during defrost operation. Their findings highlight how airflow patterns influence fog removal efficiency and visibility restoration. Such simulation-based approaches provide valuable insights into airflow dynamics; however, they primarily address air movement rather than direct moisture interaction with the glass surface.

Recent research has explored intelligent ways to reduce windshield fogging through climate control systems. For example, in [8], the authors proposed a predictive HVAC model that estimates the likelihood of fogging using factors such as humidity and windshield temperature, allowing the system to automatically adjust airflow and temperature to improve visibility. While this approach shows the value of predictive environmental control, it mainly focuses on regulating cabin conditions rather than interacting directly with the windshield surface. In contrast, the present study focuses on a vapor-assisted wiping model that manages moisture directly at the glass surface, offering an alternative perspective based on direct surface interaction rather than overall climate adjustment.

A broader view of windshield fogging was presented by [7], who reviewed different studies addressing defogging and de-icing in automotive windshields. Their work highlights the variety of existing approaches, including climate control methods, airflow management, and surface-based solutions aimed at maintaining visibility under changing environmental conditions. While these studies provide useful insights into fogging mechanisms and possible mitigation strategies, most of the proposed solutions still focus mainly on environmental control or material-based treatments.

In [2], the authors investigated windshield demisting from an airflow and ventilation perspective, focusing on how air duct design influences fog removal performance in commercial vehicles. Their study showed that modifying duct geometry can improve airflow distribution and enhance demisting efficiency through better environmental control. While this approach improves visibility by optimizing airflow behavior, it remains primarily focused on air delivery mechanisms rather than direct moisture management at the windshield surface.

In [9], the authors introduced the concept of an intelligent windshield system aimed at enhancing automotive safety through smart sensing and visibility-related functionalities. Their work emphasizes the role of intelligent integration within windshield systems to support safer driving conditions. While this approach highlights the importance of smart windshield technologies, it focuses mainly on sensing and intelligent monitoring rather than direct moisture handling or surface-level fog management.

While previous studies have made notable strides, most current methods still focus on general environmental control, airflow tuning, or smart monitoring, often overlooking the direct management of moisture on the interior windshield surface itself. This reveals a practical disconnect between broad climate-based solutions and direct surface interaction-especially in enclosed cabins where condensation requires more precise handling. Overall, existing studies predominantly address windshield fogging through cabin-level environmental control, airflow optimization, or intelligent monitoring. However, direct surface-level moisture management remains relatively underexplored. This gap highlights the need for approaches that integrate controlled moisture delivery with mechanical interaction at the windshield surface. While these approaches demonstrate the importance of intelligent HVAC control, they mainly operate at the cabin level and do not directly address moisture accumulation on the interior windshield surface.

Unlike existing approaches that primarily rely on cabin-level environmental control, airflow optimization, or sensing-based monitoring, the proposed model focuses on direct surface-level moisture management. By introducing a coordinated mechanism between vapor delivery and mechanical wiping, the system is expected to provide more immediate and localized control of condensation on the interior windshield. This approach may be particularly beneficial in scenarios involving rapid fog formation, high humidity conditions, or situations where HVAC response is delayed. In such cases, direct interaction with the glass surface can complement existing systems by stabilizing visibility more effectively.

III. Proposed Model and System Architecture

This section presents the proposed vapor-assisted wiping model and describes the overall system design developed for interior windshield moisture management. The model is structured as an integrated system in which vapor generation, delivery, and wiping interaction operate together to improve visibility on the interior windshield surface.

As illustrated in Fig. 1, the proposed design is centered on a coordinated operational concept rather than isolated mechanical elements. The system begins with a water reservoir connected to a heating element that generates water vapor. The generated vapor is guided through a conduit pathway toward the interior wiping mechanism, where it is distributed in coordination with the wiping motion. This arrangement enables controlled moisture application instead of uncontrolled vapor release, allowing the cleaning process to remain stable within the enclosed vehicle cabin.

The design emphasizes functional integration between the vapor source and the wiping mechanism. Instead of treating vapor generation and wiping as independent processes, the model synchronizes moisture delivery with mechanical surface interaction. This coordinated configuration supports uniform moisture distribution and helps maintain optical clarity during operation.

In addition, the system design incorporates a regulated moisture-transfer stage at the wiping interface. Vapor released from the delivery pathway is moderated before reaching the glass-contact surface, allowing wiping motion to interact with a controlled moisture layer rather than free vapor flow. This design principle aims to reduce excessive condensation and avoid uncontrolled dripping while maintaining effective surface cleaning.

A. Model Components and Operational Mechanism

Fig. 1 presents an overview of the proposed vapor-assisted wiping model for interior windshield moisture management. The figure illustrates the overall system concept, beginning with a water reservoir connected to a heating source that generates water vapor during operation. The generated vapor is guided through a delivery pathway toward the wiping structure, where it is applied in coordination with the wiping motion across the interior glass surface. This configuration demonstrates how vapor generation and mechanical wiping are integrated within a single operational design to support controlled moisture application and improved windshield clarity.

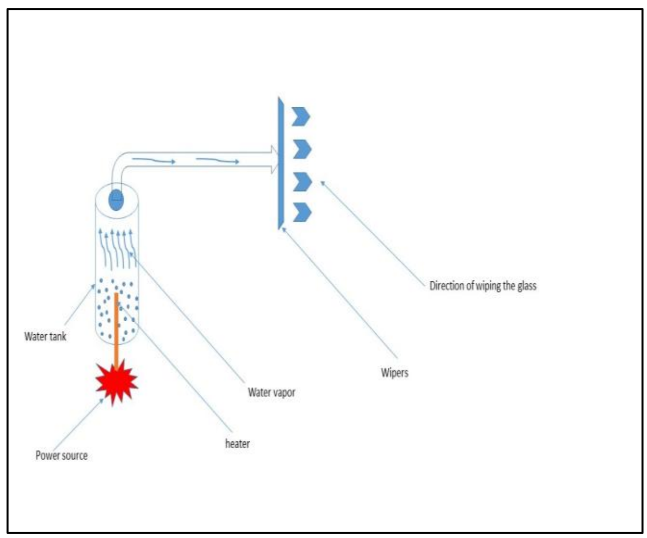

Fig. 1. Overview of the proposed vapor-assisted wiping system showing vapor generation, delivery pathway, and coordinated wiping interaction for interior windshield moisture management.

To further clarify the operation of the proposed model, Fig. 2 illustrates the internal structure of the wiper head, which represents the main interaction zone between vapor delivery and surface cleaning. While Fig. 1 presents the overall system architecture, this figure focuses on the internal design responsible for regulating moisture before it reaches the windshield surface.

As shown in Fig. 2, vapor released from the outlet apertures does not directly contact the glass. Instead, it first enters a porous plenum that guides and redistributes the vapor internally. This routing process allows moisture to spread across the structure in a more controlled manner, supporting uniform distribution and reducing localized condensation. The regulated moisture then passes through an absorbent insert before reaching the glass-contact surface, where a moderated moisture film is formed during wiping. This sequence ensures that vapor delivery remains controlled and stable, enabling the wiping mechanism to interact with a regulated moisture layer rather than uncontrolled vapor flow.

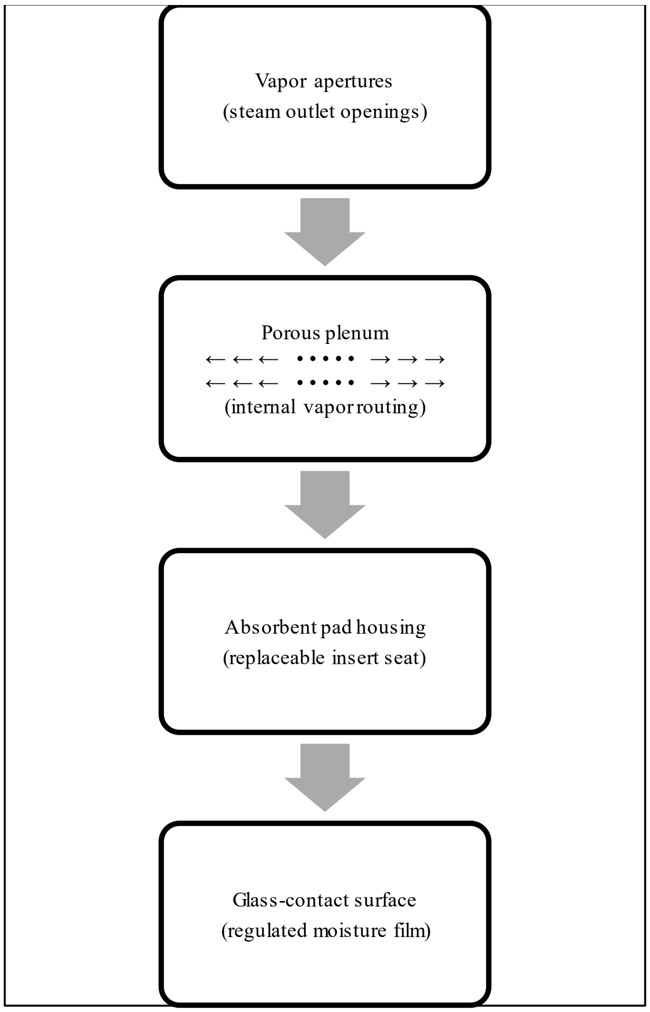

Fig. 2. View of the wiper head illustrating internal vapor routing through a porous plenum and regulated moisture transfer toward the glass-contact surface.

- Vapor Generation

The process begins with a water reservoir combined with a heating source that produces water vapor during system operation. This stage provides the moisture needed for the cleaning process and acts as the starting point of the model. The goal is not simply to generate vapor, but to supply a controlled and stable source of moisture that can be used during wiping.

- Vapor Delivery

After generation, the vapor is directed through a dedicated pathway toward the wiping structure. This pathway guides the vapor in a controlled direction instead of allowing it to disperse freely inside the cabin. By controlling the movement of vapor, the system ensures that moisture reaches the intended area in a predictable and consistent way.

- Moisture Distribution and Regulation

Before reaching the windshield surface, the vapor passes through a porous moisture-regulating structure positioned near the wiping interface. This component plays an important role in the model. Instead of releasing vapor directly onto the glass, it distributes the vapor internally through its porous body, allowing moisture to spread more evenly. This helps moderate condensation and reduces the possibility of uncontrolled dripping while maintaining a stable moisture level.

- Glass Surface Interaction

The final stage occurs when the wiping structure moves across the interior windshield surface. At this point, mechanical wiping works together with the regulated moisture layer to remove fog and residues from the glass. The cleaning effect therefore results from the interaction between controlled moisture delivery and wiping motion rather than from either action alone.

Overall, the operational mechanism shows how the model manages moisture step by step, from vapor generation to surface interaction. By coordinating these components within a single process, the proposed design aims to maintain interior windshield clarity in a controlled and stable manner.

To provide a clearer overview of the proposed model, Table I summarizes the main components and their roles within the overall moisture management process. The table highlights how each component contributes to vapor generation, routing, regulation, and interaction with the windshield surface. This summary is intended to support understanding of the system design and its operational logic.

TABLE I. SUMMARY OF MODEL COMPONENTS AND THEIR FUNCTIONS

Component	Main Function	Role in Moisture Management
Vapor Generation Unit	Produces water vapor from the reservoir	Provides a controlled moisture source
Vapor Delivery Pathway	Guides vapor toward the wiper head	Ensures directed and stable vapor movement
Vapor Outlets	Releases vapor into the internal distribution area	Enables controlled vapor entry to the wiping interface
Porous Moisture-Distribution Structure	Diffuses and regulates vapor	Prevents concentrated vapor release and supports uniform moisture spread
Glass-Contact Wiping Interface	Performs mechanical wiping	Removes fog and residues using a moderated moisture layer

IV. Design Rationale and Conceptual Advantages

The design of the proposed model is based on a simple idea: moisture should be controlled before it reaches the interior windshield surface. Instead of releasing vapor directly onto the glass, the system guides and regulates moisture through a structured path that works together with the wiping movement. This approach was chosen to reduce sudden condensation and to maintain a more stable cleaning process.

One of the main design considerations is the use of a porous distribution element inside the wiper head. The purpose of this component is to spread vapor gradually rather than allowing it to reach the glass as concentrated steam. By distributing moisture internally, the system creates a thin and more uniform moisture layer, which helps the wiping action remove fog and residues more effectively.

Another important aspect of the design is the integration between moisture delivery and mechanical wiping. In many conventional approaches, moisture control and wiping operate separately. In the proposed model, however, these two actions are coordinated. The presence of a moderated moisture layer makes wiping smoother and reduces the chance of uneven cleaning or localized fog accumulation.

The model also aims to address practical conditions inside the vehicle cabin. Since the interior environment is enclosed, uncontrolled vapor release may increase fogging instead of reducing it. For this reason, the design emphasizes regulation and gradual transfer of moisture, allowing the system to support visibility without introducing excessive humidity near the driver's field of view.

From a technical perspective, the performance of the proposed system is expected to depend on several key parameters, including the vapor generation rate, vapor flow control, permeability of the porous distribution structure, and wiping speed. These parameters influence moisture transfer behavior, condensation regulation, and the stability of the moisture layer formed on the glass surface. Although the present study does not provide a quantitative model, these factors define the operational envelope of the system and represent critical variables for future analytical and experimental investigation.

V. Discussion

The proposed vapor-assisted wiping model can be viewed as a complementary approach to existing windshield defogging solutions rather than a replacement for them. Previous studies have mainly focused on controlling environmental conditions inside the vehicle cabin, such as airflow distribution or thermal regulation. For example, in [8], the authors developed a predictive HVAC control model that adjusts cabin parameters based on fogging probability, while [2] explored improvements in airflow distribution through air duct design. These approaches demonstrate the importance of climate and ventilation control; however, they primarily operate at the cabin level and do not directly manage moisture at the glass surface.

Other works have highlighted the complexity of fogging and defogging phenomena and the range of available mitigation strategies. The review provided by [7] shows that most existing solutions rely on environmental control, material treatments, or airflow management. Similarly, computational and numerical investigations have focused on condensation prediction and mist behavior, as seen in studies such as [1], [14]. While these studies improve understanding of fog formation, they generally address the problem from an analytical or simulation perspective rather than through direct surface interaction.

The present study takes a different direction by focusing on controlled moisture handling at the interior windshield surface itself. Instead of depending solely on ambient air regulation, the proposed model introduces a structured pathway that guides vapor through a porous interface before contact with the glass. This idea aligns with earlier efforts that emphasized humidity distribution control [10], but extends the concept by combining moisture regulation with mechanical wiping in a coordinated manner.

In addition, intelligent windshield concepts and sensing-based approaches have been proposed to support safer driving conditions [9], and fog detection methods have been explored to monitor condensation behavior [13]. The current model differs from these approaches by focusing less on sensing and prediction and more on the physical interaction between moisture and the glass surface during cleaning.

From a practical perspective, the design also reflects broader discussions about future windshield applications and integrated interaction spaces [12]. By organizing vapor generation, routing, and wiping within a single operational process, the model offers a simple but structured way to address interior fogging without relying exclusively on HVAC performance or complex control systems.

The effectiveness of the proposed model is expected to vary depending on environmental conditions such as cabin humidity, temperature differences, and airflow patterns, which may influence condensation dynamics and moisture distribution.

Overall, the contribution of this study lies in shifting attention from large-scale environmental control toward local surface-level moisture management. This perspective does not conflict with existing methods; instead, it complements them by introducing a direct interaction mechanism that may support more stable visibility under varying cabin conditions.

This positioning highlights the role of the proposed model as a complementary approach rather than a replacement for existing HVAC-based solutions.

VI. Limitations and Future Work

The present study focuses on introducing and explaining the design concept of a vapor-assisted wiping model for interior windshield moisture management. As a result, the work remains at the conceptual and architectural level and does not include experimental validation or real-world performance measurements. The practical effectiveness of the system under different environmental conditions, driving scenarios, and humidity levels, therefore, requires further investigation.

Another limitation is that the current model does not evaluate energy consumption, long-term durability, or maintenance aspects of the proposed design. These factors may influence practical implementation and should be explored in future developments. In addition, the interaction between vapor flow, material properties, and wiping speed has not yet been analyzed quantitatively.

Future work can focus on building a functional prototype and conducting controlled experiments to evaluate visibility improvement and moisture regulation performance. Computational studies, such as airflow and condensation simulations, may also help optimize vapor distribution and support design refinement. Further research could additionally explore integration with existing HVAC or sensing systems to create hybrid solutions that combine environmental control with direct surface-level moisture management.

The present study is limited to a conceptual system design and does not include experimental validation, simulation analysis, or quantitative performance evaluation. As a result, the effectiveness of the proposed model under different environmental conditions, such as varying humidity levels, temperature gradients, and driving scenarios, has not yet been verified. In addition, key technical parameters-such as vapor generation rate, flow control mechanisms, porous material properties, and wiping speed-have not been quantitatively analyzed in the current work. These parameters are expected to play a critical role in system performance and require further investigation. Future work will focus on developing simulation models and prototype implementations to evaluate moisture transfer behavior, visibility improvement, and system efficiency. Experimental validation under controlled and real-world conditions will also be necessary to assess the practical applicability of the proposed approach.

VII. Conclusion

This study presented a vapor-assisted wiping model designed to improve moisture management on the interior side of vehicle windshields. The proposed approach focuses on guiding and regulating vapor before it reaches the glass surface, allowing wiping action to interact with a controlled moisture layer rather than uncontrolled vapor flow. By organizing vapor generation, delivery, and surface interaction within a single design, the model offers a practical way to support windshield clarity inside the enclosed cabin environment.

From a practical perspective, the proposed model can support improved driver visibility under conditions of high humidity and rapid fog formation, where traditional HVAC systems may respond slowly. By enabling controlled moisture application directly at the windshield surface, the system has the potential to enhance driving safety, reduce visibility fluctuations, and provide a more stable defogging performance within the vehicle cabin.

The work highlights an alternative perspective that complements existing defogging strategies, shifting attention from broad cabin climate control toward direct surface-level moisture handling. Although the model remains conceptual at this stage, it provides a clear foundation for future development and evaluation of interior windshield cleaning systems.

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AI Assistance Statement

As a non-native English speaker, Generative AI tools were used only to support language editing and improve clarity of the manuscript. All scientific ideas, system design, analysis, results, and conclusions were developed by the author. The manuscript was carefully reviewed and revised, and full responsibility for its accuracy, originality, and integrity is maintained by the author.

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