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An integrated On-Vehicle E-filtration System for Roadway Air Quality Enhancement

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Abstract - *Roadway air pollution remains a critical environmental and public health challenge due to the high concentration of particulate matter and gaseous pollutants in near-road environments. Conventional mitigation strategies largely focus on emission control at the source or large-scale infrastructure-based solutions, for dynamically polluted traffic corridors. This paper proposes an Integrated On-Vehicle E-Filtration System for Roadway Air Quality Enhancement. The proposed system utilizes vehicle-induced airflow through an aerodynamic intake duct positioned in the frontal stagnation zone, enabling passive air capture without additional propulsion energy. Particulate matter ($PM_{2.5}$ and PM_{10}) is removed using a electrostatic filtration module, where electrically charged plates capture suspended particles with low pressure drop. The filtered air is subsequently routed through a photocatalytic neutralization chamber activated by UV-LEDs, facilitating the breakdown of selected gaseous pollutants into less harmful compounds. An ACU is integrated with vehicle electronics, regulates system operation based on real-time air quality, vehicle speed, and power availability. Purified air is discharged through an angled outlet located near the upper region of the front wheel arch, strategically designed to prevent re-entrainment with tire-generated dust. The system is modular, scalable for four-wheelers, and compatible with existing automotive architectures. The system demonstrates the feasibility of a vehicle-integrated, motion-assisted approach for roadway air quality enhancement.*

***Key Words*: On-Vehicle Air Pollution Control, Roadway Air Quality Enhancement, Electrostatic Particle Filtration, Photocatalytic Air Neutralization, $PM_{2.5}$ and PM_{10} Mitigation, Adaptive Control Unit (ACU), Vehicle-Induced Airflow, Smart E-Filtration System, Near-Road Pollution Mitigation, Automotive Environmental Systems**

1. Introduction

Rapid urbanization and the continuous growth of vehicular traffic have significantly deteriorated air quality in roadway environments. Traffic corridors are characterized by elevated concentrations of particulate matter ($PM_{2.5}$ and PM_{10}) and gaseous pollutants, primarily due to vehicle exhaust emissions, tire and brake wear, and resuspension of road dust.

Prolonged exposure to such pollutants poses serious risks to public health, particularly for pedestrians, cyclists, roadside residents, and traffic personnel Despite advancements in emission regulations and cleaner propulsion technologies, near-road air pollution remains a persistent challenge in densely populated urban regions.

Conventional air pollution mitigation strategies largely focus on controlling emissions at the source or deploying stationary air purification infrastructure. While emission control technologies have achieved notable success, they do not address pollutants generated from non-exhaust sources or the accumulation of contaminants in dynamic traffic environments. Similarly, fixed roadside air purification systems are limited by high installation costs, space constraints, and restricted spatial coverage. These limitations highlight the need for innovative, mobile, and decentralized approaches capable of interacting directly with polluted roadway air.

In recent years, growing attention has been directed toward non-exhaust emission sources such as tire wear, brake wear, and resuspended road dust, which contribute substantially to particulate matter concentrations in urban traffic settings. These sources are largely unaffected by powertrain electrification and tightening emission norms, indicating that improvements in propulsion technology alone are insufficient to achieve meaningful reductions in near-road particulate pollution. Furthermore, pollutant accumulation in the immediate vicinity of moving vehicles creates highly localized exposure zones that are not adequately addressed by city-scale monitoring or centralized mitigation strategies. This context underscores the necessity for localized, adaptive, and mobility-aware pollution control solutions.

Recent research has explored advanced air filtration and photocatalytic techniques for pollutant removal in roadside environment applications. However, the integration of such technologies into moving vehicles for active treatment of roadway air remains largely unexplored. Vehicles inherently interact with large volumes of air during motion, presenting an untapped opportunity to utilize vehicle-induced airflow for environmental mitigation without substantial additional energy consumption. Motivated by this gap, this system proposes an Integrated On-Vehicle E-Filtration System for Roadway Air Quality Enhancement.

The primary objective of this work is to design and assess the feasibility of a vehicle-mounted system that combines electrostatic particle filtration, UV-assisted photocatalytic neutralization, and adaptive electronic control to treat near-road ambient air during normal vehicle operation. The proposed approach aims to complement existing emission reduction strategies by introducing a practical, scalable, and motion-assisted solution for localized air quality improvement in traffic environments.

2. Problem Statement

Roadway air pollution remains a critical concern in urban transportation environments due to the high concentration of particulate matter and gaseous pollutants in the immediate vicinity of moving vehicles. While regulatory efforts and advances in vehicle emission control technologies have significantly reduced tailpipe emissions, they do not address pollutants generated from non-exhaust sources such as tire wear, brake wear, and resuspended road dust. These non-exhaust emissions contribute substantially to $PM_{2.5}$ and PM_{10} levels along traffic corridors and continue to impact near-road air quality regardless of vehicle electrification or fuel type.

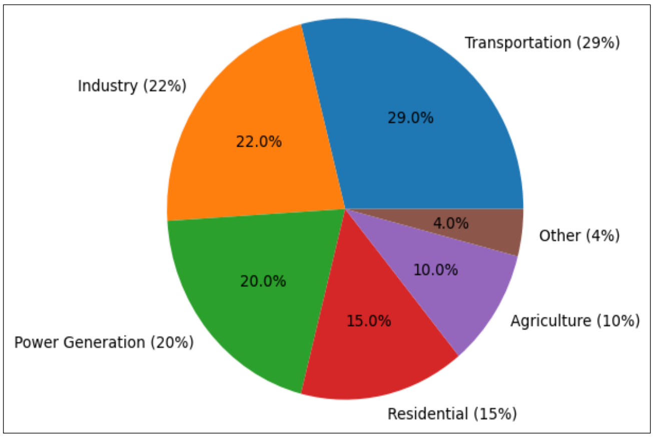

FIG -1.: Sources of air pollution: 2025 (Estimated Values)

Existing mitigation strategies predominantly rely on stationary air purification systems or large-scale urban infrastructure, which are limited by high implementation costs, space constraints, and restricted spatial effectiveness. Such approaches are inherently unable to adapt to the dynamic nature of traffic-induced pollution, where pollutant concentration varies with vehicle density, speed, and road conditions. Consequently, localized exposure zones persist around vehicles and along roadways, particularly in congested urban areas.

Furthermore, current vehicle-based technologies focus primarily on protecting the cabin air quality or reducing emissions at the source, offering little to no capability for treating ambient roadway air. The potential of utilizing vehicle-induced airflow for active air purification during normal driving operation remains largely unexploited. There is a lack of practical, vehicle-integrated systems capable of capturing, treating, and redistributing near-road air without imposing significant aerodynamic penalties or energy consumption.

Therefore, the core problem addressed in this study is the absence of a feasible, mobile, and decentralized solution that can actively mitigate near-road air pollution by leveraging existing vehicle motion and onboard electronic control. Addressing this gap is essential for developing complementary strategies that enhance roadway air quality beyond conventional emission control measures.

3.Literature Review

Air pollution in transportation corridors has been extensively studied due to its strong correlation with adverse health outcomes and environmental degradation. Numerous studies have established that near-road environments exhibit significantly higher concentrations of particulate matter ($PM_{2.5}$ and PM_{10}) compared to urban background levels, primarily due to vehicular activity. Traditional mitigation efforts have therefore focused on reducing emissions at the source through stricter emission norms, advanced combustion control, and the adoption of alternative propulsion technologies such as electric and hybrid vehicles.

Vehicle emission control technologies, including catalytic converters, diesel particulate filters, and exhaust gas recirculation systems, have proven effective in lowering tailpipe emissions. However, recent research highlights that non-exhaust sources—such as tire wear, brake wear, and resuspended road dust—now represent a dominant contribution to particulate pollution in urban traffic environments. These emissions persist irrespective of fuel type or powertrain technology and are expected to increase with vehicle mass and traffic density, thereby limiting the effectiveness of emission-only mitigation strategies.

To address ambient air pollution, several stationary and semi-stationary air purification approaches have been proposed, including roadside filtration units, photocatalytic surfaces, and urban-scale air-cleaning installations. While such systems demonstrate pollutant reduction under controlled conditions, their practical deployment is constrained by high infrastructure costs, limited coverage, maintenance challenges, and reduced adaptability to changing traffic patterns. As a result, their impact on localized roadway air quality remains limited.

Electrostatic particle filtration and photocatalytic oxidation techniques have been widely investigated for indoor air purification and industrial emission treatment due to their ability to remove fine particulates and degrade gaseous pollutants. Recent studies have explored compact electrostatic filters and UV-assisted photocatalytic systems with low pressure drop and moderate energy requirements. However, the application of these technologies in moving vehicles has largely been restricted to cabin air purification, with minimal focus on treating external ambient air.

A limited number of conceptual studies have suggested the use of mobile platforms for environmental monitoring or pollution sensing; however, the integration of active air treatment mechanisms into vehicles for near-road pollution mitigation remains insufficiently explored.

In particular, the combined use of vehicle-induced airflow, electrostatic filtration, photocatalytic neutralization, and adaptive electronic control within a single on-vehicle system has not been comprehensively addressed in existing literature.

3.1 Research Gap Summary

it is evident that there is a lack of vehicle-integrated, motion-assisted systems designed to actively treat ambient roadway air. Existing solutions either focus on emission reduction, cabin air quality, or stationary purification, leaving a gap for a decentralized, adaptive, and feasible on-vehicle roadside air filtration and neutralization approach. This gap motivates the development of the proposed Integrated On-Vehicle E-Filtration System.

4. Methodology

This section describes the proposed Integrated On-Vehicle E-Filtration System, including its overall architecture, operating principle, electronic control strategy, and technical feasibility considerations. The methodology focuses on the integration of mechanical air-handling components with electronic control to enable active treatment of near-road ambient air during normal vehicle operation.

4.1 System Architecture and Operating Principle

The proposed system is designed as a modular unit integrated into the vehicle body structure. It utilizes vehicle-induced airflow generated during motion to capture ambient roadway air without the use of additional blowers. An aerodynamic intake duct is positioned in the frontal stagnation zone of the vehicle, where air pressure is naturally elevated, enabling passive air ingestion with minimal aerodynamic penalty.

Captured air first passes through an electrostatic particle filtration module, where suspended particulate matter ($PM_{2.5}$ and PM_{10}) is removed using electrically charged collection plates. The electrostatic filtration approach is selected due to its high particle capture efficiency and low pressure drop compared to conventional mechanical filters Collected particulates are directed toward a dedicated dust collection chamber designed for periodic maintenance.

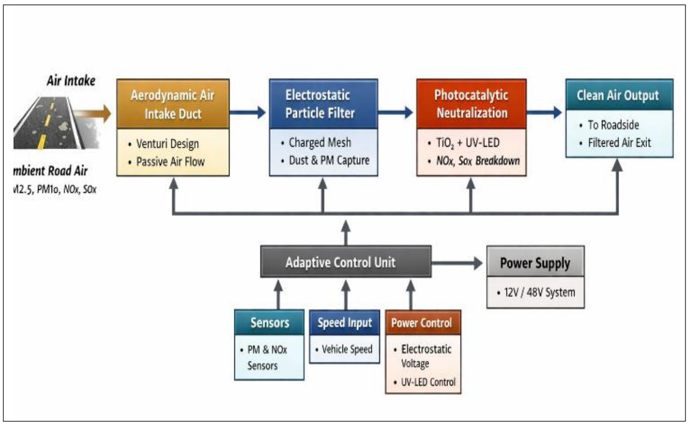

FIG -2. A: System Architecture EFS

Following particulate removal, the air flows into a UV-assisted photocatalytic neutralization chamber. In this stage, ultraviolet light activates a photocatalyst surface, facilitating the degradation of selected gaseous pollutants into less harmful compounds. The treated air is then routed toward an angled discharge outlet located near the upper region of the front wheel arch, close to the headlamp assembly. This outlet orientation is deliberately designed to promote outward dispersion while preventing re-entrainment with tire-generated dust.

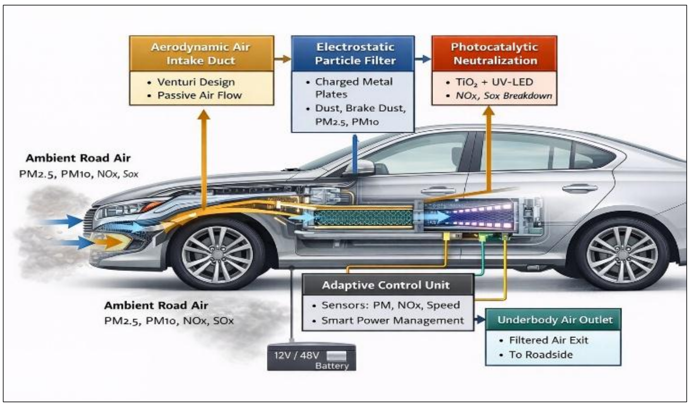

FIG -2. B: System Architecture feasibility of IOV

4.2 Electronic Architecture and Adaptive Control Unit

An Adaptive Control Unit (ACU) governs the operation of the proposed system. The ACU interfaces with onboard vehicle networks using standard automotive communication protocols such as CAN or LIN. Input signals include vehicle speed, ambient air quality indicators, system voltage, and filter status. Based on these inputs, the ACU dynamically regulates the activation of the electrostatic filter and UV-LED array to balance purification effectiveness and power consumption.

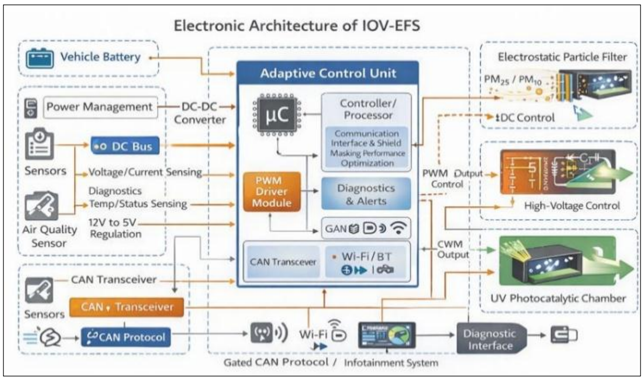

FIG -3. A: Electronic Architecture of IOV-EFS

The control strategy enables conditional system operation, ensuring that the E-filtration system is active primarily during suitable driving conditions, such as moderate vehicle speeds where airflow is sufficient for effective treatment. This adaptive approach enhances system efficiency while minimizing electrical load on the vehicle.

4.2.1 Power management Unit

The proposed system is powered by the vehicle's existing electrical supply, operating from either a 12 V or 48 V battery depending on the vehicle platform. A dedicated Power Management Unit (PMU) conditions the input voltage and provides regulated power levels required by the control electronics, sensors, and actuator driver circuits. The PMU incorporates DC–DC conversion, over-current protection, and thermal safeguards to ensure reliable and safe operation under automotive environmental conditions. This approach eliminates the need for external power sources and supports scalable deployment across different vehicle categories.

4.2.2 Sensing and Data Acquisition

A distributed sensor module is employed to monitor both environmental and system-level parameters. The sensing unit includes particulate matter sensors for $PM_{2.5}$ and PM_{10} concentration measurement, temperature sensors for thermal monitoring, and electrical sensors for voltage and current diagnostics. In addition, vehicle speed and ignition status are acquired via the vehicle communication network. These inputs provide real-time feedback to the control unit, enabling adaptive system behavior based on driving conditions and pollution levels.

4.2.3 Vehicle Communication Interface

To enable coordinated operation with existing vehicle systems, the IOV-EFS incorporates a Controller Area Network (CAN) interface, with optional Local Interconnect Network (LIN) support for low-speed communication. Through this interface, the system receives essential vehicle parameters such as speed, battery state, and operational status, while also transmitting of diagnostic and health information. This communication framework ensures compatibility with modern automotive electronic control architectures.

4.2.4 Adaptive Control Unit Design

The Adaptive Control Unit (ACU) serves as the central processing and decision-making component of the proposed system. It is implemented using an automotive-grade microcontroller capable of real-time signal processing and communication handling. The ACU continuously processes sensor data and vehicle parameters to determine appropriate operating modes for the filtration system. Control algorithms embedded within the ACU dynamically adjust actuation intensity to balance filtration effectiveness and energy consumption. Fault detection and diagnostic routines are also integrated to ensure system reliability and safety.

4.2.5 Actuation and Driver Control

A dedicated Pulse Width Modulation (PWM) driver module interfaces between the ACU and the filtration actuators. The PWM signals regulate the voltage applied to the electrostatic particle filter and control the intensity of the UV-LEDs within the photocatalytic chamber. This approach allows fine-grained control over filtration performance while minimizing power usage, particularly under varying vehicle speeds and pollution levels.

4.2.6 Electrostatic and Photocatalytic Filtration

The electrostatic particle filtration module removes suspended particulate matter such as $PM_{2.5}$, PM_{10}, brake dust, and road dust through charged collection plates. Captured particles are directed into a dedicated dust collection chamber for periodic maintenance. Downstream of the particulate filter, a UV-assisted photocatalytic chamber employs ultraviolet LEDs and a titanium dioxide-coated surface to facilitate the neutralization of selected gaseous pollutants, including nitrogen oxides and volatile organic compounds. Positioning the photocatalytic stage after particulate removal reduces catalyst fouling and improves operational longevity.

4.2.7 Diagnostic and User Interface Integration

System diagnostics and operational status are communicated to the vehicle infotainment system or an external service interface through the CAN network. This enables condition monitoring, maintenance alerts, and fault reporting without requiring additional standalone displays. Such integration supports ease of use and aligns with existing automotive service practices.

4.3 End-to-End Signal Flow of IOV-EFS

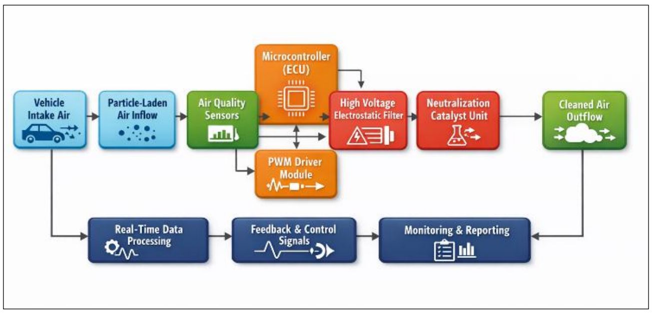

FIG -3. B: Signal flow of IOV-EFS

The signal flow starts from environmental sensing which include Particulate matter & Gaseous pollutants ($PM_{2.5}$,PM_{10},NO_x,CO,VOCs) passes through conditioning and digital processing in the controller. Parallel to sensor inputs, vehicle data arrives digitally. ACU Compares values with thresholds, after Microcontroller generates PWM signals uses vehicle CAN data for context-aware decisions, and ends with PWM-controlled actuation. PWM duty cycle represents Filtration intensity and UV intensity level of electrostatic and photocatalytic modules in a closed-loop architecture.

In Electrostatic Particle Filter High voltage creates electrostatic field after Charged particles are attracted and trapped next UV-LEDs activate TiO_2 coating and Chemical neutralization of gaseous pollutants occurs. The ACU generates a PWM-based control waveform to regulate UV LED intensity inside the photocatalytic neutralization chamber, enabling adaptive pollutant treatment with optimized power consumption Feedback Signals confirms operation and Diagnostic Signals continuously self-corrects.at the end data displayed on vehicle infotainment.

4.4 Contributions of the Proposed Methodology

The key contributions of the proposed methodology are summarized as follows:

a. Utilization of vehicle-induced airflow for ambient air treatment without auxiliary propulsion devices
b. Integration of electrostatic filtration and photocatalytic neutralization in a moving vehicle platform
c. Angled discharge strategy to prevent interaction with tire-generated particulate matter
d. Adaptive electronic control enabling intelligent, condition-based operation

4.5 Technical Feasibility Considerations

The proposed system is designed to operate within the constraints of existing automotive electrical and mechanical architectures. The electrostatic filter and UV-LED modules require relatively low power, making the system suitable for conventional internal combustion, hybrid, and electric vehicles. Maintenance requirements are addressed through a removable dust collection unit and durable photocatalytic surfaces with extended service life. Overall, the methodology emphasizes practical implementation, scalability, and minimal impact on vehicle performance.

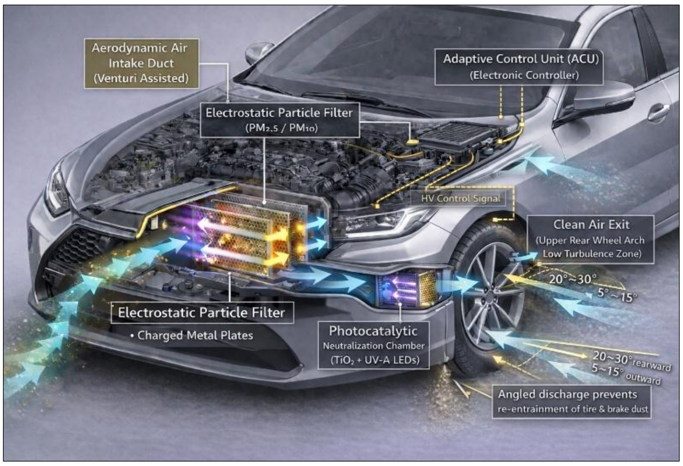

FIG -4. A: Implementation of IOV-EFS

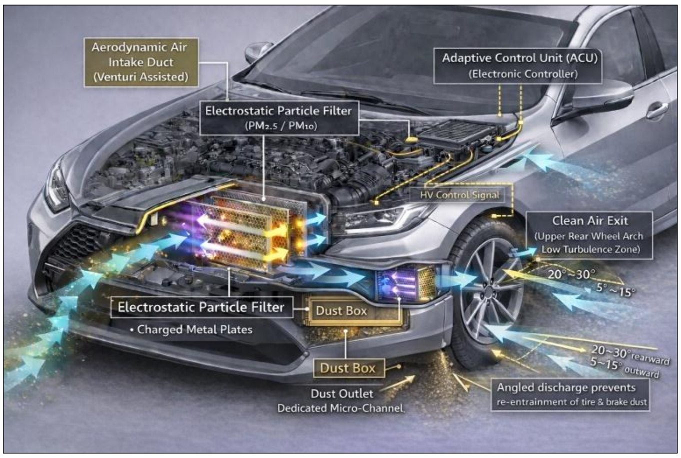

FIG -4. B: Implementation of IOV-EFS

5. Results and Discussion

This section presents a conceptual performance evaluation and feasibility-based discussion of the proposed Integrated On-Vehicle E-Filtration System. Since the study focuses on system design and technical feasibility, the results are derived from analytical reasoning, component-level characteristics reported in existing literature, and operational constraints of automotive platforms.

5.1 Expected Particulate Matter Removal Performance

Electrostatic particle filtration has been widely reported to achieve high capture efficiency for fine particulate matter, particularly in the $PM_{2.5}$ and PM_{10} size ranges, while maintaining a low pressure drop. In the proposed system, the electrostatic filtration module is positioned immediately downstream of the aerodynamic intake duct, enabling effective interception of suspended particles present in near road air.

Based on the reported performance of compact electrostatic filters, the proposed configuration is expected to provide meaningful reduction of particulate concentrations within the treated airflow volume. While absolute removal efficiency depends on factors such as particle charge density, airflow velocity, and plate geometry, the use of vehicle-induced airflow allows continuous interaction with ambient roadway air during normal driving operation.

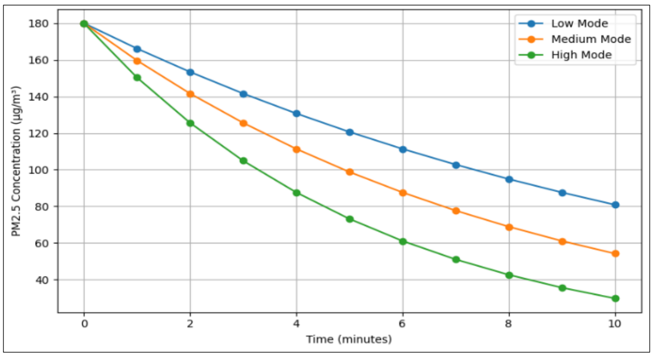

FIG -5. A: Predicted PM2.5 Reduction vs Time (IOV-EFS)

ACU implement with 3 operating modes based on sensor readings + vehicle speed. Modes come from control thresholds value. The system is evaluated under three PWM duty cycle settings representing low, medium and high actuation intensities

5.2 Gaseous Pollutant Neutralization Potential

The UV-assisted photocatalytic chamber is intended to complement particulate filtration by targeting selected gaseous pollutants commonly found in traffic environments. Photocatalytic oxidation has been shown to degrade compounds such as nitrogen oxides and volatile organic compounds under ultraviolet activation. In the proposed methodology, the photocatalytic stage is positioned after particulate removal to prevent catalyst surface fouling, thereby enhancing operational effectiveness.

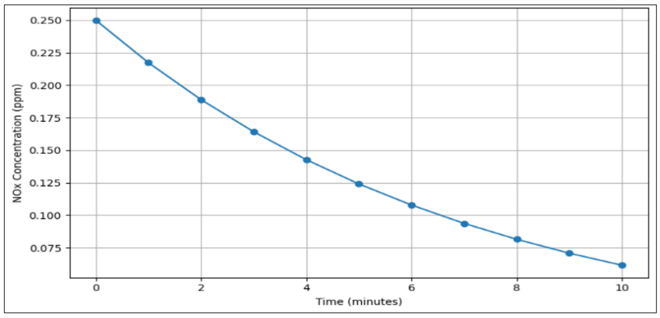

FIG -5. B: NOx Reduction vs Time graph

Although the system is not designed for complete gas removal its contribution to localized pollutant neutralization supports incremental roadway air quality enhancement. These results are obtained through analytical modeling based on exponential decay approximation and assumed airflow/filtration parameters derived from typical automotive filtration performance.
Initial NOx = 0.25 ppm (typical roadside level)
NOx reduces from 0.25 ppm to 0.062 ppm after 10 min.
Approx. Reduction: (0.25 – 0.062/0.25) *100 = 75.2%
The analytical model predicts approximately 75% NOx reduction within 10 minutes of continuous photocatalytic operation

5.3 Airflow Behavior and Discharge Strategy

The angled discharge outlet located near the upper region of the front wheel arch plays a critical role in system effectiveness. By orienting the outlet away from the tire road interaction zone, the design minimizes the risk of re-entrainment of tire-generated dust into the purified airflow. This discharge configuration promotes outward dispersion of treated air into the surrounding roadway environment while maintaining compatibility with vehicle body packaging constraints. The placement near the headlamp fender region or near the OVRM region as mentioned in the fig 4.B assists in directing airflow away from turbulent wake zones to mechanical grill provision.

5.4 Power Consumption and System Integration

From an electrical perspective, the electrostatic filtration module and UV-LED array are characterized by relatively low power demand, making the system compatible with existing automotive electrical architectures. Adaptive operation through the ACU ensures that system activation is aligned with favorable driving conditions, thereby reducing unnecessary energy consumption. Integration with standard vehicle communication protocols enables scalable deployment across different vehicle categories without significant modification to onboard systems.

Compared to stationary roadside air purification systems, the proposed on-vehicle approach offers improved spatial coverage and dynamic interaction with polluted air in traffic corridors. Unlike cabin air purification systems, the proposed design directly targets ambient roadway air, addressing an often-overlooked pollution domain. While the system does not replace emission control technologies, it provides a complementary, decentralized mechanism for localized air quality enhancement. The results of this analysis suggest that vehicle-integrated air treatment systems can play a supporting role in broader urban air pollution mitigation strategies.

6. Limitations and Assumptions

The proposed Integrated On-Vehicle E-Filtration System is subject to several limitations and assumptions that should be considered when interpreting the results of this study. the system is intended to provide localized enhancement of roadway air quality rather than large-scale or city-wide pollution reduction. Its effectiveness is inherently dependent on traffic density, vehicle speed, and ambient pollutant concentration, which vary across different driving environments. Excessive intake airflow does not inherently damage the system, but it reduces pollutant residence time and may increase particulate loading and blower power demand; therefore, adaptive flow regulation is required for safe and efficient operation

The methodology assumes the availability of sufficient vehicle-induced airflow for passive air capture. At very low vehicle speeds or during stationary conditions, airflow through the system may be reduced, limiting filtration performance. Additionally, the electrostatic filtration efficiency is influenced by particle size distribution, humidity, and electrode condition, while photocatalytic performance depends on UV intensity and catalyst surface cleanliness.

Maintenance-related limitations include the requirement for periodic removal of accumulated particulate matter from the dust collection chamber and long-term degradation of photocatalytic surfaces. The study assumes regular maintenance in line with vehicle service schedules. Furthermore, the proposed system does not address all classes of gaseous pollutants and is not designed to replace conventional emission control technologies.
As such, quantitative performance metrics are indicative rather than definitive and should be once validated through future experimental on real time vehicle with dynamic different condition & scenarios.

7. Conclusion

This paper presented an Integrated On-Vehicle E-Filtration System designed to enhance roadway air quality through active treatment of ambient near-road air during vehicle operation. By leveraging vehicle-induced airflow, electrostatic particle filtration, UV-assisted photocatalytic neutralization, and adaptive electronic control, the proposed system introduces a novel, decentralized approach to complement existing air pollution mitigation strategies. analysis demonstrates that integrating air treatment mechanisms into moving vehicles is technically achievable within current automotive mechanical and electrical constraints. The modular and scalable design enables applicability for four-wheelers without significant impact on vehicle aerodynamics or energy consumption. the proposed system has the potential to contribute to localized air quality enhancement in high-traffic corridors,

particularly in dense urban environments where non-exhaust emissions remain a dominant concern. While further experimental validation is required on different no of vehicles as mentioned in limitation. this system establishes a foundational framework for future research on vehicle-integrated for air pollution mitigation factors and supports the development of smart, mobility-assisted solutions for sustainable transportation ecosystems.

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