Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/BA08.20250324
Published: December 20, 2025

Design and Development of a Post-Ignition Exhaust Purge System for Engine Emission Control

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Abstract

This study presents the design and development of a Post-Ignition Exhaust Purge System (PIEPS) to reduce residual exhaust gases that can remain trapped in the exhaust system after engine shutdown, thereby reducing hydrocarbon retention, moisture accumulation, and unfavorable exhaust conditions before subsequent engine restart. Conventional emission-control strategies primarily operate during engine running, leaving the post-ignition window comparatively unmanaged. This study reports the design, fabrication, and experimental evaluation of a Post-Ignition Exhaust Purge System (PIEPS) that introduces a short-duration airflow into the exhaust line immediately after ignition-off. The system integrates a DC 12 V air pump, a high-temperature-resistant air injection nozzle installed between the upstream oxygen sensor and the catalytic converter, and a timer-based activation circuit triggered by ignition-off. Emission measurements were collected under controlled workshop conditions using three consecutive test days for both baseline (before PIEPS) and post-installation phases, focusing on idle and idle with A/C operating conditions. The results were compiled using three-day averages and compared using comparative tables and bar charts. Averaged emission data show reductions in HC and CO after PIEPS installation under the tested conditions, and percentage reductions were computed from the before/after averages. No ECU reprogramming was required, and the system is intended as a

retrofit-friendly approach for aging vehicles where residual gas retention and exhaust system contamination may be more pronounced.

Keywords
Exhaust purge system, catalytic converter, oxygen sensor stabilization, back pressure reduction, emission control.

1. Introduction
Modern internal combustion engine (ICE) vehicles rely on a combination of closed-loop fuel control (which adjusts the air-fuel ratio in real time based on sensor feedback), oxygen sensors (devices that measure the amount of oxygen in the exhaust), exhaust gas re-circulation (EGR, which recirculates some exhaust gas to reduce nitrogen oxide emissions), and catalytic converters (components that facilitate chemical reactions to convert harmful gases into less toxic substances) to comply with emission regulations. These technologies are highly effective while the engine is running; however, the behavior of exhaust gases after engine shutdown has received comparatively little research attention. Once the engine is switched off, exhaust gas flow abruptly ceases, leaving a mixture of unburned hydrocarbons (HC), carbon monoxide (CO), moisture, and residual combustion by-products trapped in the exhaust manifold (the component that collects exhaust gases from the engine cylinders), catalytic converter, resonator (a device that helps reduce noise), and muffler (which further reduces exhaust noise).

During the post-ignition period, these stagnant gases gradually cool and condense on internal exhaust surfaces. Over time, this process contributes to carbon deposition, moisture accumulation, oxygen sensor contamination, and increased exhaust back pressure. Such effects are especially pronounced in high-mileage vehicles, where aging components, thermal cycling, and prolonged exposure to unburned residues accelerate degradation of emission-control elements. As a result, catalytic converter efficiency declines, oxygen sensor feedback becomes unstable, and cold-start emissions tend to increase.

In developing countries like Bangladesh, this issue is worsened by long vehicle service life, frequent stop-and-go driving, inconsistent fuel quality, and limited access to advanced emission-control upgrades. Many vehicles exceed 150,000 km, at which point exhaust system contamination becomes a persistent challenge. Still, most emission-reduction strategies focus on combustion optimization, fuel delivery, or improvements to catalyst materials, leaving the post-shutdown phase largely unaddressed.

Current automotive research and industry practices lack mechanisms to clear residual exhaust gases after shutdown. Conventional systems rely on engine-driven exhaust flow, which stops once the ignition is off. As a result, gases remain trapped until the engine restarts, negatively affecting early combustion, sensor response, and converter readiness. The lack of post-ignition exhaust management is a significant gap in emission-control research.

To address this gap, the present study proposes the Post-Ignition Exhaust Purge System (PIEPS)—a simple, low-cost system operating only after engine shutdown. PIEPS provides a brief, controlled airflow into the exhaust tract after ignition-off, removing trapped gases before they stagnate and condense. By focusing on the shutdown window rather than the combustion cycle, the system creates a new opportunity to improve exhaust cleanliness and emission stability. The primary research goal is to design, build, and test PIEPS with a high-mileage gasoline engine. Emission data were collected with and without PIEPS to assess changes under idle and low-load conditions. The study seeks to determine whether post-ignition purging reduces emissions, stabilizes sensors, and preserves exhaust systems. The results are important for aging fleets in resource-limited areas that need practical retrofits.

1.1 Objectives
The primary objective of this research is to design, develop, and experimentally evaluate a Post-Ignition Exhaust Purge System (PIEPS) capable of reducing residual exhaust emissions and improving exhaust-system health in internal combustion engines, particularly under real-world, high-mileage operating conditions.

To achieve this overarching goal, the specific objectives of the study are as follows:

- To design a practical post-ignition exhaust purging mechanism that operates exclusively after engine shutdown without interfering with normal engine operation, combustion, or ECU-controlled functions.
- To fabricate and integrate a custom air-injection nozzle at an optimal location between the upstream oxygen sensor and the catalytic converter, ensuring effective purging of trapped exhaust gases.
- To develop a timed control strategy using a low-voltage air pump and timer-based logic that activates the purge process for a short, controlled duration immediately after ignition-off.
- To experimentally evaluate the effect of PIEPS on exhaust emissions, with particular emphasis on hydrocarbon (HC) and carbon monoxide (CO) levels under idle and A/C-idle conditions.
- To investigate the influence of post-ignition exhaust purging on oxygen sensor stability and catalytic converter readiness, as reflected through emission behavior and lambda consistency.
- To assess the feasibility of PIEPS as a low-cost retrofit solution for high-mileage vehicles, especially in developing regions where aging automotive fleets and emission-control degradation are common.
- To identify practical limitations and future improvement opportunities related to durability, control optimization, and system scalability across different engine types.

2. Literature Review

Emission control in internal combustion engine (ICE) vehicles has historically focused on managing combustion efficiency and treating exhaust gases during active engine operation. Modern vehicles employ a combination of electronic fuel injection, closed-loop air–fuel ratio control, oxygen sensors, and catalytic converters to reduce regulated pollutants such as hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NO_x). These systems are optimized to operate when the engine is running, relying on continuous exhaust flow and elevated catalyst temperatures to achieve effective conversion of harmful exhaust constituents.

While these technologies have significantly reduced emissions during steady-state and transient driving conditions, their effectiveness is inherently limited to periods of active combustion. Once the engine is switched off, exhaust gas flow ceases immediately, and conventional emission-control systems become inactive. As a result, the exhaust system enters a post-ignition phase during which residual gases remain trapped inside the exhaust manifold, catalytic converter, and downstream exhaust components.

2.1 Exhaust Gas Behavior After Engine Shutdown

When the ignition turns off, gases from the last combustion cycles stay in the exhaust. These gases have unburned hydrocarbons, carbon monoxide, carbon dioxide, water vapor, and by-products. With no flow, these gases cool and stagnate in the exhaust.

The post-shutdown retention of exhaust gases has several implications. First, cooling of the exhaust system leads to condensation of water vapor and heavier hydrocarbons on internal surfaces. Second, stagnation prevents rapid removal of these species, allowing prolonged contact between residual gases and exhaust components. Third, in high-mileage vehicles, the presence of accumulated carbon deposits further alters the thermal and flow characteristics of the exhaust system, potentially intensifying residual gas effects.

Despite these known phenomena, the post-ignition period is often treated as a passive cooling phase rather than an actively managed stage of exhaust behavior. As a result, residual exhaust gas retention remains an under-addressed contributor to long-term exhaust system degradation and emission performance variability.

2.2 Carbon Deposition and Aging of Exhaust Systems

Carbon deposition within exhaust systems is a well-recognized issue, particularly in vehicles with extended service life. Over time, incomplete combustion, oil consumption, and repeated cold starts contribute to the formation of carbonaceous deposits along exhaust walls and within the catalytic converter substrate. In catalytic converters, these deposits accumulate within the honeycomb structure, reducing effective flow area and altering heat transfer characteristics.

A carbon-loaded catalytic converter exhibits greater thermal inertia than a cleaner unit. This means that, after engine shutdown, the converter retains heat for a longer duration and cools more slowly. Prolonged heat retention can sustain elevated temperatures within the exhaust system, even after residual gases are trapped, extending the period during which hydrocarbons and other species remain in contact with catalyst surfaces and exhaust components.

From a system-level perspective, carbon deposition and residual gas retention interact synergistically. Carbon buildup slows exhaust cooling, while slow cooling prolongs residual gas stagnation. This feedback loop can accelerate further deposition, contamination, and degradation, especially in high-mileage vehicles operating under frequent stop-and-go conditions.

2.3 Oxygen Sensor Contamination and Signal Stability

Oxygen sensors play a critical role in modern emission-control systems by providing feedback for closed-loop fuel control. Sensor performance depends on stable exposure to exhaust gases during engine operation and clean thermal cycling behavior across repeated start–stop events. However, prolonged exposure to stagnant exhaust gases during post-shutdown cooling can negatively influence sensor condition.

Residual hydrocarbons and moisture may adsorb onto sensor surfaces during cooling, particularly when exhaust temperatures decrease slowly due to carbon-induced thermal retention. Over-extended vehicle operation can contribute to delayed sensor response, signal drift, and reduced feedback stability during subsequent cold starts.

Although oxygen sensor aging is commonly attributed to long-term thermal cycling and contamination during operation, post-ignition exposure is an additional mechanism that is rarely directly addressed. Active management of exhaust gas conditions immediately after engine shutdown may therefore offer a pathway to improving long-term sensor stability.

2.4 Catalytic Converter Performance During the Post-Ignition Phase

Catalytic converters are designed to operate efficiently within a specific temperature window and under continuous exhaust flow. During engine operation, exhaust heat and gas flow maintain catalyst activity and promote the conversion of harmful pollutants. After shutdown, however, the absence of flow and the onset of cooling fundamentally change the catalyst environment.

In the post-ignition phase, residual hydrocarbons may condense or adsorb onto catalyst surfaces, particularly when cooling is slow, and carbon deposits are present. These processes can temporarily occupy active sites and, over time, contribute to catalyst deactivation or reduced conversion efficiency.

Most emission-control research focuses on catalyst performance during engine operation, cold-start warm-up, or transient driving conditions. Comparatively little attention has been paid to catalyst behavior during the shutdown and cooling phase, even though this interval may influence long-term catalyst health and subsequent emission behavior.

2.5 Existing Emission-Control Strategies and Their Limitations

Existing emission-control strategies are largely combustion-centric. Technologies such as exhaust gas recirculation, variable valve timing, and advanced catalyst formulations aim to reduce emissions during engine operation but do not address exhaust system conditions after ignition-off. Once the engine is shut down, these systems become inactive, leaving residual exhaust gases unmanaged.

Furthermore, many advanced emission-control solutions require ECU reprogramming, additional sensors, or complex integration, limiting their applicability as retrofit solutions for aging vehicles. In regions with large fleets of high-mileage vehicles, particularly in developing economies, cost and system complexity pose significant barriers to widespread adoption of advanced emission technologies.

These limitations highlight the need for simple, externally integrated, and retrofit-friendly approaches that can complement existing systems without interfering with normal engine operation.

2.6 Post-Ignition Exhaust Management as an Emerging Concept

The post-ignition phase represents a distinct operating window that is not directly addressed by conventional emission-control systems. Managing exhaust conditions during this interval offers an opportunity to reduce residual gas retention, limit condensation and deposition, and potentially improve the exhaust system's initial conditions prior to the next engine start.

A post-ignition exhaust purge system introduces controlled airflow into the exhaust tract immediately after shutdown, displacing residual gases before they stagnate and cause prolonged cooling. Unlike combustion-phase strategies, this approach operates independently of engine firing and does not require modification of ECU logic or fuel delivery.

From a conceptual standpoint, post-ignition exhaust purging targets the consequences of exhaust aging rather than combustion inefficiency. This distinction makes it particularly relevant for high-mileage vehicles where carbon buildup and exhaust contamination are already present.

2.7 Research Gap and Motivation for the Present Study

Although the mechanisms of residual exhaust gas retention, carbon deposition, oxygen sensor aging, and catalytic converter degradation are individually recognized, the literature lacks integrated, practical solutions that address these phenomena during the post-ignition phase. Most existing approaches focus on improving combustion or catalyst efficiency during engine operation, leaving the shutdown interval largely unmanaged.

The present study addresses this gap by investigating a Post-Ignition Exhaust Purge System (PIEPS) that operates only after engine shutdown. The system aims to remove trapped exhaust gases, limit extended heat retention effects associated with carbon-loaded exhaust systems, and improve exhaust system conditions prior to subsequent operation.

By focusing on a simple, timer-based, externally integrated system, the study aligns with the practical constraints of aging vehicle fleets and emphasizes retrofit feasibility. The literature gap identified in this review provides the foundation for the system design, experimental methodology, and emission evaluation presented in the subsequent sections of this paper.

3. System Design of the Post-Ignition Exhaust Purge System (PIEPS)

The Post-Ignition Exhaust Purge System (PIEPS) was designed as a simple, robust, and low-cost auxiliary exhaust-management solution that operates exclusively during the engine shutdown phase. The primary design objective was to remove residual exhaust gases from the exhaust tract immediately after ignition-off without interfering with normal engine operation, combustion processes, or ECU-controlled functions.

To achieve this, the system architecture was divided into three integrated subsystems:
(i) The exhaust-side air injection unit,
(ii) The air supply and flow path, and
(iii) The control and activation logic.

Each subsystem was designed with consideration for high-temperature operation, mechanical reliability, and retrofit feasibility.

3.1 Design Philosophy and Operating Boundary

Unlike conventional emission-control systems that function during engine operation, PIEPS is intentionally designed to remain completely inactive while the engine is running. The system is activated only after ignition shutdown, ensuring that:

- There is no disturbance to combustion airflow
- No interference with ECU fuel-mapping strategies
- No influence on exhaust gas composition during driving conditions.

The purge duration was limited to a short time window (7–10 seconds) to balance purge effectiveness with minimal electrical power consumption.

3.2 Exhaust-Side Air Injection Design

A key design consideration was the location of purge-air introduction. The air-injection point was positioned between the upstream oxygen sensor and the catalytic converter. This location was selected based on the following reasoning:

- Injecting air upstream of the oxygen sensor may distort sensor readings

- Injecting air downstream of the catalytic converter limits purge effectiveness
- Placement between the sensor and catalyst allows efficient displacement of trapped gases without sensor interference.

A custom-fabricated, high-temperature-resistant metal air nozzle was designed and manufactured using lathe machining. The nozzle features (Figure 1- Figure 10):

- An internally hollow passage to allow airflow,
- External threading for secure mounting into the exhaust wall, and
- A directional outlet to guide purge air toward the catalytic converter substrate.

This configuration ensures controlled airflow distribution inside the exhaust system during the purge cycle.

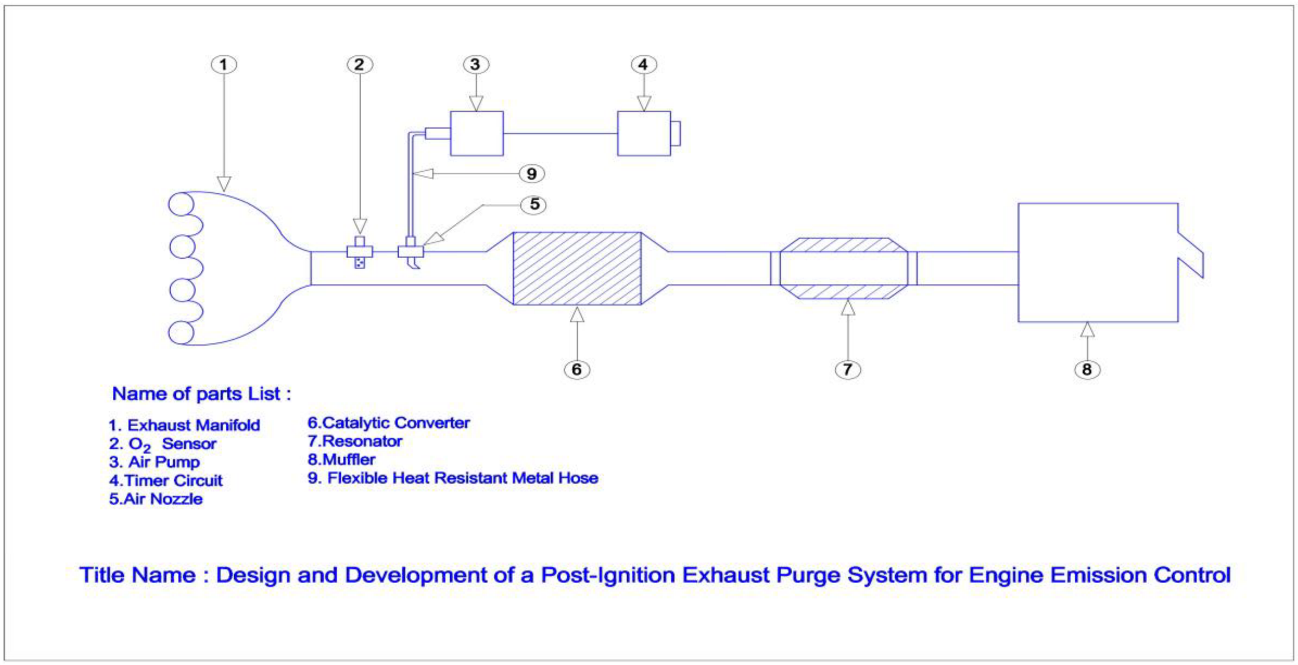

Figure 1. configuration ensures controlled airflow distribution

3.3 Air Supply and Flow Path Design

The purge airflow is generated using a compact low-voltage electric air pump. The pump was selected based on availability, power consumption, and its ability to provide sufficient airflow for short-duration exhaust scavenging.
A flexible heat-resistant metal hose connects the pump outlet to the air nozzle. This hose accommodates vibration, thermal expansion, and spatial constraints while maintaining airtight flow delivery. During activation, ambient air is drawn by the pump and injected into the exhaust tract, pushing residual gases toward the downstream exhaust components and out through the tailpipe.

The airflow path follows the natural exhaust direction, ensuring that purge air does not stagnate or reverse-flow within the system (Figure 2).

Figure 2. (a) Air pump (b) Air Nozzle

3.4 Control and Activation Logic

PIEPS employs a timer-based control strategy to regulate purge duration and ensure safe operation. The system is electrically connected to an ignition-off power source. Once the ignition is switched off:

- The timer relay is triggered
- The air pump is energized for a predefined duration (7–10 seconds)
- The pump automatically switches off after the timer expires.

This control logic ensures repeatable purge operation without requiring driver input or ECU reprogramming. The short activation window prevents unnecessary battery drain and avoids prolonged air injection into the exhaust system.

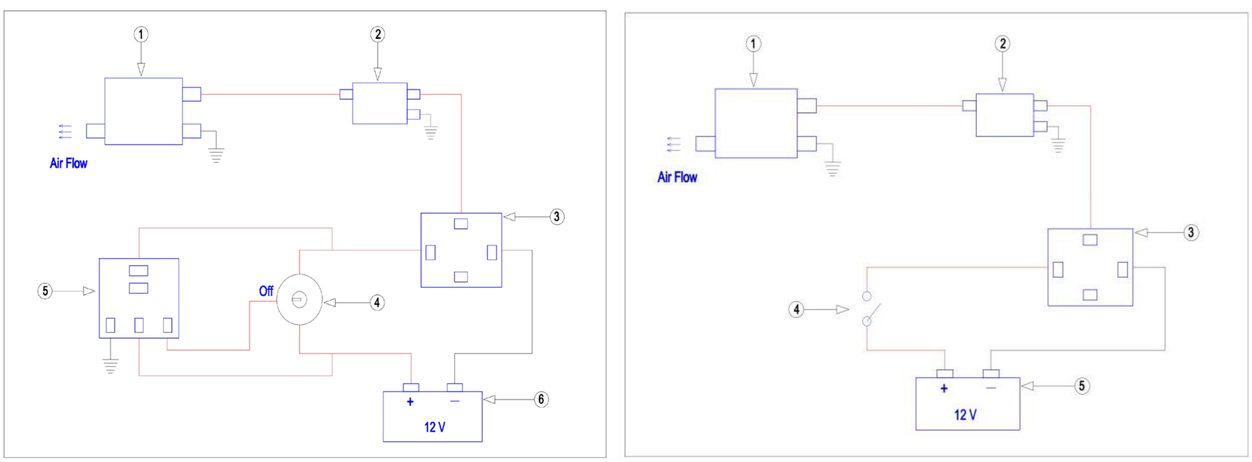

Figure 3. a. PIEPS Wiring & Timing Diagram on Figure b. PIEPS Wiring & Timing Diagram on Project

3.5 System Safety and Retrofit Considerations

Safety and retrofit compatibility were central to the system design. PIEPS does not modify fuel delivery, ignition timing, or exhaust geometry during engine operation. All components are external add-ons that can be removed without permanently altering the engine or ECU.

The use of low-voltage electrical components and passive exhaust integration minimizes the risk of electrical faults or thermal damage. Additionally, the system design allows adaptation to different exhaust layouts with minimal customization.

3.6 Design Summary

In summary, the PIEPS system design introduces a new exhaust-management function by targeting the post-ignition phase. Through a combination of strategic nozzle placement, controlled airflow delivery, and timer-based activation, the system provides an effective method for purging residual exhaust gases while maintaining simplicity, safety, and practical applicability.

Figure 4. a. Air nozzle placement

b. Prototype components (nozzle, hose, air pump)

4. Methods

This section describes the materials, fabrication steps, installation procedure, and experimental protocol used to design and evaluate the Post-Ignition Exhaust Purge System (PIEPS). The methodology was structured to ensure
(i) Repeatability of emission measurements.
(ii) Safe integration of an auxiliary purge mechanism into the exhaust tract.
(iii) A fair comparison between baseline and post-installation performance.

4.1 Study Object and Pre-Test Engine Preparation

A high-mileage passenger vehicle was selected as the test platform to reflect real-world conditions where emission-control components commonly exhibit aging effects. Prior to baseline emission testing, standard preparatory maintenance and condition checks were performed to reduce confounding factors and to stabilize the engine's operating condition. The pre-test preparation included:

- Compression testing to verify acceptable cylinder sealing condition and to document baseline mechanical health.
- Spark plug cleaning and gap adjustment to reduce misfire tendency and ensure consistent ignition quality.
- Airflow sensor cleaning to improve intake measurement reliability and reduce mixture bias.
- General servicing including engine oil, oil filter, and air filter replacement to stabilize lubrication and airflow (Figure 5).

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CYLINDER COMPRESSION TEST RESULT

CUSTOMER :	Mr. Md Ashfaque Hossain Akand
JOB NO. :	PC20251209
VEHICLE TYPE :	TOYOTA-X COROLLA-2005
VIN/REG.NO. :	DM GA 21 1513
ENGINE :	1NZ-FE
CAPACITY :	1490cc
MILEAGE :	190308 KM
COMPRESSION TEST DONE BY :	Fahim
IGNITION & FUEL TYPE :	Coil Per Plug, Octane (RON 95)
DATE :	06-12-2025

CYLINDER NUMBER	PRESENT CONDITION	RECOMMENDED PRESSURE	REMARKS
Cyl-1	11.00 Bar	Standard 14 Bar Minimum 10 Bar	Good Condition
Cyl-2	11.50 Bar		
Cyl-3	11.75 Bar		
Cyl-4	11.00 Bar		
Cyl-5			
Cyl-6			

Note: As we know below 10 bar = Poor Condition, 10 bar to 12.5 bar = Good Condition & 12.5 bar to 14 bar = Excellent Condition (1 bar = 14.5 PSI)

Authorized Signature

Sales & Service Center: 49/AB,Tejgaon I/A,Dhaka-1208.
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Figure 5. Engine cylinder compression test.

These steps were performed to ensure that emission changes observed later could be attributed primarily to the PIEPS intervention rather than unresolved maintenance issues (Figure 6).

Figure 6. Photo showing workshop preparation/setup.

4.2 PIEPS Design Overview and Component Selection

PIEPS was developed as an auxiliary, post-shutdown purge system that remains inactive during normal engine operation. The design consists of four main elements:

1. Air injection nozzle (high-temperature resistant): installed between the upstream oxygen sensor and the catalytic converter to direct purge airflow into the catalyst inlet region.

2. Flexible heat-resistant metal hose: provides a mechanically robust connection between pump and nozzle, accommodating vibration and thermal expansion.

3. Low-voltage DC air pump: generates short-duration airflow sufficient to displace stagnant exhaust gases downstream.

4. Timer/control unit: triggers the pump only after ignition-off and terminates operation after a defined duration (7–10 s).

Component selection was guided by three constraints: (i) temperature exposure near the exhaust, (ii) retrofit feasibility using locally available parts, and (iii) minimal electrical load during operation (Figure 7).

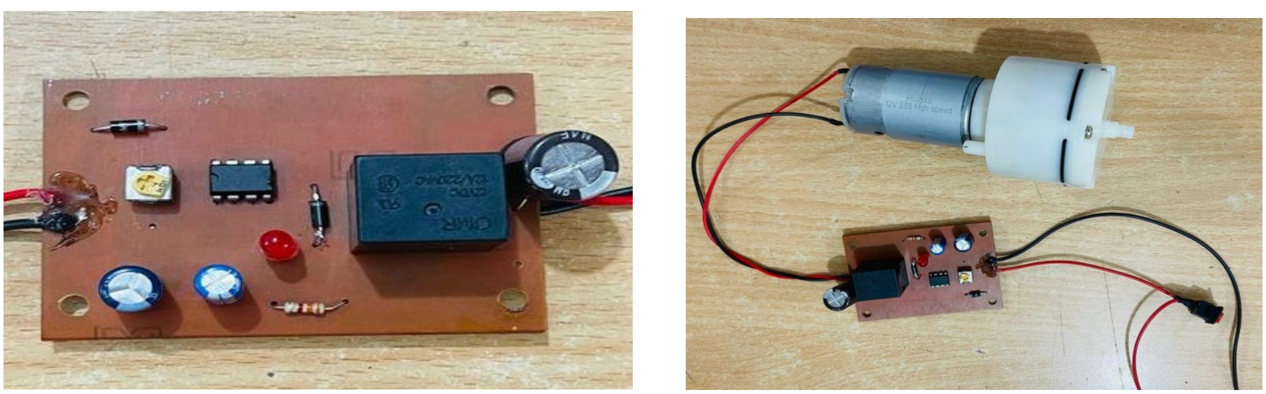


Figure 7. Photos of timer, air pump, and assembled prototype

4.3 Nozzle Fabrication and Exhaust Port Preparation

A custom nozzle was fabricated to withstand elevated exhaust temperatures and to provide secure mounting. The nozzle manufacturing process involved:

- Lathe machining of a metal rod to create an internal flow passage (hollow core).
- Cutting and finishing external threads to ensure leak-resistant fixation to the exhaust port.
- Creating a directional discharge opening to guide airflow toward the catalytic converter inlet region.

For nozzle installation, a port was created in the exhaust section located between the oxygen sensor and catalytic converter:

- The exhaust assembly was accessed and the target point was marked.
- A hole was drilled using appropriate tooling.

- The threaded nozzle was installed and tightened to ensure stable fitment.

This location was selected to avoid upstream sensor interference while maximizing purge effectiveness within the catalyst and downstream exhaust volume (Figure 8).

Figure 8. Photo of drilling between O_2 sensor and catalytic converter.

4.4 Electrical Integration and Post-Ignition Control Logic

The electrical system was integrated to ensure PIEPS operates only after engine shutdown. The control strategy used a timer relay to energize the air pump for a short, predefined duration after ignition-off. The operating logic is summarized below:

- Engine ON: PIEPS remains OFF (no airflow).
- Ignition OFF event detected: timer triggers pump.
- Purge duration: pump runs for 7–10 seconds.
- Auto stop: timer cuts power after the set time.

This timer-based approach provides consistent purge operation without requiring ECU reprogramming. The short duty cycle also limits battery load and reduces risk of overheating of auxiliary components (Figure 9).

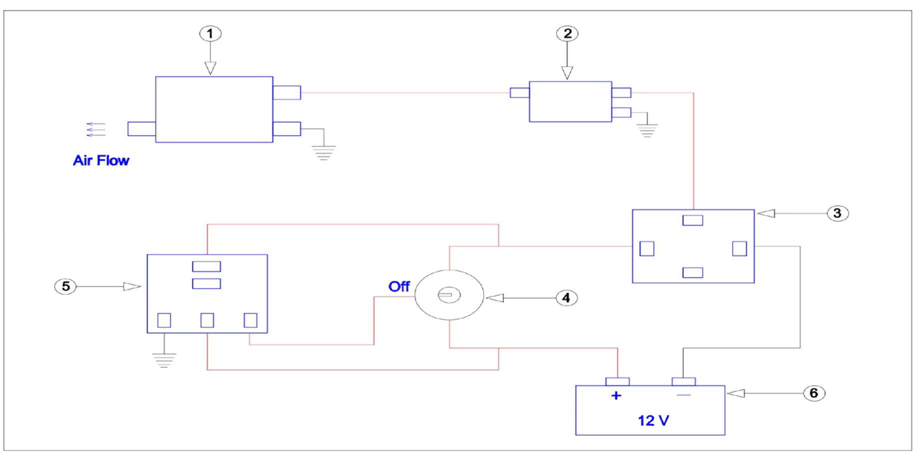


Figure 9. Wiring diagram (ignition-off trigger → timer → pump)

4.5 Test Frame Arrangement and Safety Considerations (Workshop Validation Support)

To document installation feasibility and ensure safe handling during fabrication, the exhaust system was arranged on a workshop frame for inspection, positioning, and validation of assembly fitment. Where required for frame mounting, intermediate exhaust pipe sections were adjusted and welded to accommodate the experimental setup while maintaining the flow path sequence (manifold → catalytic converter → resonator → muffler).

Safety measures included secure mounting, leak checks at the nozzle port, and routing of the hose and wiring away from direct heat and sharp edges (Figure 10).

Figure 10. Photo of the exhaust system mounted on the frame.

4.6 Emission Testing Protocol (Baseline and Post-PIEPS)

Emission testing was conducted using an engine exhaust gas analyzer under consistent workshop conditions. The protocol was designed as a before–after comparison with repeated trials across multiple days.

Baseline (Before PIEPS):

- Vehicle operated approximately 70–80 km per day for three consecutive days.
- After each driving session, emission measurements were recorded using the analyzer.

Post-installation (After PIEPS):

- PIEPS installed and verified for correct post-shutdown operation.
- Vehicle again operated approximately 70–80 km per day for three consecutive days.
- Emission measurements were repeated using the same analyzer and test procedure.

Because PIEPS functions only after shutdown, the analysis focused on conditions that are most sensitive to residual exhaust effects:

- Idle
- Idle with A/C ON

High-speed test entries produced by the service facility format were retained in the report record but were not used as primary indicators of PIEPS effectiveness.

4.7 Data Processing and Comparison Method

For each condition (Idle and A/C Idle), day-wise measurements were compiled and averaged over the three-day period for both phases:

- Mean Before PIEPS (3-day average)
- Mean After PIEPS (3-day average)

Percentage change was computed to quantify improvement:

$$\text{Reduction (\%)} = \frac{\text{Before-After}}{\text{Before}} \times 100$$

The final results are reported using (Table 1):

- Averaged values (to reduce day-to-day noise)
- Comparative tables and bar charts (to clearly visualize differences).

Table 1. Condition

Opening Condition	Engine Speed (RPM)	CO (%Vol)	HC (PPM)	CO_2 (%Vol)	O_2 (%Vol)	Lambda(λ)
Idle	727±15	0.34	237	12.17	1.64	1.115
Idle with A/C on	867±12	0.27	220	12.27	1.49	1.100

Notes:
Values represent arithmetic mean of three test cycles
HC and CO are emphasized as primary emission indicators
High-speed data are excluded from analysis as PIEPS is inactive during engine operation

Interpretation (Reviewer-friendly, later Discussion section)
Elevated HC at idle (≈237 ppm) indicates presence of unburnt hydrocarbons trapped in the exhaust system
CO values (~0.34%), although within regulatory limits, reflect incomplete oxidation under idle conditions

These baseline values establish the reference condition for evaluating PIEPS effectiveness (Table 2)

Table 2. Averaged Emission Results After PIEPS (Idle & A/C Idle)
(Based on three consecutive emission tests after PIEPS installation)

Opening Condition	Engine Speed (RPM)	CO (%Vol)	HC (PPM)	CO_2 (%Vol)	O_2 (%Vol)	Lambda(λ)
Idle	773±6	0.27	160	12.05	1.21	1.063
Idle with A/C on	895±5	0.22	148	12.08	1.14	1.054

Notes:

PIEPS was activated only after engine shutdown
High-speed data excluded from analysis as PIEPS remains inactive during operation
Results represent stabilized exhaust conditions after purge action
Table 4. Percentage Reduction in Emissions After PIEPS
(Comparison between Table 2 and Table 3 averages)

Table 3. Parameter

Parameter	Idle (%)	Idle with A/C (%)
HC Reduction	≈32.25%↓	≈32.7%↓
CO Reduction	≈20.6%↓	≈18.5%↓

Calculation basis:

$$\text{Reduction (\%)} = \frac{\text{Before-After}}{\text{Before}} \times 100$$

Bar chart description (Figure 11):

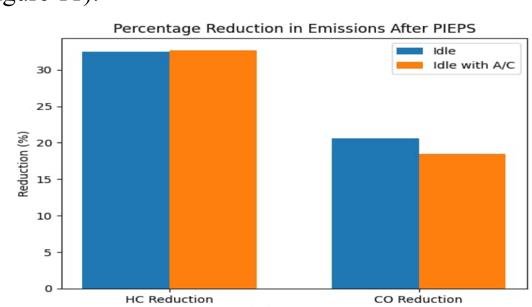


Figure 11. Reduction emission

X-axis: Operating Condition (Idle, Idle with A/C)
Y-axis: HC concentration (PPM)

Two bars per condition:
Before PIEPS (≈237, ≈220 ppm)
After PIEPS (≈160, ≈148 ppm)

5. Testing and Results

This section presents the experimental testing procedure and the corresponding results obtained before and after the installation of the Post-Ignition Exhaust Purge System (PIEPS). The objective of the testing phase was to evaluate whether post-ignition exhaust purging produces measurable improvements in emission characteristics under real-world operating conditions.

5.1 Experimental Testing Procedure

All emission tests were conducted using a calibrated engine exhaust gas analyzer under controlled workshop conditions. To ensure result reliability, the engine was brought to normal operating temperature prior to each test. Measurements were taken over three consecutive days before PIEPS installation and three consecutive days after PIEPS installation, following identical testing procedures.

The emission measurements included the following operating conditions:

- Idle condition
- Idle with air-conditioning (A/C) ON

Although high-speed emission data were recorded as part of the standard testing protocol of the service facility, these data were not considered in the analysis. PIEPS operates only after engine shutdown; therefore, its influence is reflected primarily in idle and low-load conditions during subsequent engine operation.

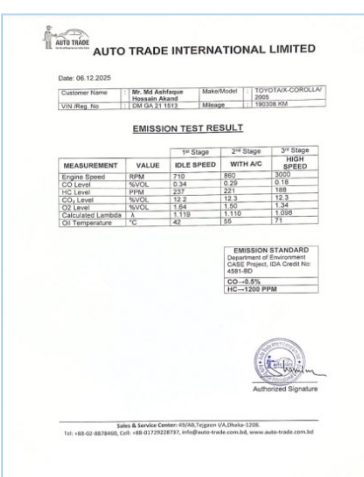
All recorded values were averaged across the three-day testing period to minimize day-to-day variation and random fluctuations.

5.2 Baseline Emission Results (Before PIEPS Installation)

Before installing PIEPS, baseline emission measurements were collected to represent the existing condition of the high-mileage engine and exhaust system. The baseline data indicate the presence of residual exhaust effects typical of aging vehicles, including elevated hydrocarbon concentration and moderate carbon monoxide levels during idle operation.

The measured baseline values showed consistent repeatability across the three testing days, confirming stable engine operation and reliable analyzer performance.

Table 4. Three-day averaged emission results before PIEPS installation (Idle and A/C Idle).



AUTO TRADE INTERNATIONAL LIMITED

Date: 06.12.2025

Customer Name	Mr. Md Ashfaque Hossain Akand	Make/Model	TOYOTA/X-COROLLA/ 2005
VIN /Reg. No	DM GA 21 1513	Mileage	190308 KM

EMISSION TEST RESULT

		1st Stage	2nd Stage	3rd Stage
MEASUREMENT	VALUE	IDLE SPEED	WITH A/C	HIGH SPEED
Engine Speed	RPM	710	860	3000
CO Level	%VOL	0.34	0.29	0.18
HC Level	PPM	237	221	188
CO_2 Level	%VOL	12.2	12.3	12.3
O2 Level	%VOL	1.64	1.50	1.34
Calculated Lambda	λ	1.119	1.110	1.098
Oil Temperature	°C	42	55	71

EMISSION STANDARD
Department of Environment CASE Project, IDA Credit No: 4581-BD
CO→0.5%
HC→1200 PPM

Authorized Signature

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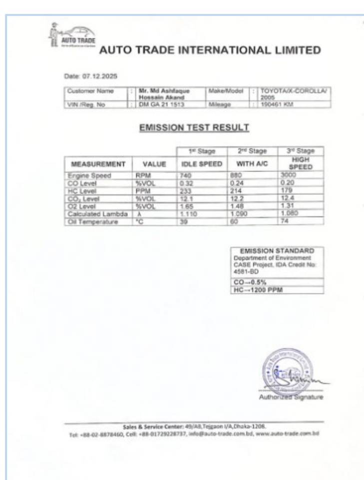

AUTO TRADE INTERNATIONAL LIMITED

Date: 07.12.2025

Customer Name	Mr. Md Ashfaque Hossain Akand	Make/Model	TOYOTA/X-COROLLA/ 2005
VIN /Reg. No	DM GA 21 1513	Mileage	190461 KM

EMISSION TEST RESULT

		1st Stage	2nd Stage	3rd Stage
MEASUREMENT	VALUE	IDLE SPEED	WITH A/C	HIGH SPEED
Engine Speed	RPM	740	880	3000
CO Level	%VOL	0.32	0.24	0.20
HC Level	PPM	233	214	179
CO_2 Level	%VOL	12.1	12.2	12.4
O2 Level	%VOL	1.65	1.48	1.31
Calculated Lambda	λ	1.110	1.090	1.080
Oil Temperature	°C	39	60	74

EMISSION STANDARD
Department of Environment CASE Project, IDA Credit No: 4581-BD
CO→0.5%
HC→1200 PPM

Authorized Signature

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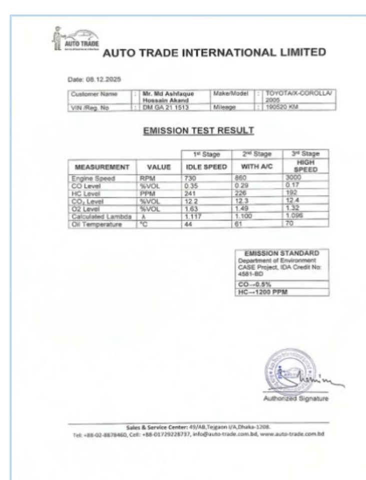

AUTO TRADE INTERNATIONAL LIMITED

Date: 08.12.2025

Customer Name	Mr. Md Ashfaque Hossain Akand	Make/Model	TOYOTA/X-COROLLA/ 2005
VIN /Reg. No	DM GA 21 1513	Mileage	190520 KM

EMISSION TEST RESULT

		1st Stage	2nd Stage	3rd Stage
MEASUREMENT	VALUE	IDLE SPEED	WITH A/C	HIGH SPEED
Engine Speed	RPM	730	860	3000
CO Level	%VOL	0.35	0.29	0.17
HC Level	PPM	241	226	192
CO_2 Level	%VOL	12.2	12.3	12.4
O2 Level	%VOL	1.63	1.49	1.32
Calculated Lambda	λ	1.117	1.100	1.096
Oil Temperature	°C	44	61	70

EMISSION STANDARD
Department of Environment CASE Project, IDA Credit No: 4581-BD
CO→0.5%
HC→1200 PPM

Authorized Signature

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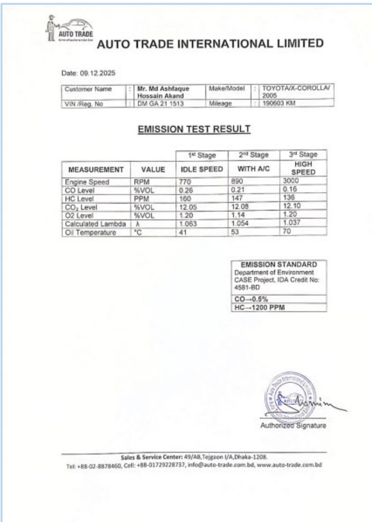
5.3 Emission Results After PIEPS Installation

Following PIEPS installation, emission tests were repeated using the same procedure and environmental conditions. The results show a clear reduction in both hydrocarbon (HC) and carbon monoxide (CO) emissions under idle and A/C-idle conditions.

The post-installation data demonstrate improved exhaust gas quality at the beginning of each test cycle, indicating that residual exhaust gases trapped after the previous shutdown had been effectively purged. Variations between testing days remained within acceptable limits, confirming consistent system operation (Table 5).

Table 5. Three-day averaged emission results after PIEPS installation (Idle and A/C Idle).



AUTO TRADE INTERNATIONAL LIMITED

Date: 09.12.2025

Customer Name	:	Mr. Md Ashfaque Hossain Akand	Make/Model	:	TOYOTA/X-COROLLA/ 2005
VIN /Reg. No	:	DM GA 21 1513	Mileage	:	190603 KM

EMISSION TEST RESULT

		1st Stage	2nd Stage	3rd Stage
MEASUREMENT	VALUE	IDLE SPEED	WITH A/C	HIGH SPEED
Engine Speed	RPM	770	890	3000
CO Level	%VOL	0.26	0.21	0.16
HC Level	PPM	160	147	136
CO_2 Level	%VOL	12.05	12.08	12.10
O2 Level	%VOL	1.20	1.14	1.20
Calculated Lambda	λ	1.063	1.054	1.037
Oil Temperature	°C	41	53	70

EMISSION STANDARD
Department of Environment
CASE Project, IDA Credit No: 4581-BD
CO→0.5%
HC→1200 PPM

Authorized Signature

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AUTO TRADE INTERNATIONAL LIMITED

Date: 11.12.2025

Customer Name	:	Mr. Md Ashfaque Hossain Akand	Make/Model	:	TOYOTA/X-COROLLA/ 2005
VIN /Reg. No	:	DM GA 21 1513	Mileage	:	190788 KM

EMISSION TEST RESULT

		1st Stage	2nd Stage	3rd Stage
MEASUREMENT	VALUE	IDLE SPEED	WITH A/C	HIGH SPEED
Engine Speed	RPM	770	895	3000
CO Level	%VOL	0.27	0.22	0.16
HC Level	PPM	159	147	135
CO_2 Level	%VOL	12.06	12.08	12.09
O2 Level	%VOL	1.21	1.13	1.10
Calculated Lambda	λ	1.061	1.052	1.035
Oil Temperature	°C	43	59	69

EMISSION STANDARD
Department of Environment
CASE Project, IDA Credit No: 4581-BD
CO→0.5%
HC→1200 PPM

Authorized Signature

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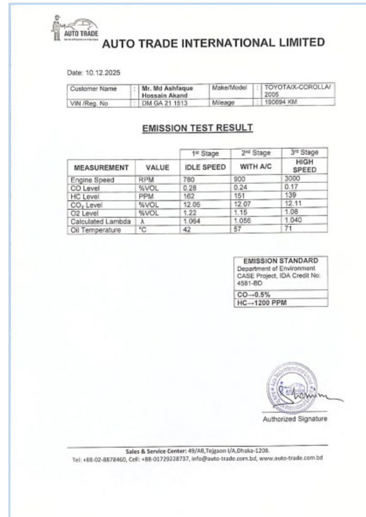

AUTO TRADE INTERNATIONAL LIMITED

Date: 10.12.2025

Customer Name	:	Mr. Md Ashfaque Hossain Akand	Make/Model	:	TOYOTA/X-COROLLA/ 2005
VIN /Reg. No	:	DM GA 21 1513	Mileage	:	190694 KM

EMISSION TEST RESULT

		1st Stage	2nd Stage	3rd Stage
MEASUREMENT	VALUE	IDLE SPEED	WITH A/C	HIGH SPEED
Engine Speed	RPM	780	900	3000
CO Level	%VOL	0.28	0.24	0.17
HC Level	PPM	162	151	139
CO_2 Level	%VOL	12.05	12.07	12.11
O2 Level	%VOL	1.22	1.15	1.08
Calculated Lambda	λ	1.064	1.056	1.040
Oil Temperature	°C	42	57	71

EMISSION STANDARD
Department of Environment
CASE Project, IDA Credit No: 4581-BD
CO→0.5%
HC→1200 PPM

Authorized Signature

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5.4 Comparative Emission Analysis

A direct comparison between pre- and post-PIEPS data reveals a significant reduction in exhaust emissions:

- Hydrocarbon (HC) concentrations decreased by approximately 30–33% under idle and A/C-idle conditions.
- Carbon monoxide (CO) levels showed a reduction of approximately 18–20%, indicating improved oxidation efficiency.

These reductions suggest that post-ignition exhaust purging helps remove unburned residues and oxygen-deficient gases that would otherwise influence the next engine start cycle.

5.5 Graphical Representation of Results

To visualize the emission improvement achieved through PIEPS, comparative bar graphs were prepared using averaged data from the testing period. The graphs clearly illustrate the reduction trend for HC and CO emissions under both operating conditions.

The graphical trends support the numerical results and demonstrate consistent emission improvement following PIEPS implementation.

5.6 Observations on System Behavior

In addition to emission reduction, several operational observations were noted during testing:

- Idle stability improved slightly after PIEPS installation.
- Oxygen sensor feedback exhibited reduced fluctuation during early idle operation.
- No abnormal noise, vibration, or electrical fault was observed during purge activation.
- Battery voltage drop during purge operation remained negligible due to the short activation duration.

These observations support the conclusion that PIEPS operates safely and consistently without adverse effects on engine performance.

Testing Result Summary

Overall, the testing results confirm that the Post-Ignition Exhaust Purge System produces measurable, repeatable improvements in exhaust emissions at idle and low load. The observed reductions in HC and CO emissions align with the system's intended function—namely, the removal of residual exhaust gases accumulated during the previous engine shutdown.

6. Conclusion

This study presented the design, development, and experimental evaluation of a Post-Ignition Exhaust Purge System (PIEPS) to address an often-overlooked phase of exhaust emission control—the period immediately after engine shutdown. Unlike conventional emission-control strategies that operate only during engine running, PIEPS targets the post-ignition window to actively remove residual exhaust gases trapped within the exhaust manifold and catalytic converter.

The experimental results from a high-mileage gasoline engine demonstrate that post-ignition exhaust purging produces measurable reductions in emissions at idle and low load. Significant reductions in hydrocarbon (HC) and carbon monoxide (CO) emissions were observed after PIEPS installation, indicating that removing stagnant, oxygen-deficient exhaust gases enhances exhaust cleanliness and improves the readiness of the catalytic converter during subsequent engine operation. The observed stabilization of oxygen sensor feedback further suggests improved combustion control at early idle stages.

Beyond emission reduction, the findings highlight additional functional benefits of the proposed system. By limiting carbon deposition and moisture retention within the exhaust system, PIEPS helps maintain lower exhaust back pressure and preserve the effective internal volume of the exhaust tract. These effects are particularly relevant for high-mileage vehicles, where aging emission-control components are more susceptible to degradation and performance loss.

The proposed system was intentionally designed as a low-cost, mechanically simple, and retrofit-friendly solution. It requires no modification of the engine control unit, fuel delivery system, or combustion parameters, allowing integration with existing exhaust architectures without disrupting normal vehicle operation. The short-duration, timer-controlled purge cycle ensures minimal electrical power consumption while maintaining operational reliability.

While the present study focused on short-term experimental validation, the results clearly demonstrate the feasibility and practical value of post-ignition exhaust purging as a supplementary emission-control approach. The findings suggest that PIEPS can serve as an effective tool for improving emission stability and exhaust-system longevity, particularly in regions with aging vehicle fleets and limited access to advanced emission-control technologies.

In conclusion, the Post-Ignition Exhaust Purge System introduces a new perspective in exhaust emission management by extending control beyond the combustion phase into the post-shutdown period. The system’s simplicity, effectiveness, and adaptability position it as a promising candidate for further development, long-term validation, and potential real-world application.

7. Future Work

While the present study demonstrates the feasibility and effectiveness of the Post-Ignition Exhaust Purge System (PIEPS) through experimental validation on a high-mileage gasoline engine, several opportunities remain for further investigation and system enhancement. Future work can expand both the technical depth and practical applicability of the proposed concept.

First, long-term durability and life-cycle testing should be conducted to evaluate PIEPS's sustained performance over extended vehicle use. Continuous operation over thousands of ignition cycles would allow assessment of air-pump reliability, nozzle integrity under thermal cycling, sealing durability, and overall system robustness in real driving environments.

Second, adaptive control strategies may be explored to replace the fixed timer-based purge duration. Integration with engine temperature signals, exhaust temperature sensors, or oxygen sensor feedback could enable dynamic adjustment of purge duration and airflow intensity, improving efficiency while minimizing electrical power consumption.

Third, future studies should evaluate PIEPS performance across different engine types and applications, including diesel engines, hybrid vehicles with frequent start–stop operation, and stationary engines such as generators. Such investigations would help determine scalability and adaptability across diverse exhaust architectures.

Fourth, computational fluid dynamics (CFD) analysis may be employed to optimize nozzle geometry, purge airflow direction, and velocity distribution within the exhaust system. CFD-based optimization could enhance scavenging efficiency and reduce unnecessary airflow losses.

Fifth, extended emission analysis, including NOx and particulate matter (PM) measurements, would provide a more comprehensive understanding of PIEPS' impact on overall emission behavior. This would be particularly relevant for diesel and lean-burn engines.

Finally, future work may focus on system miniaturization and integration to improve packaging flexibility and facilitate large-scale implementation. Development of a compact, modular PIEPS unit could support commercialization and practical deployment in regions with aging vehicle fleets.

Overall, these future research directions highlight the potential of PIEPS as a foundation for further innovation in post-ignition exhaust management and emission-control strategies.

Acknowledgements

We would like to express my sincere gratitude to Prof. Dr. Md. Mizanur Rahman (CEng, Professor & Director, IQAC), Mr. Farhan Mahbub (Associate Professor), Mr. Mustafizur Rahman (Assistant Professor), and Mr. Md. Hasibur Rahman (Teaching Assistant), Department of Mechatronics Engineering, for their continuous guidance, constructive feedback, and invaluable support throughout the course of this research.

We are also grateful to all the respected faculty members and the management of the World University of Bangladesh (WUB) for providing academic support, inspiration, and a learning environment that significantly contributed to the successful completion of this study.

Funding Statement

This project did not receive any external financial support; it was fully funded by the authors.

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Biographies

Md. Ashfaque Hossain Akand is currently pursuing a Bachelor of Science in Automobile Engineering at the World University of Bangladesh (5th semester). Prior to this, he completed a four-year Diploma in Engineering (Automobile) and has served in the automotive sector for nearly seventeen years. His professional experience includes diagnostics, thermal management systems, emission reduction engineering, and the development of aftermarket automotive technologies. His research interests include exhaust emission reduction, engine performance optimization, thermo-fluid systems, hybrid battery thermal behavior, cold-chain vehicle temperature management, and cost-effective retrofit solutions for emission improvement in older vehicles commonly used in South Asia.

Akram Hossain is a 5th semester undergraduate student in the Bachelor of Science program in Automobile Engineering at the World University of Bangladesh. Alongside his academic coursework, he has remained actively involved in voluntary initiatives through the WUB Automobile Club and the AL-Falah Helpline of DPI. He holds a four-year Diploma in Automobile Engineering and has accumulated nearly five years of hands-on professional experience in the automotive field. He is presently employed at Transcom Distribution Company Limited, where he works with vehicle diagnostics and the development of aftermarket automotive solutions. His academic and professional interests include engine performance enhancement and advanced thermal management systems, particularly for refrigerated and cold-chain transport vehicles. He is currently contributing to several ongoing projects focused on improving temperature regulation mechanisms in cold-chain logistics operations across South Asia.

Md. Shafi Ullah is a 5th semester student in the Bachelor of Science in Automobile Engineering program at the World University of Bangladesh. He previously completed a Diploma in Engineering under the Power Department of Chittagong Polytechnic Institute and completed a six-month specialized course in Automobile Technology from BKTTC. He is currently employed as a Service Engineer at Abul Khair Group, where he is acquiring practical experience in automotive maintenance. His responsibilities include diagnosing technical issues, performing maintenance operations, and providing support for heavy industrial and automotive equipment. He is deeply motivated to apply engineering principles to real-world challenges and is committed to strengthening his expertise in service, repair, and industrial maintenance practices. He aims to build a strong professional career in the service and maintenance sector and contribute to the advancement of Bangladesh's industrial landscape through continuous learning and dedicated technical service.

Ataur Rahman is pursuing a Bachelor of Science in Automobile Engineering at the World University of Bangladesh and is currently in his 5th semester. He has remained actively involved in various automotive extracurricular activities, serving as a member of the WUB Automobile Club and previously as an Advisor to the UIST Automobile Club. He also serves as the Member Secretary of the Al-Falah Helpline of DPI. Professionally, he works as an Instructor in the Department of Automobile at the As-Sunnah Skill Development Institute. Alongside his academic responsibilities, he completed a three-month training program in PLC and Industrial Automation, gaining practical experience with industry-standard automation software and control systems. His academic interests include internal combustion (IC) engines, vehicle diagnostics, sustainable mobility solutions, practical motorcycle servicing and performance tuning. Driven by a strong passion for both theoretical knowledge and hands-on application, he aspires to contribute significantly to innovation, technical skill development, and research in the evolving automotive and automation industries.